労災疾病臨床研究事業費補助金

脊椎インストゥルメンテーション患者に
アフターケアは本当に必要か？
全国労災病院と産業医科大学を含む多施設大規模調査

平成２７年度～２９年度　総合研究報告書

研究代表者　須田　浩太

平成３０年３月

Ⅰ．総合研究報告

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独立行政法人労働者健康安全機構
北海道せき損センター　須田　浩太

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Ⅰ. 総合研究報告

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平成２９年度総括研究報告書

脊椎インストゥルメンテーション患者にアフターケアは本当に必要か？
全国労災病院と産業医科大学を含む多施設大規模調査

研究代表者　須田浩太　　独立行政法人労働者健康安全機構
北海道せき損センター

研究要旨
脊椎インストゥルメンテーションに対するアフターケアの「要否」あるいは「適応基準」を定めるために本研究を計画した。研究の格子は以下の通りである。1）労災患者における脊椎インストゥルメンテーション症例のデータ集積：全労災病院（全国に３４）と産業医科大学の過去５年を目処に労災患者における脊椎インストゥルメンテーション症例のデータを集積する。2）労災患者以外の脊椎インストゥルメンテーション症例のデータ集積：労災患者以外の脊椎インストゥルメンテーション症例のデータを集積する。3）データの解析：集積したデータを基にアフターケアの要否や適応基準を検討する。脊椎インストゥルメンテーション技術の大幅な進歩に伴い大がかりな脊椎再建術が可能となった．治療成績は向上したものの、隣接椎間障害，隣接椎体骨折，脊椎アライメント異常など従来では想定外であった長期合併症も明らかとなった．脊椎インストゥルメンテーションに起因する後遺症は稀有だが、脊椎アライメント異常が新たに生じた場合はADL障害を生じるためアフターケアの可能性がある。ただし，大幅な脊椎アライメント異常をきたす症例は極めて少なく対象患者は些少と考える。

〈研究分担者〉
（独）労働者健康安全機構
北海道せき損センター
病院長　三浪　明男

（独）労働者健康安全機構
北海道せき損センター
部長　　松本　聡子

（独）労働者健康安全機構
北海道せき損センター
部長　　小松　幹

（独）労働者健康安全機構
総合せき損センター
病院長　芝　啓一郎

（独）労働者健康安全機構
総合せき損センター
副院長　植田　尊善

（独）労働者健康安全機構
総合せき損センター
部長　　前田　健

（独）労働者健康安全機構
総合せき損センター
部長　　坂井　宏旭

（独）労働者健康安全機構
吉備高原リハビリテーションセンター
病院長　徳弘　昭博

（独）労働者健康安全機構
吉備高原リハビリテーションセンター
副院長　古澤　一成

産業医科大学整形外科学教室
教授　　酒井　昭典

産業医科大学整形外科学教室
准教授　中村　英一郎

北海道大学大学院医学研究科
機能再生医学講座整形外科学分野
教授　　岩崎　倫政

北海道大学大学院医学研究科
機能再生医学講座整形外科学分野
准教授　高畑　雅彦

北海道大学大学院医学研究科
社会医学講座医学統計学分野
准教授　伊藤　陽一

独協医科大学医学部医学科
整形外科学
主任教授　種市　洋

独協医科大学医学部医学科
整形外科学
准教授　稲見　聡

独協医科大学医学部医学科
整形外科学
講師　　森平　泰

A. 研究目的

アフターケアは業務災害又は通勤災害による傷病の症状固定後における後遺症状・付随疾病に対する予防と保健措置を提供し労災患者の社会復帰を促進するための制度であり、労働能力を維持し、円滑な社会生活を営ませることを目的としている。対象疾患は限定されており①せき髄損傷、②頭頸部外傷症候群等(頭頸部外傷症候群、頸肩腕障害、腰痛)、③尿路系障害，④慢性肝炎、⑤白内障等の眼疾患、⑥振動障害、⑦大腿骨頸部骨折及び股関節脱臼・脱臼骨折、⑧人工関節・人工骨頭置換、⑨慢性化膿性骨髄炎、⑩虚血性心疾患等、⑪尿路系腫瘍、⑫脳の器質性障害、⑬外傷による末梢神経損傷、⑭熱傷、⑮サリン中毒、⑯精神障害、⑰循環器障害、⑱呼吸機能障害、⑲消化器障害、⑳炭鉱災害による一酸化炭素中毒の 20 疾病が該当する。中でも①せき髄損傷、②頭頸部外傷症候群等（頭頸部外傷症候群、頸肩腕障害、腰痛）では脊椎インストゥルメンテーションが用いられることが増えた。近年は脊椎インストゥルメンテーション技術の大幅な進歩に伴い、従来は不可能であった大規模な脊椎再建術が平常的に行われるようになった。治療成績は飛躍的に向上し、後遺症が減ったものの、中には脊椎インストゥルメンテーションに起因する症状も少なくない。脊椎インストゥルメンテーション症例に関して、1）症状固定後に如何なる症状が生じえるか？2）如何なる措置がどの程度の期間必要か？3）どの程度の症例数が見込まれるのか？を明らかにしアフターケアの要否を検討する必要がある。一方で限りある財源の有効活用、効率的分配は労災補償行政において重要課題である。脊椎インストゥルメンテーションにおいてアフターケアが必要な症例は極め

て少ないと予想するが皆無ではない。どの様な症例が該当するのか、どの程度の頻度で存在するのか、アフターケアの適応基準を定め，その際に生じる「医療コスト」を予測することが労災補償行政の上で重要である。本研究ではアフターケアの要否と基準を検討することを目的とした。

B.研究計画、方法

（1）労災患者における脊椎インストゥルメンテーション症例のデータ集積

北海道せき損センター、総合せき損センター、吉備高原医療リハビリテーションセンター、産業医科大学をコアとして全労災病院（全国に３４）と産業医科大学の 2009 年 1 月からの 5 年間に全国労災病院にて入院加療を行った労災保険患者 18,371 名、総手術 16093 件、うち脊椎インストゥルメンテーション手術 348 件を対象として疾患、年齢、性別、術前・術後レントゲン画像、固定範囲、術後合併症、治療内容、診療報酬内訳、アフターケアの有無を調査した。対象施設は以下の 35 施設。

1.北海道中央労災病院、2.北海道せき損センター、3.釧路労災病院、4.青森労災病院、5.東北労災病院、6.秋田労災病院、7.福島労災病院、8.鹿島労災病院、9.千葉労災病院、10.東京労災病院、11.関東労災病院、12.横浜労災病院、13.燕労災病院、14.新潟労災病院、15.富山労災病院、16.浜松労災病院、17.中部労災病院、18.旭労災病院、19.大阪労災病院、20.関西労災病院、21.神戸労災病院、22.和歌山労災病院、23.山陰労災病院、24.岡山労災病院、25.中国労災病院、26.山口労災病院、27.香川労災病院、28.愛媛労災病院、29.九州労災病院、30.九州労災病院門司メディカルセンター、31.長崎労災病院、32.熊本労災病院、33.吉備高原医療リハビリテーションセンター、34.総合せき損センター、35.産業医科大学

協力医師

油川修一、池田天史、岡崎裕司、奥山幸一郎、加治浩三、川添泰弘、日下部　隆、楠瀬浩一、武田宏史、千葉光穂、信田進吾、馬場秀夫、放生憲博、山縣正庸、渡邉健一、舘田聡、伊藤圭吾、岩崎幹希、岡部　聡、笠原孝一、河本正昭、菊地　廉、傳田博司、花林昭裕、平野典和、三上容司、三好光太、湯川泰紹、安藤宗治、大園健二、大西英生、大和田哲雄、岡野　徹、城戸研二、木戸健司、楠城誉朗、國司善彦、佐々木俊二、笹重善朗、壺内貢、富永俊克、生熊久敬、前原　孝、原田良昭

（2）労災患者以外の脊椎インストゥルメンテーション症例のデータ集積

2009 年 1 月からの 5 年間に産業医科大学、北海道大学、獨協医科大学にて施行された脊椎インストゥルメンテーション多椎間固定例を対象に、疾患、年齢、性別、固定範囲、固定アライメント、合併症、隣接椎間変性や骨折、術後の加療要否を調査した。

（1）、（2）で集積したデータを基に，労災患者での脊椎固定頻度、手術内容、治癒期間、治癒後の加療要否などを解析した。

C.研究結果

1. 労災患者分析

アンケート期間中に労災による脊椎・脊髄損傷患者を受け入れ脊椎インストゥルメンテーション手術を行った病院は 31 施設であった。患者数:281 例（男性 264 例、女性 17 例　男女比＝15.5：1）。入院時平均年齢:48.5 歳。平均入院期間:81.2 日。受傷部位：頚椎＝93 例、胸椎＝75 例、腰椎＝108 例、不明＝6 例。入院時 Frankel 分類：A=48 例、B=15 例、C=37 例、D＝64 例、E=107 例、不明＝10 例。調査時麻痺残存の有無：残存あり＝143 例、残存なし＝133 例、不明＝5 例。退院後外来通院患者数：104 例、アフターケア受給者数：73 例であった。頚椎損傷 75 例中、骨傷あり＝69 例、骨傷なし＝6 例、胸腰椎損傷 175 例中、骨傷あり＝156 例、骨傷なし＝19 例であった。入院時

Frankel A＝48 例中、麻痺残存あり＝44 例（91.6%）、残存なし＝4 例、入院時 Frankel B＝15 例中、麻痺残存あり＝15 例（100%）、残存なし＝0 例、入院時 Frankel C＝37 例中、麻痺残存あり＝35 例（94.5%）、残存なし＝2 例、入院時 Frankel D＝64 例中、麻痺残存あり＝44 例（68.7%）、残存なし＝20 例、入院時 Frankel E＝107 例中、麻痺残存あり＝0 例（0%）、残存なし＝107 例であった。10 代の受傷患者 3 例中、麻痺残存あり＝2 例、残存なし 1 例、20 代の受傷患者 39 例中、麻痺残存あり＝16 例、残存なし 23 例、30 代の受傷患者 36 例中、麻痺残存あり＝18 例、残存なし 18 例、40 代の受傷患者 52 例中、麻痺残存あり＝32 例、残存なし 20 例、50 代の受傷患者 64 例中、麻痺残存あり＝29 例、残存なし 35 例、60 代の受傷患者 65 例中、麻痺残存あり＝35 例、残存なし 30 例、70 代の受傷患者 14 例中、麻痺残存あり＝10 例、残存なし 4 例、80 代の受傷患者 1 例中、麻痺残存あり＝1 例、残存なし 0 例であった．労災事故による脊椎インストゥルメンテーション手術を行った症例の特徴として、壮青年、男性、胸腰椎レベルの損傷症例が多いことが明らかとなった。また，入院時麻痺を伴う脊椎損傷症例では高率に麻痺が残存していた。

2.医療費

入院医療費の総合計の中央値は 4010144.5 円、平均値は 5230406 円と乖離があり、少数の患者に高額な入院医療費がかかっていた．麻痺有の入院医療費の総合計の中央値は 5090567 円であり、麻痺無の入院医療費の総合計の中央値は 3232127 円であった。Wilcoxon の順位和検定の P 値は 0.0001 未満であった。通院の有無では、通院有が 104 例(37.1%)、無が 176 例(62.9%)であった。外来医療費の総合計の中央値は 69607 円、平均値は 149989 円であり一部の外れ値によって、中央値と平均値の乖離が生じていることが分かった。ケア医療費の総合計の中央値は 35696 円、平均値は 89755 円と乖離があり、少数の対象者に高額なケア医療費がかかっていた。麻痺有の外来医療費の総合計の中央値は 82480 円であり、麻痺無の入院医療費の総合計の中央値は 35182 円であった。麻痺有のケア医療費の総合計の中央値は 34006 円であり、麻痺無のケア医療費の総合計の中央値は 58386.5 円であった。入院医療費、外来医療費、ケア医療費ともに、特定の少数の患者に高額な医療費がかかっていること分かったが、外来医療費およびケア医療費では、欠測が多く妥当な結果が得られていない可能性がある。入院医療費は麻痺有の方が無と比較して有意に高い傾向が認められたが、外来医療費およびケア医療費では、差は認められなかった。これは、外来医療費とケア医療費の症例数が少なく、検出力が低くなっている可能性も考えられる。入院医療費は頚椎，胸椎と比較して、腰椎が低い傾向が認められた。外来医療費については、症例数が少ないものの、胸椎と腰椎が頚椎と比較して有意に高い傾向が認められた。ケア医療費も同様に胸椎と腰椎が頚椎と比較して高い傾向が認められるものの有意な差ではなかった。

3.労災患者以外の隣接椎間障害

対象患者の年齢は平均 65.8 才、女性 103 名、男性 87 名であった。外傷例が 17 例、残りは加齢変性を基盤とした変性疾患であった。手術時間は平均 349 分、出血量は 622cc でああった。固定は平均 2.6 椎間(1-13 椎間)に行われていた。平均経過観察期間 4.5 年（最低 2 年以上）の経過観察期間で固定上位隣接椎間板変性が進行したと判断されたのは 77/190 例（40.5%）であり、上記の因子のうち固定上位隣接椎間板変性に関与したのは手術時間(p=0.006)と 2 椎間以上の floating fusion (p=0.0045) であった。一方、固定下位隣接椎間板変性の進行は 67/190 例でみられたが、34/190 例が腰仙椎部の固定で下位に椎間板がない非該当例であった。そのため，実際には 67/156 例（42.9%）で固定下位隣接椎間板の変性が進行したと判断さ

れた。腰仙椎部固定を除く 154 例中上下固定隣接椎間板変性がともに進行を判断されたのは45/156例（28.8%）であった。固定下位隣接椎間板変性進行に関与する因子は外傷(p=0.0486)，手術時間(p=0089)，2 椎間以上の floating fusion(P-0.0493)および術前前弯角(p=0.0162)であった。最終経過観察時になんらかの治療を要していた患者は75/190 例（39.5%）であり、その理由は神経障害が 35 例、上下肢痛が 40 例、体幹痛が 50 例であった。なんらかの治療を要していた 75 例のうち 16 例は固定上位隣接椎間板のみ変性進行があり、8 例は固定下位隣接椎間板のみ変性が進行、25 例は固定の上位、下位ともに椎間板変性進行があった。固定上位隣接椎間板変性のあった 77 例のうち治療を継続してうけていたのは 41 例（53.2%）であり、固定上位隣接椎間板変性と最終経過観察時の治療の要否については有意な相関を認めた（p=0.0049)。一方、固定下位隣接椎間板変性のあった67例のうち34例(50.7%)が最終経過観察時にも治療を受けており、固定下位隣接椎間板変性と最終経過観察時の治療の要否についても有意な相関を認めた(p=0.011)。しかし、治療のほとんどは投薬加療や理学療法などであり、固定隣接椎間障害（骨折を除く）で手術を要した患者は全体で 2 例のみであった。

4.隣接椎体骨折

対象者は、男性 87 名、女性 103 名の計 190 名で、平均年齢は 65.8 歳であった。そのうち骨脆弱性の圧迫骨折を含む外傷が 35 名であった。固定椎間数は 1～13 椎間で、平均 3 椎間、そのうち 1 椎間固定が 75 例、2 椎間固定が 46 例、3 椎間以上の固定例が 69 例であった。頚椎例は 11 例、胸椎～L 2 までの範囲内での固定例は 43 例、L 3 以下が 136 例であった。腰椎固定例で、固定最下端が L 5 であり、L5/S を固定しなかった Floating Fusion 例は 74 例であった。ついで隣接椎体骨折をアウトカムとしてこれらの因子との関連を検討すると、固定上位の隣接椎体骨折に関連する因子はなかったが、固定下位の隣接椎体骨折に関連する因子は、年齢(P＜0.0097)、圧迫骨折を含む外傷(P＜0.031)、固定部位が、胸椎～L 2 (P＜0.014)と L 3 以下(P＜0.044)である場合に有意差が出た。すなわち、高齢であること、圧迫骨折を含む外傷、胸椎～L 2 までの固定と L 3 以下の固定である場合に下位隣接椎体骨折が起きやすいことが明らかとなった。ついで多変量解析を行ったが、上位、下位ともに有意な因子は抽出できなかった。一方、アウトカム間に相関があるか否かサブセット解析を行ったところ、下位隣接椎体骨折とその後の治療が必要であることに有意な相関が見られた。

5.アライメント

成人脊柱変形を有する患者に対する多椎間脊椎インストゥルメンテーション手術後 2 年以上経過した 48 例（年齢 60.7±9.7 歳）を対象とした。最終観察時の立位全脊柱 X 線像から、脊柱骨盤パラメータとして PI、LL、PI-LL、胸椎後弯 (TK)、胸腰椎後弯(TLK)、Pelvic tilt (PT)、Sagittal vertical axis (SVA)、側弯 Cobb 角を計測した。また、最終観察時の臨床成績を患者立脚型評価法である Oswestry disability index (ODI)にて評価した。最終観察時 ODI の 75 パーセンタイル（ODI=22%）以下を QOL 良好と定義し、QOL 良好群において PI と PI-LL の関係を回帰分析で解析し、矯正手術で目指すべき理想的な PI-LL の値を求める予測式を算出した。最終観察時の脊柱変形パラメータは、PI: 49.7±11.4°、LL: 38.6±11.0°、PI-LL: 11.0±12.6°、TK: 30.0±13.9°、TLK: 9.2±7.5°、PT: 24.9±9.8°、SVA: 36.6±44.6mm、側弯 Cobb 角: 13.3±10.2°であった。最終観察時の ODI は 14.4±9.9 (0～35.6)%であった。次に、最終観察時 ODI の 75 パーセンタイル（ODI=22%）以下の QOL 良好群(n=36)において PI と PI-LL の関係を回帰分析で解析すると、PI-LL＝0.41PI-11.12 (r＝0.45, p＝0.0059)の式が導かれた。多椎間脊椎

インストゥルメンテーション術後の QOL が良好な患者においては、脊柱変形矯正の指標である PI-LL の値は一定ではなく、患者固有の骨盤形態から求められる PI の大きさで変化することが判明した.

D.考察

アフターケアの要否

社会復帰促進等事業としてのアフターケア実施要領（平成 19 年 4 月 23 日付け基発第 0423002 号、最終改正　平成 28 年 3 月 30 日付け基発 0330 第 5 号）によれば業務災害又は通勤災害により、せき髄損傷等の傷病にり患した者にあっては、症状固定後においても後遺症状に動揺をきたす場合が見られること、後遺障害に付随する疾病を発症させるおそれがあることにかんがみ、必要に応じてアフターケアとして予防その他の保健上の措置を講じ、当該労働者の労働能力を維持し、円滑な社会生活を営ませるものとする、と定められている.

脊椎インストゥルメンテーションは脊椎固定術を目的としており、骨癒合が完成した時点で治癒と判断する。単椎間固定であれば後遺症を残すことは極めて少ない。隣接椎間障害は加齢による変性変化の影響が大きく、隣接椎体骨折は骨粗鬆症の影響を無視できない、これら全てを脊椎インストゥルメンテーションに起因すると判断するのは無理がある。調査結果からもアフターケアを必要とする病態は脊椎インストゥルメンテーションに起因するものではなく、神経麻痺の後遺症や付随する合併症と目された。一方で脊椎アライメント異常は状況が全く異なることも明らかとなった。脊椎アライメントにおいて PI-LL = 0.41PI-11.12 ($r = 0.45$, $p = 0.0059$)を大きく逸脱するような姿勢異常が傷病あるいは脊椎インストゥルメンテーションによって新たに発生した場合にはアフターケアを要する病態と考える。

アフターケア適応基準

筆者の考えるアフターケア適応基準案は小病あるいは脊椎インストゥルメンテーションにより新たなアライメント異常を生じ、ADL 障害を来した症例と考える。明らかなアライメント異常は 30 度以上の新規変化と暫定するが、これに関するエビデンスは今後の課題とする。一方で 30 度以上のアライメント異常を新たに生じる症例は稀有であり、この基準によってアフターケアの対象患者が急増することは予想されない。日本国内における脊椎インストゥルメンテーション手術は年間 6 万件と目されている。そのうち、麻痺のない労災患者を 2%と仮定すると年間症例数は 1200 例。アフターケアにかかる費用は当院平均で年間 30 万円なので、全例を 20 年間アフターケアとすれば 72 億円を要す。しかし、アライメント異常を来した症例は本調査でも該当例がなく頻度的には 1%に満たない可能性が高い。すなわち、上記基準を基に脊椎インストゥルメンテーションによるアフターケアを新設しても、新たな労災補償導入は 1 億円に満たないと想像する。

F.健康危険情報

該当なし

G.研究発表

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2.学会発表

データ集積および解析後に予定

H.知的財産権の出願・登録状況（予定を含む）

1.特許取得

なし

2.実用新案登録

なし

3.その他

Ⅱ．研究成果の刊行に関する一覧表

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Spine

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DIAGNOSTICS

Abnormal Findings on Magnetic Resonance Images of the Cervical Spines in 1211 Asymptomatic Subjects

Hiroaki Nakashima, MD,* Yasutsugu Yukawa, MD,† Kota Suda, MD,‡ Masatsune Yamagata, MD,§ Takayoshi Ueta, MD,¶ and Fumihiko Kato, MD†

Study Design. Cross-sectional study.

Objective. The purpose of this study was to determine the prevalence and distribution of abnormal findings on cervical spine magnetic resonance image (MRI).

Summary of Background Data. Neurological symptoms and abnormal findings on MR images are keys to diagnose the spinal diseases. To determine the significance of MRI abnormalities, we must take into account the (1) frequency and (2) spectrum of structural abnormalities, which may be asymptomatic. However, no large-scale study has documented abnormal findings of the cervical spine on MR image in asymptomatic subjects.

Methods. MR images were analyzed for the anteroposterior spinal cord diameter, disc bulging diameter, and axial cross-sectional area of the spinal cord in 1211 healthy volunteers. The age of healthy volunteers prospectively enrolled in this study ranged from 20 to 70 years, with approximately 100 individuals per decade, per sex. These data were used to determine the spectrum and degree of disc bulging, spinal cord compression (SCC), and increased signal intensity changes in the spinal cord.

Results. Most subjects presented with disc bulging (87.6%), which significantly increased with age in terms of frequency, severity, and number of levels. Even most subjects in their 20s had bulging discs, with 73.3% and 78.0% of males and females, respectively. In contrast, few asymptomatic subjects were diagnosed with SCC (5.3%) or increased signal intensity (2.3%). These numbers increased with age, particularly after age 50 years. SCC mainly involved 1 level (58%) or 2 levels (38%), and predominantly occurred at C5–C6 (41%) and C6–C7 (27%).

Conclusion. Disc bulging was frequently observed in asymptomatic subjects, even including those in their 20s. The number of patients with minor disc bulging increased from age 20 to 50 years. In contrast, the frequency of SCC and increased signal intensity increased after age 50 years, and this was accompanied by increased severity of disc bulging.

Key words: magnetic resonance image (MRI), abnormal findings, asymptomatic, cervical, disc degeneration, disc bulging, spinal cord compression, increased signal intensity, cervical myelopathy, aging, cross-sectional study.

Level of Evidence: 2

Spine 2015;40:392–398

Magnetic resonance image (MRI) is a useful tool for the diagnosis of cervical spine disorders. Surgeons plan spinal surgical procedures based on neurological symptoms and abnormal MRI findings. However, there is an ongoing debate on the validity of abnormal MRI findings to make such decisions because they are also frequently reported in asymptomatic subjects.[1–9] The relevance of abnormalities on MR image depends on the frequency and spectrum of asymptomatic structural abnormalities.

To our current knowledge, most of the previous studies relating to asymptomatic abnormal findings on cervical spine MR image were limited to small cohort studies[1–8] and the population were not equally distributed in each decade.[1–9] Moreover, few studies investigated abnormal findings in the spinal cord,[1,5,7,9] whereas majority of the studies reported on disc degeneration.[1–7] Finally, there are little data available on the frequency or severity of asymptomatic cervical spinal canal stenosis, or increased signal intensity (ISI) changes,[9,10] which is the representative sign on MR image for cervical compressive myelopathy.[11]

From the *Department of Orthopedic Surgery, Nagoya University Graduate School of Medicine, Aichi, Japan; †Department of Orthopedic Surgery, Chubu Rosai Hospital, Chubu, Japan; ‡Department of Orthopedic Surgery, Hokkaido Chuo Rosai Hospital Sekison Center, Hokkaido, Japan; §Department of Orthopedic Surgery, Chiba Rosai Hospital, Chiba, Japan; and ¶Department of Orthopedic Surgery, Spinal Injuries Center, Fukuoka, Japan.

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Address correspondence and reprint requests to Hiroaki Nakashima, MD, Department of Orthopedic Surgery, Nagoya University Graduate School of Medicine, 65 Tsurumai, Shouwa-ku, Nagoya, Aichi 466-8560, Japan; E-mail: hirospine@gmail.com

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In cervical compressive myelopathy, static and dynamic factors are the main contributing factors of cervical spinal cord compression (SCC).[12,13] The static factors are the structural spondylotic changes causing canal stenosis and subsequent compression.[12,13] Disc degeneration is suspected as the initiating event of these spondylotic changes that might result in SCC.[12,13] However, there are no data available on the relationship between disc degeneration and SCC.

The purpose of this study was to determine the frequency and severity of abnormal findings on cervical spine MR image in a large cohort of asymptomatic subjects, namely disc bulging, SCC, and ISI changes, and investigate the spatial relationship between disc bulging and SCC.

MATERIALS AND METHODS

A total of 1230 healthy volunteers were examined using cervical spine MR image between February 2006 and February 2008. Subjects recruited were between 20 and 79 years. We recruited the patients *via* newspaper advertisements and posters in facilities having some sort of relationship with our hospital. Thus, the majority of subjects were not patients at our hospital but healthy residents of the area. The hospital where this study was performed is in one of the biggest cities, Nagoya in Japan, and the majority of the subjects lived within its city limits. The exclusion criteria included a history of brain or spinal surgery, comorbid neurological disease (*e.g.*, cerebral infarction or neuropathy), symptoms related to sensory or motor disorders (numbness, clumsiness, motor weakness, or gait disturbances), or severe neck pain. Pregnant females, and individuals who received workmen's compensation, or presented with symptoms after a motor vehicle accident were also excluded. Subjects with other comorbidities (smoking, diabetes, hypertension, and others) were included in this study. This study was approved by the institutional review board, and each patient signed a written consent form.

All participants underwent imaging analysis and clinical examination by 2 spinal surgeons (F.K. and K.S.). The MRI data from 1211 subjects were included in the analysis, after excluding those with measurement difficulties resulting from artifacts, such as motion or metals. MRIs were performed with a 1.5-T superconductive magnet (Signa Horizon Excite HD version 12; GE Healthcare, Britain, United Kingdom). The scans were taken at slice thicknesses of 3 and 4 mm in the sagittal and axial planes, respectively. T2-weighted images (fast spin echo TR, 3500 ms; TE, 102 ms) were obtained in sagittal scans. Axial scans were performed using T2-weighted images (fast spin echo TR, 4000 ms; TE, 102 ms). All images were transferred to a computer as Digital Imaging and Communications in Medicine data to measure the anteroposterior diameter of the spinal cord, disc bulging diameter, and axial cross-sectional area of the spinal cord, both at the disc and midvertebral level, using imaging software (Osiris4; Icestar Media Ltd., Essex, United Kingdom). Disc bulging, SCC, and ISI change in T2 sagittal images were individually recorded.

By definition, SCC was identified when the anteroposterior diameter of the spinal canal at the narrowest level is less than or equal to the anteroposterior diameter of the spinal cord at the mid C5 vertebral body level (Figure 1).[14] This definition is based on the fact that (1) a sagittal diameter of the spinal canal at the C5 vertebral body level on radiograph is generally used to define developmental stenosis of the cervical spinal canal and (2) there was no case of SCC at the mid C5 vertebral body level in our previous report.[14] Disc bulging was defined as the intervertebral disc protruding posteriorly by more than 1 mm. ISI changes in the spinal cord were classified into 3 groups based on sagittal T2-weighted images as shown in our previous article[10]: grade 0, none; grade 1, light (increased intensity, but less intense compared with cerebrospinal fluid signal); and grade 2, intense (similar intensity to cerebrospinal fluid signal). Grades 1 and 2 signal-intensity changes were included in this study.

Statistical Analysis

The Fisher exact test or *t* test was used to evaluate differences in abnormal findings between 2 consecutive decades. We plotted receiver operating characteristic analysis to determine the cutoff value to know (1) how big of a disc-bulge diameter would cause SCC to occur more frequently, and (2) how much SCC would increase ISI incidence. A *P* value less than 0.05 was considered statistically significant. All analyses were conducted using SPSS version 21 (SPSS, Chicago, IL).

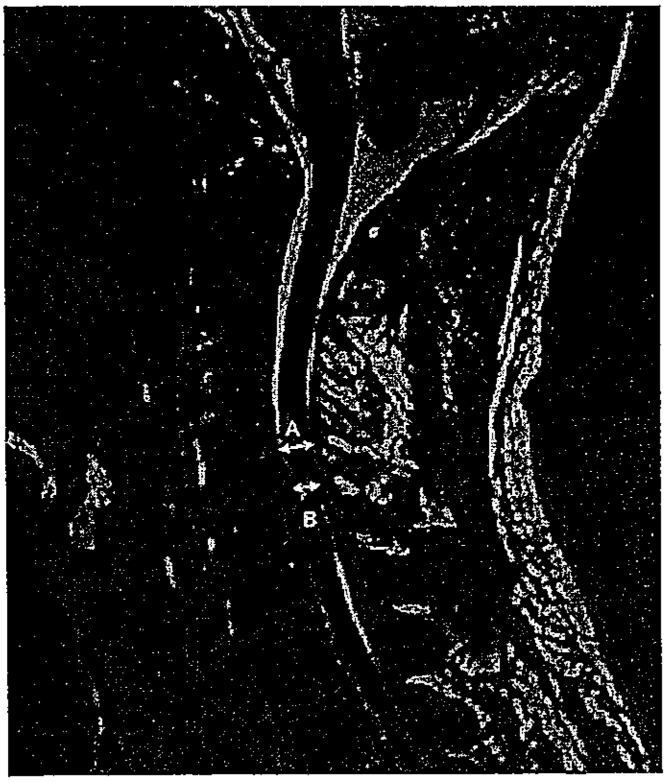

Figure 1. Definition of spinal canal compression by cervical magnetic resonance imaging.[14] The AP diameter of the spinal canal at the narrowest level (white double arrow; B) AP diameter of the spinal cord at the mid C5 vertebral body (white double arrow; A). AP indicates anteroposterior.

RESULTS

The 1211 asymptomatic volunteers included in this study were equally distributed among age classes, from the third to the eighth decade of life (Table 1). Approximately, 50% of the subjects had passive occupations, mainly as office workers, teachers, or service providers, whereas 28% of them had physically demanding occupations, like housekeepers, builders, and manufacturers (Table 2).

Disc Bulging

Most asymptomatic volunteers (87.6%) had significant disc bulging. The incidence was already very high in the subjects in their 20s, with 73.3% of the males and 78.0% of the females having disc bulging (Figure 2A). The frequencies tended to increase with age from the 20s to the 50s, with a significant increase from the 30s to the 40s in males ($P < 0.05$). The number of bulging discs in each subject also increased with age (Figure 2B). In the subjects in their 20s, the average number of levels implicated was 1.5 ± 1.3 and 1.0 ± 1.4 for males and females, respectively. Thereafter, the sex difference was lost as the number of levels increased significantly from the 20s to 40s ($P < 0.05$ to 0.001), and reached a plateau (approximately 2 levels) in the 40s. The average disk displacement gradually increased with age from the 30s to the 60s ($P < 0.05$; Figure 2C), reaching 2.5 ± 0.7 mm and 2.0 ± 0.7 mm in males and females in their 70s, respectively.

Spinal Cord Compression

The diagnosis of SCC was confirmed in 64 (5.3%) subjects. The age and sex distribution of the SCC cases is presented in Figure 3A. Ossification of the posterior longitudinal ligament (OPLL) was observed in 5 people (0.4%) as in our previous report.[14] Although our population was Japanese, the majority of SCC cases were due to other degenerative changes. There was no case of SCC in the subjects in their 20s, and the number increased gradually with age. In addition, SCC was more common in males than in females in all generations. Thirty-seven cases had SCC in 1 level, 24 in 2 levels, 2 in 3 levels, and 1 in 4 levels; they were located predominantly at C5–C6 (41%) and C6–C7 (27%; Figure 3B). The axial cross-sectional area of the dural sac was 112.5 ± 23.3 mm² in cases of SCC. The most severe case of SCC had a 77.6% reduction in cross-sectional area at C5–C6, compared with the C5 mid-vertebral body (Figure 4).

TABLE 1. Age and Sex of 1211 Asymptomatic Subjects

Age (yr)	Males	Females
20–29	101	100
30–39	104	99
40–49	100	100
50–59	99	103
60–69	101	103
70–79	101	100
Total	606	605

TABLE 2. Occupation of 1211 Asymptomatic Subjects

Occupation	No.
Office workers	196
Teachers	196
Service providers	101
Doctors, nurses, and medical coworkers	58
Sales persons	57
Students	16
Subtotal = 624 (51.5%)	
Housekeepers	193
Builders	78
Manufacturers	54
Carriers	15
Farmers	3
Subtotal = 343 (28.3%)	
Unemployed persons	124
Others	100
Unknown.	20
Subtotal = 244 (20.1%)	
Total	1211

Increased Signal Intensity

A small fraction of the subjects (N = 28; 2.3%) exhibited significant changes in ISI on T2 sagittal images. The distribution of ISI cases per decade and sex is shown in Figure 5A. This MRI abnormality was more common in males than females of all generations, as in the case of SCC. The incidence of ISI increased with age, particularly after the 50s, reaching 9% and 4% for males and females in their 70s, respectively. Most cases of ISI (89%) involved 1 level. Every ISI coincided with the level of SCC, primarily at C4–C5 (36%) and C5–C6 (54%) (Figure 5B).

The Relationship Between Disc Bulging, SCC, and ISI

A disc bulge of more than 1.35 mm was a risk factor for SCC (area under curve = 0.87, $P < 0.0001$, Figure 6A), and an SCC area of less than 128.5 mm² was a risk factor for ISI (area under curve = 0.92, $P < 0.0001$, Figure 6B).

Presentation of the Most Severe Case of SCC

The patient was a 77-year-old male with no clinical subjective symptoms, such as gait disturbance or numbness in his extremities. His manual muscle test results were 5. The result of the 10-second grip and release test[15] was 21/22 times in the

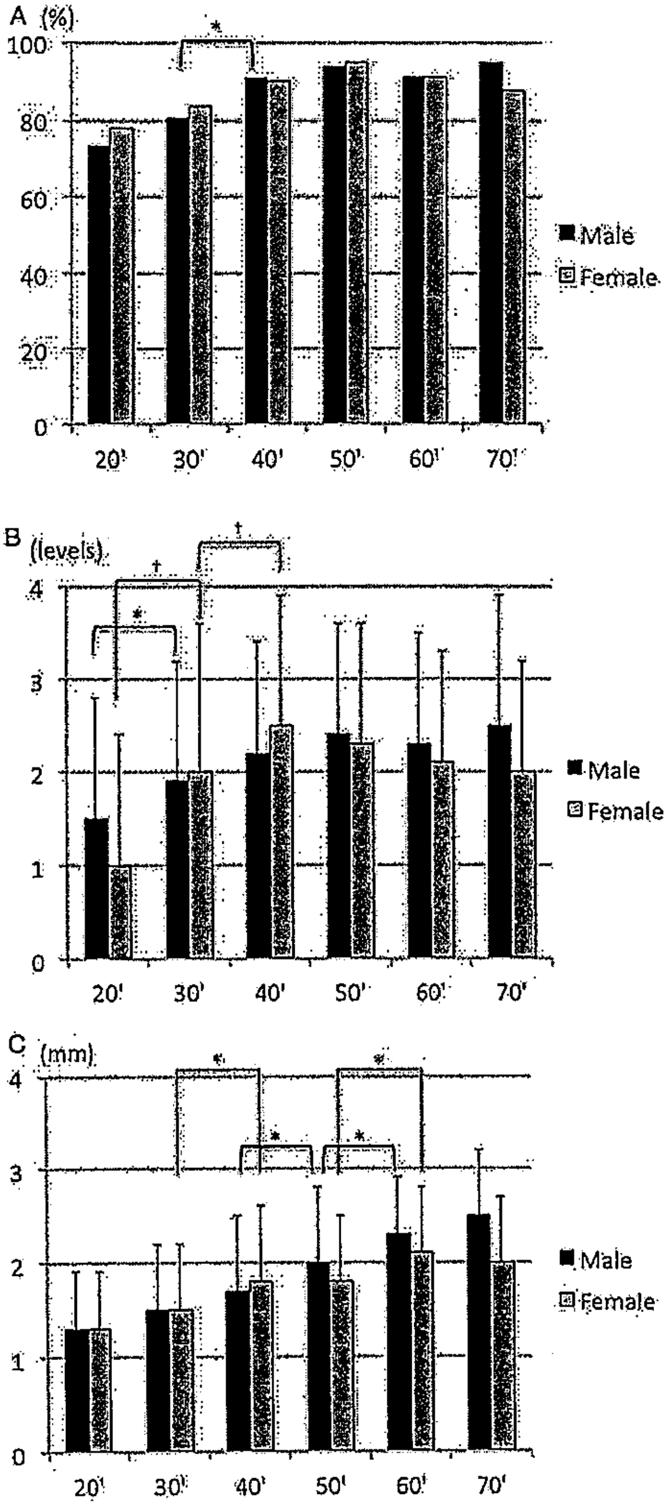

Figure 2. Frequency distribution of disc bulging in asymptomatic subjects. A, Frequency distribution of disc bulging with age and sex. B, Frequency distribution of the number of levels involved in disc bulging. C, Impact of age and sex on disc displacement (mm). Values are mean + SD. *$P < 0.05$, †$P < 0.001$. SD indicates standard deviation.

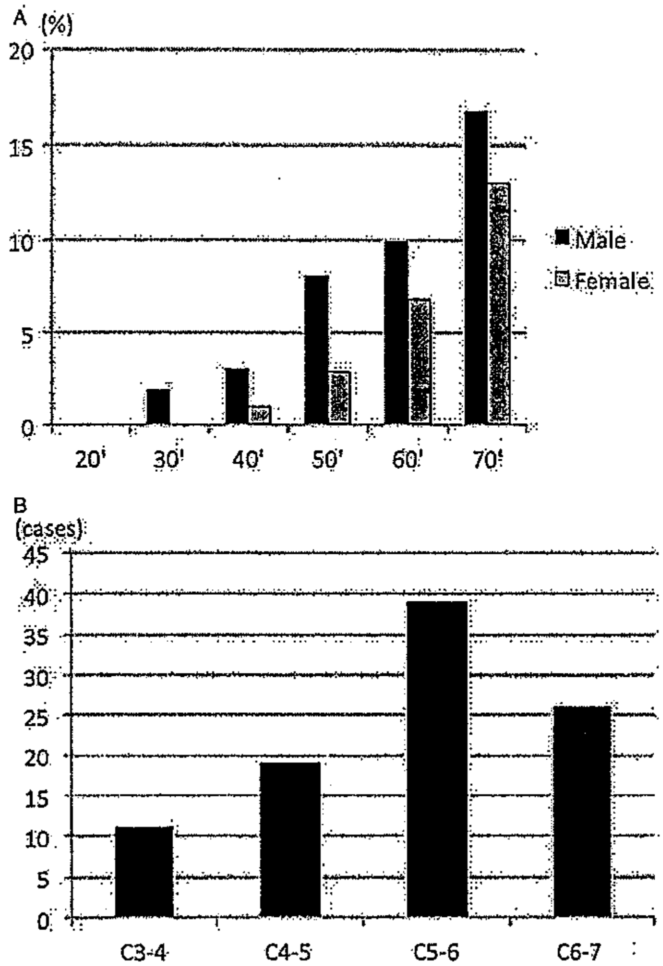

Figure 3. Frequency distribution of cervical SCC in asymptomatic subjects. A, Frequency distribution of SCC with age and sex. B, Frequency distribution of SCC along the spine. SCC indicates spinal cord compression.

right/left hand, respectively, and the result of the 10-second step test[16] was 15. The deep tendon reflex, triceps, patella, and Achilles tendon reflex were hyper, whereas the deltoid, biceps, and brachioradialis tendon reflex were normal. Tromner-Hoffman sign[17] were negative on both sides, but the Wartenberg sign[15] was positive on both sides. MR image showed fusion of the C5 and C6 vertebrae, and local kyphosis at C4–C6 (Figure 4). SCC was detected at C4–C5 and C5–C6, with ISI at C5–C6.

DISCUSSION

This study constituted the largest prospective evaluation of cervical spine MR image in asymptomatic subjects. This comprehensive survey demonstrated that small disc bulging was frequently observed even in the subjects in their 20s. In addition, the number of patients with minor disc bulging and the number of levels with small disc bulging increased from age 20 to 50 years. In contrast, the frequency of SCC and ISI increased after age 50 years, and this was accompanied by increased severity of disc bulging.

The increasing incidence of cervical disc bulging with aging among asymptomatic subjects has been extensively documented.[1–8] Cervical disc degeneration or bulging is frequently reported in asymptomatic subjects in their 40s and 50s.[1,3] In

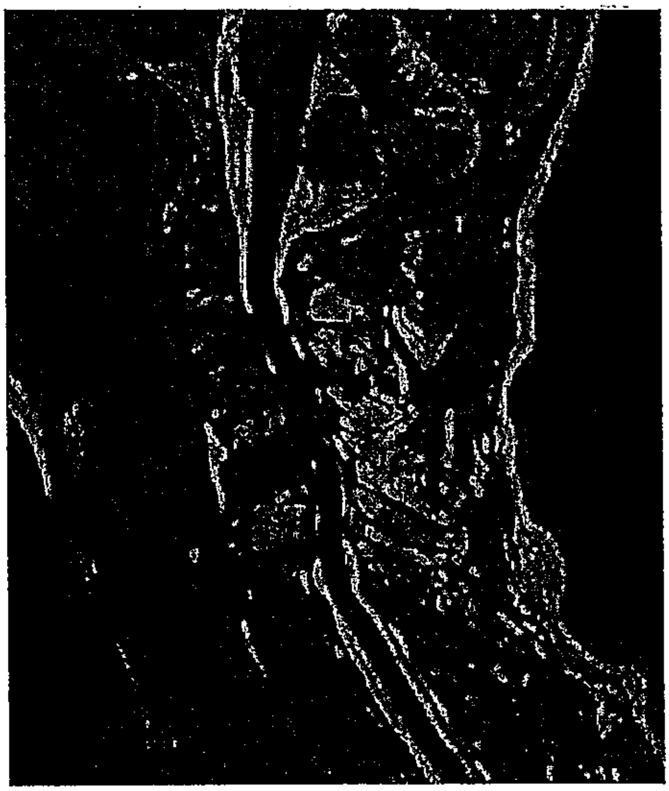

Figure 4. Spine magnetic resonance imaging T2-weighted sagittal image of a 77-year-old asymptomatic male. There is fusion of the C5 and C6 vertebrae, and local kyphosis at C4–C6. Spinal cord compression detected at C4–C5 and C5–C6, with high-signal intensity change at C5–C6.

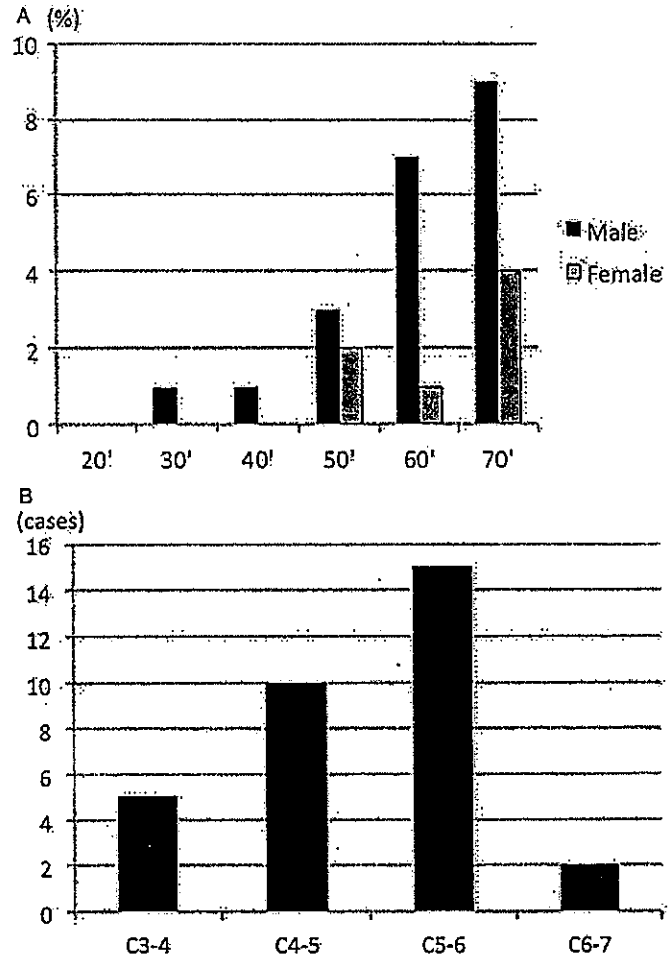

Figure 5. Frequency distribution of ISI changes on MR image in asymptomatic subjects. A, Frequency distribution of ISI with age and sex. B, Frequency distribution of ISI along the spine. ISI indicates increased signal intensity; MRI, magnetic resonance image.

this study, the number of cases and levels with small disc bulging increased and reached a plateau in the 50s. However, the severity of disc displacement continued to increase even after the 50s. Such disc bulging enlargement with age is highly suspected as a cause of spinal canal stenosis after the 50s.

Spinal canal stenosis is also known to gradually increase with age.[1,9,14] The reduction in spinal canal size occurred more frequently at the disc level than at the midvertebral level, particularly at C5–C6.[14] In addition to disc bulging, cervical spine alignment change could be another cause of SCC. Cervical lordosis in the neutral position increases with age, particularly in the 60s.[18] Changes in cervical alignment could compensate for the growing spinal canal stenosis with age. Spinal canal stenosis occurs by pincers effect, which defines pinching of the spinal cord between the ligamentum flavum and intervertebral disc. This effect is more pronounced in the lordotic alignment.[19] Accordingly, more severe pincer effects could occur in older populations with large disc bulging and lordotic alignment.

Few reports mentioned the severity of spinal canal stenosis in an asymptomatic population.[7] Teresi *et al*[7] noted that the reduction in cross-sectional area of the spinal cord never exceeded 16% in the asymptomatic population. However, in this study, the most severe case of SCC showed the reduction of the cross-sectional area exceeding 75%. Although the critical value at which symptoms manifest is not clear, a significant degree of SCC can be tolerated without any symptoms. Hamburger *et al*[20] reported the axial cross-sectional area of the dural sac in patients with cervical myelopathy; the preoperative and postoperative areas were 92 ± 37 mm^2 and 154 ± 36 mm^2, respectively. The axial cross-sectional area of the dural sac was 113 mm^2 in cases of SCC in our asymptomatic subjects, and the cross-sectional area in cases of SCC in asymptomatic subjects was not as severe as in cases with symptomatic cervical myelopathy. The severity of stenosis was just midway between that of the pre- and postoperative conditions of patients with symptomatic cervical myelopathy. This result could be valuable for knowing the degree of stenosis in symptomatic patients.

Although we performed receiver operating characteristic analysis to detect a relationship between disc bulging, SCC and ISI, disc bulge of more than 1.35 mm is not particularly severe, and so it seems likely that the combination of developmental canal stenosis, hypertrophy of ligamentum flavum,

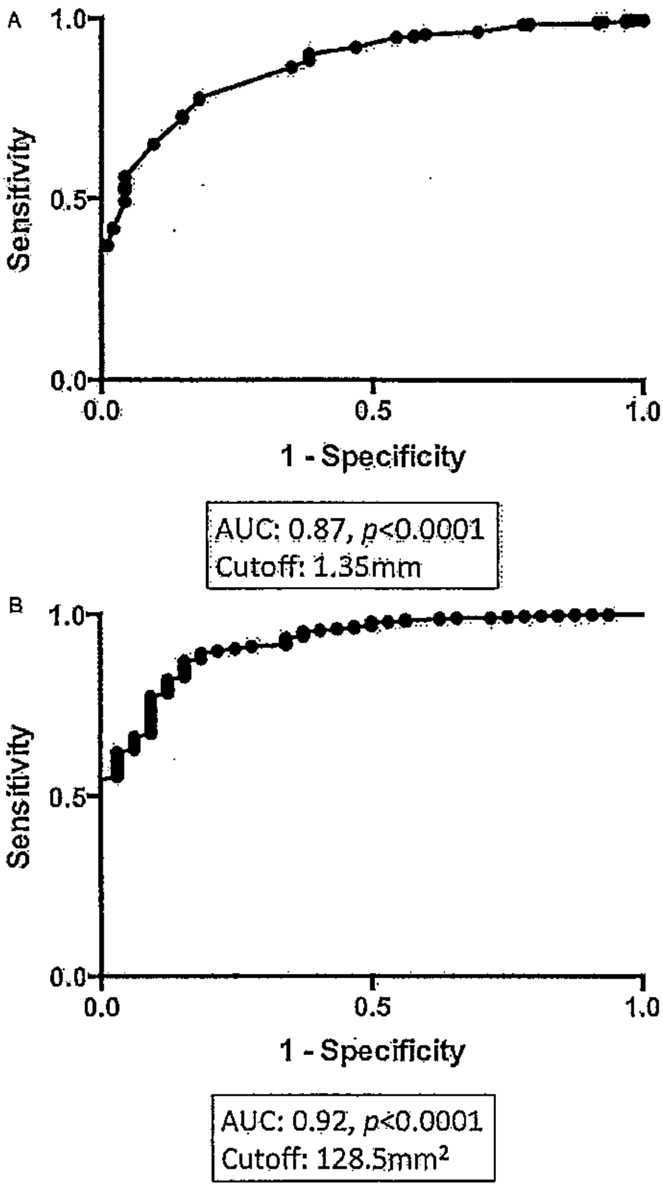

Figure 6. The ROC curves to determine (A) how big of a disc-bulge diameter would cause SCC to occur more frequently, and (B) how much SCC would increase ISI incidence. A, The relationship between disc bulging and SCC. B, The relationship between SCC and ISI. SCC indicates spinal cord compression; ISI, increased signal intensity; ROC, receiver operating characteristic.

and deformity of cervical spine is what is important for the occurrence of SCC.[12,13]

This study has some limitations. First, the survey was limited to the Japanese population, which does not rule out racial differences. Second, this large cohort included subjects with a wide variety of occupations in terms of physical demand, which may influence the progression or severity of cervical degenerative disease. Third, we used our original definition of SCC. To objectively and quantitatively evaluate SCC in asymptomatic subjects, we newly established this definition of SCC. In the other previous articles, SCC was defined as the presence of a defect in the cord, a definition that was subjective and not quantitative.[1,21] Especially in asymptomatic cases, interobserver reliability in SCC is not very high because canal compression in those cases was not severe.[21] Our definition is useful in asymptomatic subjects, however this might not be useful in symptomatic cases, especially ones with severe deformity or continuous type OPLL, and so further discussion is needed.

CONCLUSION

This large prospective analysis of cervical spine MRI data in asymptomatic subjects demonstrates the high frequency and multiple levels of degenerative change in the spinal cord and discs. Then, it is dangerous to make interventional decisions only by judging degenerative changes using MR images alone.

The results in this study alerted us to the fact that clinical decision making should be prudent, correlating MRI findings with clinical signs and symptoms. Future studies are required to monitor the progression of asymptomatic SCC to identify the MRI abnormalities that would predict the emergence of symptomatic cervical degenerative disease.

Key Points

- Cervical disc bulging, SCC, and ISI changes were evaluated on cervical MR images of 1211 healthy volunteers.
- Most subjects presented with disc bulging (87.6%); the frequency, severity, and number of levels involved significantly increased with age.
- The frequency of SCC and ISI was 5.3% and 2.3%, respectively.
- The number of patients with minor disc bulging and the number of levels with small disc bulging increased from age 20 to 50 years.
- In contrast, the frequency of SCC and ISI increased after age 50 years, and this was accompanied by increased severity of disc bulging.

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Spinal Cord (2015) 53, 306–309

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ORIGINAL ARTICLE

Prospective study of deep vein thrombosis in patients with spinal cord injury not receiving anticoagulant therapy

S Matsumoto, K Suda, S Iimoto, K Yasui, M Komatsu, C Ushiku, M Takahata, Y Kobayashi, Y Tojo, K Fujita and A Minami

Study Design: Prospective cross-sectional study.
Objectives: To investigate the timing of deep vein thrombosis (DVT) onset secondary to spinal cord injury without anticoagulant therapies.
Setting: Spinal Cord Injury Center in Hokkaido, Japan.
Methods: Between November 2012 and June 2013, patients with spinal cord injury who were admitted to our hospital within 1 day after the injury and treated surgically within 24 h underwent a neurological examination, leg vein ultrasonography and D-dimer test 1, 3, 7, 14 and 28 days after surgery. All patients received treatment with intermittent pneumatic compression and elastic stockings, but without any anticoagulant.
Results: DVT developed in 12 patients (11 men and 1 women), with a mean age of 62.2 years (range, 41–80 years; mean age of total sample, 63.2 years (range, 25–78 years)), all distal to the popliteal vein. DVT occurred more often with a more severe paralysis (66.3%, AIS A and B). The median (± standard error) length of time from the operation to DVT detection was 7.5 ± 2.2 days. The mean D-dimer level upon DVT detection was 14.6 ± 11.8 μg ml^{-1}, with no significant differences between those who developed DVT and those who did not at any of the time points.
Conclusion: These results suggest that DVT can develop at the very-acute stage of spinal cord injury and the incidence increases with a more severe paralysis. DVT detection was more reliable with ultrasonography, which should be used with DVT-preventive measures, beginning immediately after the injury, for the management of patients with spinal cord injury.
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INTRODUCTION

Deep vein thrombosis (DVT) is one of the most dangerous complications of a spinal cord injury. DVT has a high incidence in patients with spinal cord injury as compared with patients with other diseases[1] with a high mortality rate if complicated by pulmonary embolism.[2]

Although prevention, early detection and timely treatment of DVT are important during the management of patients with spinal cord injury, the timing of DVT onset secondary to a spinal cord injury has not yet been determined. In order to clarify these problems, this study aimed to investigate the timing of DVT onset by prospectively analyzing the patients immediately after a spinal cord injury.

MATERIALS AND METHODS

A prospective study was conducted in all patients with spinal cord injury admitted to our hospital between November 2012 and June 2013 within 1 day after the injury and treated surgically within 24 h. A neurological examination, leg vein ultrasonography and clotting system test (D-dimer) was performed 1, 3, 7, 14 and 28 days after surgery. Leg vein ultrasonography was carried out by using an Aplio XG (TOSHIBA, Tokyo, Japan) by experienced sonographers.

Intermittent pneumatic compression (IPC) with a calf pump (Kendall SCD EXPRESS, COVIDINE, Dublin, Ireland) and elastic stockings (ES) were used in all cases. The patient were kept foot pump attached throughout the day (except when the patient left the bed) for at least 2 consecutive weeks. The use of ES began on the day after the operation, as far as possible, with a median of 3 days between the operation and their use. Patients were advised to keep them on, except when bathing. One patient refused to wear them, and two patients had difficulty wearing them because of skin irritation. The other patients continued to use them until discharge from the hospital.

As a rule, we allowed the patients to leave the bed by using a wheelchair from the day after the surgery, with a median (± standard error) of 3 ± 0.7 days from the surgery. Ten patients were unable to leave their bed on the day after the operation because of elective surgery (six cases), mechanical ventilation (two cases) and chest tube (two cases).

We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research.

RESULTS

The sample included 25 men and 4 women with a mean age of 63.2 years (25–78 years). The spinal cord injury occurred at the cervical segment in 19 cases and thoracic/lumbar segment in 10 cases. The cause of spinal cord injury was a fall from a great height in 11 cases, fall from a low height in 2 cases, same-level fall in 8 cases, traffic accident in 4 cases, fall from a staircase in 1 case and sports accident in 3 cases. The median period from injury to hospitalization was 0 day (0–1 day). Twenty-four patients were admitted to our hospital on the day of the injury and 5 were hospitalized on the following day. The severity of paralysis at admission (American Spinal Cord Association

Spinal Cord Injury Center, Hokkaido Chuo Rosai Hospital, Higashi-4 Minami-1, Bibai, Japan
Correspondence: Dr S Matsumoto, Spinal Cord Injury Center, Hokkaido Chuo Rosai Hospital, Higashi-4 Minami-1, Bibai 072-0015, Japan.
E-mail: satmatsatmat@hokkaidoh-s.rofuku.go.jp
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(ASIA) Impairment Scale (AIS)) was A in 9 cases, B in 2 cases, C in 8 cases and D in 10 cases. The paralyzed level (ASIA Neurological Level of Injury (NLI)) was C3–4 in 11 cases, C5–8 in 8 cases, T1–12 in 6 cases and L1–4 in 4 cases. DVT developed in 12 patients (41.4%; 11 men and 1 woman), with a mean age of 62.2 years (range, 41–80 years). In all of these cases, the DVT was located distal to the popliteal vein. DVT affected both sides in 2 cases, the left side in 5 cases and the right side in 5 cases. Among these 12 patients, the injured level was the cervical segment in 7 cases and thoracic/lumbar segment in 5 cases, and the paralyzed level according to the NLI classification was C3–4 in 4 cases, C5–8 in 2 cases, T1–12 in 3 cases and L1–4 in 3 cases. The severity of paralysis (AIS) was A in 7 (58.3%) of these 12 cases, B in 1 case (8.3%), C in 3 cases (25.0%) and D in 1 case (8.3%). Thus, DVT occurred more often with paralysis of AIS grades A and B (complete motor paralysis) than with a partial motor paralysis (Tables 1a and b). DVT was detected on postoperative day 3 in 3 cases (25.0%), postoperative day 7 in 5 cases (41.7%), postoperative day 14 in 1 case (8.3%) and postoperative day 28 in 3 cases (25.0%). The median length of time from the operation to DVT detection was 7.5 ± 2.2 days (± standard error) (Table 2).

The mean D-dimer level at DVT detection was 14.6 ± 13.5 μg ml^{-1} (range, 2.78–44.3 μg ml^{-1}). There was no significant difference between the DVT negative group and DVT positive group in terms of D-dimer level upon admission or on postoperative day 1, 3, 7, 14 or 28 (Mann–Whitney test, $P = 0.117$; 0.059, 0.028, 0.075, 0.306 and 0.124, respectively).

The cutoff D-dimer levels determined from the receiver operator characteristic (ROC) curve was 7.34, 7.88, 5.82, 10.99, 11.44, and 5.88 at admission and on the postoperative days 1, 3, 7, 14 and 28, respectively. The sensitivity/specificity (%) at these points of time were 75.0/70.6, 41.7/94.1, 72.7/76.5, 55.6/88.2, 60.0/93.3 and 75.0/93.3, respectively (Table 3).

Table 1a Participants' characteristics (*N* = 29)

Variable	*Total* (N = 29) n(%)	*DVT Positive* (N = 12) %
Age (median years)	63.2 (25–78)	62.2 (41–80)
Gender		
Male	25 (86)	11 (92)
Female	4 (14)	1 (8)
Lesion level		
Cervival	19 (66)	7 (58)
Thoracic	4 (14)	2 (17)
Lumbar	6 (20)	3 (25)
Causes		
High fall	11 (38)	5 (42)
Low fall	2 (7)	3 (25)
Fall at ground level	8 (28)	2 (17)
Road traffic accidents	4 (14)	1 (8)
Stairs	1 (3)	0
Sports	3 (10)	1(8)
AIS		
A	9 (31)	7 (58)
B	2 (7)	1 (8)
C	8 (28)	3 (25)
D	10 (34)	1 (8)
Neurological level of injury		
C3–4	11 (38)	4 (27)
C5–8	8 (27)	2 (17)
T1–12	6 (21)	3 (25)
L1–4	4 (14)	3 (25)
Comorbid injury		
Fracture		
Rib	1 (3)	0
Clavicle	1 (3)	0
Scapula	1 (3)	0
Radius	2 (7)	0
Patella	0	1 (8)
Skull	1(3)	0
Pneumo/hemothorax	2 (7)	0
Period from injury to hospitalization (median days)	0 (0–1)	0 (0)

Abbreviations: AIS, The American Spinal Cord Injury Association Impairment scale; DVT, deep vein thrombosis; n, number of subject; U/E, upper extrimities; L/E, lower extrimities. Multiple injury of the same patient.

Table 2 Days of DVT detection

Variable	
Day detected (days)	
POD 1	0 (0)
POD 3	3 (25)
POD 7	5 (41)
POD 14	1 (8)
POD 28	3 (25)
Days from operation (mean, s.d.)	7.2 (2.2)

Table 1b DVT participants' characteristics (*N* = 12)

Variable	*Case*											
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Age	78	72	63	60	66	41	63	63	53	49	80	67
Gender	Male	Male	Male	Male	Female	Male	Male	Male	Male	Male	Male	Male
Lesion level	Cervival	Lumbar	Cervival	Thoracic	Lumbar	Thoracic	Cervival	Cervival	Cervival	Cervival	Lumbar	Cervival
Causes	Low fall	Low fall	High fall	High fall	High fall	Sports	Low fall	Ground	High fall	Traffic	High fall	Ground
AIS	A	C	A	A	C	B	A	A	A	A	C	D
Neurological level of injury	C6	L1	C3	T11	L3	T6	C4	C4	C3	C5	L2	T8
Comorbid injury	–	–	–	–	–	–	–	–	–	Patella Fx	–	–
Period form injury to hospitalization	Day 0	Day 0	Day 0	Day 0	Day 0	Day 0	Day 0	Day 0	Day 0	Day 0	Day 0	Day 1
From injury to operation	Day 0	Day 0	Day 0	Day 0	Day 0	Day 0	Day 0	Day 0	Day 0	Day 0	Day 1	Day 1
Day of DVT detetion form injury	Day 3	Day 7	Day 28	Day 7	Day 7	Day 3	Day 7	Day 28	Day 7	Day 14	Day 29	Day 4
From operation	Day 3	Day 7	Day 28	Day 7	Day 7	Day 3	Day 7	Day 28	Day 7	Day 14	Day 28	Day 3
Ventilator Tx at DVT detection	–	–	–	–	–	–	+	–	–	–	–	–

Abbreviations: AIS, The American Spinal Cord Injury Association Impairment scale; DVT, deep vein thrombosis; Ground, fall at ground level; Traffic, road traffic accident; Tx, treatment; –, none.

Table 3 Value of D-dimer in DVT positive group

Variable	Mean D-dimer level (range) (μg ml⁻¹)			Cutoff (μg ml⁻¹)	Sensitivity (%)	Specificity (%)
	DVT positive	DVT negative	P-value			
At admission	30.9 (1.2–99.6)	16.7 (1.1–84.0)	0.117	7.34	75	70.6
POD 1	7.5 (2.9–21.0)	3.8 (0.8–7.9)	0.059	7.88	41.7	94.1
POD 3	11.6 (1.8–35.4)	5.4 (1.5–16.4)	0.0287	5.82	72.7	76.5
POD 7	13.5 (4.6–44.3)	6.2 (1.6–16.8)	0.075	10.99	55.6	88.2
POD 14	8.5 (2.8–14.5)	6.9 (1.5–22.0)	0.306	11.44	60	93.3
POD 28	9.9 (1.9–21.0)	4.7 (1.1–15.0)	0.124	5.88	75	86.7

Abbreviation: DVT, deep vein thrombosis.
Mann–Whiteney U test.

DISCUSSION

Timing and incidence of DVT in spinal cord injury patients

Concerning the pathogenesis of DVT, the three major factors in Virchow's triad (blood retention, capillary wall disorder and blood coagulopathy) are well known.[3] After spinal cord injury, paralysis is accompanied by reduced vascular contraction (because of a sympathetic nerve disorder) and reduced venous return (because of disturbed muscle contraction), leading to blood retention.[4] Furthermore, a possible loss of the circadian variation in hemostatic and fibrinolytic function has also been suggested in patients with spinal cord injury. Thus, DVT is quite likely to develop in the presence of spinal cord injury. Considering the known mechanisms for the onset of DVT, we need to bear in mind that the risk for DVT increases with more severe paralysis and the incidence of DVT is particularly high in patients with complete motor paralysis associated with spinal cord injury.[5,6] In other words, the incidence of DVT is high in paralyzed patients with spinal cord injury; therefore, early detection and treatment are essential in such cases.

For early detection, we need to understand the timing associated with DVT onset; however, we have little information regarding the timing of DVT onset. In a retrospective analysis of 52 patients, Sugimoto *et al.*[7] reported that they observed DVT 2–13 days after injury of the cervical segment of the spinal cord, suggesting that DVT can develop soon after spinal cord injury. To the best of our knowledge, the present study is the first to prospectively document the timing of DVT onset in patients with a spinal cord injury, with analysis commencing immediately after their injury. We detected no DVT positive patient on Day 1 but 3 patients were positive on Day 3, 5 on Day 7, 1 on Day 14 and 3 on Day 28.

As a result, DVT was detected 3 days after injury in 25% of the patients who developed DVT. Especially in the group of AIS A as complete paralysis, DVT occurred in 78% of patients. These findings indicate that proactive DVT prevention and diagnosis, beginning immediately after the injury, are indispensable in the management of the patients with a spinal cord injury.

How to diagnose DVT in spinal cord injury patients

D-dimer measurement and leg ultrasonography are predominantly used for the diagnosis of DVT. However, according to a study of patients who developed DVT after total knee or hip replacement surgery, both the sensitivity and specificity of D-dimer are low, indicating that D-dimer alone does not provide a sufficient means of DVT diagnosis.[8,9] Similar results were obtained in the present study, and the D-dimer level varied depending on the timing of the measurement, indicating a limitation in the accuracy of diagnosis based on D-dimer levels. DVT-inducing pulmonary embolism is a potentially fatal complication, and it seems advisable to use D-dimer only as an auxiliary indicator.

Diagnostic reliability is highest with leg ultrasonography. The sensitivity of ultrasonography in detecting leg DVT is reported to be 98–100% and its specificity to be 75–100%.[10–12] This is an excellent method for the noninvasive screening of DVT.[13] Shortcomings of this modality include the amount of time and labor required. For spinal cord injury accompanied by paralysis, periodic leg ultrasonography is indispensable. The results of the present study suggest that frequent leg ultrasonography, beginning immediately after injury, is needed for patients with severe paralysis (AIS A-C).

Prevention of DVT

In patients with a spinal cord injury, the incidence of DVT is quite high, and active measures for prevention are important, beginning from the acute stage of injury.[1] The basic principles for DVT prevention include the prevention of venous retention, stimulation of venous return, and anticoagulation, with the use of ES, IPC and low-dose unfractionated heparin (LDUH), respectively. In the present study, ES and IPC were used immediately after injury, but this approach could not prevent DVT from occurring. These results indicate that it is necessary to include LDUH in the treatment of paralyzed patients with spinal cord injury. However, since patients with spinal cord injury often have hemorrhaging around the spine or spinal cord, physicians are often cautious about the use of LDUH because bleeding inside/outside the spinal cord is likely to aggravate the paralysis.

Recommendations provided in the American College of Chest Physicians Guidelines[13] include the use of low-molecular weight heparin (LMWH) upon confirmation of hemostasis (Grade 2B), combined use of IPC and LDUH (Grade 2C), combined use of IPC and ES in cases where anticoagulants are contraindicated (Grade 1C+), and treatment with LMWH or an oral-dose vitamin K antagonist during rehabilitation (Grade 1C). Christie *et al.*[14] recommended treatment with LMWH within 72 h after injury or re-treatment with the same drug within 24 h after surgery. Further, no difference has been detected in the incidence of DVT or hemorrhagic complications between patients receiving 5000 U of unfractionated heparin every 8 h and those receiving 30 mg LMWH every 12 h, if treatment was started within 72 h after injury.[15] We have no objection to the view that LMWH or LDUH has a central role in the prevention of DVT among patients with spinal cord injury, even in the patients treated surgically. However, there is a particular need to establish the use of these drugs during the acute stage of spinal cord injury.

CONCLUSION

1. DVT can develop at the very-acute stage of spinal cord injury.
2. The incidence of DVT increased with more severe paralysis.
3. Ultrasonography is a simple and valid means of detecting DVT.
4. Frequent ultrasonogtraphy during early stage is useful for detecting asymptomatic DVT in acute SCI patients.

DATA ARCHIVING

There were no data to deposit.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Advantage of Pedicle Screw Placement Into the Sacral Promontory (Tricortical Purchase) on Lumbosacral Fixation

Minori Kato, MD, PhD, Hiroshi Taneichi, MD, PhD,*† and Kota Suda, MD, PhD**

Study Design: Retrospective clinical study.

Objective: To evaluate the clinical outcome of the tricortical method for lumbosacral fixation.

Summary of Background Data: Despite advances in surgical techniques, failure to achieve solid arthrodesis of the lumbosacral junction continues to be significant clinical problems. To overcome these problems, tricortical purchase fixation has recently been advocated and studied. In this method, a trajectory directly into the medial sacral promontory is used to gain purchase in the dorsal, anterior, and superior cortices. This fixation method has been shown to double the insertional torque of the classic bicortical technique.

Methods: Patients who had undergone lumbosacral fixation were included in this study. The average area of fusion was 1.7 segments. The patients were divided into a tricortical fixation group (TF, n = 98) and a nontricortical fixation group (non-TF, n = 33). We examined clinical outcome [Japanese Orthopaedic Association scoring system (JOA score)], fusion status, and the characteristics and safety of pedicle screwing in both groups. To identify risk factors for postoperative loss of lordosis (postoperative loss of >5 degrees in L5/S1 disk angle), risk factor analysis was performed by multivariate logistic regression.

Results: In TF and non-TF, the JOA score changed from 13.4 and 13.8 points at surgery to 24.9 and 23.8 points, respectively, at final follow-up, and the recovery rate was 73.7% and 64.2%, respectively. Pseudoarthrosis of the fused L5/S1 occurred in 3 patients in whom the lumbosacral spine had not been fixed by tricortical purchase. The screw angle was 22.0 and 16.1 degrees in TF and non-TF, respectively, that is, a significant difference was shown. Significantly fewer TF cases encountered the risk of injured vascular tissue compared with non-TF. Non-TF (OR, 3.37) and correction of the L5/S1 disk angle (OR, 1.11) were significant risk factors for postoperative loss of lordosis.

Conclusions: In patients who underwent short-segment lumbosacral fusion, TF enhanced postoperative stability at the lumbosacral junction. Pseudoarthrosis did not occur in patients who underwent TF, and the risk of vascular injury was less. TF is regarded as a successful technique in short-segment lumbosacral fixation.

Key Words: lumbosacral spine, fixation, pedicle screw, pseudoarthrosis

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Despite advances in surgical techniques, failure to achieve solid arthrodesis of the lumbosacral junction continues to be a significant clinical problem. This is the result of various anatomic, biological, and mechanical factors relating to the sacrum, such as the fused structure of bony somites, low bone quality, a thin cortical shell, and very large, medially convergent S1 and sub-S1 pedicles.[1–3] Thus, indications of lumbosacral fixation include complications such as pseudoarthrosis, loss of lordosis, sacral fracture, and failure of instrumentation (loosening, pullout, screw breakage, implant migration, and so on).[4–8] An understanding of the sacral bony anatomy and the structures at risk is key to a well-considered sacral fixation.

The principal starting point for any sacral fixation is usually the use of S1 pedicle screws. There are 2 basic insertion techniques for S1 pedicle fixation, unicortical and bicortical. Because of the largely cancellous nature of the S1 pedicle, unicortical insertion results in poor fixation with toggling, loss of fixation, and screw pullout. Consequently, bicortical purchase has been the standard for many years. The classic trajectory is described as paralleling the S1 endplate, with appropriate medial convergence necessary to avoid the common iliac vessels located on the anterior surface of the sacrum.[9,10] However, the ideal method for fusion to the sacrum thus remains controversial. Options for posterior fixation to the sacrum, including sacral screws with extension to the ilium or combined anterior and posterior surgery, have been selected in cases of severe osteoporosis or in those requiring long fusion.

To overcome these problems, tricortical purchase fixation has recently been advocated and studied

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From the *Spinal Cord Injury Center, Hokkaido Chuo Rosai Hospital, Bibai; and †Department of Orthopaedic Surgery, Dokkyo Medical University School of Medicine, Tochigi, Japan.
The authors declare no conflict of interest.
Reprints: Hiroshi Taneichi, MD, PhD, Department of Orthopaedic Surgery, Dokkyo Medical University School of Medicine, Kitakobayashi 880 Mibu, Shimotsuga-gun 321-0293, Tochigi, Japan. (e-mail: htane@sea.plala.or.jp).

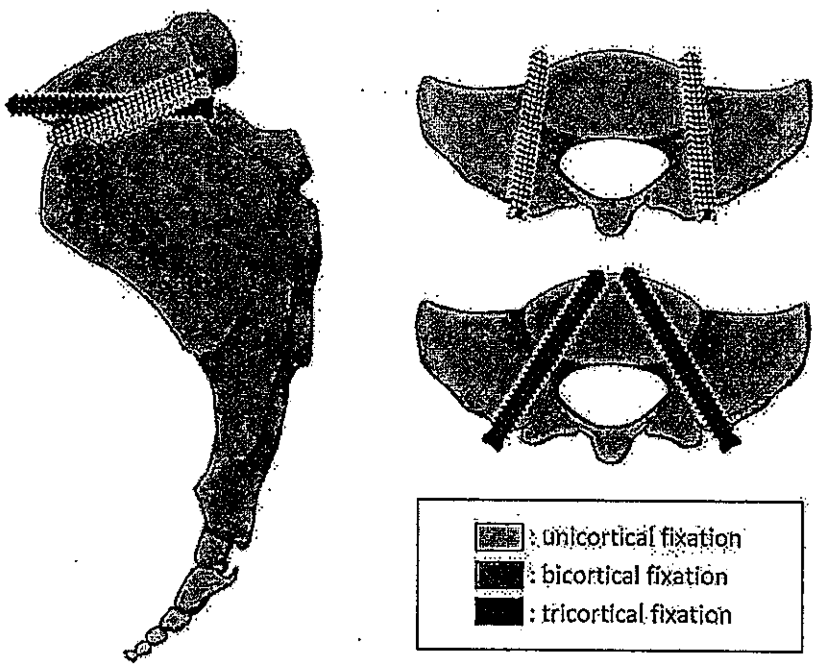

FIGURE 1. A lateral view of the sacrum demonstrates the 3 trajectories of S1 pedicle screwing including unicortical, bicortical, and tricortical fixation.

(cf. Fig. 1).[11,12] In this method, a trajectory directly into the medial sacral promontory is used to gain purchase in the dorsal, anterior, and superior cortices. This fixation method has been shown to double the insertional torque of the classic bicortical technique.[13] In addition, this trajectory is considered to introduce less risk of vascular injury compared with the trajectory of the bicortical method. Although this new fixation technique has been studied, its clinical advantages in short-segment lumbosacral fixation have not been documented. The purpose of this study was to evaluate the fixative efficacy and safety of tricortical purchase fixation in lumbosacral fixation.

MATERIALS AND METHODS

Between 2002 and 2006, 131 patients at the Hokkaido Chuo Rosai Hospital (formerly Bibai Rosai Hospital) who had undergone lumbosacral fusion with bilateral lumbar and sacral pedicle screws systems for degenerative lumbar disease were included in this study (80 men and 51 women). The average age of subjects at the time of surgery was 56.5 years (range, 27–85 y) and the mean follow-up period was 31 months (range, 24–41 mo). The initial consecutive material comprised 155 patients, 24 of whom were lost to follow-up. These comprised 38 cases of congenital or isthmic spondylolisthesis, 37 of degenerative spondylolisthesis, 18 of lumbar canal stenosis with instability, 17 of lumbosacral foraminal stenosis, 8 of degenerative lumbar scoliosis, and 13 others (multiple operative back, and so on). The area of fusion was L3–S1 in 21 patients, L4–S1 in 57 patients, and L5–S1 in 53 patients, the average being 1.7 segments. The fusion method was either transforaminal lumbar interbody fusion (TLIF) or posterior lumbar interbody fusion (PLIF) with pedicle screws. Pedicle screw fixation using the Kaneda Anterior Posterior Spinal System was performed. In both TLIF and PLIF procedures, a carbon open box cage was placed anteriorly at L5–S1.

Surgical Procedure

We aimed to fuse the lumbosacral joint with tricortical fixation (TF) using transparent lateral imaging. Our starting point for S1 screw insertion was the inferolateral angle of the S1 superior articular process. Orientation of the screw trajectory was directed as medially as possible to sacral midline in the horizontal plane. Under lateral fluoroscopy, we inserted into the anterior and superior cortices of the sacral promontory in the sagittal plane. When the ilium obstructed the trajectory of the pedicle screw, compromising tricortical purchase, the ilium was partially resected to facilitate implantation of the screw. Surgeons aimed to penetrate the anterior cortex of the sacrum by concomitantly probing and checking the screw position on lateral fluoroscopy. After inspecting the tunnel with a sounder, the screw was inserted with an identical trajectory.

Evaluation

Patients were divided into 2 groups, a TF group (n = 98) and a non-TF group (n = 33). The success of TF was evaluated based on the direct trajectory of the S1 pedicle screw into the medial sacral promontory to gain purchase in the dorsal, anterior, and superior cortices using axial and sagittal plane computed tomography (CT) images. We examined the clinical outcome (fusion status) and surgical features of pedicle screwing in both groups. Clinical outcome was evaluated using the Japanese Orthopaedic Association scoring system (JOA score) and postoperative recovery rate (JOA recovery rate), which was calculated as follows: recovery rate (%) = (postoperative JOA score − preoperative JOA score) × 100/(29 − preoperative JOA score). Fusion status was evaluated on the final follow-up radiographs, including dynamic lateral flexion-extension films, and was assigned according to the Brantigan criteria[14]; that is, fusion (bone in the fusion area is radiographically more dense and more mature than originally achieved at surgery) and probable fusion (bony bridge in the fusion area is at least as dense as that originally achieved at surgery) were both considered to represent radiographically demonstrable fusion.

To assess the surgical features of pedicle screwing, the authors investigated the length, diameter, angle of the screw, and fenestration of the anterior cortex. The safety aspect of the pedicle screw's trajectory was also evaluated by verifying the relative positions of the internal iliac artery and the trajectory on postoperative CT images. The authors concluded that screwing is a high-risk technique whenever a screw and iliac artery come into contact, and that it is low risk when there is no contact (cf. Fig. 2). We compared the risk between the 2 groups.

Statistically significant differences in these studies were determined by 1-way ANOVA, Mann-Whitney *U* test, or χ^2 tests. *P*-values <0.05 were considered significant.

To identify risk factors for postoperative loss of lordosis after short-segment lumbosacral fixation, risk factor analysis was performed by multivariate logistic regression with a software analysis system (JMP version 7). Postoperative loss of lordosis was defined as a postoperative loss of >5 degrees in the L5/S1 disk angle. For statistical analysis, postoperative loss of lordosis was used as a dependent variable, along with the independent variables age, sex, number of fixed vertebrae, correction of L5/S1 disk angle, sagittal alignment of total spine, depth of L5 within the pelvis, form of promontory, average length and diameter of S1 pedicle screw, implementation of TF, and implementation of penetration of the anterior sacral cortex with the S1 pedicle screw. The quality of the fit and significance of the model were evaluated with likelihood ratio test statistics in a stepwise manner. The sagittal balance was quantified by translation of the C7 plumb line from a vertical line drawn from the posterior-superior cortex of the S1 vertebral body. The depth of L5 within the pelvis was assessed by measuring the vertical distance between the midpoint of the L5 pedicles and the interiliac crest line on the preoperative coronal standing radiograph. When the pedicles of L5 were positioned below the interiliac crest line, the depth was considered "deep" and, conversely, the measurement was "shallow" when the pedicles were above the interiliac crest line. The form of promontory was decided as follows: angles of the anterior-superior cortical surface of the S1 vertebral body <70 and >70 degrees were judged as sacral and lumbar type, respectively (Fig. 3).

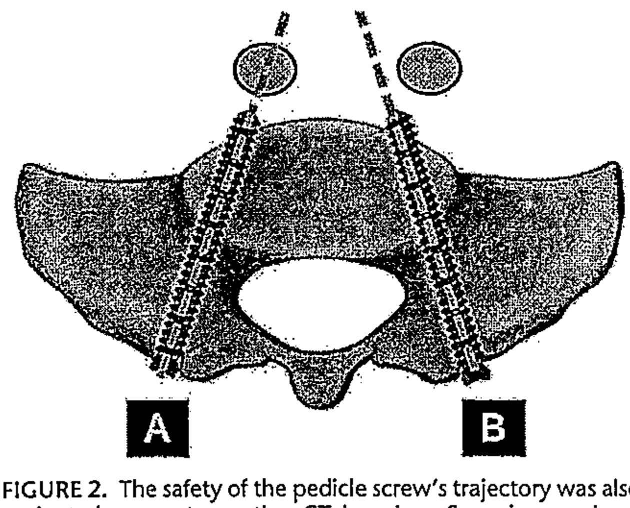

FIGURE 2. The safety of the pedicle screw's trajectory was also evaluated on postoperative CT imaging. Screwing carries a high-risk factor whenever a screw and an iliac artery come into contact (A, screw), but the risk is low when the iliac artery and screw trajectory make no contact (B, screw). Circles represent blood vessels (common iliac artery and vein).

RESULTS

Clinical Outcome

The demographic characteristics for patients are shown in Table 1. Among the 98 TF patients and 33 non-TF patients there were no significant differences in demographic characteristics. Over both groups, the average ratio of recovery of JOA score was 71.3%. No patients exhibited serious neurological complications or iliac vascular injury. Disturbance of adjacent segments after lumbosacral fusion necessitating reoperation occurred in 3 cases (2 TF and 1 non-TF). All 3 cases were fused at L4–S1, as the L3/4 disks were impaired. Adding on fracture was present in 1 case, and 1 patient suffered infection accompanied with meningitis 4 years after the operation.

For TF patients, the JOA score increased from 13.4 at surgery to 24.9 at final follow-up, and the recovery rate was 73.7%. For non-TF patients, the JOA score increased from 13.8 to 23.8, and the recovery rate was 64.2%. Patient recovery rate for TF was high compared with non-TF, although this difference was not significant.

Pseudoarthrosis of the fused L5/S1 occurred in 3 cases in which the lumbosacral vertebrae were not fixed by TF. These cases were fused at L3–S1, L4–S1, and L5–S1, respectively; the screws had become loosened by surrounding osteolytic change, with 1 case requiring reoperation. Pseudoarthrosis of fused vertebrae at other level (L4/5) occurred in 2 cases fixed by non-tricortical technique. The recovery rate of JOA score in these 3 cases

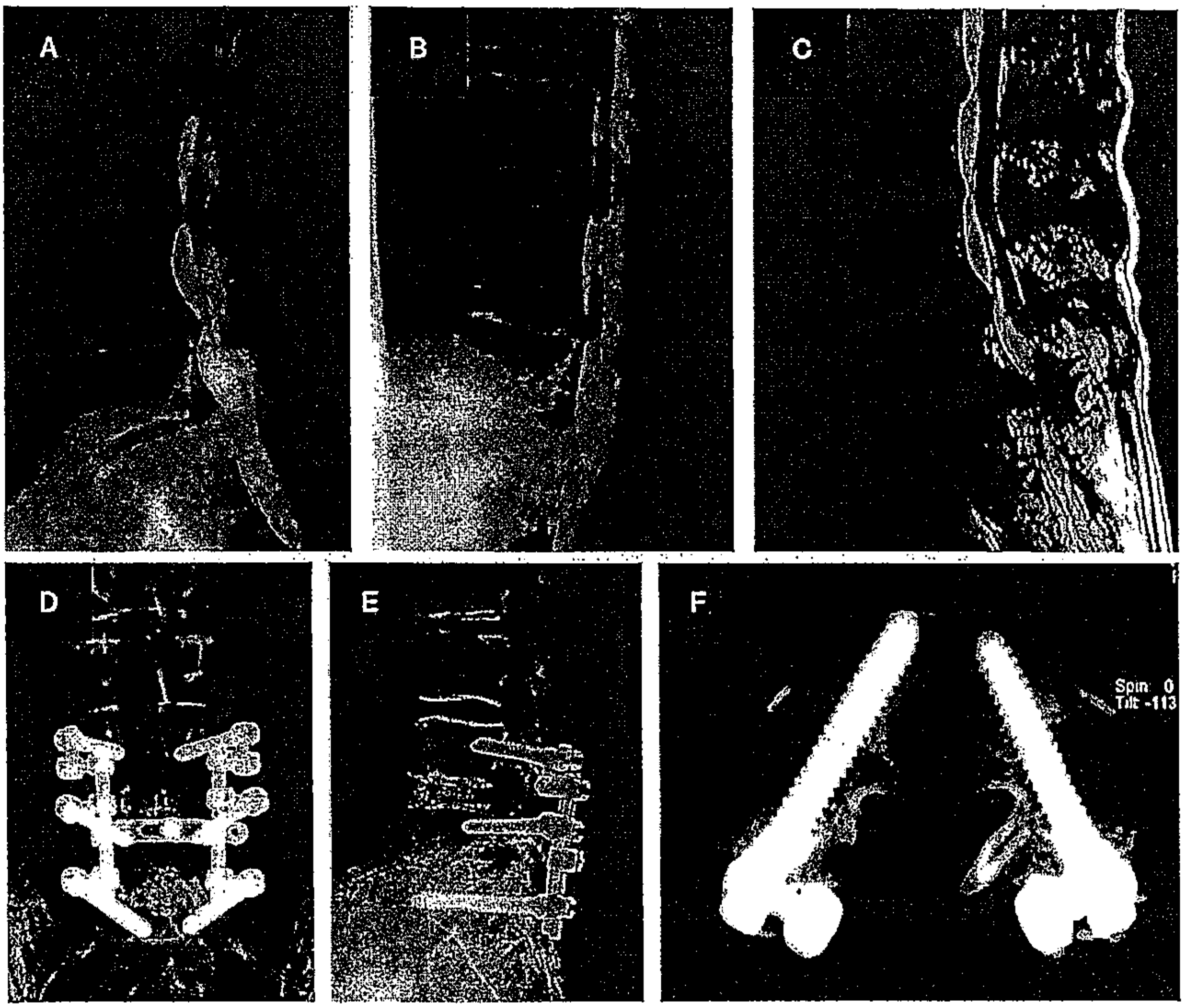

FIGURE 3. A 67-year-old woman with L4 degenerative spondylolisthesis and L5/S1 degenerative disk underwent L4–S1 transforaminal lumbar interbody fusion. Preoperatively, she had pain in the right lower limb and lower back. The lumbosacrum was fixed using the tricortical method. The JOA score was 19 preoperatively and 28 postoperatively. A and B, Preoperative myelogram (A, extension; B, flexion). C, Preoperative T2-weighted MR image (sagittal plane). D and E, Postoperative plain roentgenogram (D, AP view; E, lateral view). F, Postoperative CT image.

of pseudoarthrosis of the fused L5/S1 in non-TF patients was 31.3%, which was significantly lower than that of cases without lumbosacral nonunion.

Characteristics and Safety of Pedicle Screwing

Screw length was 45.0 and 38.9 mm, and diameter 6.9 and 6.8 mm, in TF and non-TF, respectively, that is, there were no significant difference between groups. However, there was a significant difference in the angle of the screw (TF, 22.0 degrees; non-TF, 16.1 degrees). To achieve tricortical screwing, the surgeons performed partial resection of the ilium in 29 TF cases (29.6% of all TF cases), and this was considered to have resulted in securing a deeper angle for implant trajectory. Evaluation of the penetration of the anterior cortex of the sacrum by the S1 screw revealed that the right side was penetrated in 80 TF and 29 non-TF cases, the left side in 81 TF and 30 non-TF cases, and bilaterally in 77 TF and 29 non-TF cases. The prevalence of penetration through the anterior sacral cortex with the S1 pedicle screw was lower in TF than in non-TF (78% and 87%, respectively). Table 2 summarizes the characteristics of pedicle screwing.

In TF, the trajectory of the S1 pedicle screw put 26 cases at risk of vascular injury (26.5%), whereas 15 non-TF cases (45.4%) were at risk. Significantly fewer TF cases encountered the risk of injured vascular tissue compared with non-TF (Table 3).

Loss of Lordosis

Postoperative loss of lordosis was present in 23 patients, with an incidence of 19%. Factors examined in stepwise analysis were age, sex, implementation of TF,

TABLE 1. Demographic Characteristics

Characteristic	Group TF (98 cases)	Group Non-TF (33 cases)
Age (y)	56.1 (15.6)	57.7 (13.4)
Sex (male/female)	60/38	20/13
Preoperative JOA score (points)	13.4 (4.2)	13.8 (4.1)
Time of operation (min)	289 (90.1)	305 (106)
Blood loss during operation (mL)	868 (491)	884 (467)
Follow-up period (mo)	30 (8.5)	34 (9.9)
No. fused segment	1.7 (0.95)	1.7 (0.89)
Sagittal balance (mm)	45.9 (41.1)	39.6 (44.4)
Depth of L5 within pelvis (case)		
Fair	62	19*
Deep	25	12
Shallow	11	2
Form of promontory (case)		
Sacral type	87	17
Lumbar type	11	16*

Values are mean (SD).
*Significant difference in comparison with group TF.
TF indicates tricortical fixation.

sagittal alignment of total spine, correction of L5/S1 disk angle, and depth of L5 within the pelvis. The implant angle, length, and diameter of the S1 pedicle screw, and achieving anterior sacral cortical penetration by the S1 pedicle screw in TF were not significant risk factors. Table 4 shows the adjusted effect estimates [odds ratio (OR)] for the final predictive model as determined by multivariate logistic analysis. Nonimplementation of TF (OR, 3.37) and correction of the L5/S1 disk angle (OR, 1.11) were significant risk factors for postoperative loss of lordosis. These findings demonstrate that the implementation of TF decreases the occurrence of postoperative loss of lordosis.

DISCUSSION

As lumbosacral fixation techniques and their related theories have continued to develop, several studies have reported various instrumentation strategies for lumbosacral fixation and the use of anterior grafts, anterior instrumentation, supplementary points of sacral fixation, or iliac extension to improve stabilization of the lumbosacral junction. However, increasing the level of internal fixation may increase implant-related complications. Methods to expand an anchor to the ilium feature longer lever arms but are associated with the problems of iliac implant breakage or sacroiliac joint arthritis and pain.[15] Bulky implants are associated with prominent and painful hardware.[16,17] Placement of an intrasacral rod through the S1 screw into the ala of the sacrum, as reported by Jackson, is a complicated operative technique.[18] To achieve solid arthrodesis in long fusion to the sacrum, such as that required for the treatment of neuromuscular scoliosis and severe degenerative scoliosis and in patients with severe osteoporosis, fixation to expand an anchor to the ilium may be needed. However, an S1 pedicle screw system alone is ideal for short-segment fixation of the lumbosacral spine.

The present study revealed that TF effectively enhanced the postoperative stability of lumbosacral reconstruction in patients with short-segment fusion. In this method, which does not require a complex surgical technique, the lumbosacral spine is fixed by an independent sacral anchor. This fixation technique may be useful as an alternative to the standard bicortical approach. One principal reason for the biomechanical superiority of S1 pedicle screw fixation, using the tricortical technique, over unicortical or bicortical fixation is that the bone mineral density (BMD) of the sacral promontory is higher than that of other S1 body layers and the bone in the lateral sacral alar region.[19] It has been reported that BMD is a useful preoperative predictor of sacral screw fixation strength. With increase in BMD comes an increase in screw insertion torque and potentially, a subsequent increase in screw pullout strength after cyclic loading.[20–22] Lehman et al[13] reported that TF doubled the insertional torque of the classic bicortical technique. In this study, pseudoarthrosis of the fused L5/S1 did not occur in cases of lumbosacral vertebrae with TF, and we assume it did not occur due to strong fixation of the lumbosacral spine. Furthermore, in cases of the lumbosacral joint being fused by the tricortical technique, postoperative lumbar lordosis was maintained. Many studies have shown the negative effects of reduced lumbar lordosis with a fixed spine after spinal instrumentation.[23–25] Optimal lumbar lordosis prevents the anticipated progression of degenerative change that follows lumbar spine-instrumented fusion. Pseudoarthrosis

TABLE 2. Characteristics of Pedicle Screwing

Characteristic	Group TF		Group Non-TF	
	Right	Left	Right	Left
Screw length (mm)	45 (4.8)	45 (4.5)	38.5 (4.3)	39 (5.3)
Screw diameter (mm)	7.0 (0.2)	6.9 (0.2)	6.8 (0.2)	6.8 (0.2)
Angle of screw (deg.)	22.2 (4.7)	21.8 (5.2)	16.1 (3.8)*	16 (2.4)*
Fenestration of anterior cortex (case)	80	81	29	30

Values are mean (SD).
*Significant difference in comparison with group TF.
TF indicates tricortical fixation.

TABLE 3. Risk of Vascular Injury*

Risk	Group TF	Group Non-TF
Risk (+)	26	15
Risk (−)	72	18

Values are case.
*Significant difference by the χ^2 tests.
TF indicates tricortical fixation.

of the fused L4/5 occurred in 2 cases wherein the lumbosacral vertebrae were not fused by TF. This occurrence might be attributable to nonstrong fixation and the loss of fused lumbar lordosis, both of which can result in the screw loosening. TF can reduce the pseudoarthrosis of the fused spine and the postoperative lumbar lordosis that could induce poor clinical outcome, so TF is regarded as a successful technique for lumbosacral fixation.

The structures that surgeons usually put at risk while implanting S1 pedicle screws include the common iliac artery and vein, the L5 nerve root, the colon, and the sympathetic chain.[10,26,27] The classic trajectory is described as paralleling the S1 endplate with the appropriate medial convergence necessary to avoid the common iliac vessels located on the anterior surface of the sacrum. Several studies have suggested that anteromedial screw placement also provides a larger "safe zone" for avoiding neurological injury.[1,28] Furthermore, while implanting bicortical S1 pedicle screws, the surgeon must penetrate the sacral anterior cortex to obtain sufficient biomechanical strength, yet this procedure of penetration might enhance the risk that the screws will cause neurovascular injuries. Therefore, we wanted to confirm that the trajectory of tricortical screwing is more convergent than that of classic screwing as well as to examine whether penetrating the sacral anterior cortical bone is necessary for implanting tricortical S1 screws. The present study showed that the screw trajectory in TF is more convergent and incurs a lower risk of vascular injury. In addition, the strength of fixation obtained by the tricortical technique, which provides sufficient purchase in the hard sacral promontory, is such that it is not always necessary for the screw to penetrate the anterior cortex. In contrast, the bicortical method requires that the screw penetrate the anterior cortex, thus increasing the risk of vascular injury.

TABLE 4. Risk Factors for Postoperative Loss of Lordosis

Variables	OR (95% CI)	P
Age	1.02 (0.56–4.2)	0.22
Men (vs. women)	0.97 (0.93–1.01)	0.39
Non-TF (vs. TF)	3.37 (1.24–9.26)	0.016*
Sagittal balance	1.05 (0.99–1.01)	0.41
Correction of L5/S1 disk angle	1.11 (1.03–1.2)	0.033*
Deep-seated L5	0.6 (0.24–1.42)	0.252

*Significant difference.
CI indicates confidence interval; OR, adjusted odds ratio; TF, tricortical fixation.

The tricortical method is therefore beneficial by reducing the risk of neurovascular injury.

Compared with conventional fixation (unicortical and bicortical), tricortical purchase requires accurate targeting of the apex with the exact length of screw, which is time consuming and technically difficult. Use of transparent lateral imaging and partial resection of the ilium to obtain a proper implant angle for the screw are keys to success. Kaptanoglu et al[29] suggested that the level of iliac resection should be decided preoperatively by evaluating CT scans acquired parallel to the trajectory of the S1 screws. In this study, 98 patients (74.8%) were fused by TF, of which approximately one third required partial resection of the ilium for an appropriate implant angle to be achieved. Ota et al[30] reported that the paraspinal approach can lead to easier placement of medially oriented screws. TF may be regarded as an implant method that is not technically difficult using the above techniques.

There are some limitations to this study: the first and major being that it was retrospective. This study was not a precise comparative study and may include bias. A prospective comparative study would be necessary to demonstrate the efficacy of TF. The present study demonstrated that TF effectively enhances the postoperative stability of lumbosacral reconstruction in patients with relatively short-segment fusion. Failure to achieve solid arthrodesis in long fusion, including the lumbosacral junction, continues to be a significant clinical problem. Further research is needed to determine the effectiveness of a combination of TF and other spinopelvic fixation (ie, Jackson technique or iliac screw fixation) for long fusions to the sacrum, such as those required for treatment of neuromuscular scoliosis and severe degenerative scoliosis and in patients with severe osteoporosis.

CONCLUSIONS

TF enhanced postoperative stability at the lumbosacral junction in patients who underwent short-segment lumbosacral fusion. This study demonstrated that pseudoarthrosis did not occur in patients after TF, in comparison with those undergoing non-TF; tricortical screwing carries a lower risk of vascular injury. TF is regarded as a successful technique in lumbosacral fixation.

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Spine

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Cervical Disc Protrusion Correlates With the Severity of Cervical Disc Degeneration

A Cross-Sectional Study of 1211 Relatively Healthy Volunteers

Hiroaki Nakashima, MD,* Yasutsugu Yukawa, MD,† Kota Suda, MD,‡ Masatsune Yamagata, MD,§ Takayoshi Ueta, MD,¶ and Fumihiko Kato, MD†

Study Design. Cross-sectional study.

Objective. The purposes of this study were (1) to investigate the frequency and degree of cervical disc degeneration and protrusion on cervical spine magnetic resonance (MR) images and (2) to analyze the correlation between the severity of disc degeneration and disc protrusion.

Summary of Background Data. Cervical disc degenerative changes or protrusion is commonly observed on MR images in healthy subjects. However, there are few large-scale studies, and the frequency and range of these findings in healthy subjects have not been clarified. Moreover, there are no reports regarding the correlation between cervical disc degeneration and disc protrusion.

Methods. Cervical disc degeneration and protrusion were prospectively measured using magnetic resonance imaging in 1211 relatively healthy volunteers. These included at least 100 males and 100 females in each decade of life between the 20s and the 70s. Cervical disc degeneration was defined according to the modified Pfirrmann classification system, and the amount of disc protrusion was evaluated using the anteroposterior diameter of disc protrusion on sagittal MR image.

Results. Mild disc degeneration was very common, including 98.0% of both sexes in their 20s. The severity of cervical disc degeneration significantly increased with age in both sexes at every level. The disc degeneration predominantly occurred at C5–C6 and C6–C7. The difference between sexes was not significant except for individuals in their 50s. The average anteroposterior diameter of disc protrusion increased with aging, especially from the 20s to the 40s. The anteroposterior diameter of disc protrusion increased with a progression in the disc degeneration grade.

Conclusion. Cervical disc degeneration and protrusion were frequently observed in healthy subjects even in their 20s and deteriorated with age. Cervical disc protrusion was significantly correlated with cervical disc degeneration, and spatial cervical disc protrusion was affected by biochemical degenerative changes as observed on MR images.

Key words: cervical, disc degeneration, disc protrusion, asymptomatic, magnetic resonance images, cross-sectional study, aging.

Level of Evidence: 2

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From the *Department of Orthopedic Surgery, Nagoya University Graduate School of Medicine, Nagoya, Japan; †Department of Orthopedic Surgery, Chubu Rosai Hospital, Nagoya, Japan; ‡Department of Orthopedic Surgery, Hokkaido Chuo Rosai Hospital Sekison Center, Hokkaido, Japan; §Department of Orthopedic Surgery, Chiba Rosai Hospital, Chiba, Japan; and ¶Department of Orthopedic Surgery, Spinal Injuries Center, Izuka, Japan.

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Address correspondence and reprint requests to Hiroaki Nakashima, MD, Department of Orthopedic Surgery, Nagoya University Graduate School of Medicine, 65 Tsurumai, Shouwa-ku, Nagoya, Aichi 466-8560, Japan; E-mail: hirospine@gmail.com

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The human intervertebral disc forms a fibrocartilaginous joint between the vertebrae. The intervertebral disc consists of 3 distinct components, including the nucleus pulposus, the annulus fibrosis, and the cartilaginous endplates.[1] Progressive morphologic and cellular changes occur with age and degeneration in intervertebral discs.[2,3] Biochemically, proteoglycan fragmentation increases with aging, and the overall proteoglycan and water content of the disc decreases, especially in the nucleus.[2,3]

Magnetic resonance imaging (MRI) provides a noninvasive morphologic evaluation of the cervical spine. The signal intensity of the disc on magnetic resonance (MR) image is indicative of the chemical composition and likely histological changes.[4,5] The reduction of signal intensity on T2-weighted MR image correlates with progressive degenerative changes of the intervertebral disc.[5] The brightness of the nucleus correlates particularly well with the proteoglycan concentration of the disc.[4] Although these degenerative changes in the cervical disc are often seen on MR image in healthy subjects,[6,7] some of them could be pathological, leading to associated clinical symptoms. It is difficult to distinguish between aging discs and pathologically degenerated discs that lead to clinical symptoms. Thus, it is crucial to analyze the frequency and range of degenerative changes observed on MR images in healthy subjects.

As well as signal intensity changes in the disc, disc protrusion is also frequently observed with aging. "Protrusion" is commonly used in a nonspecific general sense to signify any displacement of the disc.[8,9] A disc herniation, on the contrary, results when a crack in the outer layer of cartilage allows some of the inner fragmented annulus, nucleus, cartilage, and fragmented apophyseal bone to protrude out of the disc.[8–10] Disc herniation is usually a further development of a previously existing disc protrusion.[11]

Cervical compressive myelopathy is one of the most common causes of neurological symptoms associated with the cervical spine.[12] Disc protrusion has been suspected to initiate cervical spinal cord compression.[7] However, to our knowledge, there are no data about whether this spatial disc protrusion has any correlation with biochemical disc degeneration (DD).

The primary aim of this study was to prospectively investigate the frequency and range of cervical DD and protrusion observed on cervical spine MR image in a large cohort of relatively healthy volunteers. We also analyzed the correlation between the severity of DD and the spatial changes associated with disc protrusion and then evaluated the influence of DD on disc protrusion.

MATERIALS AND METHODS

A total of 1230 relatively healthy volunteers were examined by cervical spine MRI between February 2006 and February 2008. The subjects were relatively healthy volunteers without neurological symptoms, and the subjects recruited were approximately 100 males and 100 females in each decade of life between 20 and 79 years of age (Table 1).[13] We recruited the subjects by using newspaper advertisements and posters in facilities having some sort of relationship with our hospital. Thus, the majority of subjects were not patients at our hospital but relatively healthy residents of the area. The exclusion criteria included a history of brain or spinal surgery, comorbid neurological disease (*e.g.*, cerebral infarction or neuropathy), symptoms related to sensory or motor disorders (numbness, clumsiness, motor weakness, or gait disturbances), or severe neck pain. We excluded pregnant females, individuals who received workmen's compensation, and those who presented with the symptoms after a motor vehicle accident. Subjects with other comorbidities (smoking, diabetes, hypertension, and others) were included in this study. The institutional review board approved this study, and each patient signed a written consent form.

All participants underwent imaging analysis by 2 spinal surgeons (F.K. and K.S.). Finally, The MRI data from 1211 subjects were included in this analysis, after excluding 19 subjects with measurement difficulties resulting from artifacts, such as motion artifacts or the presence of metals. The MR images were obtained with a 1.5-Tesla superconductive magnet (Signa Horizon Excite HD version 12; GE Healthcare, Britain, United Kingdom). The images were obtained at a slice thickness of 3 mm in the sagittal plane. T2-weighted images (fast spin echo TR, 3500 ms; TE, 102 ms) were obtained in sagittal images. All images were transferred to a computer as Digital Imaging and Communications in Medicine data to measure the anteroposterior (AP) diameter of disc protrusion using imaging software (Osiris 4; Icestar Media Ltd, Essex, United Kingdom). We used a slice in which the disc protrusion was most prominent in the sagittal images and measured the AP diameter of disc protrusion. The posterior aspect line between the rostral and caudal vertebral body was used as the standard, and we measured the AP diameter of the disc protrusion from the standard line to the posterior top of the disc protrusion (Figure 1). Cervical DD was defined according to the modified Pfirrmann classification system (Figure 2).[4] To facilitate comparison of the severity of DD between decades or sexes, a total score of DD (DD score) at the 6 levels (from C2–C3 to C7–T1) was calculated by the summation of individual Pfirrmann scores at each level.

Statistical Analysis

Fisher exact test was used to compare the differences between decades and sexes in DD scores. The Jonckheere-Terpstra trend test was used to assess whether the AP diameter of disc protrusion increased depending on DD severity and is indicated by a letter "trend," followed by a *P* value. A *P* value of less than 0.05 was considered statistically significant. All analyses were conducted using SPSS version 21 (SPSS, Chicago, IL).

RESULTS

The severity of cervical DD increased with age at every level in both sexes (Figure 3). Mild DD was observed in the 20s (98% in both sexes). Although grade VI DD was not identified in the 20s and the 30s, it appeared after the 40s and then increased further with age. The C5–C6 and C6–C7 discs were the first and second most severely degenerated discs in every decade.

TABLE 1. Age and Sex of 1211 Asymptomatic Subjects

Age (yr)	20–29	30–39	40–49	50–59	60–69	70–79	Total
Male	101	104	100	99	101	101	606
Female	100	99	100	103	103	100	605

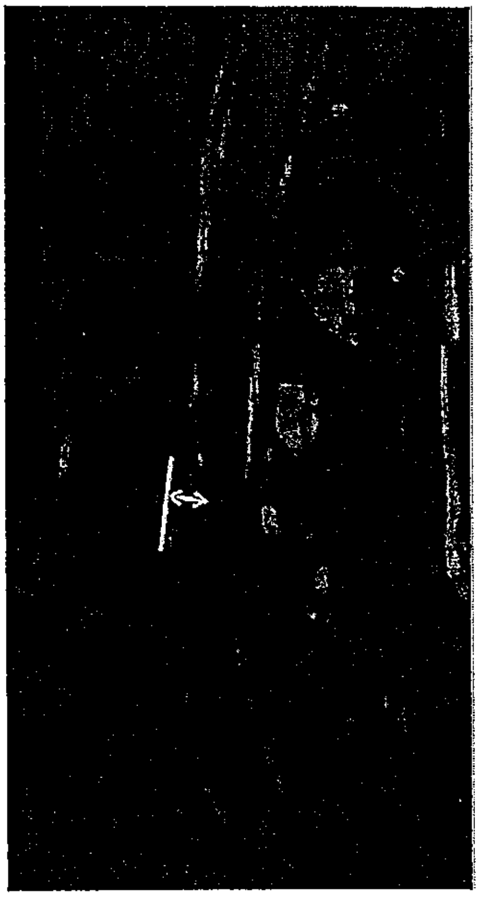

Figure 1. The measurement method for the anteroposterior diameter of the disc protrusion on magnetic resonance image. The posterior aspect line between the rostral and caudal vertebral body was used as the standard, and we measured the anteroposterior diameter of the disc protrusion from the standard line to the posterior top of the disc protrusion (white double arrow).

The DD score increased with age in both sexes (Figure 4). A DD score of 6 (the minimal score) was found only in the 20s. A DD score of 13 or more was found in more than half of the cases belonging to the 50s or older age groups. The total score was 13 or more in more than 95% of the cases in the 70s. The number of DD scores of 13 or more significantly increased with aging ($P < 0.05$ to $P < 0.001$), and the amount of the increase was very significant from the 20s to the 50s ($P < 0.005$). The difference between sexes was significant only in the 50s ($P = 0.03$), in which a DD score of 13 or more was more frequent in males.

The average AP diameter of disc protrusion increased with aging, especially from the 20s to the 40s (Figure 5). The disc protrusion at C5–C6 was most prominent, and the disc protrusion at C6–C7 was second most prominent in all decades and both sexes. On the contrary, the disc at C2–C3 protruded the least.

The relationship between the severity of DD and disc protrusion is shown in Figure 6. The AP diameter of cervical disc protrusion increased with a progression in the DD grade ($P < 0.05$ to $P < 0.001$).

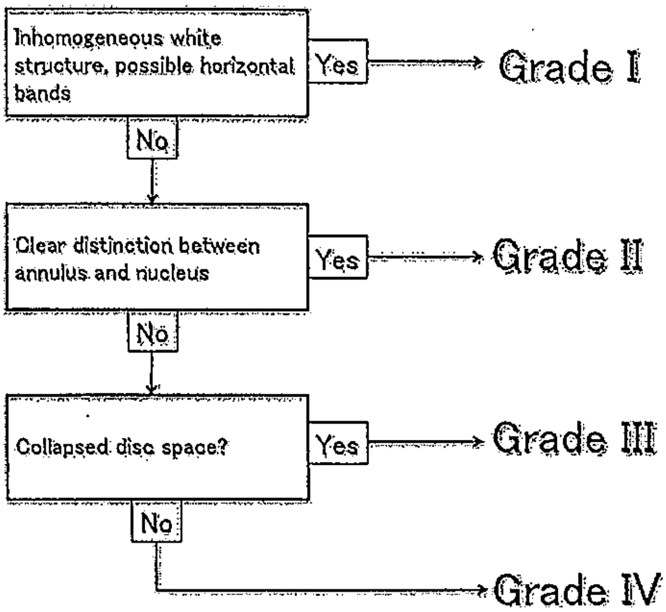

Figure 2. Algorithm for the grading system and assessment of cervical disc degeneration grade using the modified Pfirrmann classification system.

DISCUSSION

This largest cross-sectional study of cervical MR images in relatively healthy subjects showed that (1) mild cervical DD and protrusion started in the 20s, (2) cervical DD and protrusion progressed with age, especially from the 20s to the 50s, mainly at C5–C6 and C6–C7, and (3) the degree of cervical disc protrusion was significantly correlated with the severity of DD.

Cervical DD and protrusion are some of the abnormal findings most commonly seen on MR images in relatively healthy subjects, and they are frequently observed in subjects aged 40 to 50 years.[6,7] These degenerative changes, which occur throughout life, have been biochemically analyzed.[2,3] Proteoglycan fragmentation starts during childhood, and the overall proteoglycan and water content of the disc decreases with increasing age, especially in the nucleus.[2,3] These changes are enhanced by adverse genetic, biomechanical, and nutritional factors.[3]

The reduction of signal intensity on T2-weighted MR image correlates with the progressive degenerative changes of the intervertebral discs.[5] The brightness of the nucleus correlates particularly well with the proteoglycan concentration.[4] These indicators of DD on MR image are observed even in a younger population; Matsumoto *et al*[7] reported 17% and 12% prevalence in males and females in their 20s, respectively, and Boden *et al*[6] reported 8% in patients younger than 40 years. In the present largest cohort study, mild DD of at least 1 level was observed in 98% of both sexes in their 20s. DD was identified more frequently in subjects in their 20s than we previously expected, although evaluation methods of DD were different across studies. Several reports mentioned that lumbar discs in males were more degenerated than those in females,[14–16] but there were few differences in

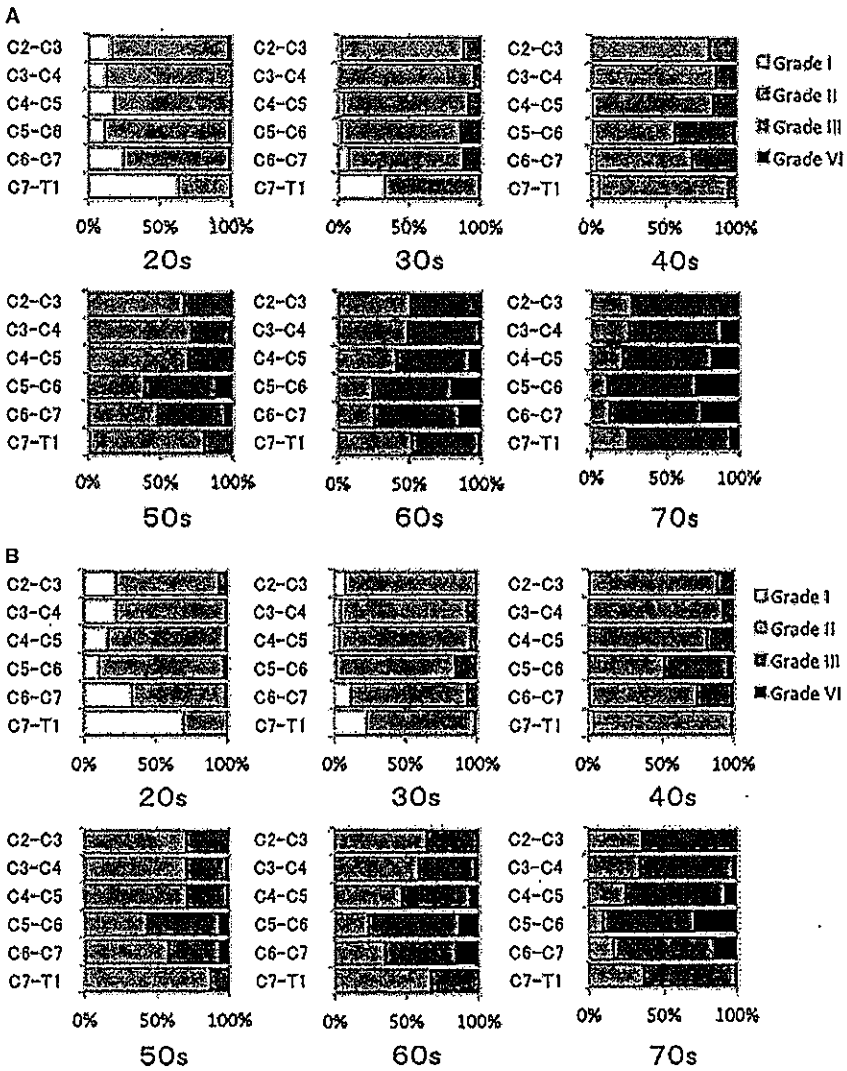

Figure 3. Cervical disc degeneration using the modified Pfirrmann classification system in each decade in (A) males and (B) females.

cervical discs. We think that the differences between lumbar and cervical disc changes are due to sex-related differences in the loading of the discs based on weight or profession. Further studies are needed to elucidate the different prevalence of DD dependent on sex between the cervical and lumbar spine.

Disc protrusion starts from an annulus tear, and this tear allows gross migration of the nucleus.[2] Disc protrusion has been simulated in cadaveric discs, and mechanically induced prolapse occurs most in discs from patients aged 30 to 40 years.[17] It is difficult to induce disc protrusion in severely degenerated discs in the laboratory. It has been

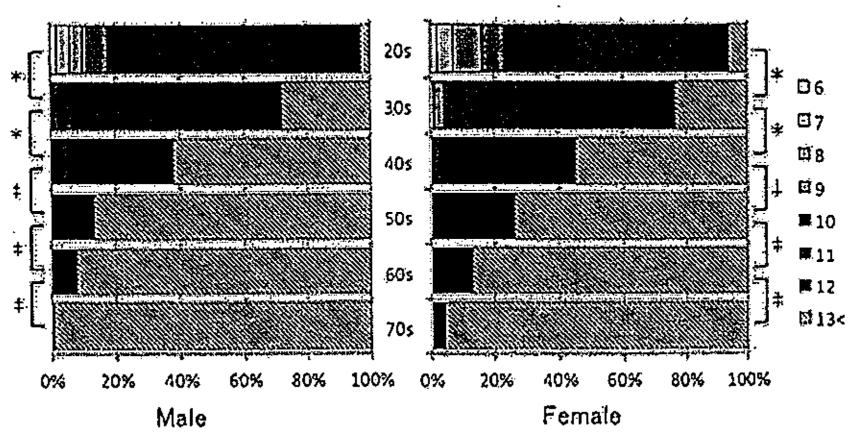

Figure 4. Disc degeneration scores in each decade and sex. $^{*}P < 0.05$; $^{\dagger}P < 0.005$; $^{\ddagger}P < 0.001$.

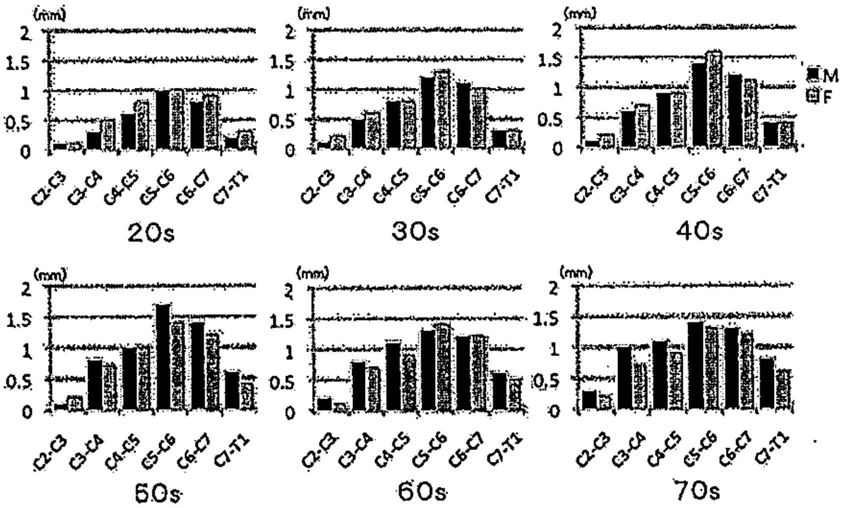

Figure 5. Mean anteroposterior diameter of cervical disc protrusion in each sex. M indicates male; F, female.

suggested that this is because the nucleus is no longer able to exert hydrostatic pressure on the annulus.[2,17] However, the amount of disc protrusion was significantly larger in the severely degenerated discs in the current study. Proteoglycan works as a resistance against compression forces.[3] Discs might protrude further if relatively large vertical forces were loaded onto severely degenerated discs. Thus, cervical disc protrusion was highly correlated with biochemical degeneration in the disc.

There were some limitations to the present study. First, the survey was limited to the Japanese population, so racial differences were not taken into account. Second, only relatively healthy subjects were enrolled in this study. This could have led to a selection bias in favor of relatively healthy participants. Third, we compared different individuals between ages because this study was cross-sectional rather than longitudinal. Fourth, although the subjects were all relatively healthy, some had pathological backgrounds or occasional mild neck pain, and these pathological or mild symptomatic backgrounds could affect the results. Fifth, the MR images were not evaluated by radiologists but spine surgeons. This might have affected the sensitivity and specificity of the radiographical evaluation. Sixth, the AP diameter of the disc protrusion was measured in sagittal images to reduce interobserver measurement error. This was because, in the axial images, the location of the anterior standard point from which the AP diameter was measured differed from observer to observer. Care must be taken when the measurement data are used in future because the AP diameters measured in axial and sagittal images are different.

In conclusion, this large-scale cross-sectional analysis of cervical spine MRI data in healthy subjects demonstrates that cervical DD and protrusion occur more frequently at an earlier age than what was previously reported. Spatial disc protrusion is highly correlated with the progression of DD. By comparing the DD and protrusion data from the relatively healthy subjects in this study with that of symptomatic patients in future, we think that the current data in relatively healthy volunteers could be helpful for determining the DD pattern resulting in symptoms.

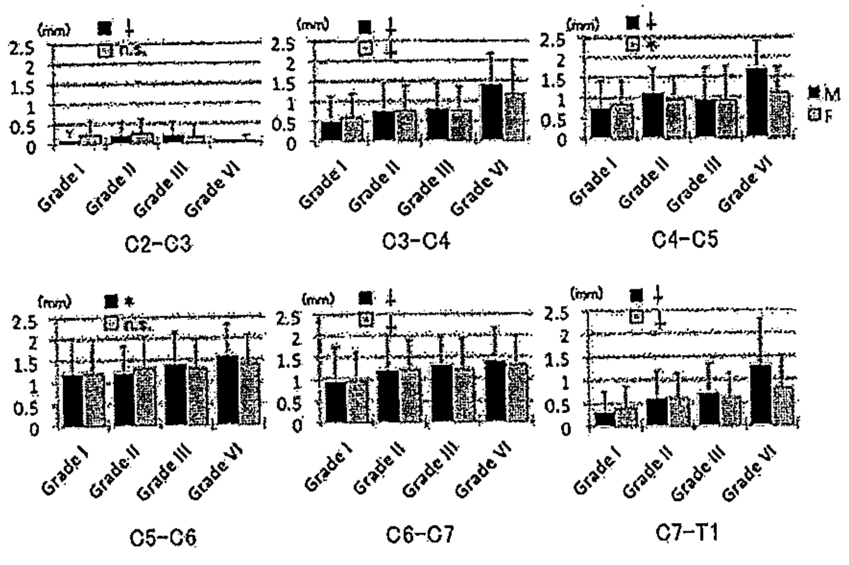

Figure 6. Mean anteroposterior diameter of cervical disc protrusion in each cervical disc degeneration grade at each level. Values are mean ± SD. *$P < 0.05$; †$P < 0.001$. M indicates male; F, female; ns, not significant.

Key Points

- Cervical disc degeneration and protrusion were evaluated on cervical MR images of 1211 relatively healthy volunteers.
- Mild cervical disc degeneration of at least 1 level was observed in 98% of healthy subjects in their 20s, and it progressed with aging.
- The average amount of cervical disc protrusion increased with aging, especially from the 20s to the 40s.
- Both cervical disc degeneration and protrusion were predominantly observed at the C5–C6 and C6–C7 levels.
- The degree of cervical disc protrusion was significantly correlated with the severity of disc degeneration as observed on MR image.

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Spine

SPINE Volume 41, Number 9, pp 764–771

CLINICAL CASE SERIES

A Study of Risk Factors for Tracheostomy in Patients With a Cervical Spinal Cord Injury

Jun Tanaka, MD,* Itaru Yugue, MD, PhD,† Keiichiro Shiba, MD, PhD,† Akira Maeyama, MD, PhD,* and Masatoshi Naito, MD, PhD*

Study Design. A retrospective, consecutive case series.
Objective. To determine the risk factors for a tracheostomy in patients with a cervical spinal cord injury.
Summary and Background Date. Respiratory status cannot be stabilized in patients with a cervical spinal cord injury (CSCI) for various reasons, so a number of these patients require long-term respiratory care and a tracheostomy. Various studies have described risk factors for a tracheostomy, but none have indicated a relationship between imaging assessment and the need for a tracheostomy. The current study used imaging assessment and other approaches to assess and examine the risk factors for a tracheostomy in patients with a CSCI.
Methods. Subjects were 199 patients who were treated at the Spinal Injuries Center within 72 hours of a CSCI over 8-year period. Risk factors for a tracheostomy were retrospectively studied. Patients were assessed in terms of 10 items: age, sex, the presence of a vertebral fracture or dislocation, ASIA Impairment Scale, the neurological level of injury (NLI), PaO_2, $PaCO_2$, the level of injury on magnetic resonance imaging (MRI), the presence of hematoma-like changes (a hypointense core surrounded by a hyperintense rim in T2-weighted images) on MRI, and the Injury Severity Score.
Items were analyzed multivariate logistic regression, and $P<0.05$ was considered to indicate a significant difference.
Results. Twenty-three of the 199 patients required a tracheostomy, accounting for 11.6% of patients with a CSCI. Univariate analyses of the risk factors for tracheostomy revealed significant differences for six items: age, Injury Severity Score, presence of fracture or dislocation, ASIA Impairment Scale A, NLI C4 or above, and MRI scans revealing hematoma-like changes. Multivariate logistic regression analyses revealed significant differences in terms of two items: NLI C4 or above and MRI scans revealing hematoma-like changes. Thirty patients had both an NLI C4 or above and MRI scans revealing hematoma-like changes. Of these, 17 (56.7%) required a tracheostomy.
Conclusion. Patients with an NLI C4 or above and MRI scans revealing hematoma-like changes were likely to require a tracheostomy. An early tracheostomy should be considered for patients with both of these characteristics.
Key words: arterial blood gases, ASIA impairment scale, cervical spinal cord injury, hematoma-like changes on magnetic resonance imaging, imaging assessment, injury severity score, neurological level of injury, risk factors, tracheostomy, vertebral fracture or dislocation.
Level of Evidence: 3
Spine 2016;41:764–771

Respiratory status cannot be stabilized in patients with a cervical spinal cord injury (CSCI) for various reasons, so a number of these patients require long-term respiratory care and a tracheostomy. Numerous studies have reported that respiratory dysfunction is closely associated with morbidity and mortality in CSCI,[1–3] and respiratory dysfunction leads to massive financial expenses.[3] The cause of death for patients with a CSCI is often a urinary complication or a respiratory complication.[4,5] A recent study from abroad has reported that respiratory complications represent the leading cause of death in patients with a CSCI,[5] and the same is true in Japan.[4]

In the acute phase of CSCI, spinal shock can have an effect and the patient's respiratory status might be unstable, so temporary ventilator management is often required.[6–16] If the patient's respiratory status fails to improve with temporary ventilator management and long-term intubation is required, a tracheostomy is often performed. Performing a tracheostomy early on is known to be useful in reducing respiratory complications, as various studies have reported[6,9,16–18]; however, unnecessary intubation and unnecessary tracheostomies are known to increase

From the *Faculty of Medicine, Department of Orthopaedic Surgery, Fukuoka University; and †Department of Orthopaedic Surgery, Spinal Injuries Center, Iizuka city, Fukuoka, Japan.

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Address correspondence and reprint requests to Jun Tanaka, MD, Faculty of Medicine, Department of Orthopaedic Surgery, Fukuoka University, 7-45-1 Nanakuma, Jonan-ku, Fukuoka 814-0180, Japan;
E-mail: jt0120jt@gmail.com

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the risk of complications in both the short and long term.[9] Exaggerating the usefulness of an early tracheostomy can result in unnecessary tracheal intubation or an unnecessary tracheostomy. Thus, predicting true risk factors for intubation or a tracheostomy in patients with a CSCI is important.

Various studies have described risk factors for a tracheostomy in patients with a CSCI. These include advanced age,[7,12] complete paralysis,[1,6–8,14,17,19–22,23] a high level of neurological paralysis,[6,12,14,21] the patient's general condition prior to the injury and a prior history of lung disease,[1,8,12] a high injury severity score (ISS),[8,17] a history of smoking,[19] and a low forced vital capacity upon admission.[7,9]

Nevertheless, no previous studies have indicated a relationship between imaging assessment (radiographs, computed tomography, or magnetic resonance imaging [MRI]) and the need for a tracheostomy. The current study used imaging assessment and other approaches to assess and examine the risk factors for a tracheostomy in patients with a CSCI.

METHODS

Subjects were 199 patients who were treated by the Department of Orthopedic Surgery of the Spinal Injuries Center within 72 hours of a CSCI over 8-year period from January 1, 2005 to December 31, 2012. Patients consisted of 165 males and 34 females ranging in age from 14 to 91 years with a mean age of 61.9 years.

All patients were examined by two or more physicians and a physical therapist upon admission, and patients were assessed neurologically. In addition, the presence or absence of a vertebral fracture or dislocation was assessed using X-ray films or computed tomography scans and the presence or absence of cord damage was assessed using MRI scans in all patients upon admission. Surgery (anterior spine fusion, posterior spine fusion, or anterior spine fusion and posterior spine fusion,) was performed on patients with apparent spinal instability. Arterial blood gases were measured in all patients upon admission. If patients had apnea or ventilatory failure prior to initial admission and they needed assistance breathing, a tracheostomy was performed on the day of admission. If, however, a patient's respiratory status gradually worsened after admission, intubation was performed at the discretion of the patient's primary physician in accordance with the patient's respiratory status. When long-term ventilator management was considered necessary, a tracheostomy was performed. This Center has not formulated definite standards for intubation and tracheostomy, although blood gas results of PaO_2 70 mm Hg or less and $PaCO_2$ at least 50 mm Hg serve as somewhat of a guide, regardless of whether O_2 is administered.

Medical records, the patient's discharge summary, and imaging findings upon admission and discharge were retrospectively studied.

The following items were studied retrospectively: age, sex, the presence or absence of a vertebral fracture or dislocation at the level of injury, the American Spinal Association (ASIA) Impairment Scale (AIS), the neurological level of injury (NLI), PaO_2 according to a blood gas analysis, $PaCO_2$ according to a blood gas analysis, the level of injury on MRI, hematoma-like changes on MRI (presence or absence of a hypointense core surrounded by a hyperintense rim in T2-weighted images), and the ISS.

Statistical analyses were done using the Jump11 statistical software package from SAS Institute Inc. (Cary, NC).

In instances wherein there was no avulsion fracture of the anterior aspect of the vertebral body or a spinous process fracture in conjunction with a hyperextension injury, no bone injury on MRI scans, and no need for surgery due to the lack of spinal instability, bone injury or dislocation was deemed to be absent. In addition, the NLI was the most caudal segment wherein normal motor and sensory function were intact. If hematoma-like changes were present, the level of those changes served as the level of injury on MRI. If those changes were absent, the segment wherein the center of a wider ranging hyperintensity was located on T2-weighted images served as the level of injury on MRI (Figure 1A, B).

Age, PaO_2, $PaCO_2$, and the ISS were assessed as continuous variables. To increase statistic power, the AIS, the NLI, and the level of injury on MRI were dichotomized as an AIS A or not, an NLI C4 or above or not, and a level of injury on MRI C3/4 or less or not.

RESULTS

A total of 199 patients with a cervical spinal cord injury were treated at this center over 8-year period. Patients consisted of 165 males and 34 females ranging in age from 14 to 91 years with a mean age of 61.9 years. All of the patients had suffered blunt trauma. Sixty patients (30.1%) had a vertebral fracture or dislocation.

The extent of paralysis upon admission was AIS A in 66 patients (33.2%), AIS B in 38 (19.1%), AIS C in 51 (25.6%), and AIS D in 44 (22.1%). The NLI upon admission was C2 in 1 patient (0.5%), C3 in 10 (5.0%), C4 in 90 (45.2%), C5 in 62 (31.2%), C6 in 19 (9.6%), C7 in 6,(3.0%), C8 in 1 (0.5%), and T1 in 10 (5.0%) (Table 1).

All of the patients underwent an MRI upon admission, and hyper-intensity changes on T2-weighted images were noted in all of the patients. The level of injury on MRI was C2/3 in 5 patients (2.5%), C3 in 2 (1.0%), C3/4 in 70 (35.2%), C4 in 4 (2.0%), C4/5 in 49 (24.6%), C5 in 10 (5.0%), C5/6 in 29 (14.6%), C6 in 4 (2.0%), C6/7 in 24 (12.1%), C7 in 1 (0.5%), and C7/T1 in 1 (0.5%). Hematoma-like changes were noted in 46 patients (23.1%) and such changes were not noted in 153 (76.9%) (Table 2).

Twenty-three of the 199 patients required a tracheostomy, accounting for 11.6% of patients with a cervical spinal cord injury. The average time from injury until a tracheostomy was performed was 4.69 days (day of injury–13 days later). Details on the 23 patients who underwent a tracheostomy are indicated below (Table 3).

Eleven patients had a vertebral fracture or dislocation; a bone injury was not noted in 12 patients. Seventeen patients had an AIS A, 4 had AIS B, and 2 had AIS C. The NLI was C2

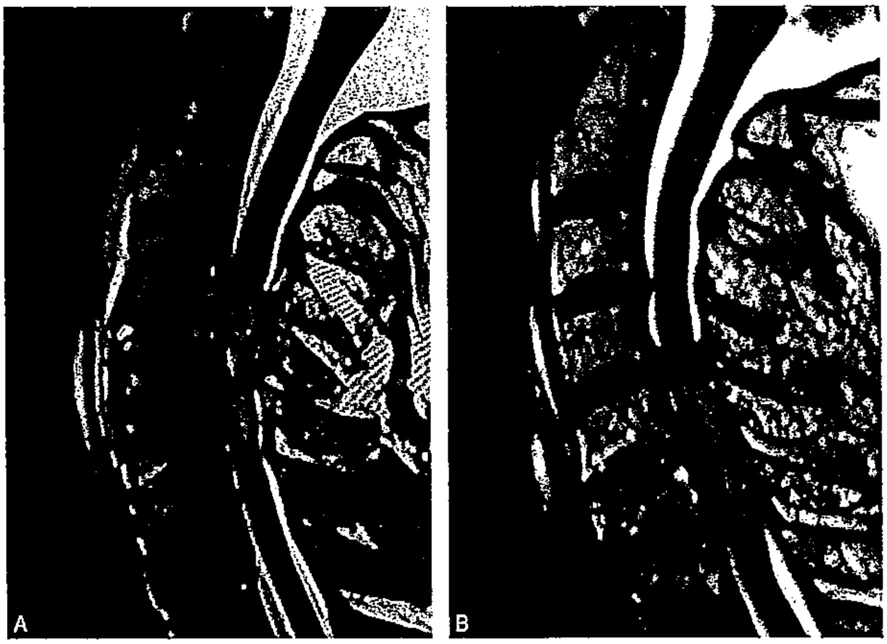

Figure 1. "Hematoma-like changes" and the level of injury on MRI. A, MRI findings of a hypointense core surrounded by a hyperintense rim in a T2-weighted image. We described these changes as "hematoma-like changes." When these changes were present, the level of the changes served as the level of injury on MRI. This patient's level of injury on MRI was "C3/4". B, When hematoma-like changes were absent, the segment containing the center of a wider-ranging hyperintensity area served as the level of injury on MRI. This patient's level of injury on MRI was "C5/6." MRI indicates magnetic resonance imaging.

in 1 patient, C3 in 5, C4 in 15, C5 in 1 and T1 in 1. The level of injury on MRI scans was at C2/3 in 1 patient, at C3/4 in 9, at C4/5 in 7, at C5/6 in 5, and at C6/7 in 1. Hematoma-like changes were noted on MRI images of 17 patients.

The final outcome (state at final follow-up) was death for one patient and permanent ventilator management for seven. The respiratory status of 15 patients stabilized, and they were weaned from the ventilator.

TABLE 1. Patients Demographic Data

Mean ± SD	Overall (n = 199)	Tracheostomy (n = 23)	No Tracheostomy (n = 176)
Age (yrs)	61.9 ± 17.7	69.1 ± 15.8	60.9 ± 17.8
Sex			
Male	165 (82.9%)	17 (73.9%)	148 (84.1%)
Female	34 (17.1%)	6 (26.1%)	28 (15.9%)
Fracture or dislocation			
+	60 (30.1%)	11 (43.5%)	49 (27.8%)
−	139 (69.9%)	12 (56.5%)	127 (72.2%)
Initial AIS			
A	66 (33.2%)	17 (73.9%)	49 (27.8%)
B	38 (19.1%)	4 (17.4%)	34 (19.4%)
C	51 (25.6%)	2 (8.7%)	49 (27.8%)
D	44 (22.1%)	0	44 (25.0%)
Initial NLI			
C2	1 (0.5%)	1 (4.4%)	0
C3	10 (5.0%)	5 (21.7%)	5 (2.8%)
C4	90 (45.2%)	15 (65.3%)	75 (42.6%)
C5	62 (31.2%)	1 (4.4%)	61 (34.7%)
C6	19 (9.6%)	0	19 (10.9%)
C7	6 (3.0%)	0	6 (3.4%)
C8	1 (0.5%)	0	1 (0.5%)
T1	10 (5.0%)	1 (4.4%)	9 (5.1%)
Arterial blood gases			
PO_2 (mm Hg)	91.9 ± 40.7	104.1 ± 71.2	90.3 ± 34.9
PCO_2(mm Hg)	38.3 ± 5.1	39.9 ± 5.4	38.1 ± 5.0
ISS	21.4 ± 10.6	31.7 ± 18.9	20.1 ± 8.2

AIS indicates American Spinal Association impairment scale; ISS, injury severity score; NLI, neurological level of injury; SD, standard deviation.

TABLE 2. Level of Spinal Cord Injury and Hematoma-Like Changes on MRI

	Overall (n=199)	Tracheostomy (n=23)	No tracheostomy (n=176)
Level of spinal cord injury on MRI			
C2/3	5 (2.5%)	1 (4.4%)	4 (2.3%)
C3	2 (1.0%)	0	2 (1.1%)
C3/4	70 (35.2%)	9 (39.1%)	61 (34.7%)
C4	4 (2.0%)	0	4 (2.3%)
C4/5	49 (24.6%)	7 (30.4%)	42 (23.9%)
C5	10 (5.0%)	0	10 (5.7%)
C5/6	29 (14.6%)	5 (21.7%)	24 (13.6%)
C6	4 (2.0%)	0	4 (2.3%)
C6/7	24 (12.1%)	1 (4.4%)	23 (13.1%)
C7	1 (0.5%)	0	1 (0.5%)
C7/T1	1 (0.5%)	0	1 (0.5%)
Hematoma-like changes on MRI			
+	46 (23.1%)	17 (73.9%)	29 (16.5%)
–	153 (76.9%)	6 (26.1%)	147 (83.5%)

MRI indicates magnetic resonance imaging; SD, standard deviation.

Univariate analyses of the risk factors for tracheostomy revealed significant differences for six items: age ($P=0.0422$, odds ratio [OR]$=1.035$), ISS ($P=0.0002$, OR$=1.065$), presence of fracture or dislocation ($P=0.0209$, OR$=2.827$), AIS A ($P<0.0001$, OR$=7.344$), NLI C4 or above ($P=0.0008$, OR$=12.599$), and MRI scans revealing hematoma-like changes ($P<0.0001$, OR$=9.504$) (Table 4).

The aforementioned items with significant differences in the univariate analyses were further analyzed using multivariate logistic regression. The results revealed significant differences for two items: NLI C4 or above ($P=0.0058$, OR$=9.681$) and MRI scans revealing hematoma-like changes ($P=0.0212$, OR$=3.941$) (Table 5).

In addition, 17 of 30 patients (56.7%) who had both an NLI C4 or above and MRI scans revealing hematoma-like

TABLE 3. Demographic Data of Tracheostomy Patients

Case No.	Age	Sex	Type of Fracture	AIS	NLI	T2 High Level	Hematoma-like changes on MRI	PO2 on Admission (mm Hg)	PCO2 on Admission (mm Hg)	Final Form
1	80	F	C6 fracture dislocation	A	C4	C6/7	+	74.73	45.2	Trach collar
2	47	M	C3 tear drop fracture T4 fracture dislocation	A	T1	C3/4	–	80.9	36	Closed
3	49	M	C5 burst fracture	A	C4	C5/6	+	66.7	41.8	Closed
4	64	M	C4 fracture dislocation	A	C4	C4/5	+	72.1	36.5	Trach collar
5	82	F	C3 fracture dislocation	C	C4	C3/4	+	145.7	45.1	Closed
6	84	M	C4 fracture dislocation	A	C3	C4/5	+	74.5	34.4	Mechanical ventilation
7	75	M	C5 fracture (post ASF)	C	C3	C4/5	–	45.8	46.6	Closed
8	61	F	C5 fracture dislocation	A	C4	C5/6	+	116.9	37.4	Closed
9	80	F	C3 burst fracture	B	C4	C3/4	+	59.0	40.0	Closed
10	76	M	C5 fracture dislocation	A	C4	C5/6	+	161.0	33.0	Trach collar
11	70	M	C3 fracture dislocation	A	C3	C3/4	+	166.0	46.7	Mechanical ventilation
12	51	M	No fracture	A	C3	C5/6	–	97.0	49.0	Mechanical ventilation
13	77	M	No fracture	A	C4	C4/5	+	48.6	47.6	Mechanical ventilation
14	22	M	No fracture	A	C3	C2/3	+	392 (intubated)	40.7 (intubated)	Closed
15	63	M	No fracture	B	C4	C3/4	–	63.4	33.8	Closed
16	89	M	No fracture	A	C4	C4/5	+	93.6	34.8	Died
17	72	M	No fracture	B	C4	C3/4	–	86.5	33.4	Closed
18	69	F	No fracture	A	C4	C3/4	+	123	43.9	Closed
19	61	M	No fracture	B	C2	C3/4	+	127	35.7	Mechanical ventilation
20	85	F	No fracture	A	C4	C4/5	+	69.5	43.1	Closed
21	83	M	No fracture	A	C5	C5/6	–	72.5	37.2	Closed
22	66	M	No fracture	A	C4	C4/5	+	72.7	31.6	Mechanical ventilation
23	84	M	No fracture	A	C4	C3/4	+	86.2	43.9	Mechanical ventilation

AIS indicates American Spinal Association impairment scale; ASF, anterior spine fusion; MRI, magnetic resonance imaging; NLI, neurological level of injury.

TABLE 4. Results of the Simple Logistic Regression Model

	P	OR	95% Confidence Interval
Age	0.0422	1.035	1.004–1.074*
ISS	0.0002	1.065	1.032–1.106*
PO_2 on admission	0.1445	1.006	0.997–1.014
PCO_2 on admission	0.1055	1.076	0.986–1.183
Sex	0.2284	1.866	0.629–4.939
Fracture or dislocation (+)	0.0209	2.827	1.166–6.931*
AIS A	<0.0001	7.344	2.870–21.353*
NLI ≥C4	0.0008	12.599	3.550–80.260*
Injury level on MRI ≥C3/4	0.6169	1.251	0.508–3.004
Hematoma-like changes on MRI	<0.0001	9.504	3.780–25.604*

Age, ISS, PO_2, and PCO_2 were calculated by the continuous variable function unit odds ratio.

AIS indicates American Spinal Association impairment scale; ISS, injury severity score; MRI, magnetic resonance imaging; NLI, neurological level of injury; OR, odds ratio.

$^*P<0.05$.

changes required a tracheostomy, whereas 15 of 40 patients (37.5%) who had both an NLI C4 or above and AIS A on admission required a tracheostomy.

DISCUSSION

Various complications can occur after a CSCI, although the most frequent are respiratory complications.[1–5] Typical complications include atelectasis, pneumonia, and ventilatory failure. These complications often occur in the acute phase within 5 days of injury.[13]

The diaphragm is innervated by nerves originating from C3–C5 (primarily from C4), and damage to the spinal cord at a higher level will immediately necessitate ventilator management. Sputum is expelled and coughing is accomplished primarily with the intercostal muscles and abdominal muscles. Even if the injury occurred at a lower level and the diaphragm still functioned, paralysis of these muscles causes sputum to pool, thereby facilitating atelectasis and pneumonia.[10,16] In the acute phase of injury, the sympathetic nerves are interrupted and the vagus nerve predominates. Furthermore, tracheobronchial secretions increase and the airway constricts. The amount of sputum increases and the sputum cannot be readily expelled. This phenomenon is one reason for why respiratory complications are so frequent.

In the first week after injury, a patient's vital capacity will decrease by 30% or more. About 5 weeks after injury, vital capacity will begin to recover, and 3 months after injury the vital capacity will double.[11,16] If the period of an unstable respiratory status in the acute-subacute phase of injury can be weathered, then the respiratory status will subsequently stabilize for the most part. Thus, predicting risk factors for intubation or tracheostomy in patients with a CSCI is important.

Studies cite widely differing figures for the percentage of patients requiring a tracheostomy after CSCI. These figures range from 15.2% to 81%, and recent studies have noted that a relatively high percentage of those patients require a tracheostomy.[6–9,12,17,19,21,24] Numerous studies have reported that performing a tracheostomy early on is useful in reducing respiratory complications.[6,9,16–18] This might be the reason for the substantial difference in the percentage of patients with a tracheostomy. That said, one possibility is that intubation or tracheostomy is performed unnecessarily, and such situations should be avoided.

The current study found that 11.6% of patients with a CSCI require a tracheostomy, and this is lower than the percentages described in other studies. This Center is a dedicated facility with a Department of Orthopedic Surgery and in principle this facility does not accept patients in the

TABLE 5. Results of the Multiple Logistic Regression Model

	P	OR	95% Confidence Interval
Age	0.0782	1.031	0.999–1.071
ISS	0.2784	1.025	0.983–1.077
Fracture or Dislocation (+)	0.2477	2.049	0.597–6.970
AIS A	0.2180	2.329	0.600–9.154
NLI ≥ C4	0.0058	9.681	2.362–66.748*
Hematoma-like changes on MRI	0.0212	3.941	1.243–13.131*

Age and ISS were calculated by the continuous variable function unit odds ratio.

AIS indicates American Spinal Association impairment scale; ISS, injury severity score; MRI, magnetic resonance imaging; NLI, neurological level of injury; OR, odds ratio.

$^*P<0.05$.

acute phase of multiple trauma. This Center sees a small proportion of patients with complications such as a brain contusion, multiple rib fractures, a hemopneumothorax, or injuries to the abdominal viscera, which might explain why so few of the current patients required a tracheostomy. The aforementioned reasons are also presumably the reason why tracheal intubation or a tracheostomy is so often indicated for a simple CSCI seen at this Center. In this study, univariate analyses and multivariate analyses yielded significant differences in terms of two items: an NLI C4 or above and MRI scans revealing hematoma-like changes. The aforementioned reasons are presumably why these two items were predictors for a tracheostomy, in a true sense, in patients with a CSCI.

Numerous studies have reported that complete paralysis is a risk factor for intubation or a tracheostomy.[1,6–8,14,17,19–22,23] In the current study, univariate analyses indicated that AIS A was a risk factor for tracheostomy, whereas multivariate analyses revealed no significant differences in AIS A.

This might be because complete paralysis means that the intercostal muscles and abdominal muscles are paralyzed, regardless of the level of the CSCI; however, Yugue *et al*[7] reported that 18.8% of patients who were AIS A upon admission had an improved level of paralysis (a grade other than A) at final follow-up. Similarly, 66 patients in the current study were AIS A upon admission, although eight (12.1%) had improvement at final follow-up. The period of spinal shock might have been included in the 72 hours after injury. Given this possibility, improvement in the level of paralysis needs to be assessed.

The ISS was similarly found to be a risk factor for tracheostomy according to univariate analyses. ISS is a score for the severity of multiple trauma. Several studies have reported that a high ISS is a predictor for tracheostomy in patients with a CSCI[8,21]; however, Velmahos *et al*[21] stated that assessment of the ISS is difficult in the acute phase of trauma, and they recommended that the ISS not be used as a predictor of tracheostomy.

No studies have indicated the relationship between imaging assessment and the need for a tracheostomy. The current study is the first to do so. In the acute phase of injury, blurred hyperintensity on T2-weighted MRI indicates spinal cord contusion or edema.[25–27] This imaging finding suggests injury to the spinal cord. If cord damage is severe and hematomyelia is present, hypointensities will be found inside hyperintensities in T2-weighted images. This finding mostly suggests severe spinal cord injury,[28,29] and we described those change as "hematoma-like changes." Bozzo *et al*[29] reported that 93% of patients with MRI scans revealing a hypointense core surrounded by a hyperintense rim in T2-weighted images (hematoma-like changes) were AIS A upon admission. Of these, 95% were AIS A at final follow-up. In the current study, 82.6% of patients who were found to have hematoma-like changes were AIS A upon admission. All of the patients were AIS A at final follow-up, and this grade might be correlated with severe paralysis.

In the current study, univariate analyses and multivariate analyses revealed significant differences in MRI scans revealing hematoma-like changes. The AIS grade might change over time because of its relationship to spinal shock. Consequently, the ISS might change as well. Thus, these indicators change. In contrast, MRI images revealing hematoma-like changes do not change with spinal shock, making these MRI findings an independent indicator.

Of course, MRI was performed within a few hours after the injury. Therefore, there was a possibility that hematoma-like changes (hypointense core surrounded by a hyperintense rim) did not appear on T2-weighted images, even if a hematomyelia occurred, reflecting the intracellular oxyhemoglobin[30]; however, if hypointensity changes were revealed on T2-weighted image within 72 hours after the injury, they reflected deoxyhemoglobin, suggesting that a hemorrhage had occurred in the spinal cord and that the damage was severe.

In addition, significant differences in the level of injury on MRI scans were not noted, although an NLI C4 or above was a risk factor for tracheostomy.

The level of injury on MRI and the NLI did not necessarily coincide. Results suggested that the NLI is important because of its greater clinical significance.

Several studies have reported that an NLI at a high level is a predictor for tracheotomy.[6,12,14,21] Nerves innervating the diaphragm originate at levels C3–C5. The diaphragm is

TABLE 6. Results of the Multiple Logistic Regression Model in CSCI Patients Who Had NLI ≥ C4 on Admission

	P	OR	95% Confidence Interval
Age	0.1383	1.031	0.993–1.078
ISS	0.4848	1.016	0.974–1.066
Fracture or dislocation (+)	0.1476	2.617	0.101–1.411
AIS A	0.2180	1.705	0.386–7.369
Hematoma-like changes on MRI	0.0049	6.101	1.779–22.842*

Age and ISS were calculated by the continuous variable function unit odds ratio.

AIS indicates American Spinal Association impairment scale; CSCI, cervical spinal cord injury; ISS, injury severity score; MRI, magnetic resonance imaging; NLI, neurological level of injury; OR, odds ratio.

$^*P < 0.05$.

involved in about 65% of breathing. The current study yielded significant differences at C4 or above. Paralysis due to an injury at C4 or above causes motor paralysis of the diaphragm, which is likely to result in the patient's respiratory status worsening.

Several studies have reported that the risk of tracheostomy is related to age[7,12]; however, multivariate analyses revealed no significant differences in patient age. In addition, this study found no significant differences in patient sex.

Studies have reported that the forced vital capacity upon admission is correlated with the risk of tracheostomy,[7,9] although this characteristic might present problems for facilities that do not have a simple spirometer on hand. Blood gas analysis is simple and convenient, and the results might serve as an indicator in place of forced vital capacity. In actuality, however, significant differences in blood gas results were not evident.

An extensive search yielded no studies indicating a relationship between bone injury or dislocation and the risk of tracheostomy. The current study noted no significant differences in terms of the presence or absence of a vertebral fracture or dislocation in multivariate analyses. This is probably because the damage to the spinal cord is a more important factor than the presence or absence of a vertebral fracture or dislocation.

In the current study, multivariate analyses revealed significant differences in terms of two items: an NLI C4 or above and MRI scans revealing hematoma-like changes.

Multivariate-analyses revealed significant differences in terms of two items in 30 patients. Of these patients, 17 (57%) required a tracheostomy, suggesting that patients with both of the aforementioned characteristics are likely to require a tracheostomy.

In addition, we examined the risk factors for a tracheostomy in a total of 101 CSCI patients who had NLI C4 or above on admission. As a result, hematoma-like changes on MRI only showed a significant difference in the multivariate logistic regression model ($P = 0.0049$, OR = 6.101) (Table 6). This finding raises the possibility that hematoma-like changes on MRI are an optimal indictor of the risk for tracheostomy in patients with a CSCI.

The current study had several limitations. One is that this study was a retrospective study that studied a relatively small sample over an 8-year period. In addition, this study was conducted at a single special facility, that is, the Spinal Injuries Center, and not at other facilities. In addition, definite eligibility criteria for a tracheostomy have yet to be formulated at this facility, and the final decision is left to the discretion of the patient's primary physician. In addition, there is a possibility that hematoma-like changes did not appear on T2-weighted images, when MRI was performed within a few hours after the injury. Moreover, this study did not examine aspects such as patient history, original respiratory status, or whether or not the patient smoked.

Despite these limitations, however, the current study identified significant differences in terms of the two items: an NLI C4 or above and MRI scans revealing hematoma-like changes. These two items are statistically independent risk factors. If patients have both of these characteristics, they are extremely likely to have respiratory failure even if they had a satisfactory respiratory status upon admission. These characteristics can serve as important indices with which to study early tracheal intubation and early tracheostomy.

Key Points

- The current study used imaging assessment and other approaches to assess and examine the risk factors for a tracheostomy in patients with a CSCI.
- Univariate analyses of the risk factors for tracheostomy revealed significant differences for six items: age, ISS, presence of fracture or dislocation, AIS A, NLI C4 or above, and MRI scans revealing hematoma-like changes.
- Multivariate logistic regression analyses of the risk factors for tracheostomy revealed significant differences in terms of two items: NLI C4 or above and MRI images revealing hematoma-like changes.
- Spinal shock has an effect in the acute phase of injury, hampering assessment of the AIS. In contrast, MRI scans revealing hematoma-like changes do not change with spinal shock, making these MRI findings an independent indicator.
- Patients with an NLI C4 or above and MRI scans revealing hematoma-like changes were likely to require a tracheostomy.

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Risk factors for adjacent segment pathology requiring additional surgery after single-level spinal fusion: impact of pre-existing spinal stenosis demonstrated by preoperative myelography

Itaru Yugué, Seiji Okada, Muneaki Masuda, Takayoshi Ueta, Takeshi Maeda & Keiichiro Shiba

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ORIGINAL ARTICLE

Risk factors for adjacent segment pathology requiring additional surgery after single-level spinal fusion: impact of pre-existing spinal stenosis demonstrated by preoperative myelography

Itaru Yugué[1] · Seiji Okada[2] · Muneaki Masuda[1] · Takayoshi Ueta[1] · Takeshi Maeda[1] · Keiichiro Shiba[1]

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Abstract

Purpose We determined the incidence of and risk factors for clinical adjacent segment pathology (C-ASP) requiring additional surgeries among patients previously treated with one-segment lumbar decompression and fusion surgery.
Methods We retrospectively analysed 161 consecutive patients who underwent one-segment lumbar decompression and fusion surgery for L4 degenerative spondylolisthesis. Patient age, sex, body mass index (BMI), facet orientation and tropism, laminar inclination angle, spinal canal stenosis ratio [on myelography and magnetic resonance imaging (MRI)], preoperative adjacent segment instability, arthrodesis type, pseudarthrosis, segmental lordosis at L4–5, and the present L4 slip were evaluated by a log-rank test using the Kaplan–Meier method. A multivariate Cox proportional-hazards model was used to analyse all factors found significant by the log-rank test.
Results Of 161 patients, 22 patients (13.7 %) had additional surgeries at cranial segments located adjacent to the index surgery's location. Pre-existing canal stenosis ≥47 % at the adjacent segment on myelography, greater facet tropism, and high BMI were significant risk factors for C-ASP. The estimated incidences at 10 years postoperatively for each of these factors were 51.3, 39.6, and 32.5 %, and the risks for C-ASP were 4.9, 3.7, and, 3.1 times higher than their counterparts, respectively. Notably, spinal canal stenosis on myelography, but not on MRI, was found to be a significant risk factor for C-ASP (log-rank test $P < 0.0001$ and 0.299, respectively).
Conclusions Pre-existing spinal stenosis, greater facet tropism, and higher BMI significantly increased C-ASP risk. Myelography is a more accurate method for detecting latent spinal canal stenosis as a risk factor for C-ASP.

Keywords Degenerative spondylolisthesis · Adjacent segment pathology · Pre-existing spinal stenosis · Body mass index · Facet tropism

The manuscript does not contain information about medical device(s)/drug(s).

✉ Itaru Yugué
iyugue@orange.ocn.ne.jp

1 Department of Orthopaedic Surgery, Japan Labour Health and Welfare Organization Spinal Injuries Center, 550-4 Igisu, Iizuka, Fukuoka, Japan

2 Department of Orthopaedic Surgery, Kyushu University, Fukuoka, Japan

Introduction

During the past few decades, spinal arthrodesis has become a common treatment component for a variety of spinal disorders. However, it alters the biomechanical and kinematic properties of the lumbar spine [1, 2]. Pathological development at mobile segments above or below the site of spinal fusion is known as adjacent segment pathology (ASP). ASP is considered a potential late complication of spinal arthrodesis that requires further surgical treatment. The clinical failure rate of adjacent segments at 5 years after the index spinal fusion surgery has been reported to range from 3 to 32.3 % [3–7].

Several risk factors for ASP have been reported, such as age [4, 5, 7], sex [4], multilevel arthrodesis [3–5], sagittal imbalance [8], the type of arthrodesis [7], facet tropism [9], and laminar inclination [9]. However, few studies have focused on asymptomatic pre-existing spinal stenosis as a risk factor for clinical ASP (C-ASP) that requires additional surgery at an adjacent segment [10]. In fact, when patients demonstrate asymptomatic spinal stenosis adjacent to the fusion segment, there is often controversy as to whether the segment should be included within the surgical site or not.

This study analysed the preoperative prognostic risk factors for C-ASP, and we calculated the survival times of the patients with significant risk factors.

Materials and methods

From January 2000 to December 2006, 204 L4 degenerative spondylolisthesis (DS) patients with radicular pain and/or neurological claudication after unsuccessful conservative treatment underwent either instrumented posterolateral fusion (PLF) or posterior lumbar inter-body fusion (PLIF) at the single level of L4–5. All surgeries were performed using the same procedures at a single institution. Patients with an acute fracture, dislocation, or malignancy were excluded. Informed consent was obtained from all patients. Medical records of all patients were reviewed, and this study was approved by our local ethics committee. Forty-three patients were excluded because of a short follow-up (<2 years) or a lack of preoperative magnetic resonance imaging (MRI) and/or myelography data. The remaining 161 patients with a follow-up period of longer than 2 years were finally selected.

PLF had been performed in 137 patients (85 %) and PLIF in 24 patients (15 %). In all patients undergoing PLF, autogenous cancellous iliac bone was used as a graft. PLIF was performed using a rectangular ceramic cage with morselised local bone from neural decompression in all patients. When patients had spinal stenosis on myelography or MRI at the L3–4 segment, as well as neurological findings (including the presence of patellar tendon reflex and no sensory and motor disturbance associated with the L4 nerve root) and negative findings of L4 nerve root infiltration, we did not include the L3–4 segment in the operation site.

Radiographic evaluation

In all patients, computed tomography (CT), myelography, and MRI were performed within 2 weeks before the index fusion surgery. In this series, no patients required additional surgery at the L5–S1 segment during follow-up, so radiographic evaluations were performed at the L3–4 and L4–5 segments. Standard biplanar anteroposterior, lateral radiography with the lumbosacral spine in neutral, flexion, and extension positions was performed preoperatively, at 24 months after surgery, and at the final follow-up.

The anteroposterior vertebral slip and intervertebral disc angle were measured on lateral radiographs of the L3–4 and L4–5 taken in the neutral, flexion, and extension positions. To minimise the errors due to different magnifications, the vertebral slip was expressed as a percentage of the caudal vertebral body width (% slip). The ranges of motion (ROM) of the L3–4 and L4–5 segments were defined as the sum of the intervertebral disc angles in the flexion/extension view (Fig. 1). Pseudarthrosis was present if there was no continuity in the PLF fusion mass between the cephalad and caudad transverse processes, no continuity between graft bone and vertebra in PLIF fusion, or if lateral flexion–extension radiographs demonstrated >2° of angular motion or >2 mm of sagittal motion at L4–5 [11].

The criteria for adjacent segment instability were well-defined spondylolisthesis or dynamic instability with slippage >4 mm and/or an ROM >10° [12]. The laminar inclination angle at L3 was measured as previously described [9] on lateral radiographs (Fig. 2a). Facet orientation and tropism were determined by CT images that were coplanar with the disc and transected the facet joints, as described previously [9]. The sum of the right and left facet angles and the difference between the right and left facet angles were defined as the facet orientation and tropism, respectively (Fig. 2b).

Myelography measurements

After lumbar puncture and injection of radiographic contrast material into the dural sac under fluoroscopic guidance, the physician moved the patient's lower back to maximum flexion and extension in the left lateral decubitus position and obtained lateral radiographs in the neutral, flexion, and extension positions under fluoroscopy. The narrowest anteroposterior dural sac diameter at L3–4 was measured on lateral myelography in the neutral, flexion, and extension positions and on the sagittal view of T2-weighted MRI. The dural sac diameter at the midpoint of the L2 vertebral body was also measured. The spinal canal stenosis ratio (SCSR) was calculated as $x/y \times 100$ (Fig. 3).

All measurements were performed twice by two independent observers blinded to the patient name and clinical findings using an electronic digitiser (MicroAnalyzer; Japan Poladigital Corp., Tokyo, Japan) with an accuracy of 0.01 mm: measurements were averaged. The inter-observer correlation of all measurement was evaluated by the Pearson's correlation coefficient test. The kappa statistic was used to assess inter-observer agreement of pseudarthrosis and preoperative instability at L3–4.

Statistical analysis

The final follow-up examination was defined as the last visit. In patients undergoing re-operation at L3–4, the survival period was defined as the interval from the index operation to the second operation due to C-ASP. C-ASP

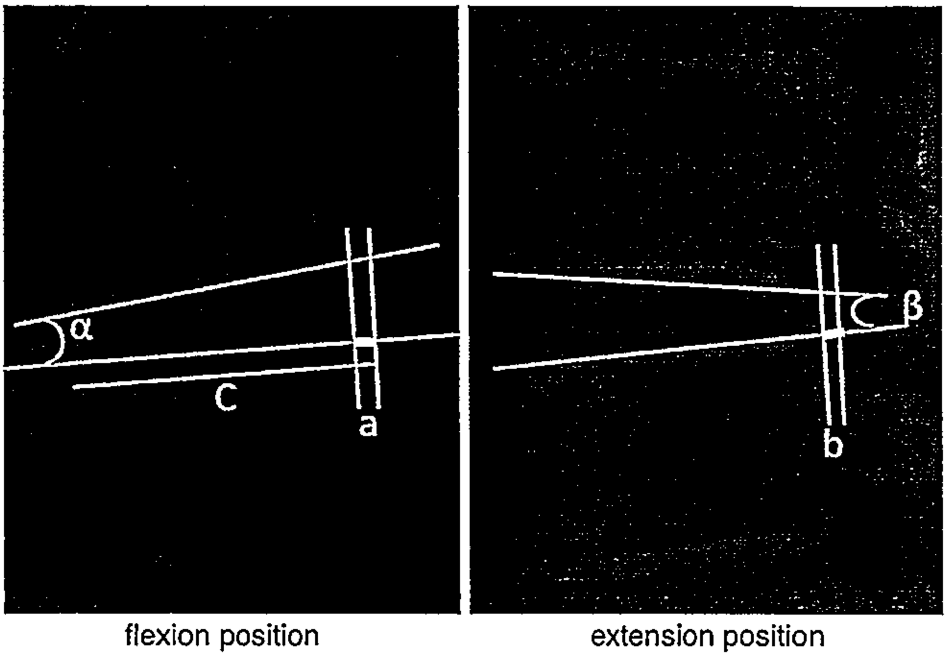

Fig. 1 Plain radiography measurement. *a* Anterior slip in the flexion position, *b* posterior slip in the extension position, *c* vertebral body width. The total percent slip is $(a + b)/c \times 100$. α Intervertebral disc angle in flexion position, β intervertebral disc angle in the extension position. The range of motion is $\alpha + \beta$ in degrees

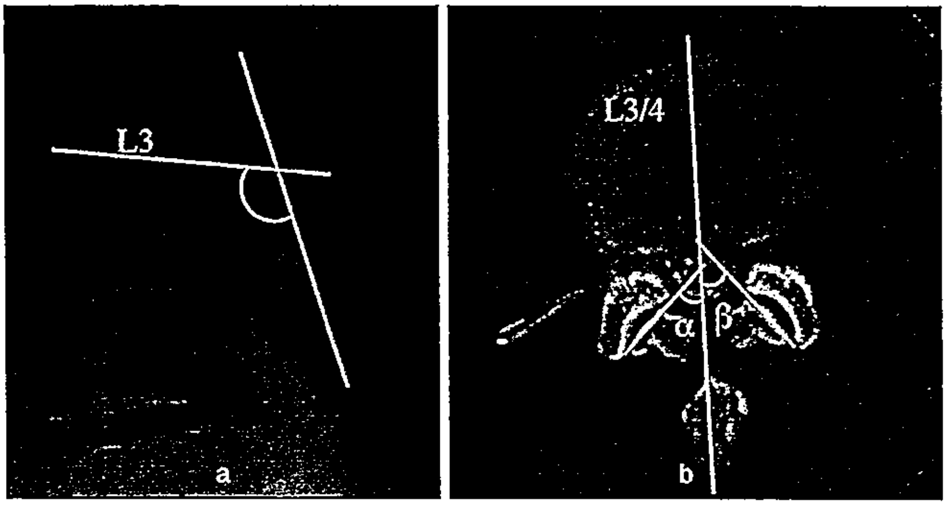

Fig. 2 *a* The laminar inclination angle at L3 was defined as the angle formed by a *straight line* connecting the base of the superior facet with the base of the inferior facet, and a *straight line* connecting the midpoints of the anterior and posterior L3 vertebral cortices on lateral radiographs. *b* Facet orientation and tropism were determined by computed tomography images that were coplanar with the disc and transected the facet joints. The sum of the right and left facet angles and the difference between the right and left facet angles were defined as the facet orientation and tropism, respectively

was defined as a condition where an additional surgery at L3–4 was required to treat symptomatic neurological deterioration.

The following prognostic risk factors were examined: age, sex, body mass index (BMI), facet orientation, facet tropism, laminar inclination angle, SCSR by myelography and MRI, preoperative adjacent segment instability, type of fusion, presence of pseudarthrosis, segmental lordosis at L4–5, and the %slip of L4–5 after 2 years postoperatively. Continuous variables were dichotomised to increase the statistical power using the Youden index from the receiver operating characteristic curve (ROC).

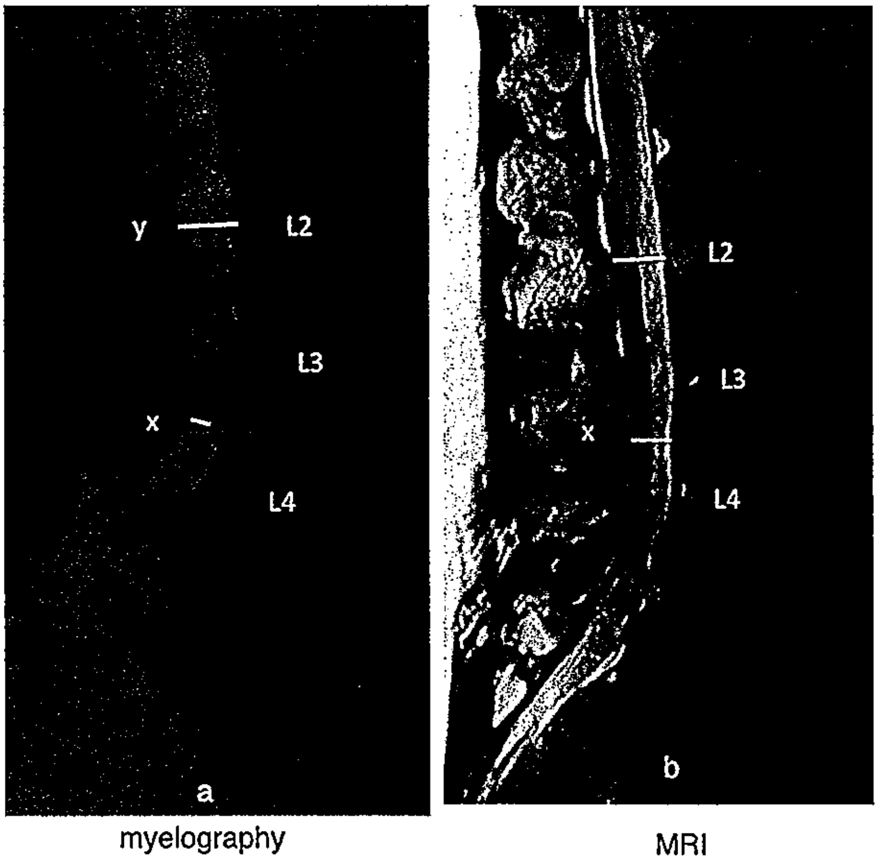

Fig. 3 The narrowest anteroposterior dural sac diameter at L3–4 (*x*) was measured on lateral myelographs taken in the extension position (**a**) and on MRI (**b**) in the same patient. The dural sac diameter at the midpoint of the L2 vertebral body (*y*) was also measured. The spinal canal stenosis ratio (SCSR) was calculated as $x/y \times 100$

A log-rank test was used for univariate analyses using the Kaplan–Meier method, and survival curves for all patients with significant risk factors were constructed to calculate the survival time. A multivariate Cox proportional-hazards model was used to assess all factors demonstrated to be significant by the log-rank test to adjust for confounding factors.

Statistical analyses were performed using the JMP 10 statistical software package (SAS Institute Inc. Cary, NC). A value of $P < 0.05$ was considered to be statistically significant.

Results

There were 56 males and 105 females. The mean age at index surgery was 65.4 years (range 40–87 years). The average follow-up period was 77.3 months (range 24–183 months). The follow-up rate was 78.9 %. Among the 161 patients, 22 (13.7 %) underwent subsequent procedures at cranial segments adjacent to the L4–5 segment; five patients underwent decompression surgery with arthrodesis and 17 underwent decompression surgery alone. After the additional surgery, all patients show improved neurological symptoms. The mean duration between the index surgery and the additional surgery was 75.9 months (range 24–141 months).

The inter-observer correlation is shown in Table 1. The kappa coefficient for pseudarthrosis rated between observers was 0.82 ($P < 0.0001$) and that of preoperative instability at L3–4 was 0.89 ($P < 0.0001$).

Patients with a BMI ≥ 25 kg/m^2 had a significantly lower survival rate than their counterparts in a univariate analysis (log-rank test: $P = 0.0497$). The incidence of C-ASP in patients with a BMI ≥ 25 kg/m^2 was estimated to be 32.5 % at 10 years. Conversely, the incidence of C-ASP in patients with a BMI < 25 kg/m^2 was lower, at 21.1 % at 10 years. The median survival time for patients with a BMI ≥ 25 kg/m^2 was 141 months (Fig. 4).

Patients with facet tropism $\geq 11°$ demonstrated a lower survival rate than their counterparts (log-rank test: $P = 0.0178$). The incidence of C-ASP among patients with facet tropism $\geq 11°$ was 39.6 %, while for facet tropism $<11°$ it was 19.4 % at 10 years after the initial operation (Fig. 5).

Regarding SCSR, patients with an SCSR ≥ 47 % on myelography in the extension position showed a significantly lower survival rate than their counterparts

Table 1 Inter-observer correlations for study parameters

Parameters	P value	Pearson correlation coefficient
Facet orientation	<0.001	0.91
Facet tropism	<0.001	0.92
Laminar inclination angle	<0.001	0.86
Segmental lordosis at L4–5	<0.001	0.87
%Slip of L4	<0.001	0.89
SCSR of MRI	<0.001	0.91
SCSR of myelography (neutral position)	<0.001	0.88
SCSR of myelography(flexion position)	<0.001	0.87
SCSR of myelography(extension position)	<0.001	0.89

Significance was set at $P < 0.05$

SCSR spinal canal stenosis ratio, *MRI* magnetic resonance imaging

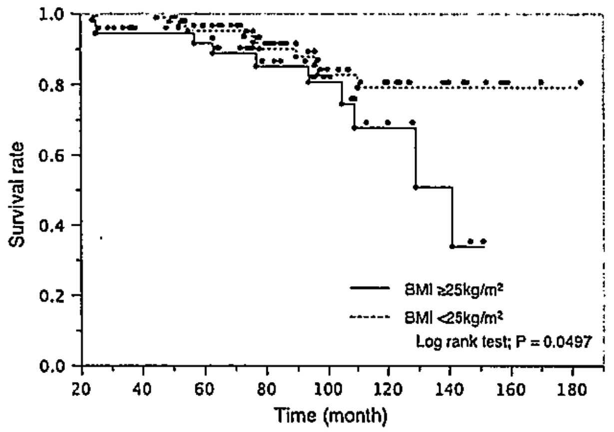

Fig. 4 The Kaplan–Meier survivorship curve of patients with BMI $\geq$ 25 kg/m^2 versus those with BMI < 25 kg/m^2

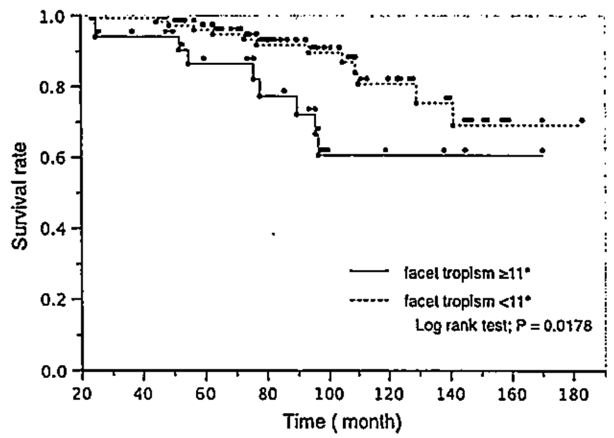

Fig. 5 The Kaplan–Meier survivorship curve of patients with facet tropism $\geq$11° versus those with facet tropism <11°

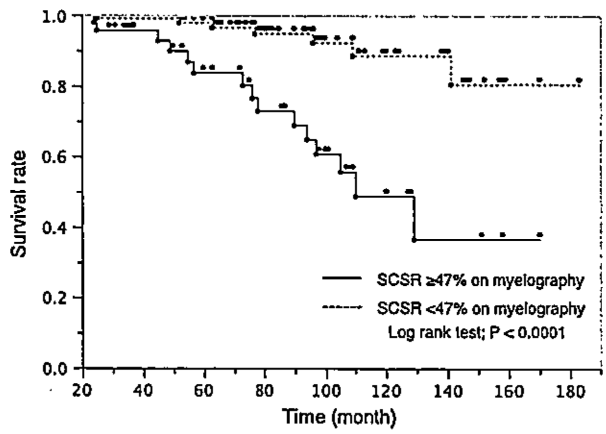

Fig. 6 The Kaplan–Meier survivorship curve of patients with an SCSR $\geq$ 47 % versus those with an SCSR < 47 % on myelography. *SCSR* spinal canal stenosis ratio

($P < 0.0001$). In these patients, the prevalence of C-ASP requiring reoperation was 51.3 % at 10 years, whereas it was 11.4 % in patients with an SCSR <47 %. The median survival time for patients with an SCSR $\geq$47 % was 110 months (Fig. 6).

Interestingly, SCSR determined by MRI was not a significant risk factor (log-rank test: $P = 0.2990$). Since a factor with a higher discrimination ability makes an ROC curve closer to the top left corner, the area under the ROC curve (AUC) is used to indicate the sensitivity and specificity of each factor. We compared the AUC values of MRI and myelography in the extension positions. In this analysis, the AUC of the SCSR determined by myelography was significantly higher than that of the SCSR determined by MRI (Fig. 7). In fact, 13.2 % of patients who exhibited SCSR on MRI <50 % had an SCSR $\geq$50 % on myelography in the extension position.

Other potential risk factors, such as age, sex, facet orientation, laminar inclination angle, preoperative adjacent segment instability, type of fusion, pseudarthrosis, segmental lordosis, the %slip, and SCSR on myelography in the neutral and flexion positions, were not statistically significant (Table 2). A multivariate Cox proportional-

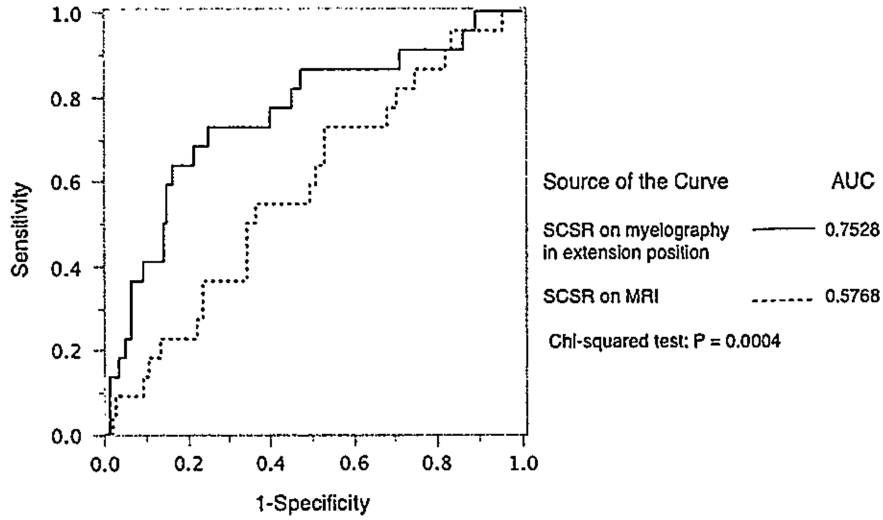

Fig. 7 Receiver operating characteristic curves of the SCSR on myelography at extension and the SCSR on MRI. *AUC* area under the ROC curve, *SCSR* spinal canal stenosis ratio

Table 2 Potential risk factors for clinical adjacent segment pathology after lumbar spinal fusion based on the log-rank test

Risk factor	*P* value
Sex (female)	0.3530
Age ≥ 68 years	0.3989
BMI ≥ 25 kg/m^2	0.0497*
Facet orientation ≥65°	0.2272
Facet tropism ≥11°	0.0178*
Laminar inclination ≥120°	0.6325
SCSR on MRI ≥ 35 %	0.2990
SCSR on myelography in extension ≥47 %	<0.0001*
SCSR on myelography in neutral ≥33 %	0.0757
SCSR on myelography in flexion ≥18 %	0.1467
Preoperative instability	0.6902
Type of fusion	0.4737
Pseudarthrosis	0.2086
Segmental lordosis at L4–5 ≥ 6.3°	0.2278
%Slip of L4 ≥ 13.4%	0.1465

Significance was set at $P < 0.05$*

BMI body mass index, *SCSR* spinal canal stenosis ratio, *MRI* magnetic resonance imaging

hazards model revealed a BMI ≥ 25 kg/m^2, facet tropism ≥11°, and SCSR ≥47 % on myelography to be significant risk factors, and patients with these factors had 3.1-, 3.7-, and 4.9-fold higher risks of adjacent segment reoperation than their counterparts, respectively (Table 3).

Discussion

The definition of C-ASP has often been reported as adjacent segment pathology, manifesting radiculopathy, neurogenic intermittent claudication, back pain, or a combination of any of these [13], and the need for additional surgeries [3–5, 8–10] on the index fusion segments. Park et al. [3] reported the incidence of C-ASP to range from 5.2 to 18.5 %. The term 'degeneration' itself suggests a time-dependent phenomenon. Therefore, the survival function estimated by the Kaplan–Meier method and the multivariate Cox regression model are good ways to analyse the development of ASP as a late complication of spinal arthrodesis.

Regardless of the use of spinal arthrodesis, the clinical course of patients with severe spinal stenosis often deteriorates over time during conservative treatments [14]. This indicates that pre-existing spinal stenosis in itself may be a significant risk factor for C-ASP. Cho et al. [10] reported a significant relationship between pre-existing spinal stenosis and C-ASP. However, they did not indicate a cutoff point for spinal stenosis that may increase the likelihood of C-ASP. In the current study, patients with an SCSR ≥47 %

Table 3 Risk factors for clinical adjacent segment pathology after lumbar spinal fusion

Risk factor	*P* value	Hazard ratio	95 % confidence interval
BMI ≥ 25 kg/m^2	0.0212*	3.12	1.18–8.49
Facet tropism ≥11°	0.0114*	3.74	1.35–10.30
SCSR in myelography ≥47 %	0.0003*	4.87	2.05–12.78

Significance was set at $P < 0.05$*

BMI body mass index, *SCSR* spinal canal stenosis ratio on myelography in the extension position exhibited a 4.87-fold higher risk of adjacent segment reoperation than their counterparts. Interestingly, spinal stenosis demonstrated by MRI was not a significant factor. We attempted to change the cutoff point for SCSR on MRI from 35 to 60 %; however, the MRI findings were not a significant factor. Moreover, the AUC of SCSR on myelography in the extension position (0.7528) was significantly larger than that on MRI (0.5768) (Chi squared; $P = 0.0004$). These results suggest that myelography has a significantly higher sensitivity and specificity to detect not only latent spinal canal stenosis, but also the risk of ASP requiring additional surgery.

While these results indicate that pre-existing severe stenosis can be a significant risk factor for C-ASP, this does not lead directly to a recommendation for performing laminectomy during the index surgery, since performing laminectomy adjacent to a fusion segment demonstrated a significant association with ASP [5, 15–17]. Imagama et al. [15] recommended that the adjacent segment with asymptomatic spinal stenosis should not be subjected to a concomitant decompression from the viewpoint of preventing ASP. We therefore recommend that surgeons should have thorough discussions with patients to determine whether a concomitant operation at adjacent segments with asymptomatic stenosis should be performed.

Facet tropism is defined as asymmetry in the facet joint that causes an abnormal rotation of the spinal segment, which increases the mechanical stress on the disc and could lead to lumbar degeneration or disc herniation [18, 19]. Several studies have reported greater facet tropism to have a significant relationship with C-ASP [9]. In the current study, patients with facet tropism ≥11° had a 3.74-fold higher risk of adjacent segment reoperation compared to their counterparts. We hypothesised that facet tropism may affect the rotational stability, which accelerates the thickening of the ligamentum flavum, thus resulting in spinal canal stenosis. However, some authors have reported no association between facet tropism and the occurrence of C-ASP [10]. Further studies are required to clarify this issue.

It remains controversial as to whether an association exists between BMI and ASP. Some studies reported no association between BMI and radiographic ASP [20]; however, Cho et al. [10] reported BMI to be a significant risk factor for C-ASP, and Liuke et al. [21] reported that a BMI ≥ 25 kg/m^2 increased the risk of lumbar disc degeneration on MRI. It is assumed that being overweight might cause disc degeneration [22], resulting in earlier ASP over the long term. In this series, a BMI ≥ 25 kg/m^2 was identified as a significant risk factor for C-ASP, and patients with this factor had a 3.12-fold higher risk of needing adjacent segment reoperation than their counterparts. Patients with high BMI appear to have a higher risk of C-ASP; however, a large prospective study is needed to confirm this finding.

In this study, other factors were not significant risk factors for C-ASP. The association between the conditions of fused segments and the occurrence of ASP also remains controversial. Since almost all past studies were retrospective analyses that contained potential bias, a randomised prospective study will be necessary to resolve these issues.

There are several possible limitations associated with this study. First, it was a retrospective study. Second, the predictors derived were not prospectively validated in an independent population. Third, the sample size was relatively small. Finally, whole spinal radiographs were not routinely taken for DS patients who underwent one-segment spinal fusion and decompression and, therefore, a whole spinal radiographic analysis was not possible in this study. Despite these limitations, the factors identified in this study may assist both surgeons and patients when making decisions about whether or not to include an adjacent segment at the time of index fusion surgery.

In conclusion, a BMI ≥ 25 kg/m^2, facet tropism ≥11°, and pre-existing stenosis ≥47 % demonstrated on myelography in the extension position were found to be important risk factors for C-ASP requiring a second operation. Careful consideration of the type and extent of surgery is therefore necessary when these risk factors are present.

Compliance with ethical standards

Conflict of interest No funds were received in support of this work. No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript.

Ethical standards The study was approved by the local ethics committee.

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ORIGINAL ARTICLE

Subacute T1-low intensity area reflects neurological prognosis for patients with cervical spinal cord injury without major bone injury

A Matsushita, T Maeda, E Mori, I Yugue, O Kawano, T Ueta and K Shiba

Study design: A retrospective imaging and clinical study.
Objectives: To evaluate the relationship between magnetic resonance imaging (MRI) features and neurological prognosis in patients with traumatic cervical spinal cord injury (CSCI) without major bone injury.
Methods: A total of 72 patients with CSCI without major bone injury were treated conservatively in our hospital. MRI was performed for all patients at admission and 1 month following injury. We measured the antero-posterior and cranio-caudal diameter of intramedullary intensity changed area with T1-weighted images at the injured segment. Neurological evaluations were performed using the American Spinal Injury Association (ASIA) motor score and the modified Frankel grade at the time of admission and discharge.
Results: There was a significant relationship between the antero-posterior diameter ratio of the T1-weighted low-intensity area on MRI at the subacute stage and the ASIA motor score. The optimal threshold of the T1-weighted low-intensity diameter ratio for predicting the patient's ability to walk with or without assistance at discharge was determined to be 46%. Moreover, 96.8% of the patients with <50% T1-weighted low-intensity area recovered to walk with or without a cane at discharge.
Conclusion: The T1-low intensity area may be an important predictive factor for the neurological recovery of CSCI without major bone injury.
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INTRODUCTION

The incidence of cervical spinal cord injuries (CSCIs) without major bone injury has been increasing. Patients with these injuries show no evidence of fracture or dislocation of the spine on plain radiographs or computed tomography scans.[1,2] The incidence, pathogenesis and severity of CSCI without major bone injury are different for different age groups because of the anatomical and biomechanical differences in the spine.[3,4]

Magnetic resonance imaging (MRI) is the best clinical tool for evaluating traumatic CSCI and is therefore invaluable for examining patients with CSCI without major bone injury. MRI can show the degree of spinal canal stenosis, as well as reveal the intramedullary state of the spinal cord in detail.[5]

To our knowledge, there have been only few reports on the MRI features of patients with CSCI without major bone injury.[6,7] The most common acute MRI pattern described is no change of signal intensity on T1-weighted images with a blurred high-intensity area on T2-weighted images. In the subacute and chronic stages, a low-intensity area begins to appear on T1-weighted images. The characteristic finding in the chronic stage is usually an oval-shaped area of signal change.[8] On the basis of previous studies on the histopathological features of SCI, the blurred high-intensity area on T2-weighted images is thought to represent edema or petechial hemorrhage. On the other hand, the low-intensity area on T1-weighted images obtained in the subacute and chronic stages is thought to indicate necrosis, myelomalacia or an intramedullary cyst.[5,9]

Some papers have described the early relationship between MRI features and clinical outcomes in patients with CSCI at the acute stage following trauma.[8,10,11] However, to the best of our knowledge, there are few papers reporting about this relationship at subacute or chronic stages following trauma.

In the present study, we evaluated T1- and T2-weighted MRI findings of patients with CSCI in the subacute stages. The purpose was to investigate the relationship between the MRI features and neurological prognosis of patients with CSCI without major bone injury at subacute and chronic stages.

MATERIALS AND METHODS

Patients with acute CSCI without major bone injury who were admitted to our hospital within 10 days after trauma were included in this study. The patients' imaging (radiographs, CT, MRI) was reviewed when they were admitted to our hospital. Small avulsion fractures of the vertebral body, spinous process fractures or bone bruises in the vertebral body without noticeable vertebral collapse were considered to be minor bony injuries. Any patient who had undergone previous cervical surgery and those who were likely to have recoil flexion injury were excluded, because of the artifacts from surgery implants in MRI. Recoil flexion injury requires fixation. It was difficult to do a correct evaluation in surgery cases. We also excluded patients who had no cord signal changes on MRI to rule out patients with cervical concussion or hysteria or those with a cord compression rate >20%. The rate of spinal cord

Department of Orthopedic Surgery, Spinal Injuries Center, Iizuka, Japan
Correspondence: Dr A Matsushita, Department of Orthopedic Surgery, Spinal Injuries Center, 550-4, Igisu, Iizuka 820-0053, Japan.
E-mail: a-matsu@ortho.med.kyushu-u.ac.jp
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compression was measured on sagittal MRI. The spinal cord diameter was measured at both the non-compressed and injured levels on T1-weighted MRI images, and the percent change was calculated by the following equation:

(antero-posterior diameter of the cord at no compression level − antero-posterior diameter of the cord at compression level)/antero-posterior diameter of the cord at no compression level × 100% (Figure 1). A value of 20% was defined as a cut-off for the spinal cord compression rate based on a previous report.[12]

From January 2005 to May 2010, 72 consecutive patients were included in this study. The mean patient age at the time of trauma was 62.4 years (34–81 years), and there were 60 men and 12 women. Using the American Spinal Injury Association (ASIA) impairment scale, paralysis at the time of admission was graded as A in 4 patients, B in 16, C in 43 and D in 9. The mean period from traumatic injury to admission was 1.5 days (0–10 days), and the mean duration of hospital stay was 240.9 days (35–1423 days). All patients were treated conservatively and rehabilitated as quickly as possible with a simple neck brace.

MRI was performed in all patients at hospital admission (acute stage) and 1 month after trauma (subacute stage). Using sagittal MRI images, an intramedullary high-intensity changed area on T2-weighted MRI images was determined to be the injured level of the cervical spinal cord. We measured the antero-posterior diameter and cranio-caudal diameter of intramedullary intensity changed area on sagittal T1-weighted images (Figure 2). It was difficult to detect the intensity changed area on axial T1-weighted image. The measurement was taken at the largest spinal cord slice. The T1-weighted low-intensity changed area ratio (T1-LCAR) was calculated by the following equation: antero-posterior diameter of low-intensity changed area/spinal cord antero-posterior diameter × 100% (Figure 2).

All measurements were performed by two observers. Each measurement was performed three times, and the average value was calculated. All MR imaging examinations were performed with a 1.5-T magnet (MAGNETOM; Siemens Healthcare, Munich, Bayern, Germany). Standardized MR imaging protocols for the acutely injured spine were used: for sagittal T1-weighted imaging, a two-dimensional spin-echo sequence was performed by using a conventional imaging option with no phase wrap, 525/11 (repetition time msec/echo time msec), a receiver bandwidth of 147 Hz/Px, a matrix of 320 × 224 (frequency encoding × phase encoding), three acquired signals and no phase correction. For sagittal T2-weighted imaging, a two-dimensional fast-recovery fast spin-echo (accelerated) sequence was performed by using imaging options that included the following: no phase wrap, an extended dynamic range, tailored radiofrequency and fast recovery; 3500/99; an echo train length of 15; a receiver bandwidth of 150 Hz/Px; a matrix of 384 _ 229; four acquired signals; and phase correction. Both the T1- and the T2-weighted examinations were performed in the antero-posterior frequency direction by using an Neck Matrix coil, a section thickness of 3.0 mm, an intersection gap of 0.3 mm, a 24-cm field of view and no contrast medium enhancement.

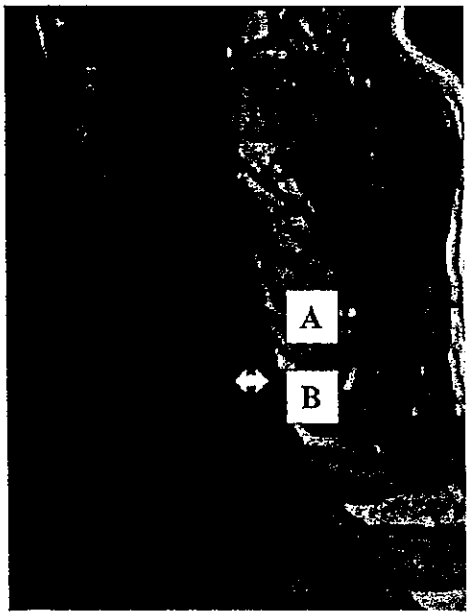

Figure 1 T1-weighted image. Black arrow (A) intact cervical spinal cord. White arrow (B) cervical spinal cord compressed by a disc and ligament flavum. Compression rate was 34%.

The ASIA impairment scale and the ASIA motor score (ranging from 0 to 100) were documented at admission and discharge for each patient. Neurologic recovery was evaluated as the following:

Improvement rate (%) = ((motor score at discharge − motor score at admission)/(100 − motor score at admission)) × 100.[13]

All neurological evaluations were performed by senior spinal surgeons. In addition, we also documented each patient's score with the modified Frankel grading system (Table 1).[14,15]

All data were analyzed using the JMP 8.0.2 software program (SAS Institute, Cary, NC, USA). The relationships between T1-LCAR and the ASIA motor scores and the recovery rate were analyzed using the Spearman rank-correlation coefficient. $P<0.05$ was considered statistically significant. The relationships between cranio-caudal diameter and the ASIA motor scores were also analyzed using the Spearman rank-correlation coefficient. The chance-corrected κ-coefficient was calculated to determine intra-observer agreement. Intra-observer reliability was almost good ($\kappa = 0.92$, $P<0.001$).

RESULTS

The neurologic statuses as evaluated by the ASIA and modified Frankel grading scales at admission and discharge are summarized in Tables 2 and 3. None of the patients demonstrated neurological deterioration during follow-up, and 60 (81.9%) and 68 (94.4%) demonstrated neurological recovery as evaluated by ASIA and modified Frankel grading, respectively.

The mean ASIA motor scores at admission and discharge were 37.3 ± 29.2 and 78.3 ± 22.8, respectively. The mean improvement rate of the motor score was 68.9 ± 24.7%, which was significant.

T1-weighted low-intensity changed areas were observed in 53 cases (73.6%) at 1 month after injury. A total of 16 patients with final ASIA D and 3 patients with final ASIA E did not demonstrate intramedullary low-intensity change on T1-weighted MRI at the time of discharge. The T1-LCAR of these 19 patients was set as 0%. The correlation between the T1-CAR and the ASIA motor score at discharge and the improvement rate were examined in all 72 patients, as shown in Figures 3 and 4. There was a significant negative correlation between T1-LCAR and ASIA motor score at discharge ($P<0.0001$, Figure 3). There was also a significant negative correlation

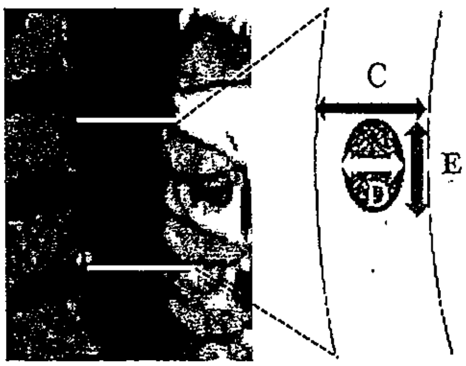

Figure 2 T1-weighted image. Black arrow (C) cervical spinal cord antero-posterior diameter. White arrow (D) T1-low antero-posterior diameter. T1-low diameter ratio was D/C(%). Gray arrow (E) T1-low cranio-caudal diameter (mm).

Table 1 The modified Frankel grading system

Grade	*Neurological status*
A	Complete: no motor or sensory function
B	Sensory only: some sensation preserved, no motor function
B1	Touch sensation remains in only sacral lesion
B2	Touch sensation remains in L/E
B3	Pain sensation remains in sacral lesion or L/E
C	Motor useless: some sensory and motor function, but motor function not useful
C1	Unable to flex the hip and knee from supine (Hip flexors 0–2)
C2	Able to flex the hip and knee from supine (Hip flexors 3–5)
D	Motor useful: sensory function preserved, moter function weak but useful
D0	MMTs of L/E are 4–5, but because of an acute phase, it is impossible to test the walking ability
D1	Able to walk with a walker, but not practiced, usually use a wheel chair
D2	Independent gait with a cane
D3	Independent gait without a cane
E	Normal: normal sensory and motor function (hyperreflexia and numbness are permitted)

Table 2 Diagram showing change in American Spinal Injury Association (ASIA) impairment scale between the status at admission (vertical axis) and at discharge (horizontal axis)

admission \ discharge	A	B	C	D	E
A	1	0	3	0	0
B	0	3	3	10	0
C	0	0	2	39	2
D	0	0	0	7	2

between T1-LCAR and the recovery rate ($P=0.0072$, Figure 4). On the other hand, there was no correlation between cranio-caudal diameter of T1 low-changed area and the ASIA motor score at discharge ($P=0.2797$). There was also no correlation between cranio-caudal diameter of T1 low-changed area and the recovery rate ($P=0.2184$).

A total of 60 patients (83.3%) recovered to walk with or without a cane (higher or equal Frankel D). Receiver operator characteristic curve analysis demonstrated that the optimal T1-LCAR cut-off value for patients who were able to walk at discharge was 46% (Figure 5). If the T1-LCAR cut-off value was <50%, there was a significant positive correlation with being able to walk at discharge ($P<0.0001$, Pearson's χ^2 test, Table 4).

DISCUSSION

The reported incidence of CSCI without major bone injury ranges from ~10 to 16% of all cervical cord injury in North America and India,[6,16] but they are the largest proportion of cervical cord injury in Japan as described by Koyanagi *et al.*[16] The number of CSCI without major bone injury has been increasing as the population ages; data from our institution showed an annual rate of 38.2% in 1990 and 63.2% in 2005.[17] CSCIs without major bone injury have consistently

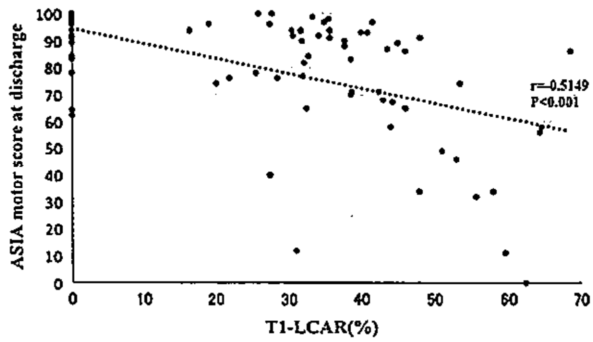

Figure 3 The relationship between the ASIA motor score at discharge and the T1-LCAR. There was a significant negative relationship between the two parameters, indicating that a larger T1-LCAR was associated with more severe paralysis.

Table 3 Diagram showing change in modified Frankel grade between the status at admission (vertical axis) and at discharge (horizontal axis)

admission \ discharge	A	B1	B2	B3	C1	C2	D1	D2	D3	E
A	1	0	0	0	2	1	0	0	0	0
B1	0	0	2	0	1	0	2	2	0	0
B2	0	0	2	0	1	0	1	0	0	0
B3	0	0	0	0	1	0	2	2	1	0
C1	0	0	0	0	1	1	9	7	7	0
C2	0	0	0	0	0	0	0	7	4	0
D0	0	0	0	0	0	0	0	1	11	3

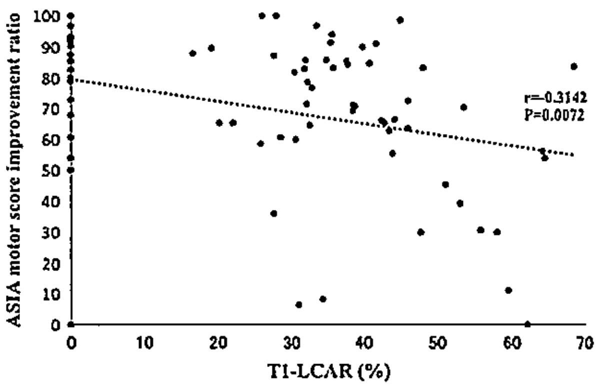

Figure 4 The relationship between the ASIA motor score improvement ratio at discharge and the T1-LCAR. There was a significant negative relationship between the two parameters, indicating that a larger T1-LCAR was associated with poor improvement.

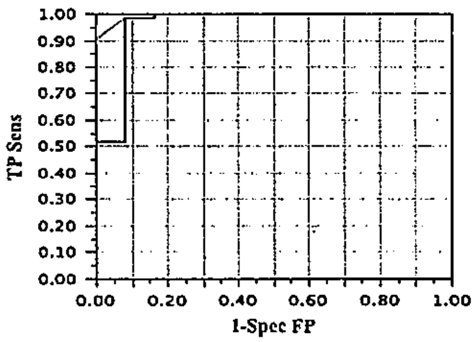

Figure 5 ROC curve of higher or equal Frankel grading D and T1-LCAR at 1 month after injury. AUC=0.95833. FP, false positive; Sens, sensitivity; Spec, specificity; TP, true positive.

been treated conservatively and rehabilitated as early as possible at our institution.

MRI is being increasingly used in the evaluation of post-traumatic myelopathy. It is useful in that it allows imaging of the injured cord, as well as an ability to predict patient outcome. The most common acute MRI pattern for CSCI is a blurred high-intensity area on T2-weighted images and no change in signal intensity on T1-weighted images. The subacute MRI pattern is iso-intensity or high-intensity on T2-weighted images, but a circumscribed low-intensity area is noted on T1-weighted images. This low-intensity area appears 3 to 6 weeks after injury.[8] On the basis of previous studies of the histopathological features of SCI, the blurred high-intensity area on T2-weighted MRI is thought to represent edema or petechial hemorrhage. On the other hand, the low-intensity area on T1-weighted MRI in the subacute and chronic stages is thought to indicate necrosis or myelomalacia.[5,9] We thought that the T1-weighted low-intensity area on MRI at the subacute stage reflected the damage area of spinal cord. It was difficult to measure accurately the changed area of the spinal cord by edema in T2-weighted image. As there was no edema change in T1-weighted image, we could measure accurately the changed area of spinal cord.

Shimada and Tokioka[18] identified four distinct patterns of MR signal intensity changes that correlated well with spinal cord damage severity and clinical outcome. Ishida and Tominaga[19] assessed predictors of neurologic recovery in patients with acute central cervical SCI and found that an absence of MR signal intensity in the spinal cord and good early neurologic improvement were important predictors of long-term neurologic function improvement. However, no studies have reported on T1-weighted low-intensity changed area in CSCI patients. We hypothesized that the T1-weighted low-intensity area on MRI at the subacute stage of injury was predictive of neurological outcome. Indeed, we identified a significant negative correlation between the T1-LCAR and the ASIA motor score at discharge. There was also a significant negative correlation between the T1-LCAR and the recovery rate. These results suggest that there might be significant correlation between the T1-weighted low-intensity changed area on MRI and post-traumatic neurological outcome. If the T1-LCAR was <50%, the patients achieved a neurological status higher or equal ASIA D or modified Frankel D. These patients were able to walk with or without a cane at discharge.

Table 4 T1-LCAR and modified Frankel grade at discharge. If the cut-off point for the T1-LCAR was <50%, a significant positive correlation was found between T1-LCAR <50% and the patients who recovered to ASIA D or higher or to modified Frankel D or higher ($P<0.0001$)

	T1-LCAR<50%	T1-LCAR>50%
Lower Frankel D	2	10
Higher or Equal Frankel D	60	0

In this study, we researched the relationship between the outcome and the MRI 1 month after injury. All patients who did not have low-intensity area 1 month after injury were able to walk at discharge. Two months after injury, the low-changed area might be getting larger. However, this is the relationship between the outcome and the MRI 1 month after injury. MRI 1 month after injury reflects the patient's ability to walk.

This study had several limitations; it was retrospective, and the number of patients was small. Further research with larger patient populations and prospective evaluation may help resolve the questions raised in this study. In this study, the relationship between the imaging immediately after injury and the outcome was not performed. We did not consider the relationship between the outcome and the transverse diameter, cross-sectional area and volume of signal alteration, which will be considered in future study. Moreover, the etiology of CSCI without major bone injury should be studied in more detail.

In conclusion, we identified a significant relationship between T1-weighted low-intensity areas on T1-weighted MRI 1 month following injury and neurological recovery prognosis at discharge. Low-intensity changed area on T1-weighted MRI may be an important predictive factor in the natural course of neurological recovery for CSCI.

DATA ARCHIVING

There were no data to deposit.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Authors: Please review all authors' names, academic degrees, affiliations, and contributions, as well as the Disclosure, for spelling and accuracy.

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JNS SPINE

CLINICAL ARTICLE

Effect of preservation of the C-6 spinous process and its paraspinal muscular attachment on the prevention of postoperative axial neck pain in C3–6 laminoplasty

Eiji Mori, MD, Takayoshi Ueta, MD, PhD, Takeshi Maeda, MD, PhD, Itaru Yugué, MD, PhD, Osamu Kawano, MD, PhD, and Keiichiro Shiba, MD, PhD

Department of Orthopaedic Surgery, Spinal Injuries Center, Iizuka, Fukuoka, Japan

OBJECT Axial neck pain after C3–6 laminoplasty has been reported to be significantly lesser than that after C3–7 laminoplasty because of the preservation of the C-7 spinous process and the attachment of nuchal muscles such as the trapezius and rhomboideus minor, which are connected to the scapula. The C-6 spinous process is the second longest spinous process after that of C-7, and it serves as an attachment point for these muscles. The effect of preserving the C-6 spinous process and its muscular attachment, in addition to preservation of the C-7 spinous process, on the prevention of axial neck pain is not well understood. The purpose of the current study was to clarify whether preservation of the paraspinal muscles of the C-6 spinous process reduces postoperative axial neck pain compared to that after using nonpreservation techniques.

METHODS The authors studied 60 patients who underwent C3–6 double-door laminoplasty for the treatment of cervical spondylotic myelopathy or cervical ossification of the posterior longitudinal ligament; the minimum follow-up period was 1 year. Twenty-five patients underwent a C-6 paraspinal muscle preservation technique, and 35 underwent a C-6 nonpreservation technique. A visual analog scale (VAS) and VAS grading (Grades I–IV) were used to assess axial neck pain 1–3 months after surgery and at the final follow-up examination. Axial neck pain was classified as being 1 of 5 types, and its location was divided into 5 areas. The potential correlation between the C-6/C-7 spinous process length ratio and axial neck pain was examined.

RESULTS The mean VAS scores (± SD) for axial neck pain were comparable between the C6-preservation group and the C6-nonpreservation group in both the early and late postoperative stages (4.1 ± 3.1 vs 4.0 ± 3.2 and 3.8 ± 2.9 vs 3.6 ± 3.0, respectively). The distribution of VAS grades was comparable in the 2 groups in both postoperative stages. Stiffness was the most prevalent complaint in both groups (64.0% and 54.5%, respectively), and the suprascapular region was the most common site in both groups (60.0% and 57.1%, respectively). The types and locations of axial neck pain were also similar between the groups. The C-6/C-7 spinous process length ratios were similar in the groups, and they did not correlate with axial neck pain. The reductions of range of motion and changes in sagittal alignment after surgery were also similar.

CONCLUSIONS The C-6 paraspinal muscle preservation technique was not superior to the C6-nonpreservation technique for preventing postoperative axial neck pain.

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KEY WORDS laminoplasty; axial neck pain; paraspinal muscle; cervical spine; spinous process; trapezius muscle

Laminoplasty, which evolved from extensive laminectomy in the treatment of cervical spinal cord compression, is an established posterior cervical decompression procedure for multisegmental cervical myelopathy.[5,9,20] Although acceptable neurological improvement after laminoplasty is achieved, postoperative complications or problems such as axial neck pain, reduction of cervical range of motion (ROM), and changes in spinal alignment are often induced.[1,3,7,12] Axial neck pain, typified by persistent pain around the neck and shoulder, is a notorious postoperative complication after laminoplasty.[8,12,18] The incidence of axial neck pain has been reported

ABBREVIATIONS CSM = cervical spondylotic myelopathy; JOA = Japanese Orthopaedic Association; OPLL = ossification of the posterior longitudinal ligament; ROM = range of motion; VAS = visual analog scale.

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DISCLOSURE The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

to range from 5% to 80%.[6,13,18] Several techniques have been developed by surgeons who attempted to reduce axial neck pain after laminoplasty.[14,17,21] In a comparative study between C3–6 and C3–7 laminoplasty, Hosono et al.[6] reported that postoperative axial neck pain was significantly less severe after C3–6 laminoplasty than after C3–7 laminoplasty. They suggested that preservation of the C-7 spinous process and the origin of the trapezius and rhomboid minor muscles on the C-7 spinous process was key to preventing postoperative axial neck pain. The C-7 spinous process is an important muscular attachment point for the trapezius and rhomboid minor muscles connecting to the scapula. They hypothesized that disruption of the musculotendinous connection between the C-7 spinous process and the scapula was one of the causes of postoperative axial neck pain. The C-6 spinous process is the second longest spinous process after the C-7 process, and it also serves as an attachment point for the rhomboid minor and the speculum rhomboideum section of the trapezius, which is composed of the middle fibers of the trapezius and contains a very strong tendinous component.[16] Therefore, we postulated that preservation of the paraspinal muscles of the C-6 spinous process in addition to the C-7 spinous process might decrease postoperative axial neck pain. The relationship between preservation of the paraspinal muscles of the C-6 spinous process and axial neck pain is not well understood. The purpose of the current study was to clarify whether preservation of the paraspinal muscles of the C-6 spinous process reduces postoperative axial neck pain.

Methods

Patient Population

In total, 81 patients with no history of cervical surgery underwent a C3–6 spinous process–splitting double-door laminoplasty for the treatment of cervical spondylotic myelopathy (CSM) or cervical ossification of the posterior longitudinal ligament (OPLL) between January 2009 and December 2010. Thirty-three patients were treated with a paraspinal muscle preservation technique at the C-6 level (C6-preservation group), and 48 were treated with a paraspinal muscle nonpreservation technique at the C-6 level (C6-nonpreservation group). A surgeon (I.Y.) who was interested in preservation techniques performed the C6-preservation laminoplasties, and others (T.U. and T.M.) performed the C6-nonpreservation laminoplasties, our conventional technique. Although selection of the surgeon and the patients was not randomized in the current study, the patients were not informed about the C-6 spinous process preservation procedure. Of the patients, 60 were followed up and examined for more than 1 year. The ethics committee of our institution approved the study. Of the 60 patients, 44 were men, and the mean age of the group was 66.5 years (range 47–81 years). Forty-three patients had CSM and 17 had cervical OPLL. The mean follow-up durations were 3 years 1 month (range 1.8–3.8 years) in the C6-preservation group and 2 years 10 months (range 1.5–3.8 years) in the C6-nonpreservation group. Twenty-five patients underwent C6-preservation laminoplasty, and 35 underwent C6-nonpreservation laminoplasty. No significant differences in age, sex, or diagnosis were observed between the 2 groups (Table 1).

Surgical Procedures

In both of the groups, a midline skin incision was made from the C-2 spinous process to the C-7 spinous process. The nuchal ligament was incised in the midline. Then, the incision was continued between the bilateral splenius capitis and semispinalis capitis down to the spinous processes from C-3 to C-6. All the bilateral muscles attached to the C-2 and C-7 spinous processes were preserved by the procedures performed in both groups.

In the C6-preservation procedure, the paraspinal muscles were dissected, detached from the C-3 to C-5 posterior aspect while the attachment points of the paraspinal muscles such as rotators, multifidus, semispinalis cervicis, rhomboid minor, and the speculum rhomboideum of the trapezius (if attached to the spinous processes of C-6) were left intact, and retracted to ensure exposure of the laminae and the medial border of the facet joints. The epidural space was exposed after opening the C-3 split spinous process using a surgical bur, with lateral gutters at the medial border of the facet joint bilaterally. After midline blunt dissection with cutting of the interspinous process ligament between the C-6 and C-7 spinous processes, the epidural space was minimally exposed. The attachments of the paraspinal muscles to the C-6 and C-7 spinous processes were left intact. The C-4, C-5, and C-6 spinous processes were split longitudinally by a thread saw passed through the epidural space from C-3 to C-6/C-7, and lateral gutters were made bilaterally. At the C-6 level, bilateral gutters were made after minimal exposure of the medial border of the facet joint by retracting the paraspinal muscles from the lamina with a Penfield elevator while leaving the muscular attachment to the spinous process undisturbed. Bilateral halves of split spinous processes and laminae were lifted and bilaterally opened. A ceramic spacer was placed between the split spinous processes at each level (Fig. 1).

In the C6-nonpreservation procedure, the paraspinal muscles were dissected and detached thoroughly from the C-3 to C-6 posterior aspect. Longitudinal splitting of the spinous process from C-3 to C-6 was performed with a thread saw passed through the epidural space from C-6/C-7 to C-2/C-3. The procedures for opening the split

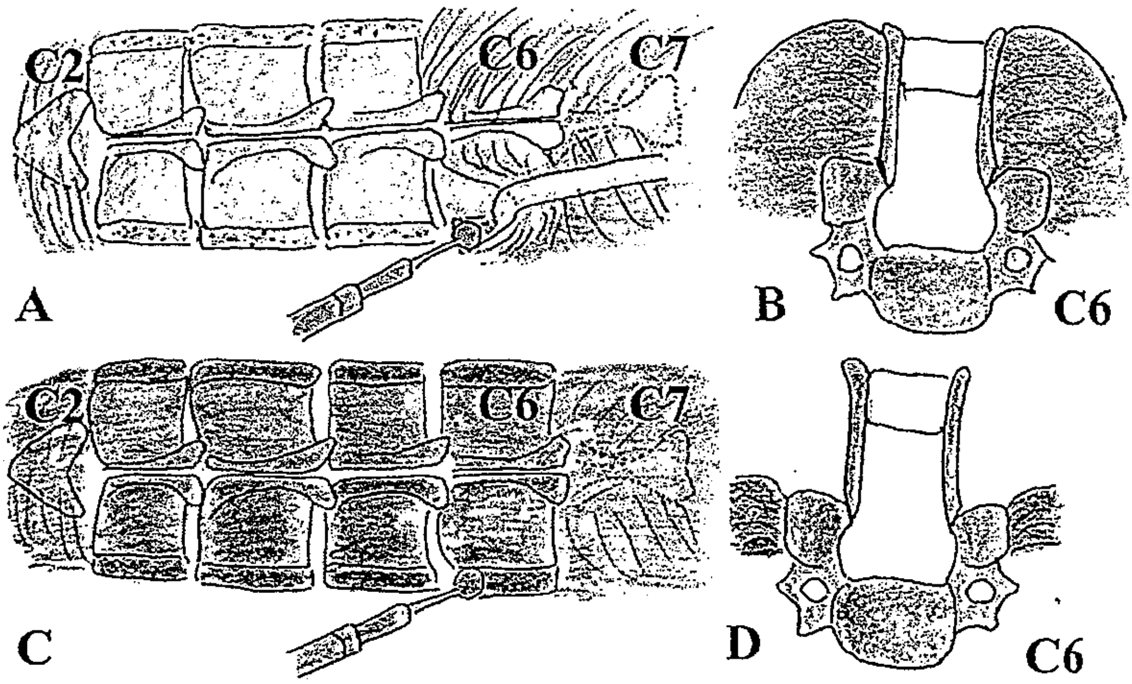
TABLE 1. Patient characteristics and surgical invasion

Characteristic	C6-Preservation Group (n = 25)	C6-Nonpreservation Group (n = 35)	p Value
Mean age in yrs (range)	66.1 (47–79)	66.7 (48–81)	NS
Sex (male/female)*	19:6	25:10	NS
CSM*	17	26	NS
OPLL*	8	9	
Mean op time (mins)†	132.5 ± 34.2	81.8 ± 20.9	<0.0001
mean EBL (g)†	60.2 ± 41.7	40.6 ± 32.0	<0.05

EBL = estimated blood loss; NS = not significant.

* Values are the number of patients.

† Values are mean ± SD.



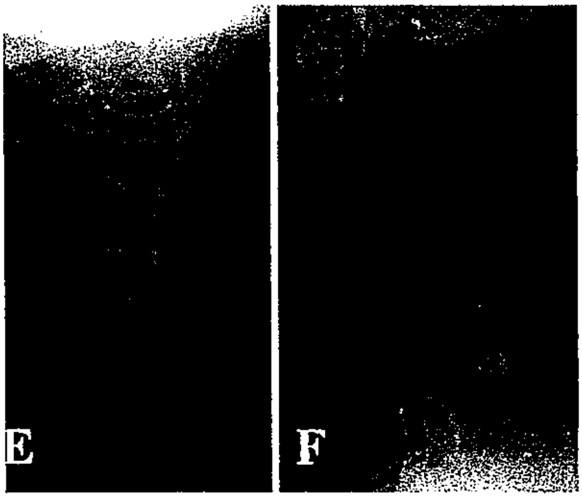


FIG. 1. A and B: In the C6-preservation procedure, the paraspinal muscles were dissected and detached from the C3–5 posterior aspects. The C3–6 spinous processes were cut longitudinally at the midline using a thread saw, and the attachments of the paraspinal muscles, such as rotators, multifidus, semispinalis cervicis, rhomboid minor, and the speculum rhomboideum of the trapezius, if it was attached, to the spinous processes of C-6 were left intact. At the C6 level, bilateral gutters were made after minimal exposure of the medial border of the facet joint by retracting the paraspinal muscles from the lamina with a Penfield elevator while leaving the muscular attachment to the spinous process undisturbed. C and D: In the C6-nonpreservation procedure, the paraspinal muscles were dissected and detached thoroughly from the C3–5 and C-6 posterior aspects. E and F: Anteroposterior and lateral radiographs after the C6-preservation procedure. Copyright (A–D) Eiji Mori. Published with permission.

spinous processes and placement of ceramic spacers were the same as those described for the C6-preservation procedure (Fig. 1).

Each patient in both groups wore a cervical orthosis for 10 days after surgery.

Clinical Examination

A 10-point visual analog scale (VAS) and VAS grading were used to assess axial neck pain 1–3 months after surgery and at the final follow-up observation. Pain around the neck and shoulder persisting for more than 1 week in the 1–3 months after surgery or for more than 1 month after surgery was considered postoperative axial neck pain. Patients were asked to mark their level of pain under the condition of no analgesics. The VAS grades were defined as follows: Grade I, 0–2.5 points; Grade II, 2.6–5.0 points; Grade III, 5.1–7.5 points; and Grade IV, 7.6–10.0 points. Axial neck pain was classified as 1 of 5 types as follows: pain, stiffness, tension, tightness, or traction. The axial neck pain areas of distribution were defined as follows: nuchal region, suprascapular region, superior angle of the scapular region, scapular region, and interscapular region (Fig. 2).

The type(s) and area(s) of distribution of axial neck pain (patients were allowed to select multiple types and/or areas) were examined and defined as positive when patients experienced pain 1–3 months after surgery or at the final follow-up observation. The examination for axial neck pain was performed by a clerical nonsurgical staff member who was blinded to the patients' surgical status. The correlation between the ratio of the length of the C-6 spinous process to that of the C-7 spinous process (C-6/C-7 spinous process length ratio) and the VAS score for axial neck pain was examined after surgery or at the final follow-up. These items concerning axial neck pain were compared between the C6-preservation and C6-nonpreservation groups. Surgical invasion was also compared between the groups. The ROM and sagittal alignment from C-2 to C-7 were examined before and after surgery and compared between the 2 groups. Neurological function was assessed by using the Japanese Orthopaedic Association (JOA) scale (full score 17), which was administered by a doctor who was blinded to the patients' surgical status.

Statistical Analysis

The clinical parameters of the 2 groups were compared using the Mann-Whitney U-test and the Fisher exact test. The correlation between the C-6/C-7 spinous process length ratio of each patient and his or her VAS score for axial pain was analyzed using Pearson's correlation coefficient. Statistical analysis was performed using the JMP program (version 8; SAS Institute Japan). p values of < 0.05 were considered statistically significant. Means are presented ± SD.

Results

The mean surgical time was significantly longer and the estimated blood loss was significantly greater in the C6-preservation group than in the C6-nonpreservation group (Table 1).

VAS Scores for Axial Neck Pain and VAS Grades

The mean VAS score for axial neck pain in the C6-preservation group was equivalent to that in the C6-nonpreservation group 1–3 months after surgery (4.1 ± 3.1 vs 4.0 ± 3.2, respectively). Moreover, the mean VAS scores for axial neck pain were comparable between the 2 groups at the final follow-up observation (3.8 ± 2.9 vs 3.6 ± 3.0, respectively) (Fig. 3). The VAS grade distributions were comparable between the groups at both 1–3 months after surgery and the final follow-up observation (Fig. 4).

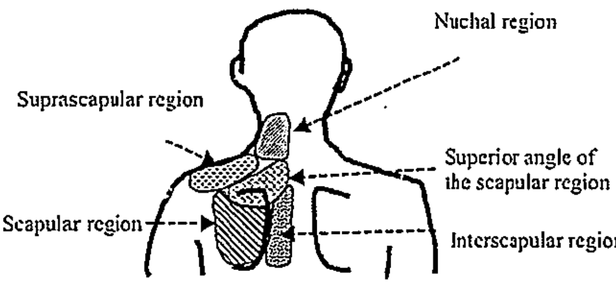


FIG. 2. Locations of axial neck pain (5 separate regions).

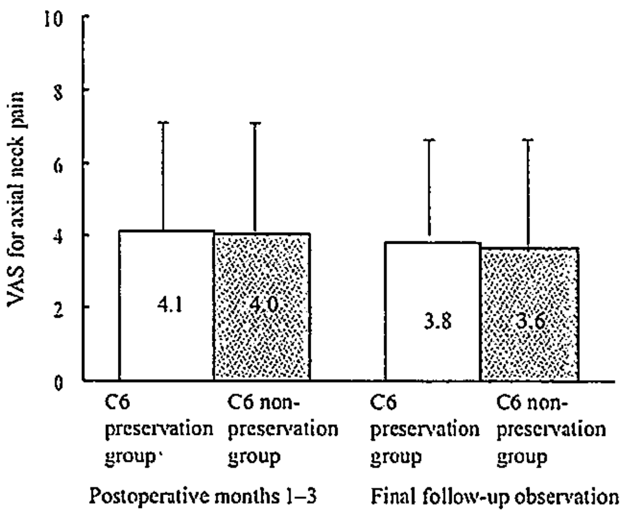


FIG. 3. VAS scores for axial neck pain in the C6-preservation and C6-nonpreservation groups 1–3 months after surgery and at the final follow-up observation. The *white columns* denote the C6-preservation group, and the *gray columns* denote the C6-nonpreservation group. There were no differences in the mean VAS scores of the 2 groups at either postoperative stage.

Type of Axial Neck Pain

Among the types of axial neck pain, stiffness was the most prevalent complaint in both the C6-preservation and C6-nonpreservation groups (64.0% and 54.5%, respectively). Subsequently, pain was prevalent in both groups (40.0% and 39.4%, respectively). The prevalences of the types of axial neck pain were comparable between the groups for all 5 types (Fig. 5).

Location of Axial Neck Pain

Among the locations of axial neck pain, the suprascapular region was the most common site in both the C6-preservation and C6-nonpreservation groups (60.0% and 57.1%, respectively). Subsequently, the nuchal region was commonly affected in both groups (48.0% and 45.7%, respectively). The prevalences of axial neck pain were comparable between the groups at all 5 regions (Table 2).

C-6/C-7 Spinous Process Length Ratio and Axial Neck Pain

The mean C-6/C-7 spinous process length ratios were comparable between the C6-preservation and C6-nonpreservation groups (76.9 ± 9.9 vs 78.0 ± 11.2, respectively). The C-6/C-7 spinous process length ratios of the patients were not significantly correlated with the VAS scores for axial neck pain either 1–3 months after surgery or at the final follow-up in the C6-preservation group (Fig. 6). Similarly, no significant correlation between the C-6/C-7 spinous process length ratios and the VAS scores for axial neck pain was observed for either postoperative stage in the C6-nonpreservation group (Fig. 7).

Radiographic and Neurological Outcomes

The reductions of ROM at the final follow-up visit, which were greater in the subgroup of patients with OPLL than in

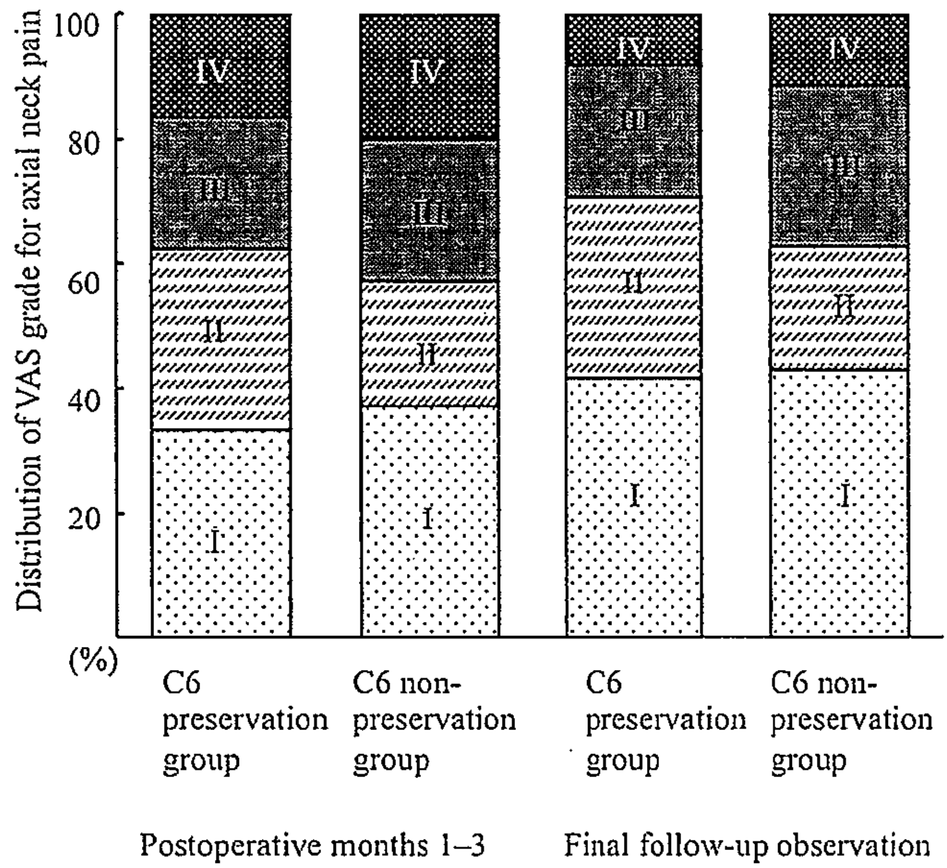


FIG. 4. The distribution of VAS grades for axial neck pain in the C6-preservation and C6-nonpreservation groups 1–3 months after surgery and at the final follow-up observation. There were no differences in the distributions of VAS grades between the 2 groups for either postoperative stage.

the subgroup of patients with CSM, were comparable between the C6-preservation and C6-nonpreservation groups in both of these subgroups (Table 3). Neither fracture of the lamina nor dislodgement of a spacer was observed in either of the 2 groups in the follow-up period. The sagittal alignment conversion of preoperative lordosis to postoperative kyphosis was observed in only 2 patients in the C6-nonpreservation group. A loss of C2–7 lordosis of > 10° was observed in 2 patients (8.0%) in the C6-preservation group and in 3 patients (8.6%) in the C6-nonpreservation group. The JOA score and its recovery rate were not significantly different between the 2 groups (Table 4). The mean hospital stay was 43.7 ± 21.3 days in the C6-preservation group and 42.5 ± 16.0 days in the C6-nonpreservation group. The patients participated in a rehabilitation program after surgery during their stay in the hospital. Therefore, they were not discharged soon after their surgery. In the C6-preservation group, 3 patients (12%) experienced dysesthesia in the upper extremities after surgery. These unpleasant symptoms were relieved in a few weeks with conservative treatment. One patient had cerebrospinal fluid pooling in the surgical site, which was identified after surgery and was associated with headache and nausea. He was treated conservatively and successfully without neurological worsening. Another patient had night delirium that lasted only a few nights. In the C6-nonpreservation group, there were 5 patients (14.3%) who experienced postsurgical dysesthesia in the upper extremities, which was relieved with conservative treatment in a few weeks. One patient was diagnosed with pneumonia after surgery and was treated successfully with antibiotics. One patient with an electrolyte abnormality and the patient with night delirium were managed conservatively. It was fortunate that neither neurological worsening (including C-5 paresis) nor any other serious complications, such as surgical site infection, nerve injury, or hematoma, occurred in either group.

Discussion

Postoperative axial neck pain typified by persistent pain around the neck and shoulders is a common problem associated with cervical laminoplasty.[7,8,12,18] There have been wide variations in the incidence of axial neck pain after various types of laminoplasty techniques.[6,13,18] Several posterior cervical decompression techniques, such as skip laminectomy,[21] segmental partial laminectomy,[17] and muscle-preserving laminoplasty,[14] have been introduced in an attempt to reduce postoperative complications, including axial neck pain. In terms of preventing axial neck pain, the results were not always favorable.[22,23] Although the exact cause of axial neck pain has not been detected, intraoperative invasion to the nuchal muscles is presumed

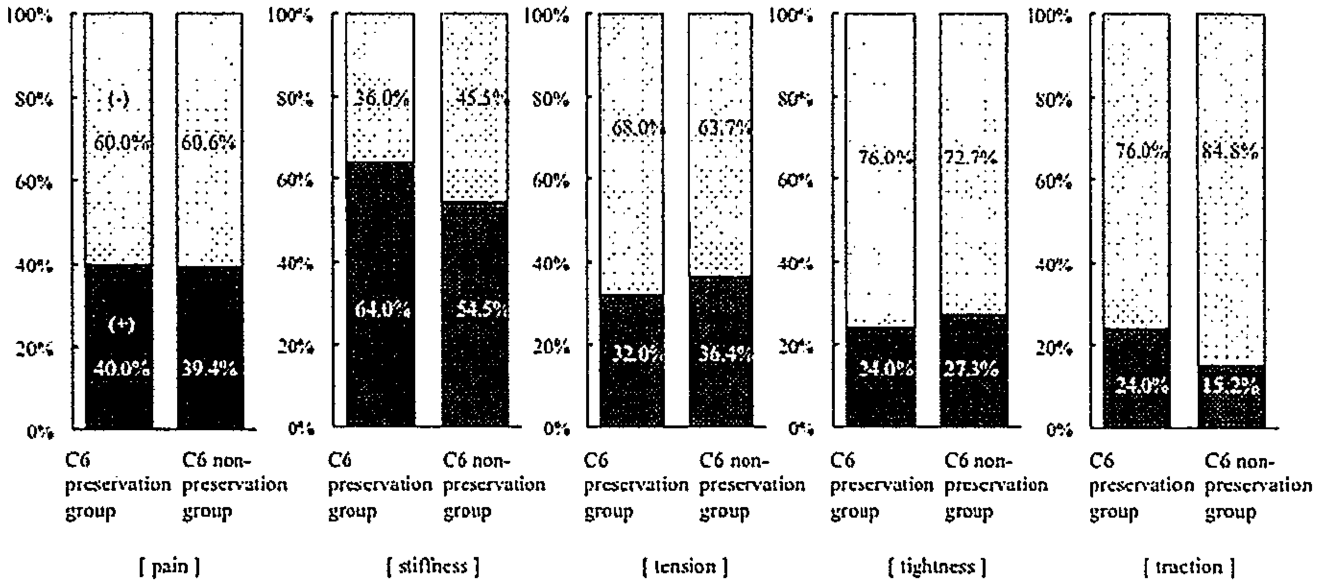


FIG. 5. Types of axial neck pain. The *dark columns* denote positivity, and the *spotted columns* denote negativity concerning the type of pain. Stiffness was the most common complaint in both groups, and pain was the second most prevalent complaint. The prevalences of axial neck pain were comparable between the 2 groups for all 5 types.

to be involved in this complication.[14,17,21] Nuchal muscles, such as the trapezius, rhomboid minor, splenius capitis, and serratus posterior superior muscles, are more densely and closely bound to the C-7 spinous process than other upper or middle cervical vertebrae.[11] Moreover, the maximum force generated by the trapezius has been reported among the cervical vertebrae to be the greatest at C-7.[10] In clinical research, the authors of one study reported that axial pain was induced after upper thoracic surgery and required detachment and spreading of the spinous process or vertebral arch at the cervicothoracic junction; these results were in contrast to those after middle or lower thoracic surgery, which was associated with no strong postoperative pain around the surgical wound.[19] These findings suggest that the connection of the nuchal muscles with the C-7 spinous process is very important and related to the pathology of postoperative axial neck pain. Focusing on preserving the large spinous process of C-7 as the important origin of the nuchal muscles, Hosono et al.[6] conducted a comparative study of conventional C3–7 laminoplasty and C3–6 laminoplasty by limiting the range of decompression with preservation of the C7 spinous process. They demonstrated the superiority of C3–6 laminoplasty over C3–7 laminoplasty in regard to axial neck pain; the incidence of postoperative axial neck pain was only 5.4% after C3–6 laminoplasty versus 29% after the C3–7 procedure. They emphasized the importance of preserving the C–7

TABLE 2. Prevalence of axial neck pain at each of the 5 locations*

Region	C6-Preservation Group (n = 25)	C6-Nonpreservation Group (n = 35)	p Value
Nuchal	12 (48.0)	16 (45.7)	NS
Suprascapular	15 (60.0)	20 (57.1)	NS
Superior angle of the scapula	4 (16.0)	7 (20.0)	NS
Scapular	1 (4.0)	3 (8.6)	NS
Interscapular	1 (4.0)	4 (11.4)	NS

* Values represent number (%) of patients.

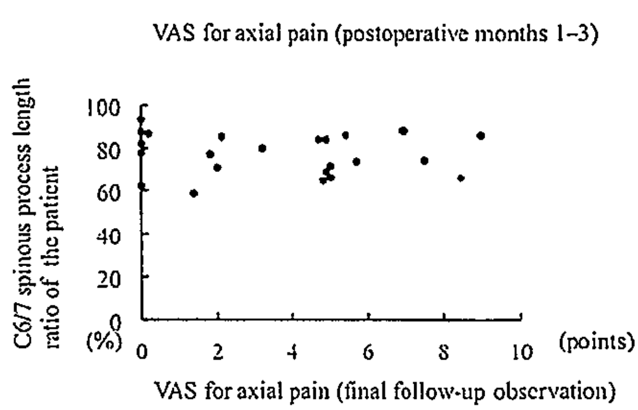


FIG. 6. Correlation between the C-6/C-7 spinous process length ratios of the patients and the VAS scores for axial neck pain in the C6-preservation group. The C-6/C-7 spinous process length ratios were not significantly correlated with the VAS scores for axial neck pain either 1–3 months after surgery (*upper*) or at the final follow-up observation (*lower*).

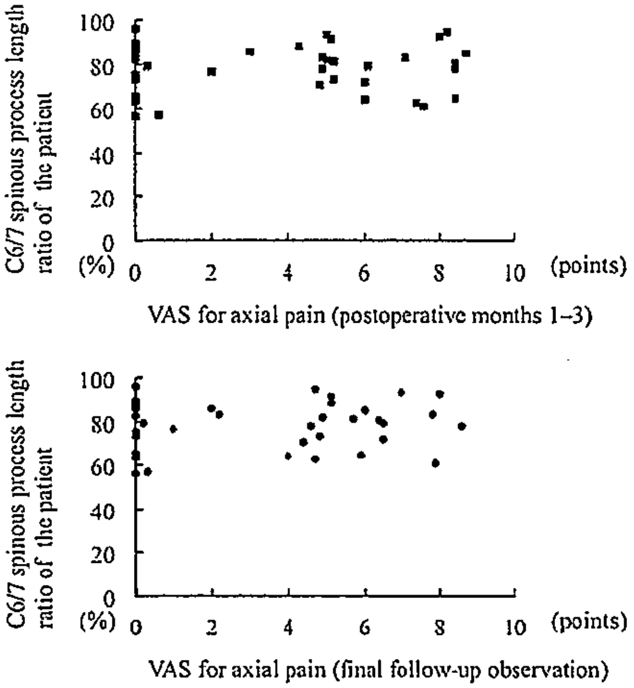


FIG. 7. Correlation between the C-6/C-7 spinous process length ratios and the VAS scores for axial neck pain in the C6-nonpreservation group. The C-6/C-7 spinous process length ratios were not significantly correlated with the VAS scores for axial neck pain either 1–3 months after surgery *(upper)* or at the final follow-up observation *(lower)*.

spinous process and the origin of the trapezius and rhomboid minor muscles on the C-7 spinous process for preventing postoperative axial neck pain. Patients with axial neck pain often experience increasing pain in the sitting or upright position, in contrast to decreasing pain in a lying position. Hosono et al.[6] provided the following explanation for the pain pattern. Downward displacement of the upper extremities occurs in the sitting position because of gravity. The trapezius and rhomboid minor muscles connecting the C-7 spinous process and the scapula are stretched by adduction of the scapula with downward displacement of the upper extremities. The disruption of the connection at the C-7 spinous process, serving as the important muscular attachment point for these muscles, might increase the stress on the remaining muscles attached to other spinous processes, resulting in persistent axial pain.

TABLE 3. ROM before and after surgery

Condition and Parameters	C6 Preservation Group (n = 25)	C6 Nonpreservation Group (n = 35)	p Value
No. of patients w/ CSM	17	26	
Preop ROM (°)*	35.2 ± 11.7	30.1 ± 13.8	NS
Final FU ROM (°)*	28.8 ± 11.2	25.8 ± 11.5	NS
% ROM†	81.8	85.7	NS
No. of patients w/ OPLL	8	9	
Preop ROM (°)*	23.5 ± 9.0	21.1 ± 13.4	NS
Final FU ROM (°)*	18.5 ± 9.7	14.8 ± 7.7	NS
% ROM (%)†	78.7	70.1	NS

FU = follow-up.
* Values are presented as the mean ± SD.
† % ROM indicates (preop ROM/ROM at final follow-up) × 100.

TABLE 4. Neurological outcome

Outcome	Mean ± SD		p Value
	C6-Preservation Group (n = 25)	C6-Nonpreservation Group (n = 35)	
Preop JOA score	10.2 ± 2.9	9.8 ± 2.7	NS
Final FU JOA score	14.1 ± 3.1	13.6 ± 3.0	NS
Recovery rate (%)*	60.8 ± 21.3	57.8 ± 29.5	NS

* Recovery rate calculated as follows: (JOA at final follow-up – preop JOA/17 – preop JOA) × 100.

The attachment of the trapezius ranges widely from the occipital bone to the T-12 spinous process. In particular, the speculum rhomboideum section, which is composed of the middle fibers of the trapezius, is very strong because of the presence of a very strong tendinous component. From an anatomical study using 50 cadavers, Ono et al.[16] reported that the speculum rhomboideus of the trapezius attached to the spinous process between C-3 and T-3, and its center was located at the C-7 spinous process in more than half of the individuals. The attachment of the rhomboid minor muscle to the spinous process occurred between C-5 and C-7. The C-6 spinous process is the second longest spinous process next to the C7 in the cervical region, and it plays a role as an attachment point for these muscles. Ono et al.[16] also stated that > 50% preservation of the attachment of the speculum rhomboideum of the trapezius was possible in 72% of the patients who underwent C3–6 laminoplasty with preservation of the C-7 spinous process and in 88% of the patients who underwent C3–C5 laminoplasty. The rhomboid minor muscle was possibly spared without complete dissection of the muscular attachment at the spinous process in 35% of the patients who underwent C3–6 laminoplasty and in > 50% of the patients who underwent C3–5 laminoplasty. Therefore, preserving the attachment of the paraspinal muscles to the C-6 spinous process in addition to the C-7 spinous process increases the preservation of the muscular attachment at the spinous process in the central area of the speculum rhomboideus of the trapezius and the rhomboid minor, potentially reducing axial neck pain more than that after using the preservation technique on the C-7 spinous process alone. However, the relationship between preservation of the C-6 spinous process and axial neck pain has not been studied thoroughly. Contrary to our expectations, the mean VAS scores and the distributions of VAS grade for axial neck pain were amazingly comparable between the C6-preservation and C6-nonpreservation groups in both the early and late postoperative stages. In addition, neck pain as assessed by VAS scores and the type of pain and its location were similar between the 2 groups. These results demonstrate that our paraspinal muscle preservation procedure for the C-6 spinous process was not superior to the C6-nonpreservation technique in terms of reducing postoperative axial neck pain.

We assume that the reason that the C6-preservation procedure did not achieve a successful result regarding axial neck pain includes anatomical and technical aspects. We did not know the range of attachment of the speculum rhomboideum of the trapezius and the rhomboid minor to the spinous process in each patient; therefore, we did not understand the extent of preservation of these muscles with regard to treatment of the paraspinal muscles at the C-6 spinous process. The maximum degree of preservation of these muscles and the resulting effect on the control of axial neck pain might be reached with preservation of the C-7 spinous process regardless of the C-6 procedure. Although we also examined the relationship between the length of the C6 spinous process and axial neck pain, the C-6/C-7 spinous process length ratios were similar in the 2 groups, and furthermore, they did not correlate with axial neck pain. From a technical viewpoint, our preservation technique for paraspinal muscles at the C-6 spinous process did not clarify whether the C-6 spinous process and its attachment of paraspinal muscles were left intact. The longitudinally split C-6 spinous process and lamina were spread similar to opening a double door while leaving the muscular attachment to the split spinous processes undisturbed, but the connections of the spinous process to the paraspinal muscles and nuchal ligament were different than those in the original alignment. Our preservation technique at the C-6 level might be insufficient for preventing axial neck pain, but another decompression technique allowing the C-6 spinous process and its paraspinal muscle attachment to be left intact could be successful.

Stiffness and tension, which were frequently observed in the patients in our study, seem to be similar to symptoms derived from back muscle diseases after lumbar surgery.[15] Almost half of the patients in the present study presented with pain in the nuchal or suprascapular region, and these areas seem to correspond to those in which nuchal muscles are stretched between the scapula and spinous processes by adduction of the scapula with downward displacement of the upper extremities. These findings suggest that the pathology of axial neck pain is mainly attributable to intraoperative invasion of the nuchal muscles.

The pathology of neck pain after posterior cervical surgery is multifactorial. Highsmith et al.[4] conducted a comparative study of laminoplasty and laminectomy with fusion in patients with cervical stenotic myelopathy. Preoperative neck pain VAS scores of 3.2 increased slightly postoperatively to 3.4 in the laminoplasty group, whereas in the fusion group, VAS scores significantly improved from 5.8 to 3.0. The authors concluded that cervical fusion significantly reduces neck pain in patients with cervical stenotic myelopathy. Motion-related pain, which is improved by stabilization with fusion, is an important factor in neck pain. This clinical study demonstrated this kind of neck pain. The pathology of preoperative neck pain is possibly different from that of postoperative neck pain. Although pain was reduced after fusion, postoperative neck pain in the fusion group was comparable to that in the laminoplasty group. Spinous processes and paraspinal muscular attachments were not preserved in either of the groups. Postoperative neck pain might have been related to the resection of spinous processes associated with the dissection and detachment of paraspinal muscles.

We used only pain characteristics such as intensity, pattern, and location to evaluate axial neck pain. We believe that our assessment for neck pain was not sufficient, because neck pain is an individual unpleasant sensory and emotional experience that is affected by various factors, including cervical pathologies and psychological issues. We found no differences in the VAS scores for axial neck pain between the CSM and OPLL subgroups 1–3 months after surgery or at the final follow-up observation (3.8 ± 3.2 vs 4.7 ± 3.0 [$p > 0.05$] and 3.5 ± 3.1 vs 4.0 ± 2.5 [$p > 0.05$], respectively). We should have adopted the use of additional instruments such as the Neck Disability Index,[24] which is most widely used to assess the effect of neck pain on the ability to manage everyday tasks, and the Self-rating Depression Scale,[2] which is used for the assessment of psychological factors. These additional evaluations probably would have helped us identify the differences in axial neck pain in our 2 groups of patients.

When VAS Grade III and IV axial neck pain (> 5.0 VAS points) in the present study was considered nearly comparable to moderate and severe axial pain (medicine or physical therapy for the painful muscles regularly needed), respectively, the incidence of axial neck pain in the late postoperative period was 34% in our study compared with 5.4% in the study of Hosono et al.,[6] in which these grades of pain were defined as axial neck pain. Although it is not precise to compare the results directly between these 2 studies because of the differences in axial neck pain measurements, the incidence of postoperative axial neck pain was higher in our study than in the study of Hosono et al. despite the use of C3–6 laminoplasty with C-7 spinous process preservation in both studies. This finding suggests that the difference in the laminoplasty techniques, double-door laminoplasty in our study and open-door laminoplasty in their study, possibly contributes to the pathology of axial neck pain. The purpose of the present study was to examine the efficacy of preserving the paraspinal muscular attachment to the C-6 spinous process in reducing postoperative axial pain. Our technique for preserving the C-6 spinous process did not effectively diminish pain.

The current study has some limitations. The study was retrospective, and the patients were not randomly assigned to their treatment group. Not only the individual surgeons but also the number of surgeons between the 2 groups were different. There are biases based on the technical variety of the surgeons and patient selection. A randomized prospective study without any biases would have been ideal. However, this was a preliminary nonrandomized comparative study aimed at investigating the advantages of the paraspinal muscle preservation technique before a randomized study is conducted. Each surgeon in each group was an expert spine surgeon with more than 10 years of experience who had no technical difficulty in handling the paraspinal muscles. Therefore, the difference in the surgeons between our 2 groups does not seem to highlight a difference in the surgeons' skills. The sample size was small, and it included a combined population of patients with CSM and cervical OPLL. There was no image assessment of the paraspinal muscles at the C-6 level, including atrophy or signal changes of muscles concomitant with postoperative clinical evaluations. A prospective randomized study with a large sample size would be required to compare the effect of differences in axial neck pain on the clinical outcome of C3–6 laminoplasty versus that of C3–5 laminoplasty with the preservation of the C-6 spinous process out of the range of decompression.

Conclusions

The VAS scores for axial neck pain and the distribution of VAS grades in both the early and late postoperative stages and the types and locations of axial neck pain were comparable between the C-6 paraspinal muscle preservation procedure and the C6-nonpreservation procedure. The C6-preservation technique was not superior to the C6-nonpreservation technique in preventing postoperative axial neck pain.

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Author Contributions

Conception and design: Mori. Acquisition of data: Mori, Ueta, Yugué. Analysis and interpretation of data: Mori, Yugué. Drafting the article: Mori. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Mori. Administrative/technical/material support: Shiba.

Correspondence

Eiji Mori, Department of Orthopaedic Surgery, Spinal Injuries Center, 550-4 Igisu, Iizuka, Fukuoka 820-8508, Japan. email: eijimori@orange.ocn.ne.jp.

Motion characteristics and related factors of Modic changes in the lumbar spine

Tetsuo Hayashi, MD, PhD,[1,2] Michael D. Daubs, MD,[1] Akinobu Suzuki, MD, PhD,[1] Trevor P. Scott, MD,[1] Kevin H. Phan, MD,[1] Monchai Ruangchainikom, MD,[1] Shinji Takahashi, MD, PhD,[1] Keiichiro Shiba, MD, PhD,[2] and Jeffrey C. Wang, MD[1]

[1]Department of Orthopaedic Surgery, University of California at Los Angeles, California; and [2]Department of Orthopaedic Surgery, Japan Labour Health and Welfare Organization, Spinal Injuries Center, Fukuoka, Japan

OBJECT Most studies of Modic changes (MCs) have focused on investigating the relationship between MCs and low-back pain, whereas the kinematic characteristics and degenerative disc disease associated with MCs are not well understood. To the authors' knowledge, no previous study has reported on the kinematics of MCs. The purpose of this study was to elucidate the relationship of MCs to segmental motion and degenerative disc disease.

METHODS Four hundred fifty symptomatic patients underwent weight-bearing lumbar kinematic MRI in the neutral, flexion, and extension positions. Segmental displacement and intervertebral angles were measured in 3 positions using computer analysis software. Modic changes, disc degeneration, disc bulging, spondylolisthesis, angular motion, and translational motion were recorded, and the relationship of MCs to these factors was analyzed using a logistic regression model. To control the influence of disc degeneration on segmental motion, angular and translational motion were analyzed according to mild and severe disc degeneration stages. The motion characteristics and disc degeneration among types of MCs were also evaluated.

RESULTS Multivariate analysis revealed that age, disc degeneration, angular motion, and translational motion were factors significantly related to MCs. In the severe disc degeneration stage, a significant decrease of angular motion and significant increase of translational motion were found in segments with MCs, indicating that a disorder of the endplate had an additional effect on segmental motion. Disc degeneration increased and angular motion decreased significantly and gradually as the type of MC increased. Translational motion was significantly increased with Type 2 MCs.

CONCLUSIONS Age, disc degeneration, angular motion, and translational motion were significantly linked to MCs in the lumbar spine. The translational motion of lumbar segments increased with Type 2 MCs, whereas angular motion decreased as the type of MC increased, indicating that Type 2 MCs may have translational instability likely due to degenerative changes. A disorder of the endplates could play an important role in spinal instability.

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KEY WORDS Modic changes; lumbar spine; kinematic analysis; magnetic resonance imaging; logistic regression analysis; degenerative disc disease

Modic changes (MCs) are bone marrow and endplate changes visible on MRI of patients with degenerative disc disease.[10,11] Modic Type 1 changes are hypointense on T1-weighted MRI and hyperintense on T2-weighted MRI, and are detected in areas with inflammation. Modic Type 2 changes are hyperintense on both T1- and T2-weighted MR images and are detected in areas with fatty degeneration. Modic Type 3 changes are hypointense on both T1- and T2-weighted MR images and detected in areas with sclerosis.

ABBREVIATIONS CI = confidence interval; MC = Modic change; OR = odds ratio.

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Many previous papers[2,10,11,16] associated with MCs in the lumbar spine have been published, but most of them are focused on the relationship between MCs and low-back pain.[5,14,17] Some previous studies[1,8,15] demonstrated the relationship between nonfusion after surgery and MCs, and have reported on the instability related to bone marrow changes without using MCs. To our knowledge, no study has reported on the kinematics of MCs. In addition, few studies have reported on the relationship between MCs and degenerative disc disease.

We hypothesized that lumbar MCs have some relationship to segmental motion and degenerative disc disease in the process of degenerative changes. The objective of this study was to evaluate how MCs relate to segmental lumbar motion and degenerative disc disease using kinematic MRI.

Methods

Patient Population

Four hundred fifty consecutive symptomatic patients (267 men and 183 women) with an average age of 44.6 ± 12.2 years (range 17–77 years) were examined from March 2011 to October 2011. The inclusion criteria were defined as patients who had low-back pain with or without neurological symptoms. The exclusion criteria were trauma, infection, rheumatoid arthritis, spinal tumors, and history of lumbar spine surgery. A total of 2250 lumbar discs from L1–2 to L5–S1 were retrospectively evaluated for all patients in this study. The Institutional Review Board of the University of California at Los Angeles approved this study and informed consent was obtained from all participants.

Kinematic MRI

MRI of the spine was performed using a 0.6-T MRI machine (Upright Multi-Position, Fonar Corp.). Two vertically orientated, opposing magnetic doughnuts placed 18 inches apart were used, allowing scanning of the patient sitting in an upright, axially loaded position. A quad-channel planar coil was used to obtain images. We examined the T1-weighted sagittal spin echo images (TR 671 msec, TE 17 msec, thickness 4.0 mm, field of view 30 cm, matrix 256 × 224, number of excitations 2) and T2-weighted fast spin echo images (TR 3000 msec, TE 140 msec, thickness 4.0 mm, field of view 30 cm, matrix 256 × 224, number of excitations 2) of each patient. All patients were scanned in the flexion, neutral, and extension positions.

MRI Analysis

Midsagittal T2-weighted MR images were marked for digitization by 3 spine surgeons on the flexion, neutral, and extension position images. Vertebral bodies were marked at 4 points (anterior-inferior, anterior-superior, posterior-superior, and posterior-inferior) from L-1 to S-1. The lowest lumbar vertebra was defined as L-5. All MRI parameters were recorded by computer-based measurements, and all calculations were performed with the MRI Analyzer anatomical software (version 3, Truemetric Corp.) for objective quantification as described in prior publications.[6,13,19,20]

Disc bulging was measured as the extension of the disc beyond the intervertebral space, with a greater value representing greater posterior bulging.[19,20] Spondylolisthesis was measured as the displacement of 1 vertebral body on the adjacent level below in the anterior or posterior direction as observed on the neutral image.[13]

Segmental mobility was measured in terms of translational motion and angular motion (Fig. 1). Translational motion was defined as an anterior to posterior shift of the vertebral body during translation and was calculated by measuring the distance of one segment over another in millimeters using T2-weighted sagittal images.[3,6,13] Angular motion was defined as the angle of difference between each vertebral body in flexion and extension.[3,6,13] This was measured by drawing lines along the superior borders of adjacent vertebrae of each motion segment and extending them until they joined. The difference between the two angles, which were not direction dependent, was then calculated.

Assessment of MCs

Modic changes were also evaluated for 2250 segments from L1–2 to L5–S1 and classified into none or Types 1, 2, and 3, according to their signal patterns on T1- and T2-weighted sagittal MR images. Type 1 MCs had a hypointense signal on T1-weighted sequences and a hyperintense signal on T2-weighted sequences. Type 2 MCs had a hyperintense signal on T1-weighted sequences and hyper- or isointense signal on T2-weighted sequences. Type 3 MCs had a hypointense signal on T1- and T2-weighted sequences.[10,11] The intra- and interobserver reliability of the ratings for MCs were assessed using the κ value with a subset of 50 cases (250 intervertebral levels).

Assessment of Degenerative Disc Change

Disc degeneration was classified into 5 grades using T2-weighted sagittal MR images according to the grading system proposed by Pfirrmann et al.[12] Grade I indicated normal, whereas Grade V indicated the most advanced disc degeneration. Intra- and interobserver reliability for this grading system was previously reported.[13]

Statistical Analysis

The Mann-Whitney U-test was used for comparisons of disc degeneration, disc bulging, spondylolisthesis, angular motion, and translational motion. According to correction with Bonferroni's inequality in the Kruskal-Wallis test, a p value less than 0.0125 (0.05/4) was considered statistically significant for comparison among types of MCs. After the variables were categorized, the chi-square test was used for the comparisons. Logistic regression analyses were used to compute odds ratios (ORs) and 95% confidence intervals (CIs) and detect the association between the existence of MCs and related factors. The variables in the multivariate model were clinically important from previous reports, regardless of statistical significance.[9,14] Disc degeneration grade was categorized into mild (Grades I–III) and severe (Grades IV and V). Age, spondylolisthesis, disc bulging, angular motion, and translational motion were di-

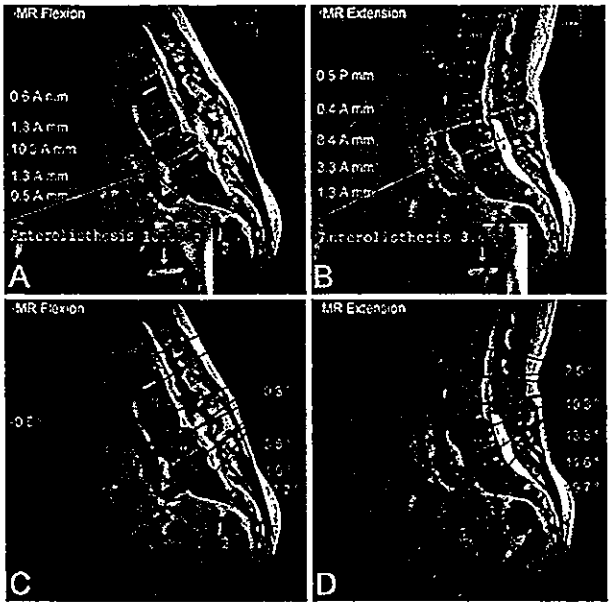

FIG. 1. Examples of translational and angular motion from flexion to extension as measured by MR Analyzer computer-based software on sagittal MR images. A: Translational motion in flexion. B: Translational motion in extension. Total translational motion was calculated as the absolute value of the difference between flexion and extension. C: Angular motion in flexion. D: Angular motion in extension. Total angular motion was calculated as the absolute value of the difference between the angle between adjacent vertebral bodies in flexion and in extension in degrees. Tan et al: Kinetic magnetic resonance imaging analysis of lumbar segmental mobility in patients without significant spondylosis. *Eur Spine J 21*:2673–2679, 2012. Copyright Springer. Reproduced with kind permission from Springer Science and Business Media. Figure is available in color online only.

vided into 2 groups, establishing the cutoff points at the median because no definitive cutoff point was found in a previous paper. Statistical analyses were performed using SPSS computer software (version 20, IBM Corp.) and values were expressed as mean ± SD. A p value less than 0.05 was considered statistically significant. According to Landis and Koch,[7] the reliability of diagnosis was assessed as follows: $\kappa = 0–0.2$ indicated slight agreement, 0.21–0.4 fair agreement, 0.41–0.6 moderate agreement, 0.61–0.8 substantial agreement, and 0.81–1 excellent agreement.

Results

Prevalence of MCs

Modic changes were observed in 129 (28.7%) of 450 patients. One hundred sixty-four (7.3%) of 2250 lumbar segments had MCs: Type 1 in 43 segments, Type 2 in 115, and Type 3 in 6. Modic changes were most frequent at L5–S1 followed by L4–5 and L3–4.

Reliability of Diagnosis of MCs

The interobserver agreement was substantial with a κ value of 0.77. Also, the intraobserver agreement was excellent with a κ value of 0.82.

Link to Disc Degeneration, Disc Bulging, Spondylolisthesis, Angular Motion, and Translational Motion at Each Level

The relationship between MCs and disc degeneration grade, disc bulging, spondylolisthesis, angular motion, and translational motion at each level are shown in Table 1. Analysis of disc degeneration revealed significant differences between the group with MCs and the group without MCs in all segments, indicating that the segments with MCs had more severe disc degeneration. A significant increase in disc bulging was observed at all segments except L5–S1 between units with MCs and those without MCs. Also, a significant increase in spondylolisthesis was observed at L1–2, L4–5, and L5–S1 in the group with MCs. In terms of kinematic analyses, a significant decrease in angular motion was found at L2–3, L3–4, and L4–5 in units with MCs, and a significant increase in translational motion was observed at all segments with MCs except L5–S1.

TABLE 1. Comparison between patients with and without MCs at each level

Variable	MCs	No MCs	p Value
Disc degeneration grade			
L1–2	3.7 ± 1.3	2.1 ± 0.7	0.001
L2–3	4.1 ± 0.9	2.2 ± 0.8	<0.001
L3–4	4.0 ± 1.0	2.3 ± 0.9	<0.001
L4–5	4.1 ± 0.7	2.6 ± 1.3	<0.001
L5–S1	4.2 ± 0.7	2.7 ± 1.2	<0.001
Disc bulge (mm)			
L1–2	3.5 ± 1.1	2.6 ± 0.9	0.038
L2–3	3.7 ± 1.2	2.9 ± 1.0	0.01
L3–4	3.7 ± 1.3	3.2 ± 1.1	0.03
L4–5	4.3 ± 1.7	3.6 ± 1.3	0.006
L5–S1	4.3 ± 1.9	4.1 ± 1.7	0.39
Spondylolisthesis (mm)			
L1–2	1.5 ± 0.9	0.6 ± 0.6	0.001
L2–3	1.1 ± 1.0	0.8 ± 0.7	0.24
L3–4	2.0 ± 2.5	0.8 ± 0.7	0.07
L4–5	2.1 ± 2.3	1.2 ± 1.1	0.02
L5–S1	3.3 ± 2.7	2.4 ± 1.7	0.007
Angular motion (°)			
L1–2	7.8 ± 4.8	6.6 ± 3.7	0.44
L2–3	6.0 ± 2.8	8.1 ± 3.9	0.03
L3–4	5.5 ± 3.5	8.2 ± 4.3	0.002
L4–5	6.0 ± 3.5	7.9 ± 5.0	0.039
L5–S1	5.2 ± 3.9	5.8 ± 4.5	0.31
Translational motion (mm)			
L1–2	2.6 ± 1.4	1.3 ± 0.9	0.003
L2–3	2.3 ± 1.7	1.4 ± 1.0	0.03
L3–4	2.3 ± 2.7	1.1 ± 0.9	0.03
L4–5	1.7 ± 2.0	1.0 ± 0.9	0.03
L5–S1	1.2 ± 1.4	1.0 ± 0.9	0.47

TABLE 2. Difference between segments with and without MCs in the mild and severe disc degeneration groups

	Mild (Grade I–III)			Severe (Grade IV & V)		
Motion	No MCs	MCs	p Value	No MCs	MCs	p Value
Angular	7.5 ± 4.3	6.8 ± 3.6	NS	6.8 ± 4.6	5.3 ± 3.7	0.002
Translational	1.2 ± 0.9	1.5 ± 1.3	NS	1.2 ± 1.0	1.6 ± 2.0	0.04

NS = Not significant.

Segmental Motion With and Without MCs in Mild and Severe Disc Degeneration Stage

To control the influence of disc degeneration on segmental motion, angular and translational motion were analyzed according to mild (Grades I–III) and severe (Grades IV and V) disc degeneration stage (Table 2). No significant differences were observed between the groups without and with MCs with mild disc degeneration, whereas a significant decrease of angular motion and significant increase of translational motion were found in the group with MCs with severe disc degeneration. This result indicates that segmental motion is affected by the presence of MCs in patients with severe disc degeneration. The disorder of the endplate would have an additional effect on segmental motion.

Factors Related to MCs

Factors potentially related to the changes were evaluated using the chi-square test and logistic regression analysis to control confounding factors (Table 3). Using univariate analysis, significant differences were found in age, disc degeneration, spondylolisthesis, disc bulging, and angular motion. Next, a multiple logistic regression model was used to adjust for age, sex, levels, disc degeneration, spondylolisthesis, disc bulging, angular motion, and translational motion, which were factors likely to relate to MCs and segmental motion. After adjustment for potential confounding factors, significantly elevated ORs were observed in segments with age > 45 years (OR 2.11, 95% CI 1.41–3.15), severe disc degeneration (OR 11.3, 95% CI 7.33–17.4), angular motion ≤ 6.8° (OR 1.70, 95% CI 1.17–2.48), and translational motion > 1.0 mm (OR 1.45, 95%

TABLE 3. Analysis of related factors to MCs

	No. of Discs (%)				
Factor	No MCs (n = 2086)	MCs (n = 164)	p Value*	Crude OR (95% CI)	Adjusted OR†† (95% CI)
Age (yrs)					
≤45	1108 (53)	42 (26)		Reference	Reference
>45	978 (47)	122 (74)	<0.001	3.29 (2.29–4.72)†	2.11 (1.41–3.15)†
Disc degeneration					
Mild (Grades I–III)	1704 (82)	31 (19)		Reference	Reference
Severe (Grades IV–V)	382 (18)	133 (81)	<0.001	19.1 (12.7–28.7)†	11.3 (7.33–17.4)†
Spondylolisthesis (mm)					
≤0.8	1123 (54)	45 (27)		Reference	Reference
>0.8	963 (46)	119 (73)	<0.001	3.08 (2.16–4.39)†	1.47 (0.98–2.20)
Disc bulge (mm)					
≤3.1	1100 (53)	46 (28)		Reference	Reference
>3.1	986 (47)	118 (72)	<0.001	2.86 (2.01–4.07)†	1.10 (0.74–1.65)
Angular motion (°)					
≤6.8	1026 (49)	112 (68)		2.23 (1.58–3.13)†	1.70 (1.17–2.48)†
>6.8	1060 (51)	52 (32)	<0.001	Reference	Reference
Translational motion (mm)					
≤1.0	1120 (54)	84 (51)		Reference	Reference
>1.0	966 (46)	80 (49)	0.541	1.10 (0.80–1.52)	1.45 (1.01–2.09)†

* Calculated using the chi-square test.
† $p < 0.05$, calculated by the univariate and multivariate analyses.
†† The logistic regression model was adjusted for age, sex, level, disc degeneration, spondylolisthesis, disc bulge, angular motion, and translational motion.

CI 1.01–2.09). Although the crude OR for translational motion was not significant (OR 1.10, 95% CI 0.80–1.52), it increased to significance after adjustment for several potential confounders.

Motion Characteristics of Types of MCs

The mean value of the disc degeneration grade in each MC type was 2.4 ± 1.0 for Type 0, 3.8 ± 0.9 for Type 1, 4.2 ± 0.7 for Type 2, and 5.0 ± 0.0 for Type 3. The analysis of disc degeneration among types of MCs showed a significant increase between Type 0 and Type 1, Type 1 and Type 2, and Type 2 and Type 3 ($p < 0.001$, $p = 0.004$, and $p = 0.004$, respectively) (Fig. 2). The analysis of angular motion among types of MCs showed Type 3 had significantly less than other types, and Type 2 was significantly less than Type 0 (Type 1 and 3, $p = 0.003$; Type 2 and 3, $p = 0.003$; Type 0 and 3, $p = 0.004$; Type 0 and 2, $p < 0.001$), indicating Types 2 and 3 had less angular motion (Fig. 3). The analysis of translational motion among types of MCs revealed a significant increase between Type 0 and 2 ($p = 0.006$), indicating Type 2 changes had more translational instability than Type 0 (Fig. 4).

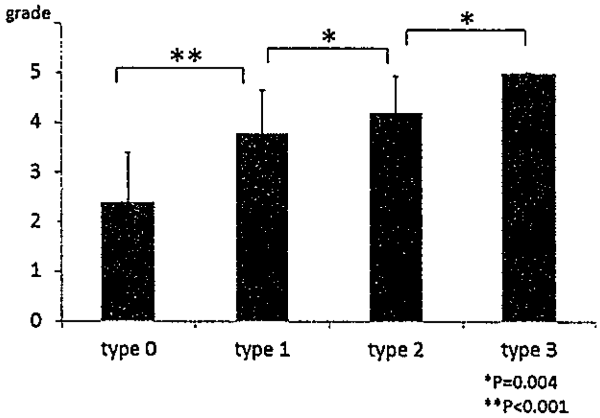

FIG. 2. Bar graph of disc degeneration grade (1–5) and types of MC. A significant increase of disc degeneration grade was observed between Type 0 and Type 1, Type 1 and Type 2, and Type 2 and Type 3. Figure is available in color online only.

Discussion

A thorough understanding of lumbar segmental motion is valuable to treat patients with degenerative lumbar disease, but kinematics associated with MCs in the lumbar spine have not been well understood. Our multivariate analysis showed MCs were significantly related to angular motion and translational motion. In addition, we were able to identify the details of the motion change among the types of MCs. Our study showed significant decreases in angular motion of Type 2 and Type 3 MCs and a significant increase in translational motion of Type 2. To the best of our knowledge, this is the first study assessing the relationship between segmental motion and MCs.

The reason for the decreased angular motion of Type 2 and Type 3 may be related to the disc degeneration grade. The relationship between disc degeneration and motion was studied by Kong et al.,[6] who reported a kinematic analysis of the relationship between the grade of disc degeneration and motion of the segmental unit of the lumbar spine, and demonstrated that angular motion significantly decreased in severely degenerated segments (Grade V). Their study was consistent with our results because we showed a significant increase of disc degeneration grade associated with an increase in the type of MCs (Fig. 2). Decreased or collapsed disc height due to degenerative change would result in decreased angular motion.

The reason for the increased translational motion also might be related to the disc degeneration grade. Translational motion was reported to be significantly increased in more advanced disc degeneration grade except for Grade V.[6] In addition, Kirkaldy-Willis and Farfan[4] postulated 3 stages with different conditions of stability and motion in the degenerative lumbar spine: dysfunction, instability, and stabilization. Their reports were consistent with our results of translational motion. Increased translational motion at Type 2 may indicate the stage of instability. The mean values of angular motion and translational motion in Type 3 were least among all types, suggesting that the segments with Type 3 may tend to ankylose and lose mobility with severe degeneration.

Interestingly, the significant difference of segmental motion between groups with and without MCs in the severe disc degeneration group suggests that segmental motion may not only be affected by disc degeneration but also by MCs themselves. Spinal instability associated with endplate disruption was reported by Zhao et al.[18] in a cadaveric motion segment experiment. They demonstrated that endplate disruption contributed more to instability than disc dehydration. Thus, in addition to disc degeneration, a disorder of the endplate would also play an important role in segmental instability and have an additional effect on segmental motion.

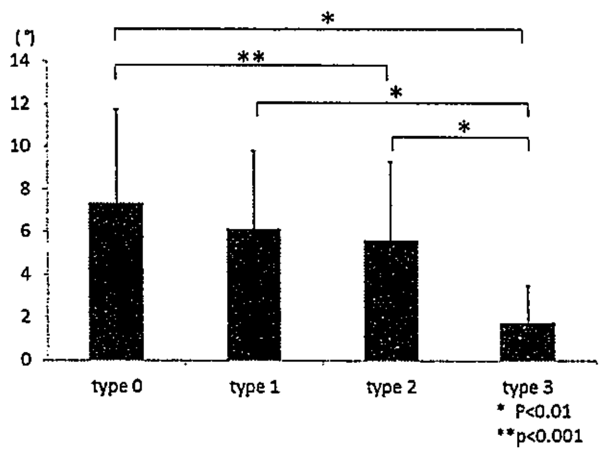

FIG. 3. Bar graph of angular motion (°) and types of MC. A significant decrease in angular motion was found between Type 3 and the other types, and between Type 2 and Type 0. Figure is available in color online only.

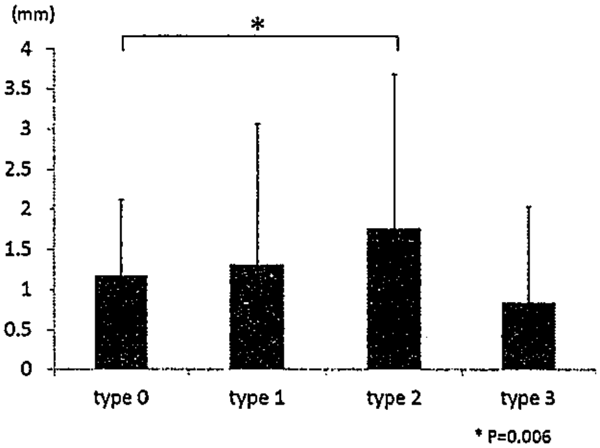

FIG. 4. Translational motion (mm) and types of MC. A significant increase in translational motion was found between Type 0 and 2. Figure is available in color online only.

Although MCs are widely accepted as the change associated with degenerative disc disease or spondylosis, few previous papers have reported on the relationship between MCs and disc bulging and between MCs and spondylolisthesis. Thompson et al.[14] reported that Type 1 MCs show some value in predicting disc herniation and spondylolisthesis compared with non–Type 1 MCs. Jensen et al.[2] reported that bulges or herniations at 40 years of age were the only predictors of new vertebral endplate signal changes at 44 years of age. Mann et al.[9] reported in their study of cervical MCs that patients with MCs are more likely to have a disc herniation at the same level. Our study showed disc bulging and spondylolisthesis were significantly related to MCs using the chi-square test and univariate regression analyses; however, after adjustment for confounding factors, the significant difference disappeared. Because disc degeneration would be the most influential factor in any kind of degenerative disc disease, the variables of disc bulging and spondylolisthesis may be statistically skewed in the multivariable analysis.

The present study has certain limitations. A relatively small number of segments with MCs, especially Type 3, may have reduced the statistical power, although the prevalence of MCs was consistent with previous studies.[17] Larger numbers of older patients in future research may resolve this limitation. Although the common method to assess the motion would be flexion and extension radiographs, we evaluated segmental motion with MRI. This difference might affect the values of measurements.

Clinically, our study suggests that the segments with MCs should be evaluated carefully because MCs may be a sign of a disc bulge or herniation. Moreover, MCs are one of the factors associated with segmental motion. The presence and status of MCs should be taken into consideration when evaluating stability in the lumbar spine. Characterizing the type of MCs observed on MRI may be one of the important factors to take into account when making a decision for or against spinal fusion.

Conclusions

Patient age, disc degeneration, angular motion, and translational motion are significantly linked to MCs in the lumbar spine. Disc degeneration grade increased significantly as the type of MC increased. Angular motion decreased as the type of MC increased, and translational motion significantly increased with Type 2 MCs compared with Type 0 MCs.

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Author Contributions

Conception and design: Hayashi. Acquisition of data: Hayashi, Suzuki, Phan, Ruangchainikom. Analysis and interpretation of data: Hayashi, Suzuki, Ruangchainikom, Takahashi. Drafting the article: Hayashi. Critically revising the article: Hayashi, Scott, Phan. Reviewed submitted version of manuscript: Hayashi, Daubs, Scott, Phan. Approved the final version of the manuscript on behalf of all authors: Hayashi. Statistical analysis: Hayashi. Administrative/technical/material support: Daubs, Suzuki. Study supervision: Daubs, Shiba, Wang.

Correspondence

Tetsuo Hayashi, Department of Orthopaedic Surgery, Japan Labour Health and Welfare Organization, Spinal Injuries Center, 550-4 Igisu, Izuka city, Fukuoka 820-8508, Japan. email: tetsuo884hayashi@yahoo.co.jp.

CHAPTER 64

Geriatric Spinal Cord Injuries: Rehabilitation Perspective

Kazunari Furusawa* ■ Fumihiro Tajima¶

Learning Objectives

At the end of this chapter, you will be able to:

- Describe the differences in etiology, complications, and outcomes between younger and older population with spinal cord injury.
- Identify the medical and social problems in older population.
- Prepare treatment strategies specifically for geriatric population.

INTRODUCTION

Elderly people (age ≥65 years) constitute a large proportion of the population (15–20%) in high-income countries, and many require hospitalization for old age-related diseases.[1] The steady increase in the age of the general population will also probably result in a larger proportion of elderly patients with spinal cord injuries (SCIs).[2]

Elderly patients with SCI have reduced functional reserves and greater comorbidity[3] and are more likely to have been physically disabled prior to the SCI, compared with younger patients with SCI.[4] Elderly patients with SCI do not need special techniques for rehabilitation therapy, but they require specialized medical consideration and rehabilitation strategies during hospitalization.

SCI in the elderly can be divided in two categories based on the time of onset: (a) onset of SCI at old age (or late-onset SCI) and (b) onset at young age with survival to old age (i.e., early-onset SCI). In this chapter, we focus on individuals with late-onset SCI.

EPIDEMIOLOGY OF TRAUMATIC SCI IN GERIATRIC POPULATION

INCIDENCE

Understanding the epidemiological pattern of SCI is the first step toward preventive strategies. However, the epidemiology of SCI varies in different countries and there is relatively little information on geriatric SCI.

The incidence is far higher in the elderly population than in the younger population.[5] One study from Canada showed that the age-adjusted incidence rates were 41.79 per million per year among adults (aged 15–64 years), and 50.87 per million per year for adults 65 years and older.[5]

In developed countries, the incidence of geriatric SCI is increasing. In Finns aged 50 years or older, the raw incidence of fall-induced cervical SCI (fracture, cord injury, or both) rose considerably between 1970 and 2004, from 52 in 1970 to 120 in 2004.[6] Among persons enrolled in the United States combined data set, the mean age at injury has increased from 28.3 years during the 1970s to 37.1 years between 2005 and 2008.[7] The proportion of participants with new injuries who were at least 60 years of age at injury increased from 4.6% in the 1970s to 13.2% between 2005 and 2008.[7] Two recent Scandinavian studies have also evaluated trends in the incidence rates over the past few decades.[8,9] In Norway, incomplete cervical SCI increased especially among men >60 years of age,[8] and in Finland, there was an increase in the SCI incidence rate among persons aged >55, including both tetraplegia and incomplete SCI.[9] These increases probably reflect the increase in aging population and the propensity for older patients to sustain SCI.[10] Interestingly, the mean age of patients

*Department of Rehabilitation Medicine, Kibikogen Rehabilitation Center for Employment Injuries, Kibichuo-cho, Kaga-gun, Okayama, Japan.
¶Department of Rehabilitation Medicine, Wakayama Medical University, School of Medicine, Wakayama City, Wakayama, Japan.

with traumatic SCI seems to be lower in less developed countries than in developed countries.[11]

ETIOLOGY

The mechanisms of injury in elderly patients with SCI differ substantially from those in younger patients.[10] Elderly patients are susceptible to minor trauma and much more likely to sustain SCI secondary to a fall.[5,6,10] A study from the United States[10] (SCI database at a single institution, $n = 3481$) examined the etiology of SCI in elderly patients (≥70 years of age) and indicated that falls accounted for 74% of SCI in elderly patients. Another study from Canada showed that falls were responsible for 63% of SCI among patients older than 65 years.[5] As mentioned above, the incidence of fall-induced severe cervical SCI seems to show an alarming rise in Finnish persons aged 50 years or older.[6]

LEVEL AND SEVERITY OF INJURY

The high rate of tetraplegic injuries account for a greater percentage of SCI in elderly patients than in adults patients.[5,10] Pickett et al.[5] reported that cervical SCI accounted for 94% of SCI in older patients (age > 60 years), compared with only 70% of SCI in patients younger than 60 years. Elderly patients, with a high incidence of ground-level falls, tend to suffer injury of the upper cervical spine when the head strikes the ground upon falling.[10]

As elderly patients often sustain vertebral spine and SCI from low-velocity trauma, they are more likely to present with incomplete, as opposed to complete neurologic, injuries.[4] Fassett et al.[10] showed that 63% of elderly patients sustained AIS grades C and D injuries compared with 40% among the younger patients.

The increase in SCI among geriatric persons poses great clinical and social concerns. The results of the studies on epidemiology of SCI indicate that preventive programs for SCI in the geriatric population should focus on the vulnerability to low falls.

Points to Remember

- The incidence of SCI in geriatric population is higher than in younger people.
- There has been an increase recently in the incidence of SCI in the geriatric population in developed countries.
- Elderly patients are susceptible to minor trauma and they are much more likely to sustain incomplete SCI secondary to a fall.

SPECIAL ISSUES IN ASSESSMENT AND CLASSIFICATION OF TRAUMA-RELATED GERIATRIC SCI

INJURY TYPES AND CLASSIFICATIONS

Assessment of elderly patients with SCI should be undertaken with understanding of the unique pathophysiology, age-related disorders, and associated comorbidities in these patients. Elderly patients are especially vulnerable to traumatic SCI due to the following factors; (a) age-related changes in bone quality,[10] (b) age-related predisposition to cervical spinal stenosis,[10] (c) propensity for fall-related injuries due to poor vision, vestibular system dysfunction, and abnormal proprioception in the lower extremity,[12] and (d) high rate of motor vehicle accidents per mile driven.[10]

In comparison with younger patients, elderly patients are less likely to have severe neurological deficits (greater percentage of AIS grades C and D injuries).[10] The International Neurological Standards Committee classified incomplete SCI into five types: central cord syndrome, Brown–Séquard syndrome, anterior cord syndrome, conus medullaris, and cauda equina syndromes. Elderly patients are at high risk of cervical spine injury.[13] The central cord syndrome (CCS), a common injury usually sustained as a result of an extension injury to the cervical spine, often occurs in elderly patients with underlying spondylotic changes. These patients experience variable degrees of functional recovery, but some degree of residual deficit and spasticity is likely. Traumatic CCS (TCCS) is generally considered to be associated with good prognosis.[14] However, the outcome is often worse in the elderly than younger people.[15,16]

It is necessary to evaluate cognitive abnormalities that can sometimes impede rehabilitation, especially in elderly patients with SCI. Age is recognized as a significant factor that negatively affects cognitive function. Furthermore, SCIs in elderly patients tend to be associated with traumatic brain injury (TBI), because trauma associated with falls that causes SCI also often results in TBI, and traumatic cervical SCI is also associated with a high rate of TBI but not more severe injuries.[17] As mentioned above, the geriatric population is prone to falls-related cervical SCI.

Point to Remember

- When we assess elderly patients with SCI, it is important to understand the unique pathophysiology, age-related disorders, and associated comorbidities, including cognitive abnormalities.

SPECIAL ISSUES IN MEDICAL MANAGEMENT AND REHABILITATION

General physical examination is important in elderly patients, due to the high post-SCI morbidity and mortality rates in this population.[18] DeVivo et al.[19] reported that the 7-year survival rate is significantly lower in patients with SCI over 50 years of age (22.7%), compared with that of the general population (86.7%). The aging-related decline in organ function is a problem faced by all elderly individuals and susceptibility to illness is one of the many consequences of aging.[20] Moreover, immobilization after injury increases the likelihood of disuse-related complications in the elderly compared with younger patients. The high mortality rate in elderly patients with SCI is probably due to limited physiological reserve.[10]

Pneumonia is the leading cause of death irrespective of the postinjury time period (up to 30 years after SCI).[21] The level and severity of SCI correlate directly with the development of respiratory complications.[22] Other factors associated with pulmonary complications in the elderly are age, preexisting medical illnesses (especially pulmonary), smoking, and major trauma.[23] In addition, dysphagia and regurgitation of gastric contents can cause aspiration pneumonia. Dysphagia is a relatively common secondary complication known to occur after acute cervical SCI, especially in the elderly. The expedient diagnosis of dysphagia is imperative to reduce the risk of development of pulmonary complications.

In geriatric population, the existing neurological conditions should be examined. SCI in neuromuscular disorders, such as Parkinson's disease has been reported.[24,25] Because neuromuscular disorders produce tremor, muscular rigidity, shuffling gait, and stooped posture, patients with these diseases are at greater risk of falling. Moreover, because patients with Parkinson's disease also usually have poor bone quality,[24] falls produce an increased risk of spinal fracture. The existing neuromuscular disorders should be reflected in any goal setting.

DeVivo et al.[4] analyzed the data of 866 in-hospital patients between 1973 and 1985 and compared the relative risks for various comorbidities in elderly (≥61 years) and young patients with SCI (Table 64.1). Outcomes were measured at discharge and 2 years after injury. Patients who were at least 61 years of age were 2.1 times more likely to have developed pneumonia, 2.7 times more likely to have experienced a gastrointestinal hemorrhage, 5.6 times more likely to have developed pulmonary emboli, and 16.8 times more likely to have had renal stones prior to first definitive discharge than their 16- to 30-year-old counterparts.

Patients who were at least 61 years of age were 3.9 times more likely to have been rehospitalized during the second postinjury year than patients in the 16- to 30-year-old age group; 2.1 times more likely to have required artificial ventilatory support prior to discharge; 22.7 times more likely to have been discharged to a nursing home; 71.8 times more likely to be in a nursing home 2 years after injury during the second postinjury year.

There is no specific information about special techniques for rehabilitation of geriatric SCI. However, the elderly patients with SCI have the following unique characteristics: (a) age-related complications and premorbid diseases such as cognitive abnormalities and pain, (b) limited physiological reserve, including difficulty to increase muscle strength, (c) a lot of incomplete neurological injuries, (d) short life expectancy, all of which should be taken into account when we determine the goal. The geriatric patients present with a complex set of issues and associated disability. This complexity requires comprehensive assessment and an integrated approach.

Table 64.1 Relative Risk of Rehabilitation Outcome in SCI Patients Aged ≥61 Years and Younger Patients[4]

Condition	Relative Risk
Pneumonia	2.1
Gastrointestinal hemorrhage	2.7
Pulmonary emboli	5.6
Renal stones before first discharge	16.8
Rehospitalization during second postinjury year	3.9
Artificial ventilator support before discharge	2.1
Discharge to nursing home	22.7
Nursing home placement within 2 years	71.8

Points to Remember

- The morbidity and mortality rates following SCI are higher in elderly patients, probably due to the limited physiological reserve.
- Pneumonia is the leading cause of death during all postinjury time periods after SCI.
- Dysphagia is a relatively common secondary complication known to occur after acute cervical SCI, especially in the elderly. Early diagnosis of dysphagia is imperative to reduce the risk of the development of pulmonary complications.
- The geriatric patients present with a complex set of issues and associated disability. This complexity requires comprehensive assessment and an integrated approach.
- The basis of rehabilitation in elderly patients is mobilized with physical training to increase residual physical functions.

PROGNOSIS AND GOAL SETTING

Fassett et al.[10] maintained SCI registry of 3481 patients at a single institution during the period extending from 1978 to the end of 2005. They demonstrated that in comparison with younger patients, senior patients (defined as ≥70 years of age) were found to be less likely to have severe neurological deficits, but the mortality rates were higher in the older age group both for the period of hospitalization (27.7% compared with 3.2%, $p < 0.001$) and during the 1-year follow-up period. The mortality rates in the elderly directly correlated with the severity of neurological injury (1-year mortality rate, AIS grade A 66%, grade D 23%, $p < 0.001$). The mortality rate in elderly patients with SCI was stable over the two decades of the above study, but the 1-year mortality rate was greater than 40% in all the analyzed time periods.

Rehabilitation produces gains in activities of daily living comparable to younger patients,[20] yet older patients achieve less objective neurological recovery and independent walking.[4] In addition, patients with concomitant neuromuscular disorders, which tend to be mostly elderly patients, are also reported to have worse outcome.[24] In addition, ventilatory impairment is a common problem in elderly patients recovering from SCI, and is associated with high morbidity rate.[26]

Although functional decline is inevitable, research suggests lack of decline in psychological well-being with aging. Despite several reports of high rates of depression in the elderly, there is evidence that perceived quality of life (QOL) is not necessarily worse in the elderly, even in those with chronic illnesses.[27] In addition, elderly patients may develop expectations that are more commensurate with adaptation to illness than younger individuals and may be more able to cope with life stresses.

Points to Remember

- In comparison with younger patients, the mortality rates are higher in the older age group.
- Goal setting is often difficult in geriatrics medicine for the following reasons:
  - They often develop age-related complications, premorbid diseases, and cognitive disorders.
  - They are more likely to present with incomplete as opposed to complete neurological injuries.

COMPLICATIONS

PRESSURE ULCER

Despite the progress in medicine, such as universal use of specialty beds and early nutrition, pressure ulcers are a common secondary condition associated with SCI. Pressure ulcers can potentially interfere with activities of daily living, occupational duties, and in severe cases, they may threaten life.

Aging itself might be a risk factor of pressure ulcers. Eastwood et al.[28] analyzed the data of 3904 persons with SCI discharged from the Model Systems between 1990 and 1997, who had follow-up interviews at 1 year postinjury. They showed that at first anniversary, lower discharge motor Functional Independence Measure, injury level, and age were related to the presence of pressure ulcers, rehospitalization, residence, and time spent out of residence in logistic regressions.

Rochon et al.[29] examined risk factors for pressure ulcers in 364 patients with SCI. They identified a pressure ulcer in 81 of 364 patients and revealed that in the univariate analyses, pressure ulcers were associated with Frankel groups A to B with an odds ratio (OR) of 5.7, low albumin with an OR of 4.9, low hemoglobin with an OR of 2.5, age > or = 60 years with an OR of 1.9 and three independent measures of comorbidity: Cumulative Illness Rating Scale with an OR of 3.7, Charlson Index with an OR of 2.2, and International Classification of Diseases, Ninth Revision, Clinical Modification count with an OR of 4.2.

Geriatric persons with SCI are more likely to develop a pressure ulcer for the following reasons: (a) these patients have increased arteriosclerotic risk factors and small vessel circulation is decreased, (b) it is difficult for them to take a posture to reduce the buttock pressure, (c) some older persons are malnourished and show extreme bony prominence. To prevent the pressure ulcer in the elderly, special consideration for pressure relief maneuvers and nutritional status is required.

PAIN

Neuropathic pain is a serious clinical symptom in SCI patients. SCI-related pain interferes with daily activities and significantly influences QOL.[30] Modirian et al.[30] studied the type and site of pain as well as the factors that exacerbate and alleviate such pain in 1295 SCI patients. Spinal cord-related pain was reported by 64.9% of their patients, while 8.8% reported history of pain but had no complaint at the time of examination, and 26.3% had never suffered any pain. The most common sites of pain were the distal lower extremities (46.5%), proximal lower extremities (40.9%), pelvic girdle (24.5%), and upper limbs (5.7%). The intensity of neuropathic pain was more severe at night than other times of the day.[31] The meta-analysis study of Dijkers et al.,[32] who analyzed 42 studies, indicated that completeness of injury (at least as simplified to complete versus incomplete) did not correlate with differences in pain prevalence. Furlan and Fehlings[33] analyzed data of the Third National Spinal Cord Injury Study and reported no significant correlation between age at the time of trauma and change in pain scores at all stages after SCI. These findings reinforce the need for continued research and education on neuropathic pain in SCI.

SPASTICITY

Assessment of spasticity is also important in the assessment of prognosis. Spasticity does have some potential benefits as it increases muscle bulk and tone, reduces osteoporosis, and enhances standing.[34] It is important to understand the balance between advantages and disadvantages of spasticity in patients with SCI.

As stated above, elderly patients are less likely to have severe neurological deficits.[10] Mobile patients require optimal spasticity with orthosis under the control of medications. Antispastic drugs are effective in reducing stretch reflexes without substantially reducing volitional torque. The differential effects of tizanidine and baclofen on reflexes of flexor and extensor muscles warrant further investigation into patient-specific management of antispastic drugs.[35] It is reported that locomotor training can reduce spasticity as measured by decreased plantar flexor excitability, ankle clonus, and quadriceps spasm.[36]

NEUROGENIC BOWEL

Neurogenic bowel represents colonic dysfunction resulting from lack of control of the central nervous system, and is a major physical and psychological problem for persons with SCI.[37]

Colorectal function can have a devastating effect on the daily life of elderly patients with SCI.[38] For example, while constipation is a frequently reported problem in numerous studies of SCI irrespective of age,[38] it is more prevalent in the elderly and those with a long history of injury.[39]

Fear of fecal incontinence frequently restricts patients from home activities.[40] Lynch et al.[41] assessed 467 persons with SCI and 668 age- and gender-matched controls, and demonstrated that continence deteriorates with increasing age in the general population but does not change with increasing age or time since injury in persons with SCI (n = 467). However, another study reported a larger proportion of elderly individuals with SCI suffered fecal incontinence.[42]

TCCS is considered the most prevalent incomplete SCI[43] and frequently occurs in elderly individuals with cervical spondylosis who sustain hyperextension injuries without spine fractures in falls. TCCS is generally considered to be associated with good prognosis and complete neurological and functional recovery.[43] One study investigated in detail the effects of age on bowel management and bowel care-related activities of daily living in individuals with TCCS.[15] The results identified significantly fewer patients aged ≥70 years with "continent spontaneous defecation" or "independent for bowel care", compared with younger patients.

The above studies suggest that management of neurogenic bowel in the geriatric SCI population can be challenging. However, alleviating bowel problems might help improve the QOL of these patients.

NEUROGENIC BLADDER

In the general population, aging is accompanied by diminished bladder capacity and urethral compliance and an increase in uninhibited detrusor contractions and residual bladder volume.[38] In addition, elderly individuals appear to be at increased risk for urinary tract infection and a gradual decline in kidney function.[38]

These changes also seem to affect individuals with SCI. However, the incidence of bladder problems, such as urinary tract infections and urinary incontinence, is reported to correlate with advancement of age (older > younger) in this population,[44,45] although other studies showed no such correlation.[42] The likely reasons for this discrepancy are differences in study methodologies and/or definition of urinary problems including urinary tract infections and urinary incontinence.

Young patients with SCI have a better outcome with regard to bladder management. Scivoletto et al.[2] compared outcome measures in elderly and young patients with SCI. With regard to the bladder, more patients of the young age group reached independence in voiding,[2,46] suggesting that the following account for the difficulties in bladder rehabilitation in elderly individuals with SCI, (a) diminished ability of elderly people to cope with the new situation, (b) pre-existing factors interfering with micturition, such as benign prostate hyperplasia and cystocele, (c) delayed or weak detrusor reflex activity, and (d) the erroneous belief, by both physicians and nurses, that continuous catheter bladder drainage is a safe and comfortable way to solve the problem.

The management of bladder dysfunction in elderly individuals with SCI is difficult, as it is in younger ones. Treatment of neurogenic bladder in the geriatric population with SCI requires comprehensive understanding of the above-mentioned factors, in addition to the neurological findings and activities of daily living.

RESPIRATORY AND CARDIOVASCULAR SYSTEMS

Rabadi et al.[47] studied the predictors of mortality in 147 veterans with traumatic SCI and concluded that there were three major causes of death: infection, such as pneumonia (21%), urinary infection (14%), and infection of pressure ulcers (11%); cardiovascular diseases, such as congestive heart failure (16%), coronary arterial disease (13%), and atrial fibrillation (2%); and malignancies (16%). In the same study, Cox regression analysis showed the age at the time of injury was the main predictor of SCI-related mortality. Their study suggested that old age at the time of injury is a significant predictor of mortality following SCI and that such patients are more likely to die from cardiovascular deaths than the general population.

Osterthun et al.[48] studied cardiovascular and respiratory functions in individuals who suffered traumatic or nontraumatic SCI during a follow-up period of 6.2 years and found that 27 persons (12.2%) died during the follow-up and the main causes of death were cardiovascular disease (37.0%), pulmonary disease (29.6%), and malignancy (14.8%). Old age at injury, nontraumatic SCI, and history of other medical conditions were independent predictors of death. They concluded that the main causes of death were cardiovascular and pulmonary diseases.

Glaser[49] indicated that cardiopulmonary (aerobic) fitness is difficult to develop and maintain and this can often be exacerbated by a sedentary lifestyle. It is evident that exercise training programs utilizing appropriate techniques can markedly improve the physical fitness, functional independence, and rehabilitation outcome of wheelchair users. Shiba et al.[50] measured maximum oxygen consumption (VO_{2max}) of eight individuals with SCI in 1986–1988 and in 2006 and found stable VO_{2max} while continuously maintaining sports activities. The results indicated that physical capacity reflected the level of sports activity in individuals with SCI who continuously performed sports activities.

Points to Remember

- To prevent and/or treat complications appropriately, we should understand the differences in complications affecting younger and older patients with SCI.
- Aging itself might be a risk factor of pressure ulcers.
- Elderly patients are less likely to have severe neurological deficits. Geriatric mobile patients greatly require optimal spasticity with orthosis under the control of medications.
- Constipation is more prevalent in the elderly and those with a long history of injury.
- In TCCS, geriatric patients are less likely to be "continent spontaneous defecation" or "independent for bowel care", compared with younger patients.
- Cardiovascular and pulmonary diseases are main causes of death in patients with SCI. Old age at the time of injury might be a significant predictor of mortality following SCI.
- Geriatric patients with SCI, just as the younger patients, should receive intensive and long-term rehabilitation to improve the physical fitness, functional independence, and rehabilitation outcome.

Key Points

- Recently, there has been an increase in the incidence of SCI in the geriatric population in developed countries.
- Elderly patients are susceptible to minor trauma and they are much more likely to sustain incomplete SCI secondary to a fall.
- Elderly patients with SCI have reduced functional reserves and greater comorbidity prior to SCI compared with younger patients with SCI.
- A significant proportion of elderly patients with SCI die from cardiovascular disease or pneumonia than the general population.
- Geriatric patients with SCI should receive intensive and long-term rehabilitation as well as younger patients.
- Geriatric patients present with a complex set of issues and associated disability. This complexity requires comprehensive assessment and an integrated approach.
- After rehabilitation, geriatric patients with SCI should maintain physical activities and/or sports to prevent any negative impacts of SCI.

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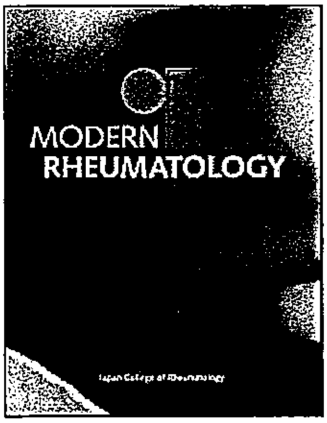

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Cervical myelopathy due to atraumatic odontoid fracture in patients with rheumatoid arthritis: A case series

Masahiko Takahata[a], Kuniyoshi Abumi[a], Hideki Sudo[a], Ken Nagahama[a] & Norimasa Iwasaki[a]
[a] Department of Orthopedic Surgery, Hokkaido University Graduate School of Medicine, Sapporo, Japan
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CASE REPORT

Cervical myelopathy due to atraumatic odontoid fracture in patients with rheumatoid arthritis: A case series

Masahiko Takahata, Kuniyoshi Abumi, Hideki Sudo, Ken Nagahama, and Norimasa Iwasaki

Department of Orthopedic Surgery, Hokkaido University Graduate School of Medicine, Sapporo, Japan

Abstract

To highlight the risk of cervical myelopathy due to occult, atraumatic odontoid fracture in patients with rheumatoid arthritis, we retrospectively reviewed radiographic findings and clinical observations for 7 patients with this disorder. This fracture tends to occur in patients with long-lasting rheumatoid arthritis and to be misdiagnosed as simple atlantoaxial dislocation. Since this fracture causes multidirectional instability between C1 and C2 and is expected to have poor healing potential due to bone erosion and inadequate blood supply, posterior spinal arthrodesis surgery is indicated upon identification of the fracture to prevent myelopathy.

Keywords

Atlantoaxial instability, Atraumatic occult fracture, Myelopathy, Odontoid fracture, Rheumatoid arthritis

History

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Introduction

Upper cervical spine lesions frequently occur in patients with rheumatoid arthritis (RA) [1]. Synovitis at C1–2 results in erosion of the odontoid process as well as rupture of the transverse ligament, leading to atlantoaxial instability and subluxation. Bone atrophy and erosion of the base of the odontoid process as well as instability at C1–2 may cause a fragility fracture of the odontoid process. The incidence of odontoid fracture in patients with RA, however, remains unclear. Although there are some case reports describing occult fractures of the odontoid process in patients with RA [2–4], it is important to emphasize the potential for these fractures because they can result in severe myelopathy.

The present study is a retrospective review of the clinical and radiologic findings, as well as the surgical outcomes of atraumatic odontoid fractures with myelopathy in patients with RA.

Materials and methods

Design

This is a retrospective case series review of seven RA patients with cervical myelopathy due to atraumatic odontoid fracture.

Patients

All of the patients were treated at the Hokkaido University Hospital between 2007 and 2012. We identified and reviewed the medical records of seven patients who underwent posterior spinal arthrodesis surgery for atraumatic odontoid fracture with myelopathy.

Assessment of clinical features and surgical outcomes of cervical myelopathy due to atraumatic odontoid fracture

We reviewed the medical records of the seven patients and obtained data regarding patient characteristics, symptoms, activities of daily living, and the clinical status of RA. The Ranawat classification of neurologic impairment was used to assess paralysis and walking disturbances. Imaging studies included plain radiograms, three-dimensional computed tomography (CT) angiograms, and magnetic resonance imaging (MRI) of the cervical spine and spinal cord.

Results

From 2007 to 2012, a total of 47 RA patients underwent surgery for atlantoaxial instability. This includes 7 RA patients with cervical myelopathy due to atraumatic odontoid fracture (Tables 1 and 2). They were 1 male and 6 females, with an average age at surgery of 67 (range, 44–88) years. Despite trends suggesting older age at surgery and higher risk in female in the 7 patients with cervical myelopathy due to atraumatic odontoid fracture compared with the remaining 40 patients (average age at surgery 63 years, 12 males and 28 females), these differences were not statistically significant. The mean follow-up period was 3 (range, 1–6) years. Average duration of RA was 15 (range, 9–28) years and rheumatic inflammation was poorly controlled in three of seven patients due to resistance to medications.

The preoperative symptoms were neck and occipital pain and quadriplegia. Five of seven cases were initially diagnosed as atlantoaxial subluxation (AAS) by plain radiograms and odontoid fracture was identified after examining results of MRI and CT. Three of seven patients were unable to walk when they were admitted. Radiologic studies revealed posterior shift or instability of fractured odontoid process in the three non-ambulatory patients, indicating that posterior instability of odontoid process is associated with severity of myelopathy. None of the patients in this series had anomalies of vertebral artery but we found that anterior and posterior ascending arteries, which provide blood supply to the odontoid process [5,6], were not depicted in any patients of this series on CT angiograph. All seven patients underwent posterior decompression and fusion surgery with autogenous iliac bone graft. The Ranawat classification of neurologic deficits improved level after surgery in all patients except 1 patient (Patient 1). Postoperative deep wound infection occurred in 1 patient (Patient 5).

Correspondence to: Masahiko Takahata, Department of Orthopedic Surgery, Hokkaido University Graduate School of Medicine, Kita-15 Nishi-7, Kita-ku, Sapporo, 060-8638, Japan. Tel: +81-11-706-5934. Fax: +81-11-706-6054. E-mail: takamasa@med.hokudai.ac.jp

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Table 1. Patient characteristics, disease activity, and medications.

Patient	Sex	Age at onset (years)	Duration of RA (years)	Steinblocker stage	Classification of functional status*	CRP (mg/mL)	ESR (mm/h)	MMP-3 (ng/mL)	Medications
Patient 1	F	78	15	IV	IV	1.7	74	N/A	Etanercept, Prednisolone 10 mg/day (Resistant to Bucillamine, Salazosulfapyridine, and Tacrolimus)
Patient 2	F	58	10	III	III	0.02	20	192	Tocilizumab, MTX 6 mg/w, Methylprednisolone 2 mg/d (Resistant to Etanercept and Infliximab)
Patient 3	F	75	12	III	II	0.24	16	79	Tacrolimus 3 mg/d, Prednisolone 5 mg/d, (Intolerant to MTX and Adalimumab)
Patient 4	F	44	16	IV	IV	2.6	N/A	165	Bucillamine 300 mg/d, Prednisolone 10 mg/d, (Intolerant to MTX)
Patient 5	M	88	9	II	II	2.7	N/A	409	Tacrolimus 1 mg/d, Predonisolone 12.5 mg/d
Patient 6	F	55	16	III	II	0.2	7	246	MTX 6 mg/w, Prednisolone 10 mg/d, Bucillamine 300 mg/d
Patient 7	F	71	28	III	II	0.5	28	96	Bucillamine 300 mg/d, Prednisolone 5 mg/d

CRP C-reactive protein, *ESR* erythrocyte sedimentation rate, *MMP-3* matrix metalloproteinase-3, *N/A* not available, *MTX* methotrexate.
*Functional status due to RA before onset of myelopathy.

Bone union at graft site was achieved within 1 year postoperatively in all 7 cases; however, none of the 7 cases achieved bone union at fracture site on X-ray or CT despite posterior fusion. One patient (Patient 4) required additional posterior decompression surgery for recurrent myelopathy due to adjacent segment degeneration 1 year after O–C3 fusion surgery. During follow-up, two patients died. Patient 1 died due to pneumonia 1 year after surgery and Patient 3 died due to cardiac arrest 6 years after surgery, respectively.

Case presentations

Patient 1

A 78-year-old woman with RA presented with neck pain and quadriplegia. She was resistant to conventional disease-modifying anti-rheumatic drugs. She suffered from neck pain for 1 year and was diagnosed with an AAS 1 year prior to the onset of myelopathy. Her neck pain worsened without any history of trauma 7 days before presenting to our clinic. Five days after the exacerbation of her neck pain, she became unable to stand or even sit unassisted. The patient was then referred to our clinic for evaluation and treatment for AAS.

On admission, she exhibited severe quadriplegia and astasia. Neurologic examination revealed motor weakness and sensory disturbance in all four extremities, clumsy hand movements, increased deep tendon reflex of the elbows and knees, and a positive Babinski's reflex.

Plain radiography revealed posterior dislocation of the odontoid process and C1 (Figure 1A–D). CT scanning revealed an odontoid fracture with extensive erosion of the fractured region (Figure 1E and F). MRI showed impingement of the spinal cord by the fractured odontoid process, periodontoid granulation tissue, and C1 posterior arch (Figure 1G).

The patient underwent a posterior occipitocervical (O–C2) fixation and C1 laminectomy (Figure 1I). Her neck pain was relieved immediately after surgery. Her motor weakness gradually improved, and she was able to sit, stand, and transfer to a wheelchair on her own at 4 weeks after surgery. Although the Ranawat classification of her neurologic deficits remained Class IIIb, her activities of daily living were recovered to the level prior to the onset of myelopathy. The patient died due to pneumonia 1 year after surgery.

Patient 3

A 75-year-old woman with a 12-year history of RA presented with neck and occipital pain, numbness in her feet, and a slight gait disturbance 3 months before admission to our clinic. She had been treated with Tacrolimus for 6 years. She was diagnosed with asymptomatic AAS 4 years before the onset of her symptoms.

On admission, she exhibited an unsteady gait. Neurologic examination revealed a hyperactive deep tendon reflex in her elbows, knees, and ankles, and motor weakness in both lower extremities. Her fingers and feet were hypoalgesic. Plain radiograms revealed anterior dislocation of the C1 and gross instability between C1 and C2 (Figure 2A–F). CT revealed a fracture of the odontoid process and vertical subluxation of C2 (Figure 2G and H). MRI showed spinal cord impingement by the fractured odontoid process and C1 posterior arch (Figure 2I).

The patient underwent posterior occipitocervical (O–C2) fusion surgery to correct the vertical subluxation (Figure 2J). Her neck pain was relieved and her motor function recovered from Ranawat Class IIIa to Class II after the surgery. She died due to cardiac arrest 6 years after surgery, at which time her motor function was sustained.

Table 2. Duration of neck pain, neurologic impairment, and surgical procedures.

Patient	Duration of neck pain (months)	Ranawat classification of neurologic impairment: Preop	Follow-up	Posterior shift or instability of odontoid process	Surgical procedure (fusion levels)
Patient 1	12	IIIB	IIIA	+	O–C2
Patient 2	24	IIIA	II	+	C1–2
Patient 3	3	IIIA	II	−	O–C2
Patient 4	8	IIIB	IIIA	+	O–C3
Patient 5	13	IIIB	IIIA	+	O–C2
Patient 6	24	II	I	−	O–C2
Patient 7	1	II	I	−	O–C2

O–C occipitocervical.

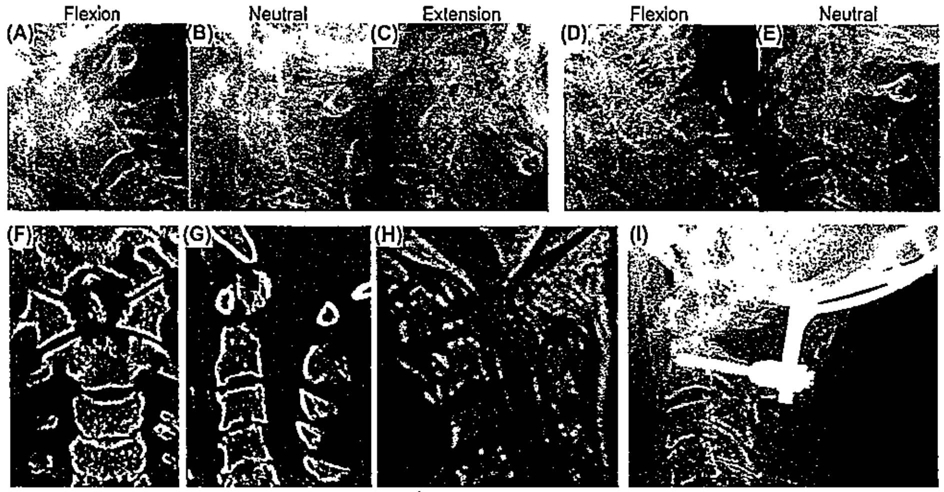

Figure 1. Patient 1. A 78-year-old woman with RA. Lateral plain radiographs in flexion (A), neutral position (B), and extension (C) at 1 year before the onset of myelopathy showing no odontoid fracture, but atlantoaxial subluxation. Lateral radiographs in flexion (D) and neutral position (E) after the onset of myelopathy, showing an odontoid fracture and posterior subluxation of C1 in neutral position. Coronal and sagittal CT scan reconstructions show the odontoid fracture and bone erosion at the base of the odontoid process (F and G). Sagittal T2-weighted MRI showing impingement of the spinal cord by the fractured odontoid process, periodontoid granulation tissue, and C1 posterior arch (H). The patient underwent a C1 laminectomy and posterior instrumented occiput–C2 fusion with an iliac bone graft (I).

Patient 5

An 88-year-old man with RA presented with gait disturbance and restriction of fine finger motion. He had a 9-year history of RA. He had slight neck and occipital pain for 2 years. Numbness in his hands and fingers appeared without any history of trauma, and motor weakness in the upper and lower extremities developed gradually. Additionally, urinary incontinence and encopresis developed. The patient was diagnosed with AAS and referred to our clinic.

On admission, he exhibited quadriplegia and astasia. Neurologic examination revealed a hyperactive deep tendon reflex in the elbows, knees, and ankles, and motor weakness in all four extremities. All four extremities were hypoalgesic. He had bowel and bladder dysfunction. CT and MRI showed C1–2 instability with an odontoid fracture. The patient underwent O–C2 fusion surgery and his motor weakness was fully recovered after surgery. Deep wound infection occurred 2 weeks after surgery. Bacterial culture revealed that the infecting organism was *Corynebacterium* species. The patient underwent open irrigation surgery without removing the instrument and was treated with antibiotics for 3 weeks. The signs of infection disappeared. Additional bone graft surgery was performed 3 months after the first surgery.

Discussion

Findings from this case series suggest that occult atraumatic fractures of the odontoid process should be suspected in patients with long-standing RA complaining of neck pain and myelopathy. There are some case reports describing occult odontoid fractures in patients with RA, but most reported cases had only vague neck pain [2,3], indicating that not all patients with atraumatic odontoid fractures develop myelopathy. Toyama et al. reported that fracture of odontoid process was seen in 6 of 58 RA patients (10%) with atlantoaxial subluxation, who underwent surgery, and that 2 of the 6 patients with spontaneous odontoid fractures had myelopathy [4]. This is not surprising because 75% of patients with traumatic odontoid fracture are reported to be neurologically intact [7]. Atraumatic odontoid fractures, however, may have a greater chance of causing myelopathy because odontoid fractures are likely to become non-union fractures, especially in patients with RA, and non-union odontoid fractures may cause progressive myelopathy [8].

Possible risk factors for atraumatic odontoid fractures with myelopathy include long-standing RA and poorly controlled rheumatic inflammation. Average duration of RA in this series was 15 years and rheumatic inflammation was poorly controlled in three of seven patients due to resistance to medications. Given that long-standing poorly controlled RA results in severe bone erosion of the odontoid process, atlantoaxial instability, and systemic bone loss, patients with long-standing RA have a potential risk for the onset of fragility odontoid fractures without major trauma.

Myelopathy caused by atraumatic odontoid fracture is likely to be misdiagnosed as AAS or exacerbation of polyarthritis. We think

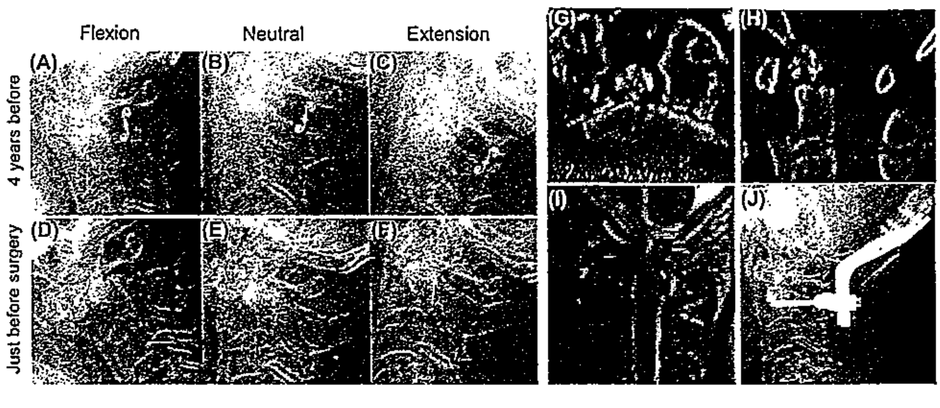

Figure 2. Patient 3. A 75-year-old woman with RA. Lateral plain radiographs in flexion (A), neutral position (B), and extension (C) demonstrating mild AAS, but no odontoid fracture 4 years before the onset of myelopathy. Lateral radiographs in flexion (D), neutral position (E), and extension (F) after the onset of myelopathy showing odontoid fracture and gross instability at C1–2. Coronal and sagittal CT reconstruction images demonstrating the odontoid fracture and vertical and anterior subluxation at C1–2 (G and H). Sagittal T2-weighted MRI image of the upper cervical region showing spinal cord compression by the base of odontoid process and C1 posterior arch (I). The patient underwent posterior correction and occiput–cervical fusion with an iliac bone graft (J).

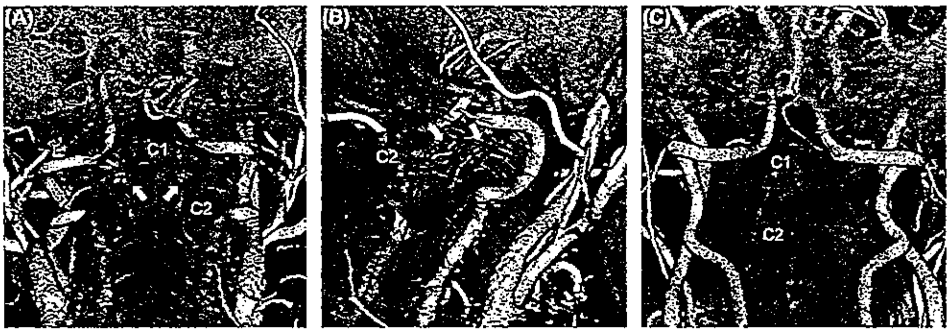

Figure 3. Poor arterial blood supply of the odontoid process in patients with an atraumatic odontoid fracture. Examples of three-dimensional CT angiography images in the posterior–anterior view (A) and oblique view (B) depicting anterior and posterior ascending arteries of the odontoid process (white arrows) in a patient with early RA. Three-dimensional CT angiogram of Patient 2 showing no ascending arteries of the odontoid process (C). Ascending arteries of the odontoid process were not observed in any patients of this series on CT angiography.

that myelopathy is caused by the progression of AAS, because AAS is very common in RA [1], while myelopathy caused by atraumatic odontoid fractures is rare. This is a very important point because the examination as well as treatment for AAS may be harmful to the spinal cord in cases of odontoid fracture. In most cases of AAS, cervical extension is safe because anterior subluxation can be reduced by extension and posterior subluxation of the C1 can be blocked by the odontoid process. On the other hand, in cases of odontoid fracture, cervical extension could cause posterior displacement of the fractured odontoid process, which compresses the spinal cord. Therefore, when patients with RA show abnormal neurologic findings on examination and posterior displacement of the C1 on X-ray, MRI and CT are indicated prior to functional plain X-ray examination.

Posterior spinal arthrodesis surgery is indicated for atraumatic odontoid fractures in patients with RA. Osteosynthesis through the anterior approach is not recommended because fracture union is difficult to achieve in these cases. None of the 7 cases in this study achieved fracture union despite posterior fusion. Possible reasons for this are bone erosion at the fracture site due to chronic inflammation and poor blood supply, which impair bone healing. We could not observe anterior and posterior ascending arteries, which provide blood supply to the odontoid process [5,6], in any patients of this series on CT angiography, supporting the idea that poor arterial blood supply to the fractured odontoid process impairs healing (Figure 3).

The difference between traumatic odontoid fractures and atraumatic odontoid fractures in terms of the surgical procedure is that traumatic odontoid fractures can be stabilized by direct anterior screw fixation as in osteosynthesis [9,10] or posterior C1–2 arthrodesis [11], but atraumatic odontoid fractures tend to require posterior occipitocervical (O–C) fusion. As described, atraumatic odontoid fractures occur in patients with long-standing poorly controlled RA and many of them have destructive bone lesions in the upper cervical spine. If patients have vertical instability, destruction of the C1–2 joints, or a retro-odontoid pannus formation that requires C1 laminectomy for spinal cord decompression, O–C fusion is indicated. Indeed, six of seven patients in this series required O–C fusion.

In conclusion, atraumatic odontoid fractures should be suspected in patients with long-standing RA complaining of neck pain and myelopathy. This condition is likely to be misdiagnosed as AAS or exacerbation of polyarthritis. Since this fracture causes multidirectional instability between C1 and C2, examination as well as treatment should be carefully performed to prevent deterioration of the myelopathy. Posterior spinal arthrodesis surgery is indicated for this fracture.

Conflict of interest

None.

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Optimum pelvic incidence minus lumbar lordosis value can be determined by individual pelvic incidence

Satoshi Inami, Hiroshi Moridaira, Daisaku Takeuchi, Yo Shiba, Yutaka Nohara & Hiroshi Taneichi

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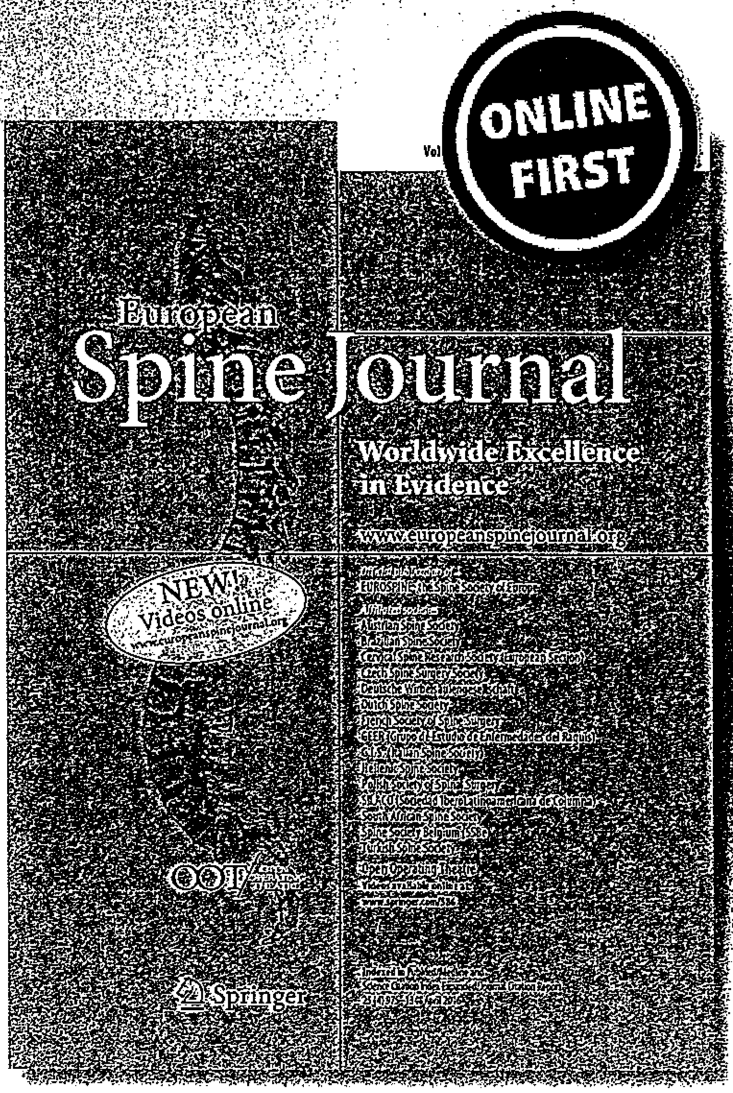

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ORIGINAL ARTICLE

Optimum pelvic incidence minus lumbar lordosis value can be determined by individual pelvic incidence

Satoshi Inami[1] · Hiroshi Moridaira[1] · Daisaku Takeuchi[1] · Yo Shiba[1] · Yutaka Nohara[1] · Hiroshi Taneichi[1]

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Abstract
Purpose Adult spinal deformity (ASD) classification showing that ideal pelvic incidence minus lumbar lordosis (PI-LL) value is within 10° has been received widely. But no study has focused on the optimum level of PI-LL value that reflects wide variety in PI among patients. This study was conducted to determine the optimum PI-LL value specific to an individual's PI in postoperative ASD patients.
Methods 48 postoperative ASD patients were recruited. Spino-pelvic parameters and Oswestry Disability Index (ODI) were measured at the final follow-up. Factors associated with good clinical results were determined by step-wise multiple regression model using the ODI. The patients with ODI under the 75th percentile cutoff were designated into the "good" health related quality of life (HRQOL) group. In this group, the relationship between the PI-LL and PI was assessed by regression analysis.
Results Multiple regression analysis revealed PI-LL as significant parameters associated with ODI. Thirty-six patients with an ODI <22 points (75th percentile cutoff) were categorized into a good HRQOL group, and linear regression models demonstrated the following equation: PI-LL = 0.41PI–11.12 ($r = 0.45$, $P = 0.0059$).
Conclusions On the basis of this equation, in the patients with a PI = 50°, the PI-LL is 9°. Whereas in those with a PI = 30°, the optimum PI-LL is calculated to be as low as 1°. In those with a PI = 80°, PI-LL is estimated at 22°. Consequently, an optimum PI-LL is inconsistent in that it depends on the individual PI.

Keywords Adult spinal deformity · Sagittal alignment · Pelvic incidence · Lumbar lordosis

✉ Satoshi Inami
inami3104@me.com

[1] Department of Orthopaedic Surgery, Dokkyo Medical University School of Medicine, 880 Kitakobayashi, Mibu-machi, Shimotsuga-gun, Tochigi 321-0293, Japan

Introduction

Adult spinal deformity (ASD) is often associated with sagittal plane malalignment [1, 2]. The correlations between sagittal radiographic parameters and self-reported pain and disability have been shown in several studies, and it has been demonstrated that sagittal plane malalignment results in the disability most consistently expressed in ASD patients [3–6].

Numerous studies have been conducted to better understand the ideal sagittal global alignment, including the pelvis. Since the work by Duval-Beaupère et al. several authors have attempted to clarify that pelvic incidence (PI) is primary importance in regulating sagittal spinal alignment, and the relationship between lumbar lordosis (LL) and PI is admitted [7–9].

Nowadays, in an effort to achieve patient-specific alignment treatment, some formulas have been developed to calculate the ideal LL matching with the PI, which helps in surgical planning when deciding the amount of correction needed. The Scoliosis Research Society (SRS)-Schwab classification has a global classification paradigm with three sagittal modifiers: PI minus LL (PI-LL), sagittal vertical axis (SVA), and pelvic tilt (PT). These parameters were classified into three categories (i.e., non-pathological, moderate, and marked) on the basis of health-related quality of life (HRQOL) [10]. In this classification, the non-pathological cutoff value of PI-LL is within 10°, and a

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excessive PI-LL mismatch is considered as a possible risk factor for adjacent segment disease and lumbopelvic fixation failure [11, 12].

To improve knowledge about spinopelvic harmonized alignment, the question to consider is whether or not the PI-LL value for sagittal balance is fixed (i.e., <10), without taking of a variety of PI values into account. The PI value varies widely among individuals. It has been demonstrated in a past study that a lower value of PI is approximately 30° and a higher value is approximately 85° [13–16]. PI determines the relative position between the sacral plate and femoral heads, and it has been shown that the PI is related to the capacity to compensate for sagittal balance through pelvic retroversion [13]. In our clinical experience, patients with a large PI sometimes have good surgical results, even with a postoperative PI-LL >10° (Fig. 1). Additionally, Yamada et al. reported that 23 % of postoperative patients acquired good SVA and satisfaction nevertheless they had PI-LL >10° [17]. An optimal formula that would incorporate these factors has not yet been proposed.

Materials and methods

In this study, we intended to investigate the relationship between PI-LL and PI in postoperative ASD patients and to determine the optimum PI-LL, specific to the individual PI value, in patients who had undergone successful surgery. Our hypothesis is that the optimal PI-LL is not constant, but changes based upon individual differences in PI.

This is a single-institutional retrospective study with institutional review board approval of consecutive patients undergoing surgery for ASD between the years 2007 and 2012. Inclusion criteria for this study were as follows: adult patients (>40 years old) presenting pain/disability caused by spinal deformity; available complete coronal and sagittal radiography from preoperative visits to final follow-up, and complete health related quality of life (HRQOL) questionnaires in final follow-up.

Data collection and radiographic measurement

All patients were observed for at least 2 years. Demographic and surgical data were retrospectively recorded from clinical charts. Preoperative and final follow-up (minimum 2 years) radiographic data consisted of full-length standing coronal and sagittal radiographs obtained in the freestanding position with fingers on clavicles and shoulders in 45° of forward elevation [18]. All radiographic measurements were made by digital analysis, using the Centricity™ Enterprise Web, version 3.0 (GE Healthcare Japan, Tokyo).

Spinal radiographic measurements included T5–T12 thoracic kyphosis (TK), T10–L2 thoracolumbar kyphosis (TLK), T12–S1 lumbar lordosis (LL), SVA, maximal coronal Cobb angle (scoliosis), and coronal balance, i.e., the distance between C7 plumb line and central sacral vertical line. Pelvic morphology and orientation were measured by PT, sacral slope (SS), and PI. PI-LL was also calculated from these data. The Oswestry Disability Index (ODI) at final follow-up was investigated for HRQOL evaluation.

Statistical analysis

Stepwise multiple regression analysis was used to determine the factors associated with good clinical results using the ODI score as the dependent variable and the above-mentioned radiographic parameters as independent variables. Patients with a postoperative ODI value less than the 75th percentile cutoff were designated into the "good" HRQOL group. Then, in this group, the relationship between the PI-LL and PI was assessed by linear regression analysis to determine the optimum PI-LL value based upon the individual PI. Furthermore, post hoc power analysis was performed, using G*Power (free program; http://www.gpower.hhu.de/) to estimate the effect size that could be detected with a sample size of good HRQOL group. The level of significance was set at 0.05.

Results

Patient data

The patients included 35 women and 13 men, with a mean age of 60.6 years (SD 9.7 years; range 40–75 years). Categorization by SRS-Schwab classification system was marked deformity in 43 patients, moderate deformity in three patients, in at least one sagittal modifier. And coronal curve types were TL/lumbar only ($n = 22$), double curve ($n = 7$), and no major coronal deformity ($n = 19$).

Forty-two patients had a posterior-only spinal fusion, five had an anterior and posterior spinal fusion, and one had an anterior fusion. Osteotomies included pedicle subtraction osteotomy ($n = 13$), vertebral column resection ($n = 2$), and Ponte osteotomy ($n = 27$). The most common uppermost instrumented vertebrae (UIV) were T10 ($n = 34$), followed by L2 ($n = 4$), T11 and T12 ($n = 2$ each), and T3, T4, T7, L1, and L3 ($n = 1$ each). The most common lowest instrumented vertebrae (LIV) were S1 ($n = 30$), followed by L5 ($n = 14$), and L3 and L4 ($n = 2$ each).

Preoperative versus final follow-up radiographic findings

The deformity correction surgery led to an increase in TK (from 14° preoperatively to 30° at follow-up), a decrease in

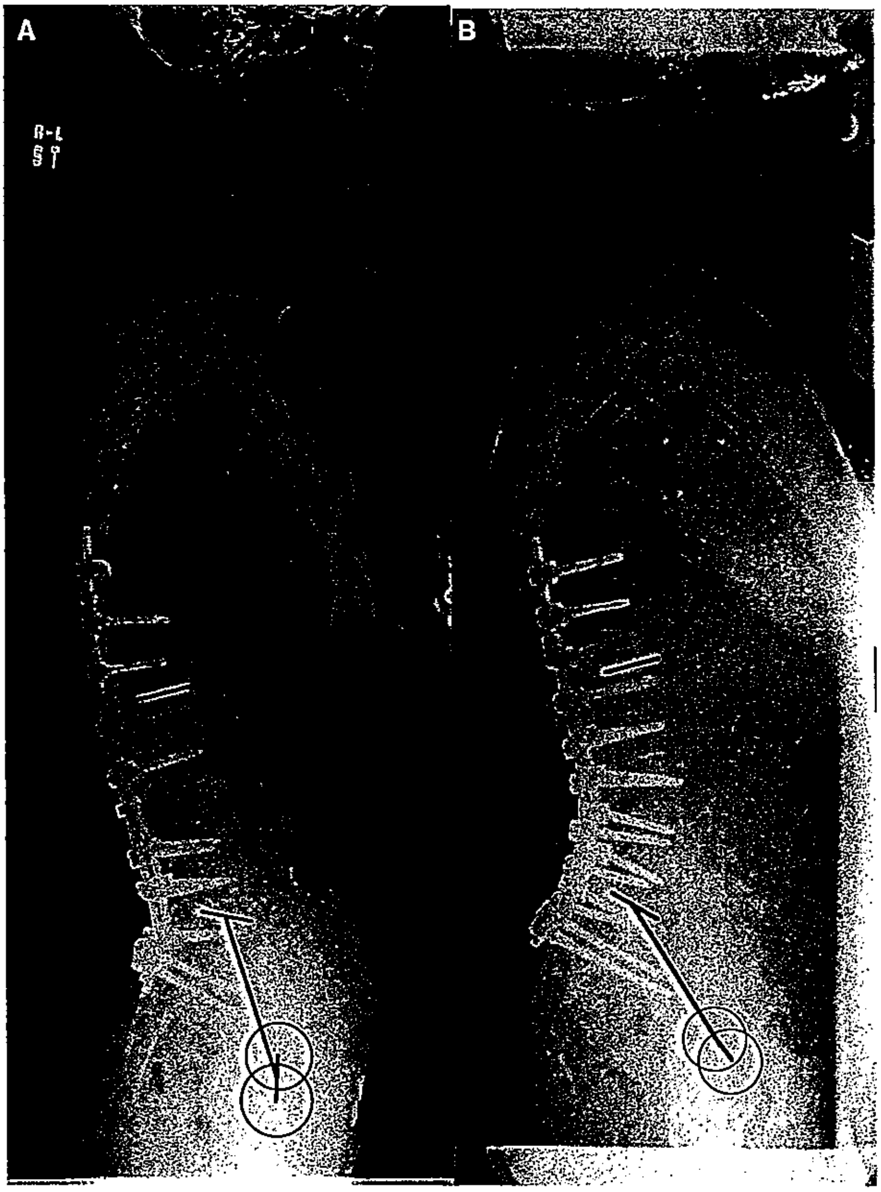

Fig. 1 A wide variety of postoperative sagittal alignment among the patients with good surgical results. Sagittal postoperative radiograph shows a case with PI-LL of 2° (PI = 29°, LL = 27°), ODI score of 10 points (a). Sagittal postoperative radiograph shows a case with PI-LL of 21° (PI = 65°, LL = 44°), ODI score of 16 points (b)

TLK (from 20° preoperative to 9° at follow-up), and an increase in LL (from 6° preoperative to 39° at follow-up). PI was 49° preoperatively and 50° at follow-up. PT decreased at follow-up (from 33° to 25°). PI-LL decreased at follow-up (from 43° to 11°), and SVA decreased at follow-up (102–37 mm) (Table 1).

QOL analysis

The median ODI score improved from 47.5 points (range 20–66) before surgery to 14.4 points (range 0–35.6) at follow-up (Table 2).

Factors associated with good clinical outcomes

Multiple regression analysis revealed TK ($P = 0.00278$), PT ($P = 0.0339$) and PI-LL ($P = 0.0001$) as the radiographic parameters most significantly associated with ODI (Table 3).

Relationship between PI-LL and PI

When subdividing the study population into the good HRQOL group by ODI score of less than 22 points (75th percentile cutoff) (Table 2), 36 patients were classified into

Table 1 Spinopelvic parameters between preoperative and final follow-up

	Preoperative (mean ± SD)	Final follow-up (mean ± SD)
Thoracic kyphosis (°)	13.9 ± 15	30 ± 13.9
Thoraco-lumbar kyphosis (°)	19.9 ± 14	9.2 ± 7.5
Lumbar lordosis (°)	6.4 ± 21.7	38.6 ± 11
Pelvic tilt (°)	32.8 ± 13.1	24.9 ± 11.4
Sacral slope (°)	16.6 ± 12.9	24.8 ± 8.6
Pelvic incidence (°)	49.4 ± 11.2	49.7 ± 11.4
PI-LL (°)	43 ± 21.1	11 ± 12.6
Sagittal vertical axis (mm)	102.3 ± 69.5	36.6 ± 44.6
Scoliosis (°)	49.2 ± 16	13.3 ± 10.2
Coronal balance (mm)	41.4 ± 33.4	11.3 ± 9

Table 2 Distribution of ODI score at final follow-up

	Minimum	25-percentile	Median	75-percentile	Maximum
ODI (points)	0	6.7	14.4	22.2	35.6

Table 3 Stepwise multiple regression analysis

Variables	*P*
Thoracic kyphosis	0.0028*
Thoraco-lumbar kyphosis	0.7375
Lumbar lordosis	0.3194
Pelvic tilt	0.0339*
Sacral slope	0.3194
PI-LL	0.0001*
Sagittal vertical axis	0.7577
Coronal balance	0.2836

* $P < 0.05$

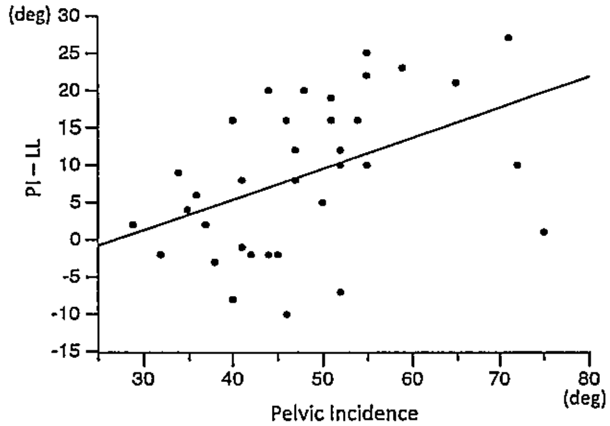

Fig. 2 Relationship between the PI-LL and pelvic incidence in the good HRQOL group

the good HRQOL group. In this group, a significant association was noted between the PI-LL and PI with a linear regression model leading to the following equation (Fig. 2):

$$\mathrm{PI} - \mathrm{LL} = 0.41 \times \mathrm{PI} - 11.12 (r = 0.45, P = 0.0059).$$

Parameters used for post hoc power analysis were, effect size = 0.45, two tailed alpha = 0.05, sample size = 36. The power was calculated as 0.8066.

Discussion

Several authors have established equations for predicting LL from pelvic and spinal parameters [8, 9, 19–22] and have improved surgical planning for the treatment of ASD. On the other hand, their efficacy and clinical relevance remain in question throughout the postoperative period; in particular, how would patients respond to a given LL predicted before surgery, because the subjects of these studies are healthy adult population [8, 9] or preoperative ASD patients [19]. Furthermore, even the formulas calculated for postoperative ASD patients did not incorporate the QOL outcome [21, 22]. To answer these questions, we intended to establish a formula from postoperative patients with successful outcomes.

Our findings showed that the PI-LL is a factor that was consistently associated with HRQOL during the postoperative period; and significant correlation was shown between PI-LL and PI. On the basis of the above-mentioned equation, we propose that an optimal PI-LL is inconsistent in that it depends on the individual PI. For example, in patients with a normal PI (PI = 50°), the optimum PI-LL is 9°, which corresponds to a normal value in the established classification system [10], whereas, in those with a small PI (PI = 30°), the optimum PI-LL is calculated to be as low as 1°. Then, in those with a large PI (PI = 80°), the ideal PI-LL is estimated at 22°.

Consequently, a smaller PI results in a smaller PI-LL, i.e., close to or equivalent to 0°, while a larger PI allows for a larger PI-LL, approximately 20°.

Other studies provide solid rationale to explain our results particularly, that an optimal PI-LL is not constant but variable, depending upon the individual PI. Duval-Beaupère et al. have expressed that low values of PI decrease the chance of an economical standing posture, because this induces a short lever arm of the hip extensor muscle [7]. Additionally, they have shown in their clinical experience that there are constant action potentials of the gluteus maximus in patients with a small PI in the standing position. This standing condition might suggest a tendency to fall into a non-economical standing condition. Roussouly et al. advocated that the ability to retrovert the pelvis is limited by a patient's own PI, and patients with a small PI have a small capacity to compensate for their sagittal balance through pelvic retroversion [23]. For reasons mentioned above, it seems reasonable to suppose that a small PI demands a strictly matched LL.

In contrast, a patient with a large PI has a long lever arm of the hip extensor muscle, and furthermore has a wide posterior offset between the sacrum and the femoral heads in the sagittal plane [13, 23]. Legaye et al. defined the overhanging of S1 as the distance between the bi-coxofemoral axis and the projection to this level of the midpoint of the sacral plate, and reported a significant correlation between the PI and the overhanging of S1; i.e., the larger the value of the PI, the larger the value of the adapted overhanging of S1 [8]. These mechanisms and anatomical features of patients with a large PI may help to keep the position of the C7 plumb line behind the femoral heads, and it is reasonable to think that a large PI value would allow a larger spinopelvic mismatch, even if the PI-LL is above 10.

As PI-LL is one of the most important indicators for successful corrective surgery [10], we aimed to determine the optimum value of the PI-LL in the specific setting of an individual's PI value. This is the reason why the PI-LL was selected as a dependent variable in the following linear equation: $\text{PI-LL} = 0.41\text{PI}-11.12$. Whereas, this equation could be rearranged simply as: $\text{LL} = 0.59\text{PI} + 11.12$.

Legaye et al. have studied the correlation between the pelvic and spinal sagittal parameters and have developed a formula indicating an ideal LL by using the PI [24]:

$$\begin{aligned}\text{LL} &= ((0.5481\text{PI} + 12.7) \times 1.087 + 21.61) \\ &= 0.596\text{PI} + 35.415\end{aligned}$$

The important point to note is that these two linear equations have a common factor (i.e., the coefficient is approximately 0.6). We would like to emphasize that the rise of the ideal LL (y-axis) is only 60 % of every increase in PI (x-axis) in these equations, whereas the value of the y-intercept is different between the Eqs. (11 versus 35), and we speculate that the main cause is the difference in the material population, i.e., the Legaye et al. study involved normal volunteers without surgery (mean age 24 years), whereas the current study included postoperative ASD patients (mean age 61 years) with successful outcomes.

The results of this study show that a smaller PI results in a smaller PI-LL, while a larger PI allows for a larger PI-LL. Our conclusion is that the optimal PI-LL is not a fixed but rather a flexible value reflecting the specific PI of the individual. We argue that this data will have a significant clinical impact on patient-specific surgical planning for procedures aimed at increasing lordosis in the lumbar spine. The majority of UIV in this study were below T10, therefore there would be a potential intraspinal compensatory mechanism [25]. Thus, a limitation of this study is that the applicability to patients with instrumentation that includes the upper thoracic spine is unknown. For the patients with thoracic malalignment being required correction, surgical planning including realignment of thoracic spine would be effective [26]. In addition, not only magnitude but also shape of LL [23] that represents geometry of lordosis should have been evaluated in the present study. Although significant correlations between PI and LL have been reported in the several manuscripts including the present study [8, 9, 24], PI can be influenced by the other parameters such as PT, SS, and so on [7]. Furthermore, LL can also be affected by TK as a reciprocal mechanism [25]. Therefor, newly developed formulas regarding the relationship between PI and LL should receive careful validation by future investigations.

Some might argue that the formula is based on only 36 patients with successful outcomes and HRQOL was evaluated by only ODI, so that the results should not be applied to all ASD patients. No doubt that higher value for power with a bigger sample size would be useful to have a good chance of detecting the effect, however power analysis in the current study calculated a power of 80 % that is the common acceptable level to detect the effect. In regarding to HROQL, evaluation with multiple instruments could bring more detailed information of disability; yet, the reason why ODI was used in the current study is that non-pathological cutoff value of radiographic parameters (i.e., PI-LL, SVA, PT, etc.) has been evaluated based on ODI in past studies [4, 5, 10, 16, 19]. It follows from what has been said that our findings would afford new perspectives on surgical planning for LL correction. Future studies addressing to the shape of LL [23] with more patients and multiple HRQOL evaluations will assist in clarifying the interaction between PI and LL in the setting of surgical treatment.

Conclusion

Our findings show that the PI-LL was consistently associated with a patient's quality of life during the postoperative period, and a significant correlation was shown between the PI-LL and PI. On the basis of our equation, we demonstrate that an optimal PI-LL value is not a constant value, e.g., the PI-LL value is 1° with a PI of 30°, whereas the value is 22° with a PI of 80°. Our study confirmed our hypothesis that an optimal PI-LL value is not constant and changes based upon the difference in PI value, and will have a clinical impact in patient-specific surgical planning to make lordosis in lumbar spine.

Compliance with ethical standards

Conflict of interest None.

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1.論文(英文)

(独)労働者健康安全機構　北海道せき損センター

Komatsu M, Suda K, Takahata M, Matsumoto S, Ushiku C, Yamada K, Yamane J, Endo T, Iwasaki N, Minami A	Delayed bilateral vertebral artery occlusion after cervical spine injury: a case report	Spinal Cord Ser Cases. 2016 Nov 24;2:1631.
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北海道大学大学院医学研究院 社会医学分野 医学統計学教室

Kokabu, T., Sudo, H., Abe, Y., Ito, M., Ito, Y. M., & Iwasaki, N.	Effects of Multilevel Facetectomy and Screw Density on Postoperative Changes in Spinal Rod Contour in Thoracic Adolescent Idiopathic Scoliosis Surgery.	PLoS One, 11(8), e0161906. doi:10.1371/journal.pone.0161906
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2.論文(和文)

(独)労働者健康安全機構 北海道せき損センター

小松 幹、須田浩太	最小侵襲脊椎安定術(MISt)の現状と課題 ～mini-pone TLIFの臨床成績から～	北海道整形災害外科学会雑誌(1343-3873)58巻1号Page51-54(2016.10)
木田博朗、須田浩太、松本聡子、小松 幹、牛久智加良、山根淳一、遠藤 努、東條泰明、神谷行宣、三浪明男	手術困難なために遅発性麻痺を生じたびまん性特発性骨増殖症(DISH)脊椎骨折の1例	北海道整形災害外科学会雑誌(1343-3873)58巻1号Page61-64(2016.10)
須田浩太、小松 幹、牛久智加良、枝條祐輔、松本聡子	頚椎脱臼骨折の初期治療 私の治療戦略	整形外科Surgical Technique(2185-7733)7巻1号Page16-22(2017.1)
福井隆史、須田浩太、遠藤 努、松本聡子、小松 幹、牛久智加良、山根淳一、東條泰明、神谷行宣、三浪明男、高畑雅彦、岩崎倫政	迅速な整復固定の重要性を示唆した頚椎脱臼骨折の1例「例え運動完全麻痺であっても超早期手術により下肢筋力は完全回復する可能性がある」	北海道整形災害外科学会雑誌(1343-3873)58巻2号Page203-206(2017.3)

SPINAL CORD SERIES AND CASES | CASE REPORT

Delayed bilateral vertebral artery occlusion after cervical spine injury: a case report

Miki Komatsu, Kota Suda, Masahiko Takahata, Satoko Matsumoto, Chikara Ushiku, Katsuhisa Yamada, Junichi Yamane, Tsutomu Endo, Norimasa Iwasaki & Akio Minami

Spinal Cord Series and Cases **2**, Article number: 16031 (2016) | doi:10.1038/scsandc.2016.31
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Abstract

Introduction:

There are considerable risks for the secondary spinal cord injury and the initial and/or delayed vertebral artery occlusion in cases of cervical fracture dislocation.

Case Presentation:

An 86-year-old man was injured in a car accident and was diagnosed with no fracture or dislocation of the cervical spine by the emergency physician. However, he was transferred to our hospital 3 days later because he had motor weakness that was evaluated to be 32 points (out of 50 points) on the upper limb American Spinal Injury Association (ASIA) motor score and was diagnosed with spontaneously reduced fracture dislocation at C5/6. Magnetic resonance images revealed that the bilateral vertebral arteries were occluded, and there were some microinfarction lesions in the brain. On the first visit to his previous doctor, he was found to have a flow void in the right vertebral artery. This indicated that it was occluded during the waiting period at his previous doctor. On the day of his arrival at our hospital, the patient underwent a C5/6 posterior spinal fusion. Three months after surgery, he recovered to 46 points on the upper extremity ASIA motor score, and blood flow in the left vertebral artery was resumed.

Discussion:

Early reduction and stabilization are necessary for cervical spine fracture dislocation; however, it is important not only for the prevention of the secondary injury but also for the reduction of the risk of vertebral artery occlusion.

Subject terms: Spinal cord diseases • Trauma

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Author information

Affiliations

Department of Orthopaedic Surgery, Hokkaido Chuo Rosai Hospital Spinal Cord Injury Center, Bibai, Japan

Miki Komatsu, Kota Suda, Satoko Matsumoto, Chikara Ushiku, Katsuhisa Yamada, Junichi Yamane, Tsutomu Endo & Akio Minami

Department of Orthopaedic Surgery, Hokkaido University Graduate School of Medicine, Sapporo, Japan

Masahiko Takahata & Norimasa Iwasaki

Competing interests

The authors declare no conflict of interest.

Corresponding author

Correspondence to Miki Komatsu.

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SPINAL CORD SERIES AND CASES | CASE REPORT

Dural penetration caused by a vertebral bone fragment in a lumbar burst fracture: a case report

Chikara Ushiku, Kota Suda, Satoko Matsumoto, Miki Komatsu, Masahiko Takahata, Norimasa Iwasaki & Akio Minami

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Abstract

Introduction:

This case report describes an unusual case of lumbar burst fracture in which a bone fragment from the vertebral body penetrated into the dorsal dura through the ventral dura mater, requiring bone fragment extraction via an intradural approach.

Case Presentation:

A 23-year-old male involved in a motor vehicle accident was admitted to our hospital complaining of right leg paresis and bladder-bowel disorder. Computed tomography (CT) revealed an L5 burst fracture of type B by the Denis classification scheme, with a bone fragment from the vertebral body that had perforated the ventral aspect of the dura mater and penetrated dorsally. We abandoned attempts to extract the bone fragment via an epidural approach and instead resected the fragment via an intradural approach with a dorsal dural incision. We corrected L4/5 kyphosis as possible and performed L4/5 posterolateral fusion. The patient's leg paralysis and bladder-bowel disorder were relieved, and he was discharged 2 months after the surgery with the ability to walk without crutches.

Discussion:

When bone fragments penetrate the dura mater, their extraction must be performed with particular care. For cases in which the dura mater cannot be pulled apart, the removal of bone fragments using an intradural approach is appropriate.

Subject terms: Fracture repair • Trauma

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Author information

Affiliations

Department of Orthopaedic Surgery, Hokkaido Chuo Rosai Hospital Spinal Cord Injury Center, Hokkaido, Japan

Chikara Ushiku, Kota Suda, Satoko Matsumoto, Miki Komatsu & Akio Minami

Department of Orthopaedic Surgery, Hokkaido University Graduate School of Medicine, Hokkaido, Japan

Masahiko Takahata & Norimasa Iwasaki

Competing interests

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Corresponding author

Correspondence to Chikara Ushiku.

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ORIGINAL ARTICLE

Normative data for parameters of sagittal spinal alignment in healthy subjects: an analysis of gender specific differences and changes with aging in 626 asymptomatic individuals

Yasutsugu Yukawa[1,2] · Fumihiko Kato[2] · Kota Suda[3] · Masatsune Yamagata[4] · Takayoshi Ueta[5] · Munehito Yoshida[1]

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Abstract

Purpose This study aims to establish normative data for parameters of spino-pelvic and spinal sagittal alignment, gender related differences and age-related changes in asymptomatic subjects.

Methods A total of 626 asymptomatic volunteers from Japanese population were enrolled in this study, including 50 subjects at least for each gender and each decade from 3rd to 8th. Full length, free-standing spine radiographs were obtained. Cervical lordosis (CL; C3–7), thoracic kyphosis (TK; T1–12), lumbar lordosis (LL; T12–S1), pelvic incidence (PI), pelvic tilt (PT), sacral slope (SS) and sagittal vertical axis (SVA) were measured.

Results The average values (degrees) are 4.1 ± 11.7 for CL, 36.0 ± 10.1 for TK, 49.7 ± 11.2 for LL, 53.7 ± 10.9 for PI, 14.5 ± 8.4 for PT, and 39.4 ± 8.0 for SS. Mean SVA is 3.1 ± 12.6 mm. Advancing age caused an increase in CL, PT and SVA, and a decrease in LL and SS. There was a significant gender difference in CL, TK, LL, PI, PT and SVA. From 7th decade to 8th decade, remarkable decrease of LL & TK and increase of PT were seen. A large increase of SVA was also seen between 60' and 70'.

Conclusion Standard values of spino-pelvic sagittal alignment were established in each gender and each decade from 20' to 70'. A remarkable change of spino-pelvic sagittal alignment was seen from 7th decade to 8th decade in asymptomatic subjects.

Keywords Standard value · Spine radiograph · Spinopelvic sagittal alignment · Gender difference · Age-related change

Introduction

The prevalence of adult spinal deformity (ASD) has been reported to be as high as 60 % in the elderly population [1]. For many years, the diagnosis and treatment of ASD was based upon coronal plane radiograph analysis using Cobb angle measurements. However, recent research has shown that sagittal spino-pelvic alignment among patients with ASD plays a critical role in pain and disability and is a primary determinant of health related quality of life (HRQOL) measures [2–5]. One of them concluded that restoration of "a more normal sagittal balance" is the critical goal for any reconstructive spine surgery. However, the definition of what constitutes normal and pathologic alignment in the spine has not been established [3].

Standard values of sagittal alignment and range of motion of the cervical spine in 1230 asymptomatic volunteers were reported in a previous study. This study revealed that cervical lordosis in the neutral position increases with age, particularly in the sixth decade and to a greater degree in females [6]. However, the total range of motion decreased linearly with age, particularly in extension and males. As

✉ Yasutsugu Yukawa
yukawa@wakayama-med.ac.jp

1 Department of Orthopedic Surgery, Wakayama Medical University, 811-1 Kimiidera, Wakayama 641-8509, Japan

2 Department of Orthopedic Surgery, Chubu Rosai Hospital, Nagoya, Japan

3 Department of Orthopedic Surgery, Hokkaido Chuo Rosai Hospital Sekison Center, Bibai, Japan

4 Department of Orthopedic Surgery, Chiba Rosai Hospital, Ichihara, Japan

5 Department of Orthopedic Surgery, Spinal Injuries Center, Iizuka, Japan

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apparent aging and gender changes were seen in cervical alignment, it should be presumed that spino-pelvic sagittal alignment is affected by age and gender.

In recent years, many authors emphasized the importance of spinal sagittal balance and investigated those parameters in healthy subjects [2, 5, 7–21]. However, there have been few studies using a large cohort with an even age and gender distribution. Accordingly, the objective of the current study was to investigate normal spinal and spino-pelvic sagittal alignment in asymptomatic volunteers of each sex and in each decade of life between the 3rd (20's) and 8th (70's), and attempt to elucidate gender related differences and age-related changes using data from radiographs of over 600 healthy subjects.

Materials and method

After obtaining institutional review board approval, healthy Japanese volunteers were sought after the purpose of this study was officially announced. The exclusion criteria included a history of brain or spinal surgery, comorbid neurologic disease such as cerebral infarction or neuropathy, symptoms related to sensory or motor disorders (numbness, clumsiness, motor weakness, and gait disturbances) or having severe low back pain. Pregnant women and individuals who received worker's compensation or presented with symptoms after a motor vehicle accident were also excluded. If radiographs measurements of sagittal parameters were difficult to assess due to lumbosacral transitional anomalies or spinal malformation, the subjects were also excluded. Finally 626 asymptomatic subjects with appropriate images were enrolled in the present study including 50 subjects at least in each gender and each decade from 3rd to 8th (Table 1).

Full length, free-standing spine radiographs with fists on clavicles were obtained in all subjects. All images were transferred to a computer as Digital Imaging and Communications in Medicine (DICOM) data. Cervical lordosis (C3–7, CL), thoracic kyphosis (T1–12, TK), lumbar lordosis (T12–S1, LL), pelvic incidence (PI), pelvic tilt (PT), sacral slope (SS) and sagittal vertical axis (SVA) were measured using measurement software (Figs. 1, 2). Each parameter was measured by experienced radiation technologists using imaging software (Osiris4; Icestar Media Ltd, Essex, UK).

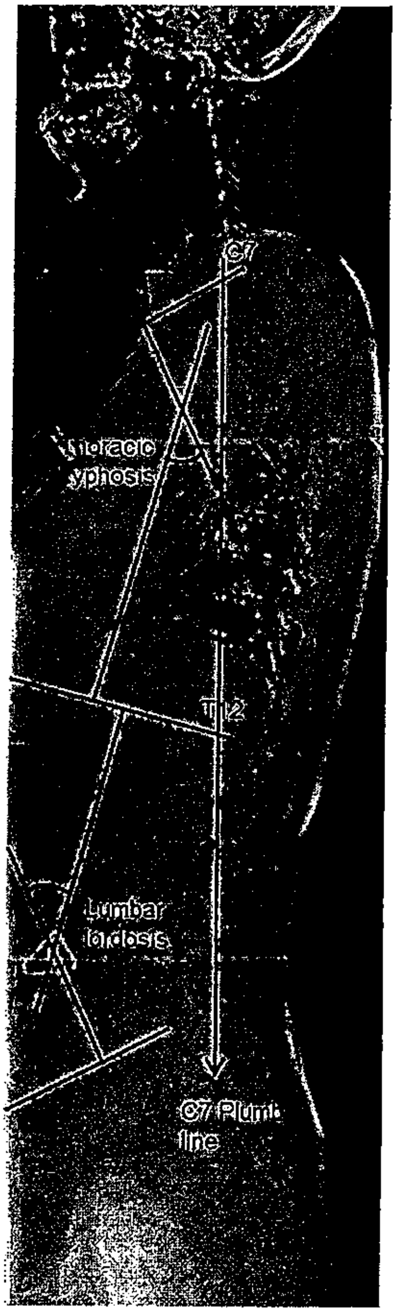

Fig. 1 Methods of measurement of spinal parameters; thoracic kyphosis (TK), lumbar lordosis (LL) and sagittal vertical axis (SVA)

Table 1 Materials; age and gender distribution

Age	Men	Women	
20–29	48	53	101
30–39	51	50	101
40–49	50	57	107
50–59	56	51	107
60–69	50	60	110
70–79	50	50	100
Total	305	321	626

Statistical analysis

The data were analyzed using the SPSS version 13.0 software (SPSS Inc., Chicago, IL). Descriptive statistics were calculated for all subjects and separately for males and females in the form of mean value and standard

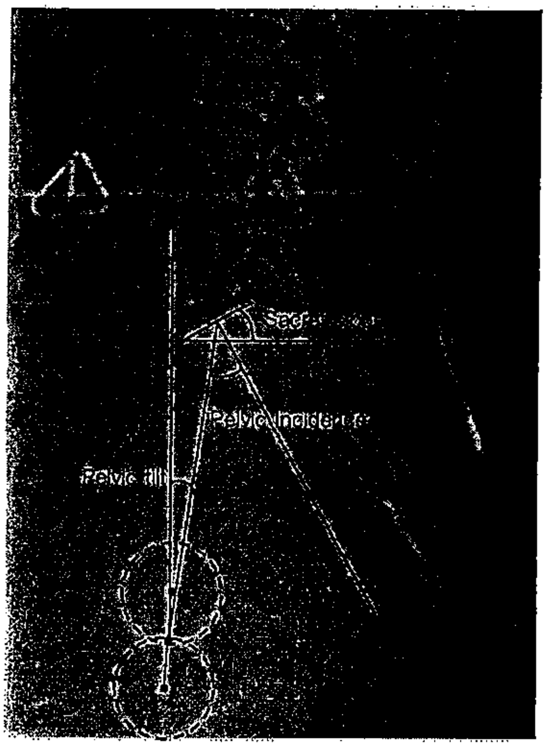

Fig. 2 Methods of measurement of spinal parameters; pelvic incidence (PI), sacral slope (SS) and pelvic tilt (PT)

deviation. Comparison between the male and the female was carried out by un-paired Student t tests. Statistical significance was set at a level of $P < 0.05$.

Results

Average height and weight [mean ± standard deviation (SD)] of all male and female subjects was 169.1 ± 6.5 cm/66.7 ± 10.3 kg and 156.2 ± 6.0 cm/52.9 ± 8.0 kg, respectively.

The average values (degrees) are 4.1 ± 11.7 of CL, 36.0 ± 10.1 of TK and 49.7 ± 11.2 of LL (Tables 2, 3, 4; Figs. 3, 4, 5). The average values of pelvic morphologic angles are 53.7 ± 10.9 for PI, 14.5 ± 8.4 for PT and 39.4 ± 8.0 for SS (Tables 5, 6, 7; Figs. 6, 7, 8). The mean SVA is 3.1 ± 12.6 mm (Table 8; Fig. 9). CL is greater in males than in females in any decade. CL is increased with age, especially after 60' (Fig. 3; Table 2). Regarding TK and LL, remarkable changes were not seen from 20' to 60'. However, a sudden decrease was detected for both TK and LL in 70' (Figs. 4, 5; Tables 3, 4). PI was higher by several degrees in females with age greater than 40 years, than that in 20' or 30', females or males (Fig. 6; Table 5). PT increased with age and the change was stressed in females (Fig. 7; Table 6). SS was almost similar between males and females, and showed a gradual decrease with aging (Fig. 8; Table 7) A negative value for the SVA was identified only in males in the 20' as well as in females in the 20' and 30'. SVA increased gradually with age from 3rd decade and 7th decade, and showed apparent increase in the 8th decade (Fig. 9; Table 8).

Table 2 Cervical lordosis (CL; C3–7)

Decade	Male	Female	P value
20–29	3.3 ± 11.6	−6.0 ± 9.7	<0.001
30–39	4.5 ± 12.7	−3.4 ± 10.7	<0.001
40–49	4.4 ± 8.6	2.4 ± 11.4	NS
50–59	5.3 ± 8.3	0.1 ± 11.1	<0.001
60–69	13.5 ± 11.4	4.7 ± 8.5	<0.001
70–79	13.2 ± 12.4	8.5 ± 12.7	0.059
All	7.3 ± 11.6	1.1 ± 11.6	<0.001
Total	4.1 ± 11.7		

NS indicates not significant

Table 3 Thoracic kyphosis (TK; T1–12)

Decade	Male	Female	P value
20–29	34.9 ± 8.1	33.9 ± 9.1	NS
30–39	37.3 ± 9.1	33.4 ± 9.0	<0.05
40–49	35.9 ± 8.5	35.9 ± 10.4	NS
50–59	39.4 ± 10.5	35.9 ± 10.7	0.088
60–69	39.7 ± 10.0	36.0 ± 11.7	0.074
70–79	35.0 ± 11.8	34.8 ± 11.6	NS
All	37.1 ± 9.9	35.0 ± 10.5	<0.05
Total	36.0 ± 10.1		

NS indicates not significant

Table 4 Lumbar lordosis (LL; T12–S)

Decade	Male	Female	P value
20–29	49.4 ± 8.6	52.4 ± 13.1	NS
30–39	48.5 ± 11.2	52.7 ± 10.3	0.057
40–49	47.6 ± 10.8	54.1 ± 10.3	<0.01
50–59	50.5 ± 9.1	51.5 ± 10.2	NS
60–69	48.5 ± 13.1	52.2 ± 10.9	NS
70–79	42.2 ± 14.8	46.7 ± 13.3	NS
All	47.8 ± 11.6	51.6 ± 11.6	<0.001
Total	49.7 ± 11.2		

NS indicates not significant

Discussion

This study represents the large cross-sectional analysis of spinal and spino-pelvic alignment with homogenous age and sex distribution, in 626 healthy subjects as studied on

Table 5 Pelvic incidence (PI)

Decade	Male	Female	*P* value
20–29	54.4 ± 10.1	51.8 ± 11.7	NS
30–39	52.9 ± 10.2	51.2 ± 9.5	NS
40–49	50.8 ± 7.8	57.0 ± 10.8	<0.001
50–59	53.0 ± 11.3	56.2 ± 11.3	NS
60–69	52.0 ± 10.9	56.0 ± 12.7	NS
70–79	52.0 ± 10.3	57.4 ± 9.5	<0.01
All	52.6 ± 10.4	54.9 ± 11.4	<0.01
Total	53.7 ± 10.9		

NS indicates not significant

Table 6 Pelvic tilt (PT)

Decade	Male	Female	*P* value
20–29	12.9 ± 8.1	11.4 ± 6.6	NS
30–39	13.1 ± 7.7	12.0 ± 6.7	NS
40–49	11.5 ± 5.8	16.2 ± 8.4	<0.001
50–59	13.3 ± 9.8	15.1 ± 7.5	NS
60–69	13.7 ± 7.1	18.4 ± 9.2	<0.01
70–79	15.3 ± 7.4	21.0 ± 7.8	<0.001
All	13.2 ± 7.7	15.8 ± 8.6	<0.001
Total	14.5 ± 8.4		

NS indicates not significant

Table 7 Sacral slope (SS)

Decade	Male	Female	*P* value
20–29	41.6 ± 7.4	40.3 ± 9.1	NS
30–39	40.0 ± 7.1	39.7 ± 6.5	NS
40–49	39.8 ± 6.9	41.1 ± 7.8	NS
50–59	40.1 ± 8.9	41.0 ± 7.6	NS
60–69	38.2 ± 8.7	37.5 ± 8.0	NS
70–79	37.2 ± 10.5	36.7 ± 9.1	NS
All	39.6 ± 8.3	39.3 ± 8.1	NS
Total	39.4 ± 8.0		

NS indicates not significant

full spine standing radiographs. Based on our findings, normative data for cervical lordosis (C3–7, CL), thoracic kyphosis (T1–12, TK), lumbar lordosis (T12–S1, LL), pelvic incidence (PI), pelvic tilt (PT), sacral slope (SS) and sagittal vertical axis (SVA) were established for each gender and each decade from 3rd to 8th. Notably, gender differences and age-related changes from the 3rd to the 8th decade were also elucidated. Remarkable changes of spinal and spino-pelvic sagittal alignment, a sudden decrease of TK and LL and a large increase of SVA, were seen from 7th decade to 8th decade.

Table 8 Sagittal vertical axis (SVA)

Decade	Male	Female	*P* value
20–29	−2.1 ± 8.2	−4.6 ± 13.5	NS
30–39	3.0 ± 9.2	−4.1 ± 13.0	<0.01
40–49	5.0 ± 13.7	0.9 ± 9.0	0.070
50–59	4.5 ± 11.8	3.4 ± 11.1	NS
60–69	5.5 ± 14.0	4.6 ± 10.4	NS
70–79	10.3 ± 14.4	10.7 ± 15.2	NS
All	4.5 ± 11.9	1.8 ± 13.1	<0.01
Total	3.1 ± 12.6		

NS indicates not significant

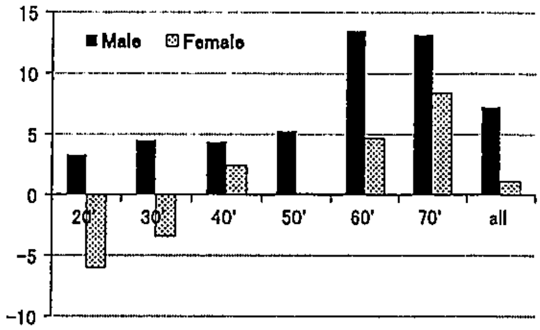

Fig. 3 Cervical lordosis (CL; C3–7)

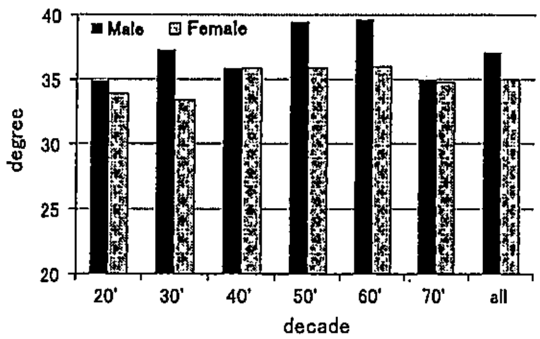

Fig. 4 Thoracic kyphosis (TK; T1–12)

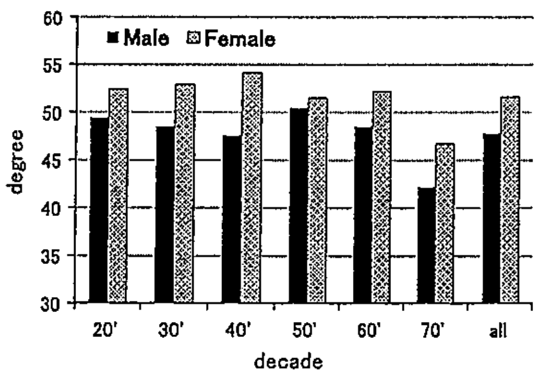

Fig. 5 Lumbar lordosis (LL; T12–S1)

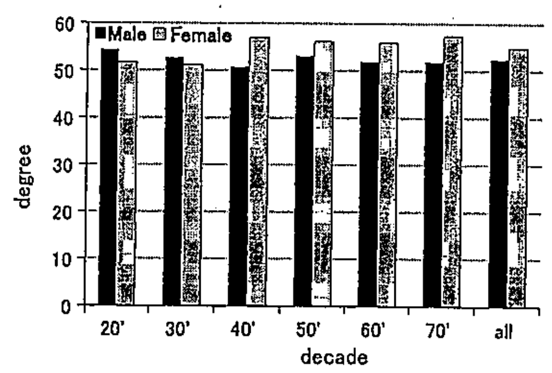

Fig. 6 Pelvic incidence (PI)

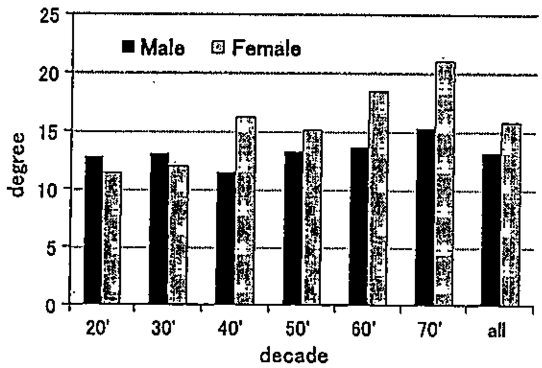

Fig. 7 Pelvic tilt (PT)

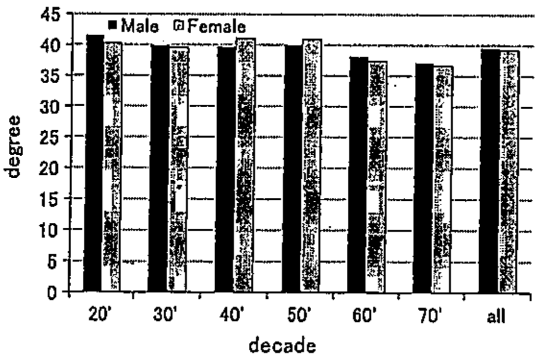

Fig. 8 Sacral slope (SS)

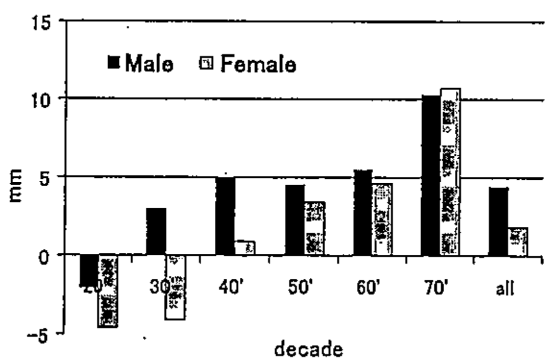

Fig. 9 Sagittal vertical axis (SVA)

Dubousset described the theory known as the "cone of economy". In this understanding, the head center of gravity is maintained over the pelvis to achieve an energy efficient mechanism for ambulation and upright posture [22]. The body adapts to changes in this balance to regulate the center of gravity over as narrow a perimeter as possible. Various compensation mechanisms would work to maintain sagittal balance to achieve an energy efficient mechanism.

In the cervical spine, Yukawa et al. reported sagittal alignment and range of motion in 1230 asymptomatic volunteers [6]. They revealed gender differences and age-related changes from 3rd decade to 8th decade in the parameters of cervical alignment. Cervical lordosis in the neutral position increased with age, particularly in the sixth decade and to a greater degree in females. However, the total range of motion decreased linearly with age, particularly in extension and males.

With the increasing evidence gathered for the clinical importance of sagittal spinal alignment, we sought to better understand neutral upright sagittal spinal alignment in asymptomatic adults in whom demographic features were similar to those in patients. Therefore, we conducted this large-scale study including more than 600 asymptomatic volunteers, to establish standard values of sagittal spinal and spino-pelvic parameters and to elucidate those gender differences and age-related changes.

Several authors have investigated upon age-related spinal alignment changes among healthy volunteers. Gelb et al. reported that increasing age corresponded to a more anterior sagittal vertical axis with a loss of lumbar lordosis, comparing asymptomatic middle- and old-aged volunteers [7]. Hammerberg and Wood demonstrated that aging induced an anterior shift of C7 plumb line and a decrease of lumbar lordosis [12]. In our data, advancing age led to an increase in CL, PT and SVA, and a decrease in LL and SS. A sudden decrease was seen from 60' to 70' in TK and LL. In response to a LL decrease, a decrease of TK and increase of PT might occur as a compensatory mechanics to maintain global for sagittal balance [23]. A large increase of SVA was also seen between 60' and 70', indicating that the compensation mechanisms for the concurrent LL decrease were not sufficient.

Regarding gender related differences among parameters of sagittal spinal and spino-pelvic alignment, Vialle et al. showed that female subjects had higher values in lumbar lordosis and PI [13]. On the other hand, Mac-Thiong reported that there was no difference in PI, SS and PT between males and females [19]. The current study demonstrated that there was a relatively large gender difference in CL, LL and PT. In females, groups with age >40 years had higher PI than that of 20' and 30'. The pelvic incidence is considered to be an inherent value for each individual unaffected by body posture. However, some gap of the value of PI was seen between young females and elder females in this study. Although we did not investigate civil status and birth experience, we may speculate that the birth experience is one of the reasons of higher PI in females aged over 40.

There were several limitations in the present study. First, the survey was limited to the Japanese population, so racial differences were not taken into account. Second, only asymptomatic subjects were enrolled in this study. This could have led to a selection bias in favor of relatively healthy participants.

Natural history of sagittal spino-pelvic alignment is gaining importance more than ever, as the number of reconstructive surgeries for adult spinal deformity increases. To detect the real natural history of sagittal alignment changes over time, a long-term follow up study is suitable. However, it seems very difficult to observe aging changes of spinal alignment over a whole life. Therefore, large-scale of cross-sectional observational study could be used as a substitute for longitudinal analysis. In this study we recruited more than 600 asymptomatic volunteers including at least 50 subjects in each gender and each decade from 3rd to 8th decade. This is the one of the largest cohort study of spinal alignment and the sex/sex ratio is almost 50:50. We believe that larger number of subjects and balanced sexual and age distribution should improve reliability of cohort study.

Conclusion

Full length, free-standing spine radiographs were obtained in 626 healthy subjects. Standard values and deviations of spino-pelvic sagittal alignment were established in each gender and each decade from 20' to 70'. A remarkable change of spino-pelvic sagittal alignment, decrease of TK & LL and increase of SVA, was seen from 7th decade to 8th decade.

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Compliance with ethical standards

Conflict of interest None of the authors has any potential conflict of interest.

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Risk factors for adjacent segment pathology requiring additional surgery after single-level spinal fusion: impact of pre-existing spinal stenosis demonstrated by preoperative myelography

Itaru Yugué, Seiji Okada, Muneaki Masuda, Takayoshi Ueta, Takeshi Maeda & Keiichiro Shiba

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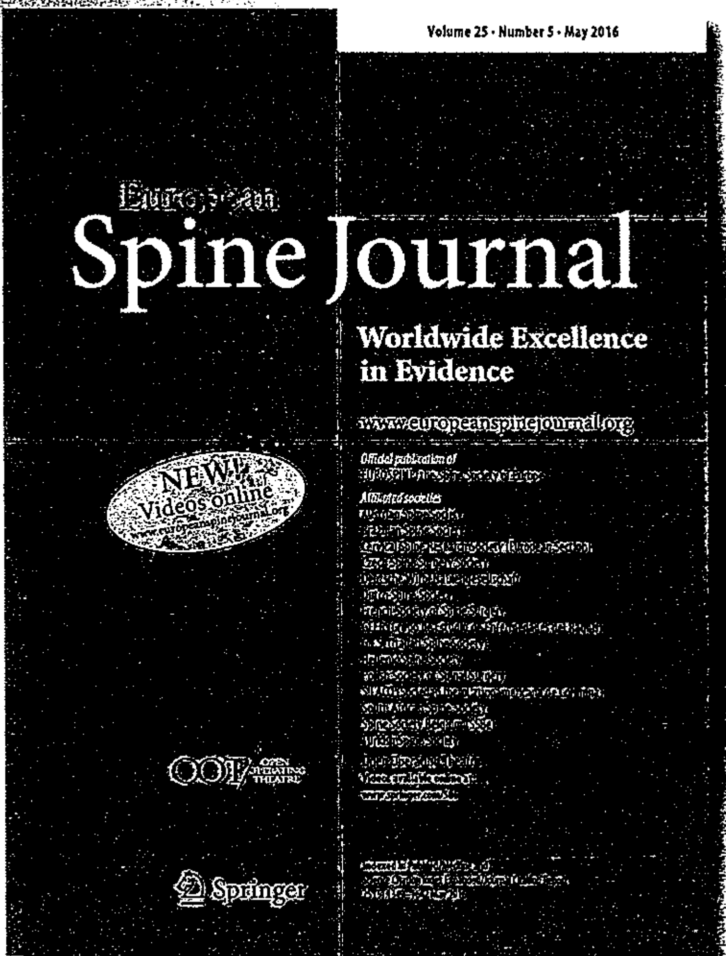

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ORIGINAL ARTICLE

Risk factors for adjacent segment pathology requiring additional surgery after single-level spinal fusion: impact of pre-existing spinal stenosis demonstrated by preoperative myelography

Itaru Yugué[1] · Seiji Okada[2] · Muneaki Masuda[1] · Takayoshi Ueta[1] · Takeshi Maeda[1] · Keiichiro Shiba[1]

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Abstract
Purpose We determined the incidence of and risk factors for clinical adjacent segment pathology (C-ASP) requiring additional surgeries among patients previously treated with one-segment lumbar decompression and fusion surgery.
Methods We retrospectively analysed 161 consecutive patients who underwent one-segment lumbar decompression and fusion surgery for L4 degenerative spondylolisthesis. Patient age, sex, body mass index (BMI), facet orientation and tropism, laminar inclination angle, spinal canal stenosis ratio [on myelography and magnetic resonance imaging (MRI)], preoperative adjacent segment instability, arthrodesis type, pseudarthrosis, segmental lordosis at L4–5, and the present L4 slip were evaluated by a log-rank test using the Kaplan–Meier method. A multivariate Cox proportional-hazards model was used to analyse all factors found significant by the log-rank test.
Results Of 161 patients, 22 patients (13.7 %) had additional surgeries at cranial segments located adjacent to the index surgery's location. Pre-existing canal stenosis ≥47 % at the adjacent segment on myelography, greater facet tropism, and high BMI were significant risk factors for C-ASP. The estimated incidences at 10 years postoperatively for each of these factors were 51.3, 39.6, and 32.5 %, and the risks for C-ASP were 4.9, 3.7, and, 3.1 times higher than their counterparts, respectively. Notably, spinal canal stenosis on myelography, but not on MRI, was found to be a significant risk factor for C-ASP (log-rank test $P < 0.0001$ and 0.299, respectively).
Conclusions Pre-existing spinal stenosis, greater facet tropism, and higher BMI significantly increased C-ASP risk. Myelography is a more accurate method for detecting latent spinal canal stenosis as a risk factor for C-ASP.

Keywords Degenerative spondylolisthesis · Adjacent segment pathology · Pre-existing spinal stenosis · Body mass index · Facet tropism

Introduction

During the past few decades, spinal arthrodesis has become a common treatment component for a variety of spinal disorders. However, it alters the biomechanical and kinematic properties of the lumbar spine [1, 2]. Pathological development at mobile segments above or below the site of spinal fusion is known as adjacent segment pathology (ASP). ASP is considered a potential late complication of spinal arthrodesis that requires further surgical treatment. The clinical failure rate of adjacent segments at 5 years after the index spinal fusion surgery has been reported to range from 3 to 32.3 % [3–7].

Several risk factors for ASP have been reported, such as age [4, 5, 7], sex [4], multilevel arthrodesis [3–5], sagittal imbalance [8], the type of arthrodesis [7], facet tropism [9], and laminar inclination [9]. However, few studies have focused on asymptomatic pre-existing spinal stenosis as a risk factor for clinical ASP (C-ASP) that requires additional surgery at an adjacent segment [10]. In fact, when

The manuscript does not contain information about medical device(s)/drug(s).

✉ Itaru Yugué
iyugue@orange.ocn.ne.jp

1 Department of Orthopaedic Surgery, Japan Labour Health and Welfare Organization Spinal Injuries Center, 550-4 Igisu, Iizuka, Fukuoka, Japan

2 Department of Orthopaedic Surgery, Kyushu University, Fukuoka, Japan

patients demonstrate asymptomatic spinal stenosis adjacent to the fusion segment, there is often controversy as to whether the segment should be included within the surgical site or not.

This study analysed the preoperative prognostic risk factors for C-ASP, and we calculated the survival times of the patients with significant risk factors.

Materials and methods

From January 2000 to December 2006, 204 L4 degenerative spondylolisthesis (DS) patients with radicular pain and/or neurological claudication after unsuccessful conservative treatment underwent either instrumented posterolateral fusion (PLF) or posterior lumbar inter-body fusion (PLIF) at the single level of L4–5. All surgeries were performed using the same procedures at a single institution. Patients with an acute fracture, dislocation, or malignancy were excluded. Informed consent was obtained from all patients. Medical records of all patients were reviewed, and this study was approved by our local ethics committee. Forty-three patients were excluded because of a short follow-up (<2 years) or a lack of preoperative magnetic resonance imaging (MRI) and/or myelography data. The remaining 161 patients with a follow-up period of longer than 2 years were finally selected.

PLF had been performed in 137 patients (85 %) and PLIF in 24 patients (15 %). In all patients undergoing PLF, autogenous cancellous iliac bone was used as a graft. PLIF was performed using a rectangular ceramic cage with morselised local bone from neural decompression in all patients. When patients had spinal stenosis on myelography or MRI at the L3–4 segment, as well as neurological findings (including the presence of patellar tendon reflex and no sensory and motor disturbance associated with the L4 nerve root) and negative findings of L4 nerve root infiltration, we did not include the L3–4 segment in the operation site.

Radiographic evaluation

In all patients, computed tomography (CT), myelography, and MRI were performed within 2 weeks before the index fusion surgery. In this series, no patients required additional surgery at the L5–S1 segment during follow-up, so radiographic evaluations were performed at the L3–4 and L4–5 segments. Standard biplanar anteroposterior, lateral radiography with the lumbosacral spine in neutral, flexion, and extension positions was performed preoperatively, at 24 months after surgery, and at the final follow-up.

The anteroposterior vertebral slip and intervertebral disc angle were measured on lateral radiographs of the L3–4 and L4–5 taken in the neutral, flexion, and extension positions. To minimise the errors due to different magnifications, the vertebral slip was expressed as a percentage of the caudal vertebral body width (% slip). The ranges of motion (ROM) of the L3–4 and L4–5 segments were defined as the sum of the intervertebral disc angles in the flexion/extension view (Fig. 1). Pseudarthrosis was present if there was no continuity in the PLF fusion mass between the cephalad and caudad transverse processes, no continuity between graft bone and vertebra in PLIF fusion, or if lateral flexion–extension radiographs demonstrated >2° of angular motion or >2 mm of sagittal motion at L4–5 [11].

The criteria for adjacent segment instability were well-defined spondylolisthesis or dynamic instability with slippage >4 mm and/or an ROM >10° [12]. The laminar inclination angle at L3 was measured as previously described [9] on lateral radiographs (Fig. 2a). Facet orientation and tropism were determined by CT images that were coplanar with the disc and transected the facet joints, as described previously [9]. The sum of the right and left facet angles and the difference between the right and left facet angles were defined as the facet orientation and tropism, respectively (Fig. 2b).

Myelography measurements

After lumbar puncture and injection of radiographic contrast material into the dural sac under fluoroscopic guidance, the physician moved the patient's lower back to maximum flexion and extension in the left lateral decubitus position and obtained lateral radiographs in the neutral, flexion, and extension positions under fluoroscopy. The narrowest anteroposterior dural sac diameter at L3–4 was measured on lateral myelography in the neutral, flexion, and extension positions and on the sagittal view of T2-weighted MRI. The dural sac diameter at the midpoint of the L2 vertebral body was also measured. The spinal canal stenosis ratio (SCSR) was calculated as $x/y \times 100$ (Fig. 3).

All measurements were performed twice by two independent observers blinded to the patient name and clinical findings using an electronic digitiser (MicroAnalyzer; Japan Poladigital Corp., Tokyo, Japan) with an accuracy of 0.01 mm: measurements were averaged. The inter-observer correlation of all measurement was evaluated by the Pearson's correlation coefficient test. The kappa statistic was used to assess inter-observer agreement of pseudarthrosis and preoperative instability at L3–4.

Statistical analysis

The final follow-up examination was defined as the last visit. In patients undergoing re-operation at L3–4, the survival period was defined as the interval from the index operation to the second operation due to C-ASP. C-ASP

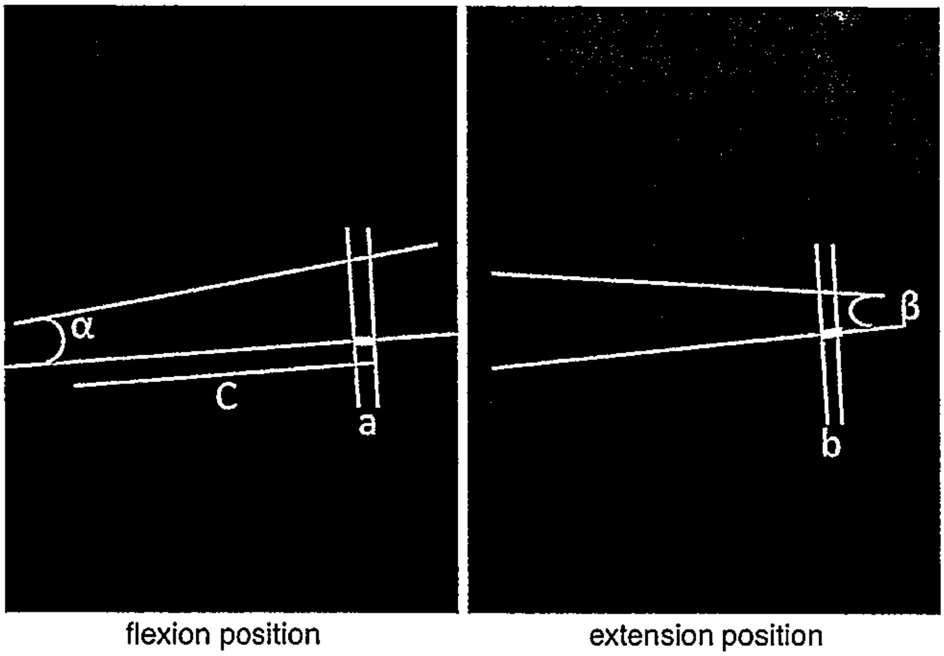

Fig. 1 Plain radiography measurement. *a* Anterior slip in the flexion position, *b* posterior slip in the extension position, *c* vertebral body width. The total percent slip is $(a + b)/c \times 100$. α Intervertebral disc angle in flexion position, β intervertebral disc angle in the extension position. The range of motion is $\alpha + \beta$ in degrees

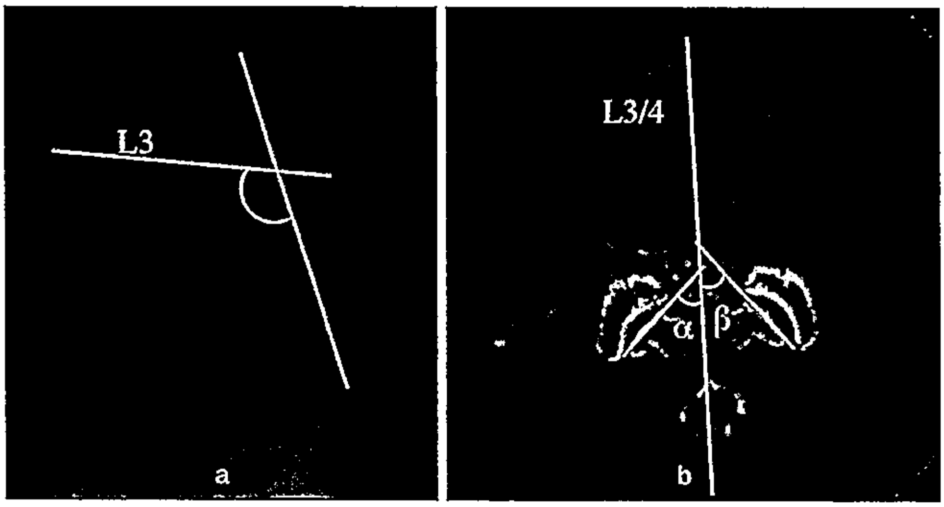

Fig. 2 *a* The laminar inclination angle at L3 was defined as the angle formed by a *straight line* connecting the base of the superior facet with the base of the inferior facet, and a *straight line* connecting the midpoints of the anterior and posterior L3 vertebral cortices on lateral radiographs. *b* Facet orientation and tropism were determined by computed tomography images that were coplanar with the disc and transected the facet joints. The sum of the right and left facet angles and the difference between the right and left facet angles were defined as the facet orientation and tropism, respectively

was defined as a condition where an additional surgery at L3–4 was required to treat symptomatic neurological deterioration.

The following prognostic risk factors were examined: age, sex, body mass index (BMI), facet orientation, facet tropism, laminar inclination angle, SCSR by myelography and MRI, preoperative adjacent segment instability, type of fusion, presence of pseudarthrosis, segmental lordosis at L4–5, and the %slip of L4–5 after 2 years postoperatively. Continuous variables were dichotomised to increase the statistical power using the Youden index from the receiver operating characteristic curve (ROC).

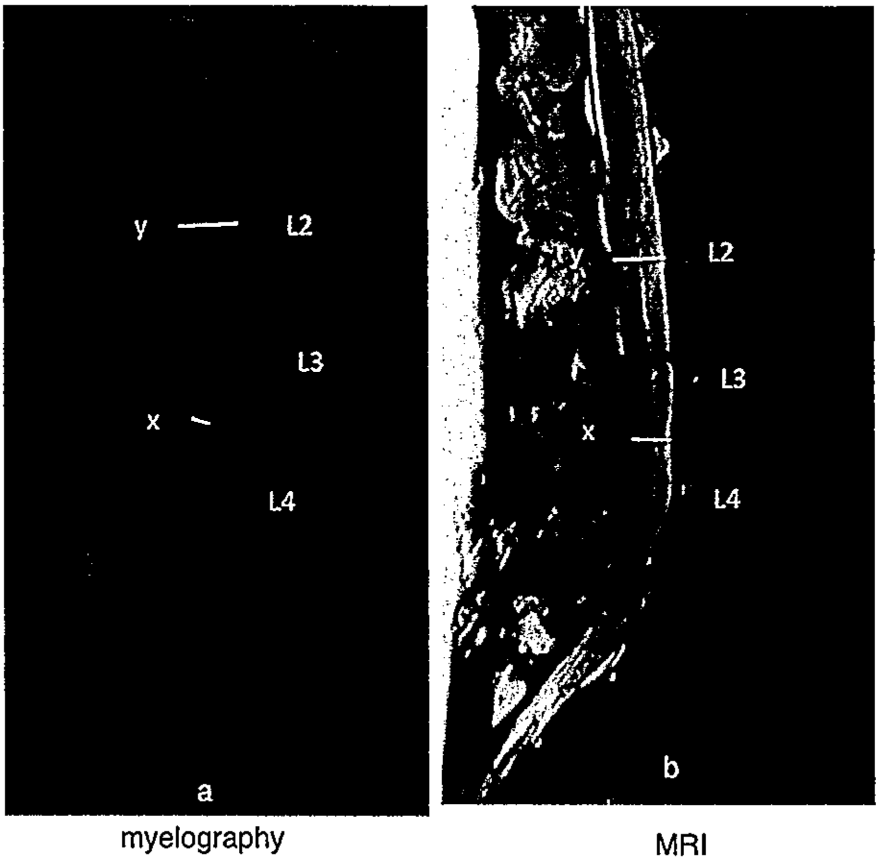

Fig. 3 The narrowest anteroposterior dural sac diameter at L3–4 (*x*) was measured on lateral myelographs taken in the extension position (a) and on MRI (b) in the same patient. The dural sac diameter at the midpoint of the L2 vertebral body (*y*) was also measured. The spinal canal stenosis ratio (SCSR) was calculated as $x/y \times 100$

A log-rank test was used for univariate analyses using the Kaplan–Meier method, and survival curves for all patients with significant risk factors were constructed to calculate the survival time. A multivariate Cox proportional-hazards model was used to assess all factors demonstrated to be significant by the log-rank test to adjust for confounding factors.

Statistical analyses were performed using the JMP 10 statistical software package (SAS Institute Inc. Cary, NC). A value of $P < 0.05$ was considered to be statistically significant.

Results

There were 56 males and 105 females. The mean age at index surgery was 65.4 years (range 40–87 years). The average follow-up period was 77.3 months (range 24–183 months). The follow-up rate was 78.9 %. Among the 161 patients, 22 (13.7 %) underwent subsequent procedures at cranial segments adjacent to the L4–5 segment; five patients underwent decompression surgery with arthrodesis and 17 underwent decompression surgery alone. After the additional surgery, all patients show improved neurological symptoms. The mean duration between the index surgery and the additional surgery was 75.9 months (range 24–141 months).

The inter-observer correlation is shown in Table 1. The kappa coefficient for pseudarthrosis rated between observers was 0.82 ($P < 0.0001$) and that of preoperative instability at L3–4 was 0.89 ($P < 0.0001$).

Patients with a BMI $\geq$ 25 kg/m^2 had a significantly lower survival rate than their counterparts in a univariate analysis (log-rank test: $P = 0.0497$). The incidence of C-ASP in patients with a BMI $\geq$ 25 kg/m^2 was estimated to be 32.5 % at 10 years. Conversely, the incidence of C-ASP in patients with a BMI < 25 kg/m^2 was lower, at 21.1 % at 10 years. The median survival time for patients with a BMI $\geq$ 25 kg/m^2 was 141 months (Fig. 4).

Patients with facet tropism $\geq$11° demonstrated a lower survival rate than their counterparts (log-rank test: $P = 0.0178$). The incidence of C-ASP among patients with facet tropism $\geq$11° was 39.6 %, while for facet tropism <11° it was 19.4 % at 10 years after the initial operation (Fig. 5).

Regarding SCSR, patients with an SCSR $\geq$47 % on myelography in the extension position showed a significantly lower survival rate than their counterparts

Table 1 Inter-observer correlations for study parameters

Parameters	P value	Pearson correlation coefficient
Facet orientation	<0.001	0.91
Facet tropism	<0.001	0.92
Laminar inclination angle	<0.001	0.86
Segmental lordosis at L4–5	<0.001	0.87
%Slip of L4	<0.001	0.89
SCSR of MRI	<0.001	0.91
SCSR of myelography (neutral position)	<0.001	0.88
SCSR of myelography(flexion position)	<0.001	0.87
SCSR of myelography(extension position)	<0.001	0.89

Significance was set at $P < 0.05$

SCSR spinal canal stenosis ratio, *MRI* magnetic resonance imaging

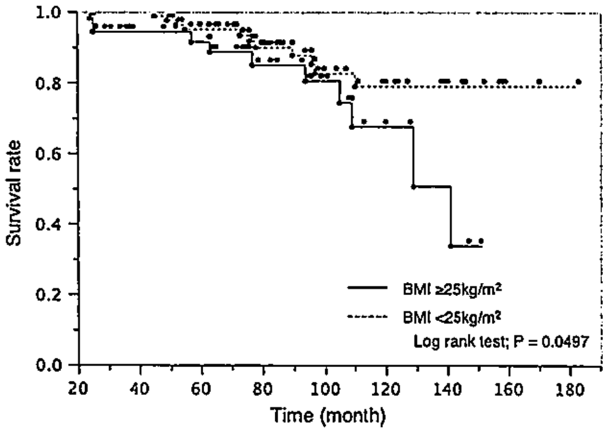

Fig. 4 The Kaplan-Meier survivorship curve of patients with BMI ≥ 25 kg/m^2 versus those with BMI < 25 kg/m^2

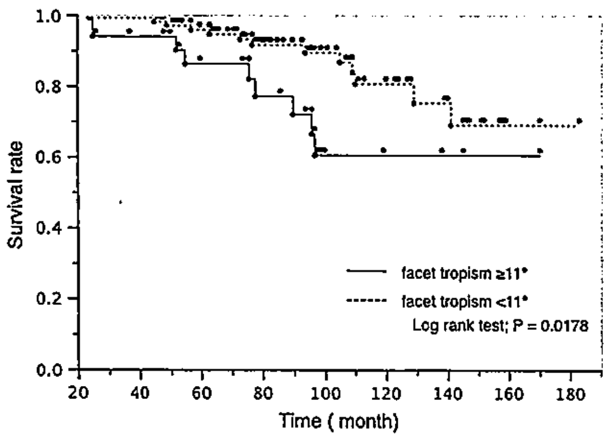

Fig. 5 The Kaplan-Meier survivorship curve of patients with facet tropism ≥11° versus those with facet tropism <11°

($P < 0.0001$). In these patients, the prevalence of C-ASP requiring reoperation was 51.3 % at 10 years, whereas it was 11.4 % in patients with an SCSR <47 %. The median

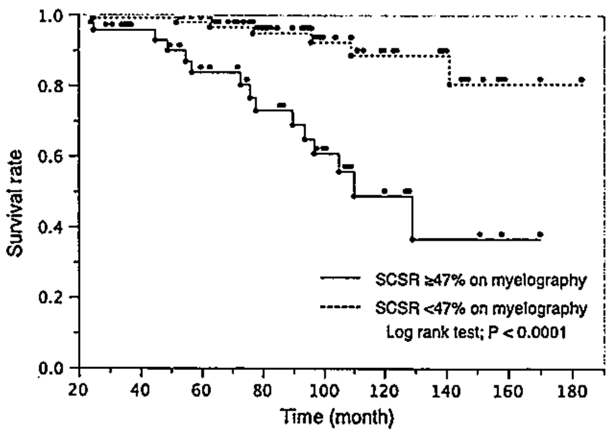

Fig. 6 The Kaplan-Meier survivorship curve of patients with an SCSR ≥ 47 % versus those with an SCSR < 47 % on myelography. *SCSR* spinal canal stenosis ratio

survival time for patients with an SCSR ≥47 % was 110 months (Fig. 6).

Interestingly, SCSR determined by MRI was not a significant risk factor (log-rank test: $P = 0.2990$). Since a factor with a higher discrimination ability makes an ROC curve closer to the top left corner, the area under the ROC curve (AUC) is used to indicate the sensitivity and specificity of each factor. We compared the AUC values of MRI and myelography in the extension positions. In this analysis, the AUC of the SCSR determined by myelography was significantly higher than that of the SCSR determined by MRI (Fig. 7). In fact, 13.2 % of patients who exhibited SCSR on MRI <50 % had an SCSR ≥50 % on myelography in the extension position.

Other potential risk factors, such as age, sex, facet orientation, laminar inclination angle, preoperative adjacent segment instability, type of fusion, pseudarthrosis, segmental lordosis, the %slip, and SCSR on myelography in the neutral and flexion positions, were not statistically significant (Table 2). A multivariate Cox proportional-

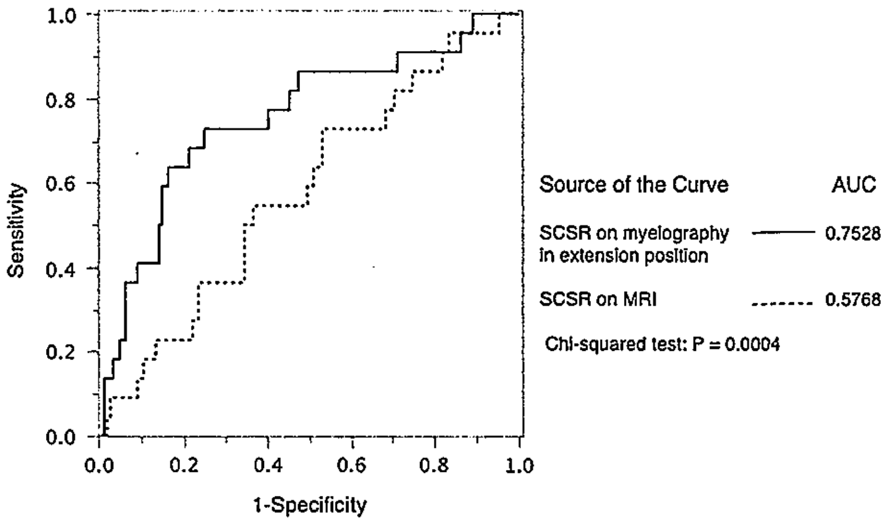

Fig. 7 Receiver operating characteristic curves of the SCSR on myelography at extension and the SCSR on MRI. *AUC* area under the ROC curve, *SCSR* spinal canal stenosis ratio

Table 2 Potential risk factors for clinical adjacent segment pathology after lumbar spinal fusion based on the log-rank test

Risk factor	*P* value
Sex (female)	0.3530
Age ≥ 68 years	0.3989
BMI ≥ 25 kg/m^2	0.0497*
Facet orientation ≥65°	0.2272
Facet tropism ≥11°	0.0178*
Laminar inclination ≥120°	0.6325
SCSR on MRI ≥ 35 %	0.2990
SCSR on myelography in extension ≥47 %	<0.0001*
SCSR on myelography in neutral ≥33 %	0.0757
SCSR on myelography in flexion ≥18 %	0.1467
Preoperative instability	0.6902
Type of fusion	0.4737
Pseudarthrosis	0.2086
Segmental lordosis at L4–5 ≥ 6.3°	0.2278
%Slip of L4 ≥ 13.4%	0.1465

Significance was set at $P < 0.05$*

BMI body mass index, *SCSR* spinal canal stenosis ratio, *MRI* magnetic resonance imaging

hazards model revealed a BMI ≥ 25 kg/m^2, facet tropism ≥11°, and SCSR ≥47 % on myelography to be significant risk factors, and patients with these factors had 3.1-, 3.7-, and 4.9-fold higher risks of adjacent segment reoperation than their counterparts, respectively (Table 3).

Discussion

The definition of C-ASP has often been reported as adjacent segment pathology, manifesting radiculopathy, neurogenic intermittent claudication, back pain, or a combination of any of these [13], and the need for additional surgeries [3–5, 8–10] on the index fusion segments. Park et al. [3] reported the incidence of C-ASP to range from 5.2 to 18.5 %. The term 'degeneration' itself suggests a time-dependent phenomenon. Therefore, the survival function estimated by the Kaplan–Meier method and the multivariate Cox regression model are good ways to analyse the development of ASP as a late complication of spinal arthrodesis.

Regardless of the use of spinal arthrodesis, the clinical course of patients with severe spinal stenosis often deteriorates over time during conservative treatments [14]. This indicates that pre-existing spinal stenosis in itself may be a significant risk factor for C-ASP. Cho et al. [10] reported a significant relationship between pre-existing spinal stenosis and C-ASP. However, they did not indicate a cutoff point for spinal stenosis that may increase the likelihood of C-ASP. In the current study, patients with an SCSR ≥47 %

Table 3 Risk factors for clinical adjacent segment pathology after lumbar spinal fusion

Risk factor	*P* value	Hazard ratio	95 % confidence interval
BMI ≥ 25 kg/m^2	0.0212*	3.12	1.18–8.49
Facet tropism ≥11°	0.0114*	3.74	1.35–10.30
SCSR in myelography ≥47 %	0.0003*	4.87	2.05–12.78

Significance was set at $P < 0.05$*

BMI body mass index, *SCSR* spinal canal stenosis ratio on myelography in the extension position exhibited a 4.87-fold higher risk of adjacent segment reoperation than their counterparts. Interestingly, spinal stenosis demonstrated by MRI was not a significant factor. We attempted to change the cutoff point for SCSR on MRI from 35 to 60 %; however, the MRI findings were not a significant factor. Moreover, the AUC of SCSR on myelography in the extension position (0.7528) was significantly larger than that on MRI (0.5768) (Chi squared; $P = 0.0004$). These results suggest that myelography has a significantly higher sensitivity and specificity to detect not only latent spinal canal stenosis, but also the risk of ASP requiring additional surgery.

While these results indicate that pre-existing severe stenosis can be a significant risk factor for C-ASP, this does not lead directly to a recommendation for performing laminectomy during the index surgery, since performing laminectomy adjacent to a fusion segment demonstrated a significant association with ASP [5, 15–17]. Imagama et al. [15] recommended that the adjacent segment with asymptomatic spinal stenosis should not be subjected to a concomitant decompression from the viewpoint of preventing ASP. We therefore recommend that surgeons should have thorough discussions with patients to determine whether a concomitant operation at adjacent segments with asymptomatic stenosis should be performed.

Facet tropism is defined as asymmetry in the facet joint that causes an abnormal rotation of the spinal segment, which increases the mechanical stress on the disc and could lead to lumbar degeneration or disc herniation [18, 19]. Several studies have reported greater facet tropism to have a significant relationship with C-ASP [9]. In the current study, patients with facet tropism $\geq 11°$ had a 3.74-fold higher risk of adjacent segment reoperation compared to their counterparts. We hypothesised that facet tropism may affect the rotational stability, which accelerates the thickening of the ligamentum flavum, thus resulting in spinal canal stenosis. However, some authors have reported no association between facet tropism and the occurrence of C-ASP [10]. Further studies are required to clarify this issue.

It remains controversial as to whether an association exists between BMI and ASP. Some studies reported no association between BMI and radiographic ASP [20]; however, Cho et al. [10] reported BMI to be a significant risk factor for C-ASP, and Liuke et al. [21] reported that a BMI ≥ 25 kg/m^2 increased the risk of lumbar disc degeneration on MRI. It is assumed that being overweight might cause disc degeneration [22], resulting in earlier ASP over the long term. In this series, a BMI ≥ 25 kg/m^2 was identified as a significant risk factor for C-ASP, and patients with this factor had a 3.12-fold higher risk of needing adjacent segment reoperation than their counterparts. Patients with high BMI appear to have a higher risk of C-ASP; however, a large prospective study is needed to confirm this finding.

In this study, other factors were not significant risk factors for C-ASP. The association between the conditions of fused segments and the occurrence of ASP also remains controversial. Since almost all past studies were retrospective analyses that contained potential bias, a randomised prospective study will be necessary to resolve these issues.

There are several possible limitations associated with this study. First, it was a retrospective study. Second, the predictors derived were not prospectively validated in an independent population. Third, the sample size was relatively small. Finally, whole spinal radiographs were not routinely taken for DS patients who underwent one-segment spinal fusion and decompression and, therefore, a whole spinal radiographic analysis was not possible in this study. Despite these limitations, the factors identified in this study may assist both surgeons and patients when making decisions about whether or not to include an adjacent segment at the time of index fusion surgery.

In conclusion, a BMI ≥ 25 kg/m^2, facet tropism $\geq 11°$, and pre-existing stenosis ≥ 47 % demonstrated on myelography in the extension position were found to be important risk factors for C-ASP requiring a second operation. Careful consideration of the type and extent of surgery is therefore necessary when these risk factors are present.

Compliance with ethical standards

Conflict of interest No funds were received in support of this work. No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript.

Ethical standards The study was approved by the local ethics committee.

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CLINICAL CASE SERIES

A Study of Risk Factors for Tracheostomy in Patients With a Cervical Spinal Cord Injury

Jun Tanaka, MD,* Itaru Yugue, MD, PhD,† Keiichiro Shiba, MD, PhD,† Akira Maeyama, MD, PhD,* and Masatoshi Naito, MD, PhD*

Study Design. A retrospective, consecutive case series.

Objective. To determine the risk factors for a tracheostomy in patients with a cervical spinal cord injury.

Summary and Background Date. Respiratory status cannot be stabilized in patients with a cervical spinal cord injury (CSCI) for various reasons, so a number of these patients require long-term respiratory care and a tracheostomy. Various studies have described risk factors for a tracheostomy, but none have indicated a relationship between imaging assessment and the need for a tracheostomy. The current study used imaging assessment and other approaches to assess and examine the risk factors for a tracheostomy in patients with a CSCI.

Methods. Subjects were 199 patients who were treated at the Spinal Injuries Center within 72 hours of a CSCI over 8-year period. Risk factors for a tracheostomy were retrospectively studied. Patients were assessed in terms of 10 items: age, sex, the presence of a vertebral fracture or dislocation, ASIA Impairment Scale, the neurological level of injury (NLI), PaO_2, $PaCO_2$, the level of injury on magnetic resonance imaging (MRI), the presence of hematoma-like changes (a hypointense core surrounded by a hyperintense rim in T2-weighted images) on MRI, and the Injury Severity Score.

Items were analyzed multivariate logistic regression, and $P < 0.05$ was considered to indicate a significant difference.

Results. Twenty-three of the 199 patients required a tracheostomy, accounting for 11.6% of patients with a CSCI. Univariate analyses of the risk factors for tracheostomy revealed significant differences for six items: age, Injury Severity Score, presence of fracture or dislocation, ASIA Impairment Scale A, NLI C4 or above, and MRI scans revealing hematoma-like changes. Multivariate logistic regression analyses revealed significant differences in terms of two items: NLI C4 or above and MRI scans revealing hematoma-like changes. Thirty patients had both an NLI C4 or above and MRI scans revealing hematoma-like changes. Of these, 17 (56.7%) required a tracheostomy.

Conclusion. Patients with an NLI C4 or above and MRI scans revealing hematoma-like changes were likely to require a tracheostomy. An early tracheostomy should be considered for patients with both of these characteristics.

Key words: arterial blood gases, ASIA impairment scale, cervical spinal cord injury, hematoma-like changes on magnetic resonance imaging, imaging assessment, injury severity score, neurological level of injury, risk factors, tracheostomy, vertebral fracture or dislocation.

Level of Evidence: 3

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Respiratory status cannot be stabilized in patients with a cervical spinal cord injury (CSCI) for various reasons, so a number of these patients require long-term respiratory care and a tracheostomy. Numerous studies have reported that respiratory dysfunction is closely associated with morbidity and mortality in CSCI,[1–3] and respiratory dysfunction leads to massive financial expenses.[3] The cause of death for patients with a CSCI is often a urinary complication or a respiratory complication.[4,5] A recent study from abroad has reported that respiratory complications represent the leading cause of death in patients with a CSCI,[5] and the same is true in Japan.[4]

In the acute phase of CSCI, spinal shock can have an effect and the patient's respiratory status might be unstable, so temporary ventilator management is often required.[6–16] If the patient's respiratory status fails to improve with temporary ventilator management and long-term intubation is required, a tracheostomy is often performed. Performing a tracheostomy early on is known to be useful in reducing respiratory complications, as various studies have reported[6,9,16–18]; however, unnecessary intubation and unnecessary tracheostomies are known to increase

From the *Faculty of Medicine, Department of Orthopaedic Surgery, Fukuoka University; and †Department of Orthopaedic Surgery, Spinal Injuries Center, Iizuka city, Fukuoka, Japan.

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Address correspondence and reprint requests to Jun Tanaka, MD, Faculty of Medicine, Department of Orthopaedic Surgery, Fukuoka University, 7-45-1 Nanakuma, Jonan-ku, Fukuoka 814-0180, Japan; E-mail: jt0120jt@gmail.com

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the risk of complications in both the short and long term.[9] Exaggerating the usefulness of an early tracheostomy can result in unnecessary tracheal intubation or an unnecessary tracheostomy. Thus, predicting true risk factors for intubation or a tracheostomy in patients with a CSCI is important.

Various studies have described risk factors for a tracheostomy in patients with a CSCI. These include advanced age,[7,12] complete paralysis,[1,6–8,14,17,19–22,23] a high level of neurological paralysis,[6,12,14,21] the patient's general condition prior to the injury and a prior history of lung disease,[1,8,12] a high injury severity score (ISS),[8,17] a history of smoking,[19] and a low forced vital capacity upon admission.[7,9]

Nevertheless, no previous studies have indicated a relationship between imaging assessment (radiographs, computed tomography, or magnetic resonance imaging [MRI]) and the need for a tracheostomy. The current study used imaging assessment and other approaches to assess and examine the risk factors for a tracheostomy in patients with a CSCI.

METHODS

Subjects were 199 patients who were treated by the Department of Orthopedic Surgery of the Spinal Injuries Center within 72 hours of a CSCI over 8-year period from January 1, 2005 to December 31, 2012. Patients consisted of 165 males and 34 females ranging in age from 14 to 91 years with a mean age of 61.9 years.

All patients were examined by two or more physicians and a physical therapist upon admission, and patients were assessed neurologically. In addition, the presence or absence of a vertebral fracture or dislocation was assessed using X-ray films or computed tomography scans and the presence or absence of cord damage was assessed using MRI scans in all patients upon admission. Surgery (anterior spine fusion, posterior spine fusion, or anterior spine fusion and posterior spine fusion,) was performed on patients with apparent spinal instability. Arterial blood gases were measured in all patients upon admission. If patients had apnea or ventilatory failure prior to initial admission and they needed assistance breathing, a tracheostomy was performed on the day of admission. If, however, a patient's respiratory status gradually worsened after admission, intubation was performed at the discretion of the patient's primary physician in accordance with the patient's respiratory status. When long-term ventilator management was considered necessary, a tracheostomy was performed. This Center has not formulated definite standards for intubation and tracheostomy, although blood gas results of PaO_2 70 mm Hg or less and $PaCO_2$ at least 50 mm Hg serve as somewhat of a guide, regardless of whether O_2 is administered.

Medical records, the patient's discharge summary, and imaging findings upon admission and discharge were retrospectively studied.

The following items were studied retrospectively: age, sex, the presence or absence of a vertebral fracture or dislocation at the level of injury, the American Spinal Association (ASIA) Impairment Scale (AIS), the neurological level of injury (NLI), PaO_2 according to a blood gas analysis, $PaCO_2$ according to a blood gas analysis, the level of injury on MRI, hematoma-like changes on MRI (presence or absence of a hypointense core surrounded by a hyperintense rim in T2-weighted images), and the ISS.

Statistical analyses were done using the Jump11 statistical software package from SAS Institute Inc. (Cary, NC).

In instances wherein there was no avulsion fracture of the anterior aspect of the vertebral body or a spinous process fracture in conjunction with a hyperextension injury, no bone injury on MRI scans, and no need for surgery due to the lack of spinal instability, bone injury or dislocation was deemed to be absent. In addition, the NLI was the most caudal segment wherein normal motor and sensory function were intact. If hematoma-like changes were present, the level of those changes served as the level of injury on MRI. If those changes were absent, the segment wherein the center of a wider ranging hyperintensity was located on T2-weighted images served as the level of injury on MRI (Figure 1A, B).

Age, PaO_2, $PaCO_2$, and the ISS were assessed as continuous variables. To increase statistic power, the AIS, the NLI, and the level of injury on MRI were dichotomized as an AIS A or not, an NLI C4 or above or not, and a level of injury on MRI C3/4 or less or not.

RESULTS

A total of 199 patients with a cervical spinal cord injury were treated at this center over 8-year period. Patients consisted of 165 males and 34 females ranging in age from 14 to 91 years with a mean age of 61.9 years. All of the patients had suffered blunt trauma. Sixty patients (30.1%) had a vertebral fracture or dislocation.

The extent of paralysis upon admission was AIS A in 66 patients (33.2%), AIS B in 38 (19.1%), AIS C in 51 (25.6%), and AIS D in 44 (22.1%). The NLI upon admission was C2 in 1 patient (0.5%), C3 in 10 (5.0%), C4 in 90 (45.2%), C5 in 62 (31.2%), C6 in 19 (9.6%), C7 in 6 (3.0%), C8 in 1 (0.5%), and T1 in 10 (5.0%) (Table 1).

All of the patients underwent an MRI upon admission, and hyper-intensity changes on T2-weighted images were noted in all of the patients. The level of injury on MRI was C2/3 in 5 patients (2.5%), C3 in 2 (1.0%), C3/4 in 70 (35.2%), C4 in 4 (2.0%), C4/5 in 49 (24.6%), C5 in 10 (5.0%), C5/6 in 29 (14.6%), C6 in 4 (2.0%), C6/7 in 24 (12.1%), C7 in 1 (0.5%), and C7/T1 in 1 (0.5%). Hematoma-like changes were noted in 46 patients (23.1%) and such changes were not noted in 153 (76.9%) (Table 2).

Twenty-three of the 199 patients required a tracheostomy, accounting for 11.6% of patients with a cervical spinal cord injury. The average time from injury until a tracheostomy was performed was 4.69 days (day of injury–13 days later). Details on the 23 patients who underwent a tracheostomy are indicated below (Table 3).

Eleven patients had a vertebral fracture or dislocation; a bone injury was not noted in 12 patients. Seventeen patients had an AIS A, 4 had AIS B, and 2 had AIS C. The NLI was C2

Figure 1. "Hematoma-like changes" and the level of injury on MRI. A, MRI findings of a hypointense core surrounded by a hyperintense rim in a T2-weighted image. We described these changes as "hematoma-like changes." When these changes were present, the level of the changes served as the level of injury on MRI. This patient's level of injury on MRI was "C3/4". B, When hematoma-like changes were absent, the segment containing the center of a wider-ranging hyperintensity area served as the level of injury on MRI. This patient's level of injury on MRI was "C5/6." MRI indicates magnetic resonance imaging.

in 1 patient, C3 in 5, C4 in 15, C5 in 1 and T1 in 1. The level of injury on MRI scans was at C2/3 in 1 patient, at C3/4 in 9, at C4/5 in 7, at C5/6 in 5, and at C6/7 in 1. Hematoma-like changes were noted on MRI images of 17 patients.

The final outcome (state at final follow-up) was death for one patient and permanent ventilator management for seven. The respiratory status of 15 patients stabilized, and they were weaned from the ventilator.

TABLE 1. Patients Demographic Data

Mean ± SD	Overall (n = 199)	Tracheostomy (n = 23)	No Tracheostomy (n = 176)
Age (yrs)	61.9 ± 17.7	69.1 ± 15.8	60.9 ± 17.8
Sex			
Male	165 (82.9%)	17 (73.9%)	148 (84.1%)
Female	34 (17.1%)	6 (26.1%)	28 (15.9%)
Fracture or dislocation			
+	60 (30.1%)	11 (43.5%)	49 (27.8%)
−	139 (69.9%)	12 (56.5%)	127 (72.2%)
Initial AIS			
A	66 (33.2%)	17 (73.9%)	49 (27.8%)
B	38 (19.1%)	4 (17.4%)	34 (19.4%)
C	51 (25.6%)	2 (8.7%)	49 (27.8%)
D	44 (22.1%)	0	44 (25.0%)
Initial NLI			
C2	1 (0.5%)	1 (4.4%)	0
C3	10 (5.0%)	5 (21.7%)	5 (2.8%)
C4	90 (45.2%)	15 (65.3%)	75 (42.6%)
C5	62 (31.2%)	1 (4.4%)	61 (34.7%)
C6	19 (9.6%)	0	19 (10.9%)
C7	6 (3.0%)	0	6 (3.4%)
C8	1 (0.5%)	0	1 (0.5%)
T1	10 (5.0%)	1 (4.4%)	9 (5.1%)
Arterial blood gases			
PO_2 (mm Hg)	91.9 ± 40.7	104.1 ± 71.2	90.3 ± 34.9
PCO_2(mm Hg)	38.3 ± 5.1	39.9 ± 5.4	38.1 ± 5.0
ISS	21.4 ± 10.6	31.7 ± 18.9	20.1 ± 8.2

AIS indicates American Spinal Association impairment scale; ISS, injury severity score; NLI, neurological level of injury; SD, standard deviation.

TABLE 2. Level of Spinal Cord Injury and Hematoma-Like Changes on MRI

	Overall (n = 199)	Tracheostomy (n = 23)	No tracheostomy (n = 176)
Level of spinal cord injury on MRI			
C2/3	5 (2.5%)	1 (4.4%)	4 (2.3%)
C3	2 (1.0%)	0	2 (1.1%)
C3/4	70 (35.2%)	9 (39.1%)	61 (34.7%)
C4	4 (2.0%)	0	4 (2.3%)
C4/5	49 (24.6%)	7 (30.4%)	42 (23.9%)
C5	10 (5.0%)	0	10 (5.7%)
C5/6	29 (14.6%)	5 (21.7%)	24 (13.6%)
C6	4 (2.0%)	0	4 (2.3%)
C6/7	24 (12.1%)	1 (4.4%)	23 (13.1%)
C7	1 (0.5%)	0	1 (0.5%)
C7/T1	1 (0.5%)	0	1 (0.5%)
Hematoma-like changes on MRI			
+	46 (23.1%)	17 (73.9%)	29 (16.5%)
−	153 (76.9%)	6 (26.1%)	147 (83.5%)

MRI indicates magnetic resonance imaging; SD, standard deviation.

Univariate analyses of the risk factors for tracheostomy revealed significant differences for six items: age ($P = 0.0422$, odds ratio [OR] = 1.035), ISS ($P = 0.0002$, OR = 1.065), presence of fracture or dislocation ($P = 0.0209$, OR = 2.827), AIS A ($P < 0.0001$, OR = 7.344), NLI C4 or above ($P = 0.0008$, OR = 12.599), and MRI scans revealing hematoma-like changes ($P < 0.0001$, OR = 9.504) (Table 4).

The aforementioned items with significant differences in the univariate analyses were further analyzed using multivariate logistic regression. The results revealed significant differences for two items: NLI C4 or above ($P = 0.0058$, OR = 9.681) and MRI scans revealing hematoma-like changes ($P = 0.0212$, OR = 3.941) (Table 5).

In addition, 17 of 30 patients (56.7%) who had both an NLI C4 or above and MRI scans revealing hematoma-like

TABLE 3. Demographic Data of Tracheostomy Patients

Case No.	Age	Sex	Type of Fracture	AIS	NLI	T2 High Level	Hematoma-like changes on MRI	PO2 on Admission (mm Hg)	PCO2 on Admission (mm Hg)	Final Form
1	80	F	C6 fracture dislocation	A	C4	C6/7	+	74.73	45.2	Trach collar
2	47	M	C3 tear drop fracture T4 fracture dislocation	A	T1	C3/4	−	80.9	36	Closed
3	49	M	C5 burst fracture	A	C4	C5/6	+	66.7	41.8	Closed
4	64	M	C4 fracture dislocation	A	C4	C4/5	+	72.1	36.5	Trach collar
5	82	F	C3 fracture dislocation	C	C4	C3/4	+	145.7	45.1	Closed
6	84	M	C4 fracture dislocation	A	C3	C4/5	+	74.5	34.4	Mechanical ventilation
7	75	M	C5 fracture (post ASF)	C	C3	C4/5	−	45.8	46.6	Closed
8	61	F	C5 fracture dislocation	A	C4	C5/6	+	116.9	37.4	Closed
9	80	F	C3 burst fracture	B	C4	C3/4	+	59.0	40.0	Closed
10	76	M	C5 fracture dislocation	A	C4	C5/6	+	161.0	33.0	Trach collar
11	70	M	C3 fracture dislocation	A	C3	C3/4	+	166.0	46.7	Mechanical ventilation
12	51	M	No fracture	A	C3	C5/6	−	97.0	49.0	Mechanical ventilation
13	77	M	No fracture	A	C4	C4/5	+	48.6	47.6	Mechanical ventilation
14	22	M	No fracture	A	C3	C2/3	+	392 (intubated)	40.7 (intubated)	Closed
15	63	M	No fracture	B	C4	C3/4	−	63.4	33.8	Closed
16	89	M	No fracture	A	C4	C4/5	+	93.6	34.8	Died
17	72	M	No fracture	B	C4	C3/4	−	86.5	33.4	Closed
18	69	F	No fracture	A	C4	C3/4	+	123	43.9	Closed
19	61	M	No fracture	B	C2	C3/4	+	127	35.7	Mechanical ventilation
20	85	F	No fracture	A	C4	C4/5	+	69.5	43.1	Closed
21	83	M	No fracture	A	C5	C5/6	−	72.5	37.2	Closed
22	66	M	No fracture	A	C4	C4/5	+	72.7	31.6	Mechanical ventilation
23	84	M	No fracture	A	C4	C3/4	+	86.2	43.9	Mechanical ventilation

AIS indicates American Spinal Association impairment scale; ASF, anterior spine fusion; MRI, magnetic resonance imaging; NLI, neurological level of injury.

TABLE 4. Results of the Simple Logistic Regression Model

	P	OR	95% Confidence Interval
Age	0.0422	1.035	1.004–1.074*
ISS	0.0002	1.065	1.032–1.106*
PO_2 on admission	0.1445	1.006	0.997–1.014
PCO_2 on admission	0.1055	1.076	0.986–1.183
Sex	0.2284	1.866	0.629–4.939
Fracture or dislocation (+)	0.0209	2.827	1.166–6.931*
AIS A	<0.0001	7.344	2.870–21.353*
NLI ≥C4	0.0008	12.599	3.550–80.260*
Injury level on MRI ≥C3/4	0.6169	1.251	0.508–3.004
Hematoma-like changes on MRI	<0.0001	9.504	3.780–25.604*

Age, ISS, PO_2, and PCO_2 were calculated by the continuous variable function unit odds ratio.

AIS indicates American Spinal Association impairment scale; ISS, injury severity score; MRI, magnetic resonance imaging; NLI, neurological level of injury; OR, odds ratio.

$^*P<0.05$.

changes required a tracheostomy, whereas 15 of 40 patients (37.5%) who had both an NLI C4 or above and AIS A on admission required a tracheostomy.

DISCUSSION

Various complications can occur after a CSCI, although the most frequent are respiratory complications.[1–5] Typical complications include atelectasis, pneumonia, and ventilatory failure. These complications often occur in the acute phase within 5 days of injury.[13]

The diaphragm is innervated by nerves originating from C3–C5 (primarily from C4), and damage to the spinal cord at a higher level will immediately necessitate ventilator management. Sputum is expelled and coughing is accomplished primarily with the intercostal muscles and abdominal muscles. Even if the injury occurred at a lower level and the diaphragm still functioned, paralysis of these muscles causes sputum to pool, thereby facilitating atelectasis and pneumonia.[10,16] In the acute phase of injury, the sympathetic nerves are interrupted and the vagus nerve predominates. Furthermore, tracheobronchial secretions increase and the airway constricts. The amount of sputum increases and the sputum cannot be readily expelled. This phenomenon is one reason for why respiratory complications are so frequent.

In the first week after injury, a patient's vital capacity will decrease by 30% or more. About 5 weeks after injury, vital capacity will begin to recover, and 3 months after injury the vital capacity will double.[11,16] If the period of an unstable respiratory status in the acute-subacute phase of injury can be weathered, then the respiratory status will subsequently stabilize for the most part. Thus, predicting risk factors for intubation or tracheostomy in patients with a CSCI is important.

Studies cite widely differing figures for the percentage of patients requiring a tracheostomy after CSCI. These figures range from 15.2% to 81%, and recent studies have noted that a relatively high percentage of those patients require a tracheostomy.[6–9,12,17,19,21,24] Numerous studies have reported that performing a tracheostomy early on is useful in reducing respiratory complications.[6,9,16–18] This might be the reason for the substantial difference in the percentage of patients with a tracheostomy. That said, one possibility is that intubation or tracheostomy is performed unnecessarily, and such situations should be avoided.

The current study found that 11.6% of patients with a CSCI require a tracheostomy, and this is lower than the percentages described in other studies. This Center is a dedicated facility with a Department of Orthopedic Surgery and in principle this facility does not accept patients in the

TABLE 5. Results of the Multiple Logistic Regression Model

	P	OR	95% Confidence Interval
Age	0.0782	1.031	0.999–1.071
ISS	0.2784	1.025	0.983–1.077
Fracture or Dislocation (+)	0.2477	2.049	0.597–6.970
AIS A	0.2180	2.329	0.600–9.154
NLI ≥ C4	0.0058	9.681	2.362–66.748*
Hematoma-like changes on MRI	0.0212	3.941	1.243–13.131*

Age and ISS were calculated by the continuous variable function unit odds ratio.

AIS indicates American Spinal Association impairment scale; ISS, injury severity score; MRI, magnetic resonance imaging; NLI, neurological level of injury; OR, odds ratio.

$^*P<0.05$.

acute phase of multiple trauma. This Center sees a small proportion of patients with complications such as a brain contusion, multiple rib fractures, a hemopneumothorax, or injuries to the abdominal viscera, which might explain why so few of the current patients required a tracheostomy. The aforementioned reasons are also presumably the reason why tracheal intubation or a tracheostomy is so often indicated for a simple CSCI seen at this Center. In this study, univariate analyses and multivariate analyses yielded significant differences in terms of two items: an NLI C4 or above and MRI scans revealing hematoma-like changes. The aforementioned reasons are presumably why these two items were predictors for a tracheostomy, in a true sense, in patients with a CSCI.

Numerous studies have reported that complete paralysis is a risk factor for intubation or a tracheostomy.[1,6–8,14,17,19–22,23] In the current study, univariate analyses indicated that AIS A was a risk factor for tracheostomy, whereas multivariate analyses revealed no significant differences in AIS A.

This might be because complete paralysis means that the intercostal muscles and abdominal muscles are paralyzed, regardless of the level of the CSCI; however, Yugue *et al*[7] reported that 18.8% of patients who were AIS A upon admission had an improved level of paralysis (a grade other than A) at final follow-up. Similarly, 66 patients in the current study were AIS A upon admission, although eight (12.1%) had improvement at final follow-up. The period of spinal shock might have been included in the 72 hours after injury. Given this possibility, improvement in the level of paralysis needs to be assessed.

The ISS was similarly found to be a risk factor for tracheostomy according to univariate analyses. ISS is a score for the severity of multiple trauma. Several studies have reported that a high ISS is a predictor for tracheostomy in patients with a CSCI[8,21]; however, Velmahos *et al*[21] stated that assessment of the ISS is difficult in the acute phase of trauma, and they recommended that the ISS not be used as a predictor of tracheostomy.

No studies have indicated the relationship between imaging assessment and the need for a tracheostomy. The current study is the first to do so. In the acute phase of injury, blurred hyperintensity on T2-weighted MRI indicates spinal cord contusion or edema.[25–27] This imaging finding suggests injury to the spinal cord. If cord damage is severe and hematomyelia is present, hypointensities will be found inside hyperintensities in T2-weighted images. This finding mostly suggests severe spinal cord injury,[28,29] and we described those change as "hematoma-like changes." Bozzo *et al*[29] reported that 93% of patients with MRI scans revealing a hypointense core surrounded by a hyperintense rim in T2-weighted images (hematoma-like changes) were AIS A upon admission. Of these, 95% were AIS A at final follow-up. In the current study, 82.6% of patients who were found to have hematoma-like changes were AIS A upon admission. All of the patients were AIS A at final follow-up, and this grade might be correlated with severe paralysis.

In the current study, univariate analyses and multivariate analyses revealed significant differences in MRI scans revealing hematoma-like changes. The AIS grade might change over time because of its relationship to spinal shock. Consequently, the ISS might change as well. Thus, these indicators change. In contrast, MRI images revealing hematoma-like changes do not change with spinal shock, making these MRI findings an independent indicator.

Of course, MRI was performed within a few hours after the injury. Therefore, there was a possibility that hematoma-like changes (hypointense core surrounded by a hyperintense rim) did not appear on T2-weighted images, even if a hematomyelia occurred, reflecting the intracellular oxyhemoglobin[30]; however, if hypointensity changes were revealed on T2-weighted image within 72 hours after the injury, they reflected deoxyhemoglobin, suggesting that a hemorrhage had occurred in the spinal cord and that the damage was severe.

In addition, significant differences in the level of injury on MRI scans were not noted, although an NLI C4 or above was a risk factor for tracheostomy.

The level of injury on MRI and the NLI did not necessarily coincide. Results suggested that the NLI is important because of its greater clinical significance.

Several studies have reported that an NLI at a high level is a predictor for tracheotomy.[6,12,14,21] Nerves innervating the diaphragm originate at levels C3–C5. The diaphragm is

TABLE 6. Results of the Multiple Logistic Regression Model in CSCI Patients Who Had NLI ≥ C4 on Admission

	P	OR	95% Confidence Interval
Age	0.1383	1.031	0.993–1.078
ISS	0.4848	1.016	0.974–1.066
Fracture or dislocation (+)	0.1476	2.617	0.101–1.411
AIS A	0.2180	1.705	0.386–7.369
Hematoma-like changes on MRI	0.0049	6.101	1.779–22.842*

Age and ISS were calculated by the continuous variable function unit odds ratio.

AIS indicates American Spinal Association impairment scale; CSCI, cervical spinal cord injury; ISS, injury severity score; MRI, magnetic resonance imaging; NLI, neurological level of injury; OR, odds ratio.

$*P < 0.05$.

involved in about 65% of breathing. The current study yielded significant differences at C4 or above. Paralysis due to an injury at C4 or above causes motor paralysis of the diaphragm, which is likely to result in the patient's respiratory status worsening.

Several studies have reported that the risk of tracheostomy is related to age[7,12]; however, multivariate analyses revealed no significant differences in patient age. In addition, this study found no significant differences in patient sex.

Studies have reported that the forced vital capacity upon admission is correlated with the risk of tracheostomy,[7,9] although this characteristic might present problems for facilities that do not have a simple spirometer on hand. Blood gas analysis is simple and convenient, and the results might serve as an indicator in place of forced vital capacity. In actuality, however, significant differences in blood gas results were not evident.

An extensive search yielded no studies indicating a relationship between bone injury or dislocation and the risk of tracheostomy. The current study noted no significant differences in terms of the presence or absence of a vertebral fracture or dislocation in multivariate analyses. This is probably because the damage to the spinal cord is a more important factor than the presence or absence of a vertebral fracture or dislocation.

In the current study, multivariate analyses revealed significant differences in terms of two items: an NLI C4 or above and MRI scans revealing hematoma-like changes.

Multivariate-analyses revealed significant differences in terms of two items in 30 patients. Of these patients, 17 (57%) required a tracheostomy, suggesting that patients with both of the aforementioned characteristics are likely to require a tracheostomy.

In addition, we examined the risk factors for a tracheostomy in a total of 101 CSCI patients who had NLI C4 or above on admission. As a result, hematoma-like changes on MRI only showed a significant difference in the multivariate logistic regression model ($P=0.0049$, $OR=6.101$) (Table 6). This finding raises the possibility that hematoma-like changes on MRI are an optimal indictor of the risk for tracheostomy in patients with a CSCI.

The current study had several limitations. One is that this study was a retrospective study that studied a relatively small sample over an 8-year period. In addition, this study was conducted at a single special facility, that is, the Spinal Injuries Center, and not at other facilities. In addition, definite eligibility criteria for a tracheostomy have yet to be formulated at this facility, and the final decision is left to the discretion of the patient's primary physician. In addition, there is a possibility that hematoma-like changes did not appear on T2-weighted images, when MRI was performed within a few hours after the injury. Moreover, this study did not examine aspects such as patient history, original respiratory status, or whether or not the patient smoked.

Despite these limitations, however, the current study identified significant differences in terms of the two items: an NLI C4 or above and MRI scans revealing hematoma-like changes. These two items are statistically independent risk factors. If patients have both of these characteristics, they are extremely likely to have respiratory failure even if they had a satisfactory respiratory status upon admission. These characteristics can serve as important indices with which to study early tracheal intubation and early tracheostomy.

Key Points

- The current study used imaging assessment and other approaches to assess and examine the risk factors for a tracheostomy in patients with a CSCI.
- Univariate analyses of the risk factors for tracheostomy revealed significant differences for six items: age, ISS, presence of fracture or dislocation, AIS A, NLI C4 or above, and MRI scans revealing hematoma-like changes.
- Multivariate logistic regression analyses of the risk factors for tracheostomy revealed significant differences in terms of two items: NLI C4 or above and MRI images revealing hematoma-like changes.
- Spinal shock has an effect in the acute phase of injury, hampering assessment of the AIS. In contrast, MRI scans revealing hematoma-like changes do not change with spinal shock, making these MRI findings an independent indicator.
- Patients with an NLI C4 or above and MRI scans revealing hematoma-like changes were likely to require a tracheostomy.

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Clinical Study
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Clinical Influence of Cervical Spinal Canal Stenosis on Neurological Outcome after Traumatic Cervical Spinal Cord Injury without Major Fracture or Dislocation

Tsuneaki Takao[1], Seiji Okada[2], Yuichiro Morishita[1], Takeshi Maeda[1], Kensuke Kubota[2], Ryosuke Ideta[3], Eiji Mori[1], Itaru Yugue[1], Osamu Kawano[1], Hiroaki Sakai[1], Takayoshi Ueta[1], Keiichiro Shiba[1]

[1]*Department of Orthopaedic Surgery, Spinal Injuries Center, Iizuka, Japan*
[2]*Department of Orthopaedic Surgery, Kyushu University, Fukuoka, Japan*
[3]*Department of Rehabilitation Medicine, Spinal Injuries Center, Iizuka, Japan*

Study Design: Retrospective case series.

Purpose: To clarify the influence of cervical spinal canal stenosis (CSCS) on neurological functional recovery after traumatic cervical spinal cord injury (CSCI) without major fracture or dislocation

Overview of Literature: The biomechanical etiology of traumatic CSCI remains under discussion and its relationship with CSCS is one of the most controversial issues in the clinical management of traumatic CSCI.

Methods: To obtain a relatively uniform background, patients non-surgically treated for an acute C3–4 level CSCI without major fracture or dislocation were selected. We analyzed 58 subjects with traumatic CSCI using T2-weighted mid-sagittal magnetic resonance imaging. The sagittal diameter of the cerebrospinal fluid (CSF) column, degree of canal stenosis, and neurologic outcomes in motor function, including improvement rate, were assessed.

Results: There were no significant relationships between sagittal diameter of the CSF column at the C3–4 segment and their American Spinal Injury Association motor scores at both admission and discharge. Moreover, no significant relationships were observed between the sagittal diameter of the CSF column at the C3-4 segment and their neurological recovery during the following period.

Conclusions: No relationships between pre-existing CSCS and neurological outcomes were evident after traumatic CSCI. These results suggest that decompression surgery might not be recommended for traumatic CSCI without major fracture or dislocation despite pre-existing CSCS.

Keywords: Cervical spinal canal stenosis; Cervical spinal cord injury without major fracture or dislocation; Magnetic resonance imaging; Neurological outcome

Introduction

Numerous previous studies have been published concerning adult traumatic cervical spinal cord injuries (CSCI) without major bony injury or dislocation, using various nomenclature, such as hyperextension dislocation [1],

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Corresponding author: Tsuneaki Takao
Department of Orthopaedic Surgery, Spinal Injuries Center, 550-4 Igisu, Iizuka 820-8508, Japan
Tel: +81-948-24-7500, Fax: +81-948-29-1065, E-mail: tsuneaki@iris.ocn.ne.jp

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Table 1. Neurological status (ASIA impairment score) at admission and discharge

On admission	No.	On discharge				
		A	B	C	D	E
A	10	2	1	6	1	-
B	11	-	1	6	4	-
C	31	-	-	1	30	-
D	6	-	-	-	5	1

ASIA, American Spinal Injuries Association.

spinal cord injury (SCI) without radiographical abnormality in adults (SCIWORA) [2-6], SCI without radiographical evidence of trauma (SCIWORET) [7-9], and CSCI without bony injury [10-11]. Most patients are elderly and may present with tetraplegia caused by a hyperextension injury, predominantly at the C3–4 segment, with cord compression as a result of a stenotic spondylotic canal [3,7,12-14]. However, the influence of cervical spinal canal stenosis (CSCS) on neurological recovery after CSCI remains unclear.

The broad definition of SCIWORA/SCIWORET includes disc injury, anterior vertebral body tip or spinous process fracture, or other ligamentous injury. We defined CSCI with or without those injuries but without spinal canal bony injury as traumatic CSCI without major fracture or dislocation. Traumatic CSCI can occur with or without CSCS and cervical cord compression. The biomechanical etiology of traumatic CSCI without major fracture or dislocation remains under discussion, and its relationship with CSCS is one of the most controversial issues in the clinical management of traumatic CSCI.

The aims of the current study were to clarify the influence of spinal canal stenosis on neurological functional recovery after traumatic CSCI without major fracture or dislocation.

Materials and Methods

1. Study population

A total of 101 subjects with traumatic CSCI without major fracture or dislocation were treated conservatively in our facility from 2010 to 2013. All patients underwent functional plain radiographs including flexion and extension, computed tomography (CT), magnetic resonance imaging (MRI), and neurologic examination by a senior spine surgeon at the time of admission. All patients wore a Philadelphia collar for 4 weeks and started their rehabilitation from sitting exercise immediately without causing any discomfort if their general conditions were stable. Of these patients, 58 had the injury at C3–4 (57.4%); 1 at C2–3 (1.0%); 26 at C4–5 (25.7%); 12 at C5–6 (11.9%); and 4 at C6–7 (4.0%). In the study, we focused on the subjects with responsible injured segment at the C3–4 segment who were admitted to our facility within 48 hours following trauma and had evidence of cervical cord injury with cervical cord intensity change on T2-weighted MRI at the C3–4 segment. A total of 58 subjects (52 men, 6 women; average age, 63.8 years [range, 42–89 years]) were included in the study. Of the 58 patients, 34 showed central cord syndrome, 20 showed transverse, 2 showed anterior cord syndrome, and 2 showed Brown-Sequard syndrome. The average period of hospitalization was 258 days (range, 61 to 550). The neurologic status of the patients at the time of admission and discharge are summarized in Table 1. Patients with the following conditions were excluded from the study: multiple segmental cervical cord injury, cervical myelopathy before trauma, apparent herniated disc at the injured segment, severe instability on functional radiographs as defined by White et al. [15] (dynamic translation >3.5 mm or 11° greater angulation than that in the adjacent segment) or indication of spontaneous reduction of dislocation at C3–4 segment, or ankylosing spondylitis.

Institutional Review Board approval was granted and informed consent was obtained from all patients included in the study.

2. Measurement of sagittal diameter of the CSF column

We used a T2-weighted mid-sagittal MRI scan obtained at the time of admission to measure the sagittal diameters of the cerebrospinal fluid (CSF) column at the C3–4 intervertebral disc level and C3 pedicle level. The rate of spinal canal stenosis was calculated using the following equation: (A-B)/A×100 (Fig. 1).

3. Neurological status (ASIA motor score)

The American Spinal Injuries Association (ASIA) motor score (range, 0 to 100) was documented at the time of admission and discharge for each patient. Neurological recovery was evaluated as an improvement rate (%) calculated as (motor score at discharge–motor score at admission)/(100–motor score at admission)×100.

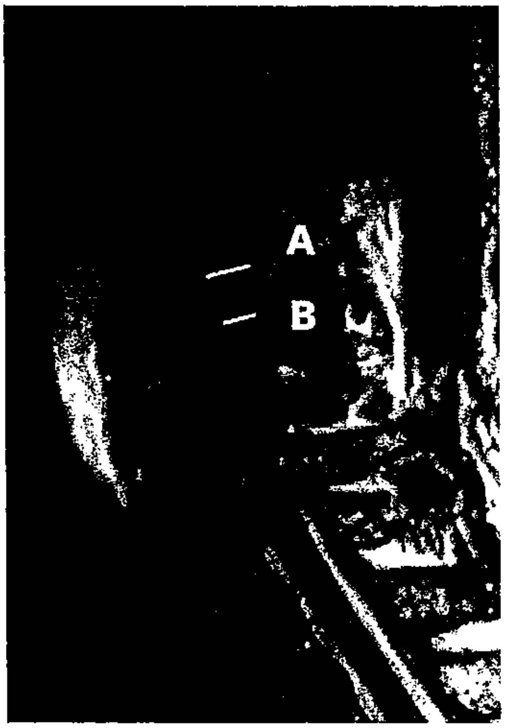

Fig. 1. T2-weighted midsagittal magnetic resonance imaging. A is the diameter of the cervical cord at the non-compression level and B is the diameter of the cervical cord at the injured level.

4. Statistical analysis

Statistical analysis was performed using the Spearman rank-correlation coefficient to evaluate the relationships between neurological status and CSCS. $p<0.05$ was considered statistically significant.

Results

The average value of the sagittal diameters of the CSF columns at the C3–4 intervertebral disc and C3 pedicle level was 6.5 mm and 8.9 mm, respectively. The average period of hospitalization was 258 days (range, 61 to 550 days). The average value of ASIA motor score at the time of admission and discharge was 28.5 and 67.7, respectively, and the improvement rate was 61.1%. The average value of the spinal canal stenosis ratio was 25.7%.

Fig. 2 shows the relationships between the sagittal diameter of the cervical CSF column at the C3–4 intervertebral disc level and ASIA motor score, which reflects neurological status at the time of admission and discharge. There were no significant relationships between the sagittal diameter of the cervical CSF column and ASIA motor scores both at the time of admission (p=0.773) and discharge (p=0.138) for the subjects with traumatic CSCI.

Fig. 3 shows the relationship between the sagittal diam-

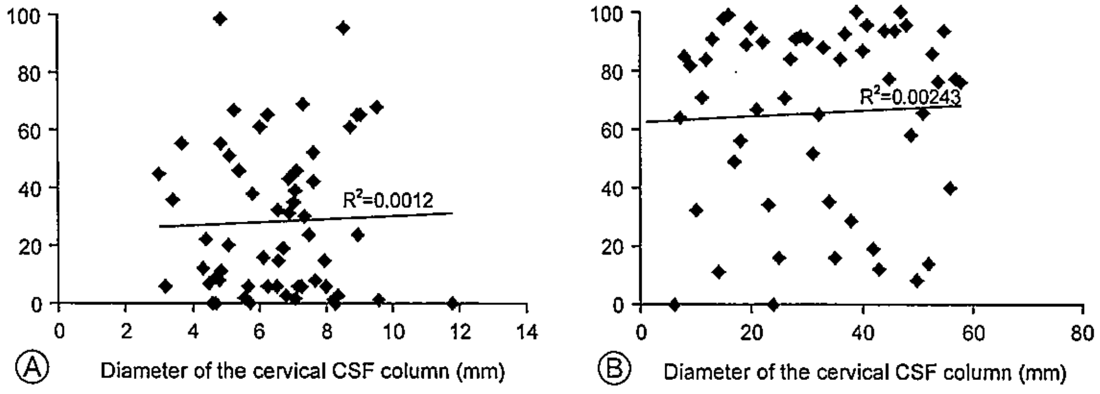

Fig. 2. The sagittal diameter of the cervical cerebrospinal fluid (CSF) column and American Spinal Injuries Association motor score (A) at admission and (B) at discharge.

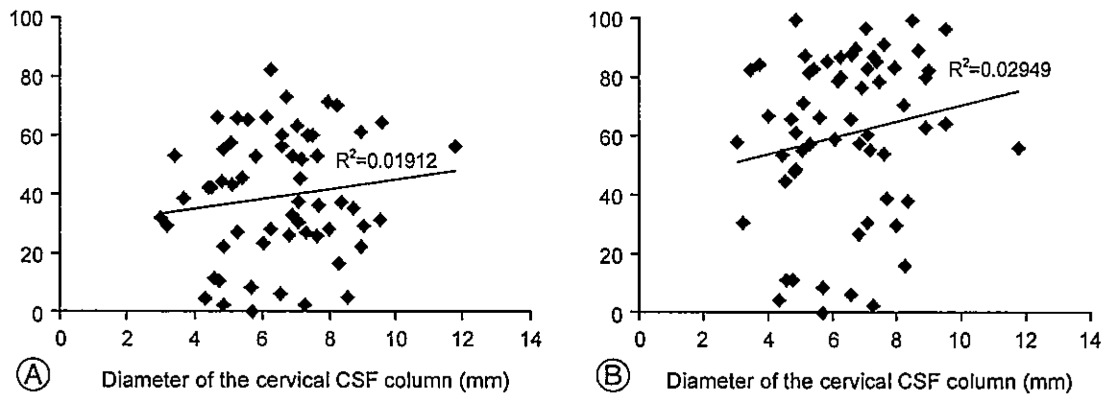

Fig. 3. Sagittal diameter of the cervical cerebrospinal fluid (CSF) column and the improvement rate according to the (**A**) subtraction score and (**B**) improvement rate (%).

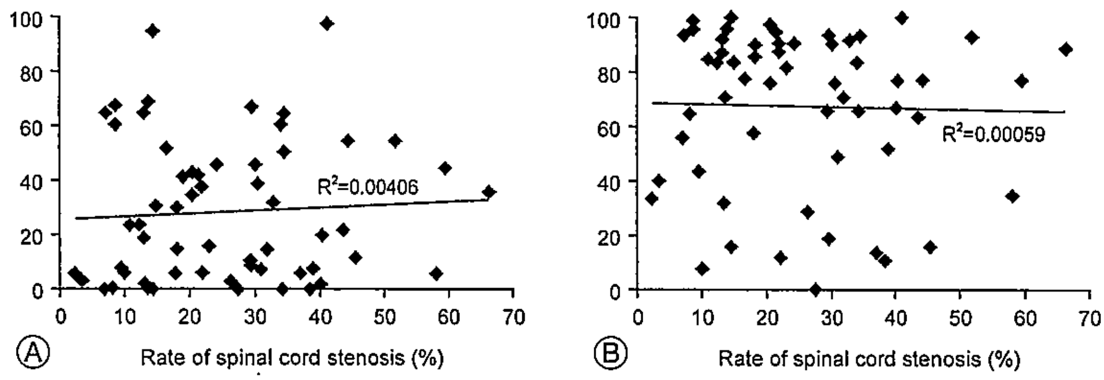

Fig. 4. The rate of spinal cord stenosis and American Spinal Injuries Association motor score (**A**) at admission and (**B**) at discharge.

eter of the cervical CSF column at the C3–4 intervertebral disc level and the improvement rate, which reflects neurological recovery at the time of discharge. We defined the subtraction score as (motor score on discharge)-(motor score on admission). There was no significant relationship between the sagittal diameter of the cervical CSF column and neurological recovery at the time of discharge (subtraction score; p=0.155, improvement rate; p=0.111).

Fig. 4 shows the relationships between the rate of spinal canal stenosis and ASIA motor scores. There were no significant relationships between the rate of spinal canal stenosis and ASIA motor scores both at the time of admission (p=0.897) and discharge (p=0.315).

Fig. 5 shows the relationship between the rate of spinal canal stenosis and improvement rate. There was also no significant relationship between the rate of spinal canal stenosis and neurological recovery at the time of discharge (subtraction score; p=0.441, improvement rate; p=0.277).

Discussion

The number of CSCI without major fracture or dislocation has been increasing as the population ages [16]. However, the clinical management of traumatic CSCI is contentious.

Some authors recommend surgery for patients with pre-existing canal stenosis, as persistent cord compression may hinder neurological improvement [17-19]. La Rosa et al. [17] reported that early decompression surgery within 24 hours after trauma had a significantly better outcome compared with late surgical management. Chen et al. [18] recommended surgical treatment to achieve rapid neurological recovery and shorter hospitalization despite the level of functional recovery in the surgical and conserva-

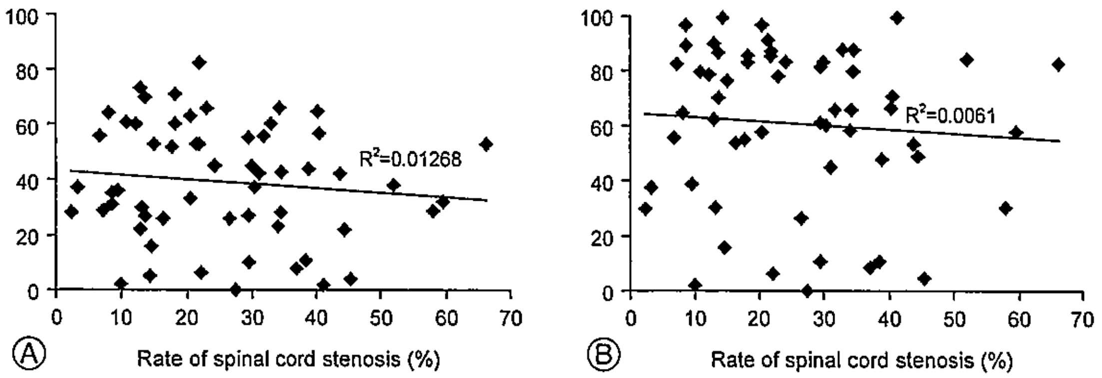

Fig. 5. The rate of spinal cord stenosis and the improvement rate according to the (A) subtraction score and (B) improvement rate (%).

tive treatment groups. Yamazaki et al. [19] reported that the canal diameter was a reliable predictor of recovery and recommended early decompression surgery. However, these studies were retrospective comparisons with small data sets and so likely had an inherent selection bias for surgical management.

In contrast, other researchers have reported no additional benefit with surgery compared to conservative treatment [20-22]. For example, Itoh et al. [20] reported no significant difference in neurological improvement between surgical and conservative management of CSCI without major bony injury; a higher frequency of postoperative complications was observed in subjects who were treated surgically. Kawano et al. [21] reported that surgical treatment was not superior to conservative treatment for CSCI without major bony injury with spinal cord compression in the acute phase. Although this study is not a comparison of conservative and operative treatment, our results propound prudence for surgical decompression until unequivocal evidence demonstrating improved neurological recovery or the prevention of delayed deterioration through surgery is presented.

In our facility, CSCI patients without major fracture or dislocation have consistently been treated conservatively and rehabilitated as early as possible, thus providing an appropriate study cohort to examine whether cervical canal stenosis is a risk factor for a deteriorative neurological course. We focused on the subjects with CSCI injured at C3–4 segment because of its high frequency (57.4%). Several studies have reported the frequent incidence of traumatic CSCI at the level of C3–4 segment. However, under the circumstances, this remains a matter of debate. In the study, there were no significant relationships between sagittal C3–4 cord diameters and ASIA motor scores both at the time of admission and discharge. Moreover, no significant relationship between CSCS and neurological recovery was seen in CSCI subjects. These results appear to be unreasonable, since pathophysiology is closely related with stenotic factors, especially in degenerative cervical myelopathy [23,24]. Yet, careful consideration of the mechanism of traumatic SCI could provide accountable interpretations. At the moment of traumatic injury, the unphysiological and instantaneous dynamic stenosis would most significantly affect the neurological outcomes [16]. In the present study, what we consider to be most important finding is that canal stenosis on radiographs is a different condition from the unphysiological stenosis at the moment of injury. For this reason, the neurological outcome varies greatly, even among patients with the same canal diameter. Our data are consistent with those of earlier studies that showed that motor deficit severity does not statistically correlate with spinal canal stenosis degree [16,25,26]. Our results suggest that decompression surgery might not be necessary for CSCI without major fracture or dislocation with asymptomatic pre-existing stenosis in the acute phase.

Nevertheless, some questions remain unanswered even after the current study and so this study can only serve as a pilot study for further research using larger populations, which may help resolve several issues not addressed in this study and further clarify the clinical management of traumatic CSCI without major fracture or dislocation.

Conclusions

Our results showed no relationships between pre-existing

CSCS and neurological outcomes after traumatic CSCI. These results suggested that decompression surgery might not be recommended for traumatic CSCI without major fracture or dislocation despite pre-existing CSCS.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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Clinical Study

"Knee-up test" for easy detection of postoperative motor deficits following spinal surgery

Itaru Yugué, MD, PhD[a,*], Seiji Okada, MD, PhD[b], Muneaki Masuda, MD[a], Takayoshi Ueta, MD, PhD[a], Takeshi Maeda, MD, PhD[a], Keiichiro Shiba, MD, PhD[a]

[a]*Department of Orthopedic Surgery, Spinal Injuries Center, 550-4 Igisu, Iizuka 820-8508, Fukuoka, Japan*
[b]*Department of Orthopedic Surgery, Kyushu University, 3-1-1 Maedashi, Higashi-ku 812-8582, Fukuoka, Japan*

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Abstract

BACKGROUND CONTEXT: Neurologic motor deficit is a serious complication of spinal surgery. Early diagnosis of complications by neurologic examination immediately after spinal surgery is mandatory. However, patients cannot always cooperate with the physician in the very early stages of recovery.
PURPOSE: The aim of the present study is to prospectively investigate the usefulness of the "knee-up test" for easy detection of postoperative motor deficits.
STUDY DESIGN: A prospective clinical study was carried out.
PATIENT SAMPLE: Patients with spinal disorder operated upon at a single institute were administered the knee-up test after an anesthesiologist had judged that endotracheal extubation was possible.
OUTCOME MEASURES: The outcome measures were preoperative and postoperative Manual Muscle Testing.
METHODS: A simple yet reliable method known as the "knee-up test" was developed to easily assess postoperative deficits before endotracheal extubation. When the patient's knee is passively lifted up and the patient is able to maintain this position in both legs, the result is negative, whereas when the patient is unable to maintain the knee in an upright position for one or both legs, the result is positive. The presently accepted criterion for a new-onset postoperative neurologic motor deficit is motor weakness leading to a decrease in function of at least two grades in more than one muscle function within 12 hours of spinal surgery, as evaluated by the Manual Muscle Testing. The association between the presence of new-onset motor deficits and the results of the knee-up test was prospectively investigated.
RESULTS: Seventeen patients exhibited positive results when evaluated using the knee-up test, whereas 521 patients exhibited negative results. Sixteen of the patients with positive results were determined to have new-onset motor deficits, whereas no new-onset motor deficits were observed in the remaining patient. Of the 521 patients with negative knee-up test results, only 2 were determined to have new-onset motor deficits, whereas no new-onset motor deficits were observed in the remaining 519 patients. The sensitivity, specificity, positive predictive value, and negative predictive value were 88.9, 99.8, 94.1, and 99.6, respectively.
CONCLUSIONS: The knee-up test may allow for early and easy detection of postoperative motor deficits with high probability in very early stages.

Keywords: Clinical evaluation; Diagnosis method; Neurologic deficits; Postoperative complication; Spinal Injures Center test; Spinal surgery

FDA device/drug status: Not applicable.

Author disclosures: *IY:* Nothing to disclose. *SO:* Nothing to disclose. *MM:* Nothing to disclose. *TU:* Nothing to disclose. *TM:* Nothing to disclose. *KS:* Nothing to disclose.

Itaru Yugué had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis as well as the decision to submit for publication.

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1529-9430/

Conflict of interest and sources of funding: None declared.

The study was approved by the local ethics committee.

* Corresponding author. Department of Orthopaedic Surgery, Spinal Injuries Center, 550-4 Igisu Iizuka 820-8508, Fukuoka, Japan. Tel.: 81-948-24-7500; fax: 81-948-29-1065.

E-mail address: iyugue@orange.ocn.ne.jp (I. Yugué)

Introduction

Neurologic complications immediately after spinal surgery present a serious problem for both patients and spinal surgeons [1]. Previous studies have reported that the incidence of significant perioperative spinal cord or cauda equina injury ranges from approximately 0% to 15% but is usually less than 2% [2–19]. Early diagnosis of neurologic complications immediately after spinal surgery is very important for preventing the development of permanent neurologic deficits; surgeons must promptly investigate the etiologies of complications with imaging methods such as magnetic resonance imaging (MRI) and computed tomography (CT) scans [12,20] to determine whether re-operation is required [2]. However, just after operation, patients cannot always cooperate with physicians in undergoing a neurologic examination, especially before airway extubation.

In a previous study, the present authors developed a simple and reliable test for hysterical paralysis known as the Spinal Injuries Center (SIC) test [21]. This test showed that patients with severe organic paralysis were unable to keep the knee in a lifted position. Notably, the greatest merit of the test lies in not requiring the patient's cooperation. The purpose of the present study is to prospectively investigate the usefulness of the knee-up test for easy identification of postoperative motor deficits in the very early stages of recovery using a modified version of the Spinal Injuries Center test (ie, the knee-up test) to assess potential deficits following spinal surgery.

EVIDENCE & METHODS

Context

Postoperative motor deficits can portend serious complications and adversely impact outcomes following surgery. Early and effective detection are of paramount importance to maximize the potential for intervention and reversal. However, patients are not always able to participate in examination during the immediate postsurgical period. To address this concern, the authors describe a novel and simple "knee-up test" for detection of postoperative motor deficits.

Contribution

The authors evaluated 537 patients at a single center using this postsurgical test. The sensitivity, specificity, positive predictive value and negative predictive value were determined to be 88.9, 99.8, 94.1, and 99.6, respectively.

Implications

The authors' study provides metrics for a useful postoperative test that may be applied to the clinical setting. Given that this study was conducted in the center where the test was devised, there may be differences in its performance in the hands of other practitioners. As the authors recognize, the number of postsurgical defects was small and the sample may be clinically heterogeneous. As a result, the accuracy of this test has not been completely described and remains to be determined through further study. In light of this fact, the current study presents Level II evidence.

—*The Editors*

Materials and methods

Study sample

The present study enrolled 544 consecutive patients with spinal disorder who had been operated upon by a single surgeon (IY) in the same institution between May 1, 2006 and May 31, 2015. The knee-up test was administered to patients after an anesthesiologist had determined that endotracheal extubation was possible. Informed consent was obtained from all patients before enrollment in the study, and the study was approved by our local ethics committee. A precondition to performing the "knee-up test" is that the knee can be lifted up preoperatively on both sides; patients whose knees could not be lifted preoperatively because of severe motor deficits in the lower extremity were excluded from the study. However, patients who could not bend the knee more than 100 degrees because of hip- or knee-joint osteoarthritis (OA) were not excluded from this study. Six of the 544 patients were excluded because of preoperative inability to sustain the lifted position as a result of severe paralysis. The remaining 538 patients (324 men, 214 women) were selected for inclusion in the final sample (Fig. 1). The mean patient age was 63.9 years (range 16–89 years). The operated spinal region was broadly categorized as cervical (145 patients), thoracic (38 patients), or lumbar or sacral (355 patients). The preoperative disease process was broadly categorized as degenerative, traumatic, neoplastic, infectious, or other (Fig. 2).

Experimental test procedure

The knee-up test is performed as follows. The patient is placed on a bed in the supine position, and the surgeon flexes the patient's hip to near 90 degrees while the knee is maximally flexed with the foot of the flexed leg on the table. The surgeon then gradually releases without any intention of keeping the knee in its lifted position (Fig. 3A and B). When the patient is unable to maintain one or both knees in an upright position, then the result is considered positive (Fig. 3C). When the patient is able to maintain both knees in the upright position, then the result is considered negative (Fig. 3D). In the present study, this test was performed twice, once by each of two independent observers (IY and MM) who were blinded to the results obtained by the other observer. When the results obtained by two observers disagreed, the result was classified as negative. It is better to examine the right and left sides separately with this test because administering this test to both legs at the same time risks twisting the waist (Fig. 3E). The

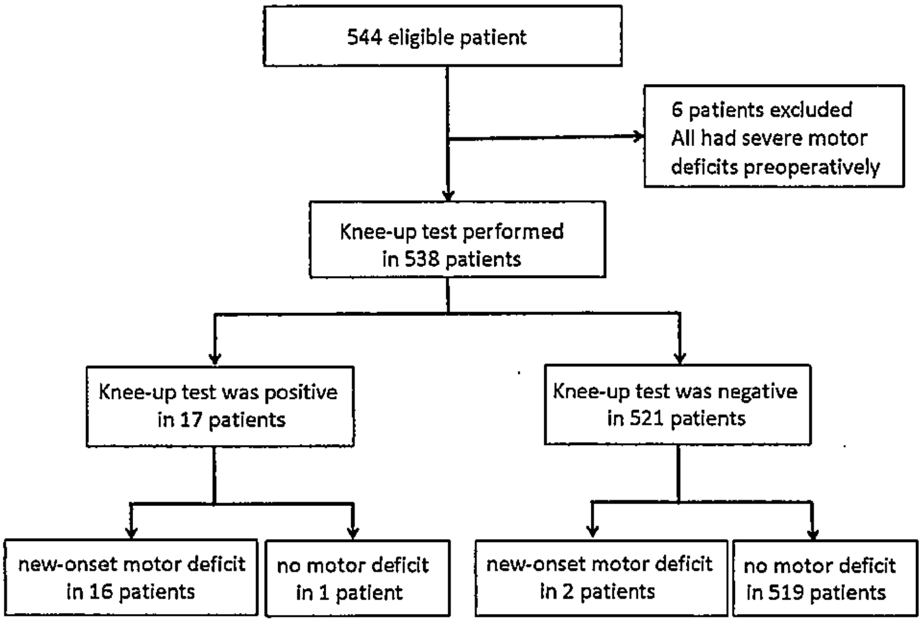

Fig. 1. Flow chart of the study.

knee-up test is performed just before the time of endotracheal extubation, which is determined by an expert anesthesiologist. The criteria for extubation are that the patient can maintain a patent airway and generate adequate spontaneous ventilation. Generally, this requires the patient to possess adequate level of the following: central inspiratory drive, cough strength to clear secretions, laryngeal function, consciousness (awake and oriented), stability of hemodynamic function, clearance of sedative and neuromuscular blocking effects, and respiratory muscle strength. The latter is defined as respiratory rate <35 breaths per minute during spontaneous breathing, vital capacity >10 mL/kg of ideal body weight, and spontaneous exhaled minute ventilation <10 L/min [22].

The muscle function test procedure

Preoperative and postoperative Manual Muscle Testing was performed by the attending surgeon, who was blinded to the results of the knee-up test. The functional strength of each muscle was graded on a six-point scale as follows: 0=total paralysis; 1=palpable or visible contraction; 2=active movement with full range of motion (ROM), provided that gravity is eliminated; 3=active movement with full ROM against gravity; 4=active movement with full ROM against moderate resistance; and 5=(normal) active movement with full ROM against gravity and sufficient resistance [23]. For patients with cervical-region disease, the following muscles were exam-

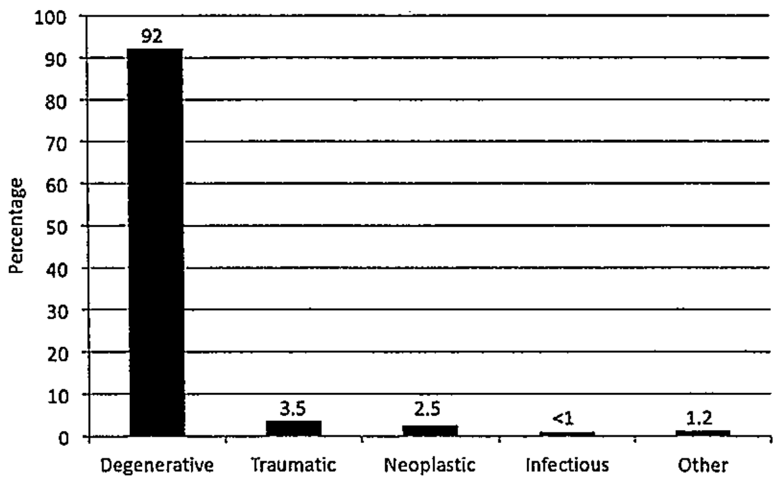

Fig. 2. Bar graph showing distribution of preoperative disease processes for spinal operations. Numbers above the bars indicate the percentage of 544 patients undergoing spinal operations.

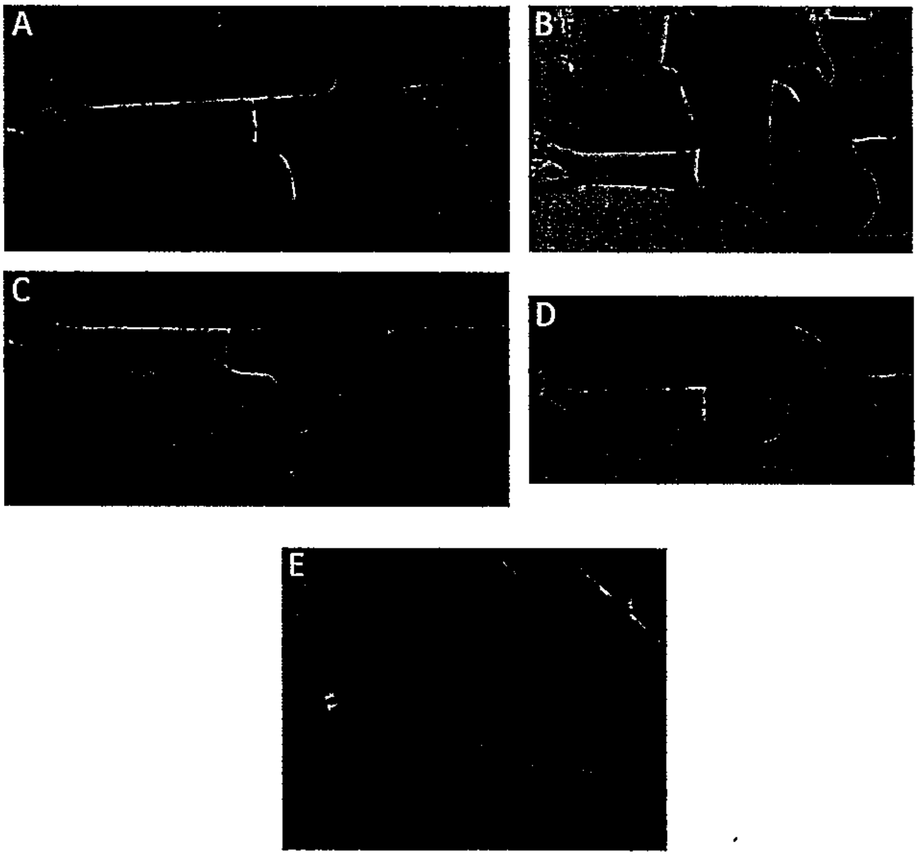

Fig. 3. (A) The "knee-up test" placing the patient in a supine position. (B) The patient's knee is raised passively on the bed. Then, the knee is released gently. A key point of this test is to lift the knee until it is in maximally flexed. (C) When the patient is unable to maintain the knee upright, the knee-up test is positive. Usually, the positive patient's leg comes to rest with the hip joint in an externally rotated position and the knee joint in a slightly extended position. (D) When the patient is able to maintain the knee upright in both sides, the knee-up test is negative. (E) Applying the knee-up test to both legs at the same time for a bilaterally positive patient may risk twisting the waist.

ined bilaterally and graded using the aforementioned scale: shoulder abductors, elbow flexors, wrist extensors, finger flexors, small-finger abductors, hip flexors, hip adductors, hip abductors, knee extensors, ankle dorsiflexors, long-toe extensors, and ankle plantar flexors. For patients with thoracic or lumbar or sacral-region disease, the following muscles were examined bilaterally and graded as above: hip flexors, hip adductors, hip abductors, knee extensors, ankle dorsiflexors, long-toe extensors, and ankle plantar flexors. The Manual Muscle Testing criteria for new-onset neurologic motor deficit after spinal surgery consisted of motor weakness leading to a decrease in score of at least two points compared with the preoperative score in more than one muscle within 12 hours after spinal surgery.

Methods of statistical comparison

The association between the presence of a new-onset motor deficit and the results of the knee-up test was investigated. We used Fisher exact test for categorical comparisons of the data and a logistic regression analysis to calculate both the odds ratio and the 95% confidence interval. The sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) were also calculated. The kappa statistic was used to assess the inter-observer agreement on the knee-up test. Statistical analyses were performed using the JMP 11 statistical software package (SAS Institute Inc, Cary, NC, USA). A value of $p<.05$ was considered to be statistically significant.

Results

Seventeen patients exhibited positive results when evaluated using the knee-up test, whereas 521 patients exhibited negative results. Sixteen of the patients with positive results were determined to have new-onset motor deficits, whereas no new-onset motor deficits were observed in the remaining patient. Of the 521 patients with negative knee-up test results, only 2 were determined to have new-onset motor deficits, whereas no new-onset motor deficits were observed in the remaining 519 patients (Fisher exact $p<.0001$; odds ratio, 4152; 95% confidence interval, 357.8–48185.4) (Table 1). The sensitivity, specificity, PPV, and NPV of this test for all cases were 88.89,

Table 1
Relationship between the presence of postoperative new onset motor deficit and knee-up test findings

The presence of postoperative new onset motor deficit			
	Yes	No	Total
Knee-up test positive	16 patients	1 patient	17 patients
Knee-up test negative	2 patients	519 patients	521 patients
Total	18 patients	520 patients	538 patients

Fisher exact p<.0001; odds ratio, 4152; 95% confidence interval, 357.8–48185.4. The sensitivity, specificity, positive predictive value, and negative predictive value of this test were 88.89, 99.81, 94.12, and 99.62, respectively.

99.81, 94.12, and 99.62, respectively. The kappa coefficient for the knee-up test between observers was 0.91 (p<.0001).

Of the 18 patients with new-onset motor deficits, 16 exhibited positive knee-up test results (Table 2). Interestingly, patients whose lesions were below the L3–L4 level exhibited positive knee-up test results when hip abductor function had decreased by two points or fewer. However, two patients with normal hip abductor function exhibited negative knee-up test results.

Patients with positive knee-up test results underwent detailed neurologic examination immediately following extubation, and MRI and CT scans were performed if deemed necessary. The causative factors leading to the motor deficits were as follows: damage caused by intraoperative manipulation of neural tissue in 11 cases, epidural hematoma in 3 cases, insufficient decompression in 2 cases, bony fragment in 1 case, and unknown cause in 1 case. All case of epidural hematoma and one of insufficient decompression required immediate re-operation, following which neurologic deteriorations fully recovered.

One patient with intramedullary thoracic spinal cord tumor exhibited a false-positive result on the knee-up test. This patient had completely lost position sensation after tumor resection but had no postoperative motor weakness.

Discussion

Many patients with new-onset major neurologic deficit require further surgical procedures [2,3,5–7,11,12]. Early diagnosis of such deficits following spinal surgery may allow enough time for MRI and CT evaluation and prompt decisions regarding re-operation [5,9].

The use of electrophysiological monitoring for neurologic safety during spinal surgery has become widespread. Efficacy requires multimodal monitoring, associating somatosensory evoked potentials to motor potentials evoked by transcranial stimulation [8,17,24]. Despite the usefulness of multimodal monitoring, it is not applied to all cases of spinal surgery. Hamilton et al. [18] reported that neuromonitoring was used in 65% of 108,419 operative cases from 2004 to 2007. However, the sensitivity and PPV for neuromonitoring with regard to new-onset neurologic complication were surprisingly low (sensitivity, 0.43; PPV, 0.21).

In any case, neurologic examination upon awakening is mandatory for detecting new-onset neurologic motor deficit. However, some patients may not be able to cooperate with the physician in performing the neurologic examination because of age, language barriers, or mental status [17]. The absence of deep tendon reflexes secondary to spinal shock provides good indication for the onset of new motor deficits. However, 46% (n=247) of the 538 patients included in the present study exhibited preoperative areflexia, so evaluation of postoperative areflexia is not always useful for detecting new-onset motor deficits. Moreover, three patients with incomplete spinal cord damage exhibited no signs of areflexia.

What are the key muscles for keeping the knee in its lifted position? We re-analyzed the 96 legs of the 48 patients reported in our previous article confirmed to have myelomalacia [21]. All legs were evaluated on their ability to maintain the knee in an upright position, and the relationship of this result with the strength of each leg muscle was analyzed using a multiple logistic regression model. According to these results, hip flexors, hip adductors, and hip abductors were the statistically significant muscles for keeping the knee in its lifted position (Table 3). Anatomically, the hip flexors are innervated by the L1–L4 nerve roots, whereas the hip adductors are innervated by the L2–L4 nerve roots, and the hip abductors are innervated by the L4–S2 nerve roots [25], indicating that results of the knee-up test may be influenced by dysfunction of nerve roots L1–S2. Because of the aforementioned anatomical features, it may be possible to identify severe new-onset motor deficits below the level of L3–L4. However, when the patient had motor weakness in muscles unrelated to these hip functions, the knee-up test could not detect new-onset motor deficit. This is a limitation of the knee-up test. A second limitation is that patients with severe joint OA who cannot lift the knee into an upright position will seem to have difficulty maintaining the knee-up position. Disagreement over the results occurred in two patients with severe knee OA; thus, it is necessary to evaluate the results of the test carefully. A third limitation is that the knee-up test is not applicable to patients with severe paralysis who are unable to preoperatively lift both knees—a precondition for performing the knee-up test.

Although the knee-up test presents an easy method for detecting new-onset postoperative motor deficits without the patient's cooperation, the exact time frame for performing the test is of little importance. Garreau de Loubresse [24] emphasizes the importance of repetition of the neurologic examination by a co-medical care staff who should be alerted in case of any change in motor parameters. For the co-medical staff, the knee-up test upon awakening is not only very easy to perform without the patient's cooperation but is also easy to evaluate.

There are several possible limitations associated with this study. First, the sample size was relatively small. Second, the knee-up test was performed at a single institution. Finally, despite the fact that this test was performed

Table 2
Details of new-onset motor deficits observed in study participants

Case	Preoperative diagnosis	Operation	Knee-up test	Motor deficits	Cause of deficits	Progress of case
1	Intradural-extramedullary spinal tumor	Extirpation of tumor at T2–T4	Left side positive	Left HAB decreased from 5 to 2, ADF from 5 to 3, LE from 5 to 3, and AF from 5 to 4.	Damage caused by intraoperative manipulation of neural tissue (tumor resection)	Re-operation was not required. Leg motor function fully improved within 2 mo of operation.
2	Intradural-extramedullary spinal tumor	Extirpation of tumor at T4–T7	Left side positive	Left HAB decreased from 4 to 2, ADF from 5 to 3, and LE from 5 to 4.	Damage caused by intraoperative manipulation of neural tissue (tumor resection)	Re-operation was not required. Leg motor function fully improved within 1 y of operation.
3	Intradural-extramedullary spinal tumor	Extirpation of tumor at T9–T12	Right side positive	Right HAB decreased from 4 to 2 and KE from 5 to 3.	Damage caused by intraoperative manipulation of neural tissue (tumor resection)	Re-operation was not required. Leg motor function fully improved within 1 y of operation.
4	Intramedullary spinal tumor	Extirpation of tumor at C1–C2	Right side positive	Right FF decreased from 4 to 3, SFA from 3 to 2, HAB from 4 to 2, ADF from 4 to 2, and LE from 4 to 2.	Damage caused by intraoperative manipulation of neural tissue (tumor resection)	Re-operation was not required. Leg motor function fully improved and upper limb function partially improved within 1 y of operation.
5	Intramedullary spinal tumor	Extirpation of tumor at C4–C5	Right side positive	Right EF decreased from 5 to 4, WE from 5 to 2, EE from 5 to 2, FF from 5 to 3, SFA from 4 to 2, HF from 5 to 3, HAD from 5 to 3, HAB from 5 to 2, ADF from 5 to 3, LE from 5 to 3, and AF from 5 to 3.	Damage caused by intraoperative manipulation of neural tissue (tumor resection)	Re-operation was not required. All motor function except FF and SFA fully improved within 1 y of operation.
6	Intramedullary spinal tumor	Extirpation of tumor at C3–C4	Both sides positive	AIS deteriorated from D to B.	Damage caused by intraoperative manipulation of neural tissue (tumor resection)	Re-operation was not required. AIS improved from B to D within 1 y of operation.
7	OPLL	Posterior decompression and fusion at T9–T11	Both sides positive	AIS deteriorated from D to C.	Damage caused by intraoperative manipulation of neural tissue (ossification resection)	Re-operation was not required. Leg motor function fully improved within 1 y of operation.
8	OPLL	Posterior decompression and fusion at T7–T9	Both sides positive	AIS deteriorated from D to B.	Damage caused by intraoperative manipulation of neural tissue (ossification resection)	Re-operation was not required. AIS improved from B to C within 1 y of operation
9	OPLL	Laminoplasty at C3–C7	Negative	Both EE decreased from 4 to 2.	Unknown (probably root tethering)	Re-operation was not required. Both EE improved from 2 to 3 within 1 y of operation.
10	Arachnoid cyst	Removal of cyst at T5–T11	Left side positive	Left HAB decreased from 4 to 2, ADF from 5 to 3, and AF from 5 to 3.	Damage caused by intraoperative manipulation of neural tissue (cyst resection)	Re-operation was not required. Left HAB improved from 2 to 5, AF from 3 to 5 within 1 y of operation.
11	Lumbar disc herniation	Discectomy at L3–L4	Left side positive	Left HAB decreased from 5 to 2 and ADF from 4 to 2.	Damage caused by intraoperative manipulation of neural tissue (nerve root neurolysis)	Re-operation was not required. Left HAB improved from 2 to 5, ADF from 2 to 3 within 1 y of operation.
12	Lumbar degenerative spondylolisthesis	Posterior decompression and fusion at L4–L5	Negative	Left ADF decreased from 5 to 4 and LE from 5 to 3.	Damage caused by intraoperative manipulation of neural tissue (nerve root neurolysis)	Re-operation was not required. Leg motor function fully improved within 8 mo of operation.

(Continued)

Table 2
(Continued)

Case	Preoperative diagnosis	Operation	Knee-up test	Motor deficits	Cause of deficits	Progress of case
13	Osteoporotic burst fracture	Posterior fixation at T11–L1 with vertebroplasty at T12	Right side positive	Right HAB decreased from 4 to 2, KE from 5 to 4, and AF from 4 to 3.	Leaked bony fragment from posterior vertebral wall.	Motor weakness gradually improved day by day so re-operation was not required. Right HAB improved from 2 to 4, KE from 4 to 5, and AF from 3 to 5 within 6 mo of operation.
14	Lumbar canal stenosis	Laminectomy at L3–L5	Both sides positive	Both of HAB decreased from 4 to 2, right ADF from 5 to 4, left ADF from 5 to 1, right LE from 5 to 3, left LE from 5 to 1, and right AF from 5 to 4.	Insufficient decompression and possible operative manipulation (dural tear)	Dural tear was sutured in the 1st operation; however, cauda equina syndrome developed. Patient received rehabilitation, but the paralysis gradually progressed. Myelography showed complete block at L2–L3. Posterior decompression and fusion was performed 1 mo later; however, patient had no improvement.
15	Vertebral fracture with OLF at T9–T10	Posterior fixation at T1–L5	Both sides positive	AIS deteriorated from D to B.	OLF (insufficient decompression)	Myelography showed complete block at T9–T10 after 1st operation. Laminectomy was performed and 1 y later, AIS improved from B to D.
16	OLF	Laminectomy at T1–T2	Both sides positive	AIS deteriorated from D to C.	Epidural hematoma	MRI showed epidural hematoma. Re-operation was performed and motor weakness fully improved within 2 d.
17	Idiopathic epidural hematoma	Removal of hematoma at C3–T1	Both sides positive	AIS deteriorated from D to C.	Epidural hematoma	MRI showed epidural hematoma. Re-operation was performed and motor weakness fully improved the next day.
18	Lumbar degenerative spondylolisthesis	Posterior decompression and fusion at L4–L5	Right side positive	Right HAB decreased from 5 to 2, ADF from 4 to 3, and LE from 3 to 0.	Epidural hematoma	MRI showed epidural hematoma. Re-operation was performed and motor weakness fully improved within 3 mo of operation.

SA, shoulder abductors; EF, elbow flexors; WE, wrist extensors; EE, elbow extensors; FF, finger flexors; SFA, small-finger abductors; HF, hip flexors, HAD, hip adductors; HAB, hip abductors; KE, knee extensors; ADF, ankle dorsiflexors; LE, long-toe extensors; AF, ankle plantar flexors; AIS, ASIA Impairment Scale; OLF, ossification of the ligamentum flavum; OPLL, ossification of posterior longitudinal ligament.

Table 3
Multiple logistic regression by combined muscle functions for keeping the knee in its lifted position in organic paralysis patients

Combined muscl e functions	p	Odds ratio	95% Confidence interval
Hip flexors	0.0359*	28.4	1.18–162506
Hip adductors	0.0168*	375.4	1.75–37852
Hip abductors	0.0424*	43.2	1.08–11666191
Knee extensors	0.6078	0.53	0.001–4.98
Ankle dorsiflexors	0.3550	0.36	0.0009–2.56
Ankle plantar flexors	0.1383	0.01	0.0001–2.06

* p<.005.

after an anesthesiologist had judged that endotracheal extubation was possible, peripheral nerve stimulators with train-of-four ratio were not routinely used for confirmation of complete disappearance of neuromuscular block at the time of examination. Despite these limitations, we have established that the knee-up test is very easy to perform and can alert the surgeon or physician to the outbreak of postoperative motor deficits with high statistical power at very early stages. In addition, this test is useful for evaluating patients with impaired hearing or advanced age, who may find it difficult to voluntarily coordinate their movements with instructions from the physician.

In conclusion, the sensitivity, specificity, PPV, and NPV of the knee-up test were 88.89, 99.81, 94.12, and 99.62, respectively. When patients cannot maintain the knee in a lifted-up position upon awakening, the surgeon must correct their neurologic condition after the operation. On the other hand, when patients can maintain the knee-up position, in over 99% of cases, they have no severe motor deficit.

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Morphologic Evaluation of Lumbosacral Nerve Roots in the Vertebral Foramen

Measurement of Local Pressure of the Intervertebral Foramen

Yuichiro Morishita, MD, PhD, Muneaki Masuda, MD, Takeshi Maeda, MD, PhD, Takayoshi Ueta, MD, PhD, and Keiichiro Shiba, MD, PhD

Study Design: The prospective cohort study.

Objective of the Study: The objective was to evaluate the relationships between local pressure changes of the intervertebral foramen during lumbar spine extension and lumbar foraminal morphology.

Summary of Background Data: The physiological states of lumbosacral nerve roots in the vertebral foramen remain controversial.

Methods: We evaluated 56 lumbosacral vertebral foramens in 21 patients with L4-degenerative spondylolisthesis. All patients underwent L4-5 posterolateral fusion (PLF). The local pressure of the intervertebral foramen was measured intraoperatively, and measurement was performed before and after L4-5 PLF. We defined the changes in the ratio of local pressure between lumbar flexion to extension as percent pressure. The sagittal angular motion, distance between the inferior cortex of the cranial pedicle and superior cortex of the caudal pedicle, posterosuperior margin of the superior vertebral body and superior articular facet, posteroinferior edge of the superior vertebral body and inferior articular facet, and the intervertebral disc height were measured using preoperative functional plain radiographs and CT images.

Results: The average local pressure of the intervertebral foramen significantly increased during lumbar extension. However, the L4-5 vertebral foraminal pressure after PLF were nearly identical. There was no significant correlation between percent pressure and lumbar range of motion. Furthermore, there were no significant correlations between percent pressure and each morphologic parameter of the lumbar foramen.

Conclusions: There were no significant relationships between the lumbar foraminal morphology and intervertebral foraminal pressure changes during lumbar extension, and L4-5 vertebral foraminal pressure was not affected by the lumbar posture after L4-5 posterior fusion. On the basis of the results, the external dynamic stresses on the nerve roots in the vertebral foramen might be improved by lumbar posterior fusion using instrumentation without direct decompression of the vertebral foramen.

Key Words: local pressure of the intervertebral foramen, percent pressure, morphology of lumbar foramen, lumbar range of motion, intervertebral disc height, posterolateral fusion, lumbosacral nerve root, L4-degenerative spondylolisthesis, vertebral foramen, foraminal stenosis

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The anatomic boundaries of the intervertebral foramen consist of the adjacent vertebral pedicles superiorly and inferiorly, posteroinferior margin of the superior vertebral body, the intervertebral disc, the posterosuperior vertebral notch of the inferior vertebral body anteriorly, and the ligamentum flavum and superior and inferior articular facets posteriorly.[1] In addition, transforaminal or intraforaminal ligaments are present in the inferior aspect of the foramen.[2,3] The geometry of the lumbar foramen has been described as an oval, round, or inverted teardrop-shaped window in the lateral aspect of the lumbar spine.[4]

The lumbosacral nerve roots traverse through the lateral canal after originating from the thecal sac. The existing nerve root and dorsal root ganglion (DRG), often located in the superior and anterior region of the foramen or subpedicular notch, are surrounded by fat and radicular vessels. The location of the DRG can vary; it can be intraforaminal or intraspinal in the lumbosacral spine.[5,6] The S1 DRG, found in a more cephalad or intraspinal location, is larger than the lumbar DRG. The L4 and L5 DRG are more commonly located intraforaminally.[5,6] The spatial relation of the DRG in the lumbar foramen is a clinically important concept to understand because of its association with lumbar symptomatology.

There are numerous studies regarding the anatomic or morphologic evaluation of the lumbar foramen. However, to the best of our knowledge, the physiological state of lumbosacral nerve roots in the vertebral foramen has been described in only a few reports. We previously

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From the Department of Orthopedic Surgery, Spinal Injuries Center, Iizuka, Japan.
The authors declare no conflict of interest.
Reprints: Yuichiro Morishita, MD, PhD, 550-4, Igisu, Iizuka 820-0053, Japan (e-mail: uchiro1968@mac.com).

reported that the local pressure of the intervertebral foramen significantly increased during lumbar spine extension.[7–9] Furthermore, the electrophysiological values of the L5 nerve roots, as evaluated from the compound muscle activation potentials from the tibialis anterior muscle after L5 nerve root stimulation, deteriorated with the increasing local pressure of the L5-S intervertebral foramen.[8,9] The local pressure of the intervertebral foramen reflected the electrophysiological values of the spinal nerve roots in the vertebral foramen. The objective of this current study was to determine the relationships between local pressure changes of the intervertebral foramen during lumbar spine extension and lumbar foraminal morphology.

MATERIALS AND METHODS

Measurement of the Local Pressure of the Intervertebral Foramen[7–9]

A total of 21 L4-degenerative spondylolisthesis patients with lumbar spinal canal stenosis at the L4-5 and/or L3-4 segments (8 men and 13 women; average age, 66.0 y; age range, 47–79 y) were included in the study. The following subjects were excluded from the study: patients diagnosed as having isthmic spondylolisthesis, obvious foraminal stenosis on magnetic resonance imaging or responsible lesion in the intravertebral or extravertebral foramen, or Meyerding[10] grade of degenerative spondylolisthesis > II. Fifty-six lumbosacral vertebral foramens, including 26 L4-5 and 30 L5-S vertebral foramens, were finally evaluated.

All patients underwent L4-5 and/or L3-4 bilateral laminotomy with L4-5 posterolateral fusion (PLF) using instrumentation. The operation was performed with the patients under general anesthesia and placed in the prone position with both hip joints in flexion.

A micro-tip 5F flexible catheter transducer (MPC-500, Millar Instruments Inc., TX) was used as a pressure transducer. Before measuring the pressure, the tip of the catheter transducer was placed in saline at a constant temperature of 37°C for 30 minutes. Zero balancing of the transducer was performed after a few minutes after temperature equilibrium was reached. Before recording, the output signals of the pressure measurement equipment were calibrated.

Intraoperatively, after L4-5 and/or L3-4 bilateral laminotomy, the pedicle screws were inserted into L4 and L5 pedicles bilaterally. For the subjects treated with laminotomy at both L4-5 and L3-4 segments, the L4-5 and L5-S vertebral foraminal pressures were measured. Although for the subjects treated with laminotomy at only L4-5 segment, the L5-S vertebral foraminal pressure was measured. The catheter transducer was inserted from the decompressed segments (L3-4 or L4-5) into the caudal vertebral foramen (L4-5 or L5-S1), and the tip of the catheter transducer was placed just below the pedicle in the vertebral foramen (pedicle zone in the vertebral foramen) dorsal to the spinal nerve root. The local pressure was continuously measured while the lumbar spine

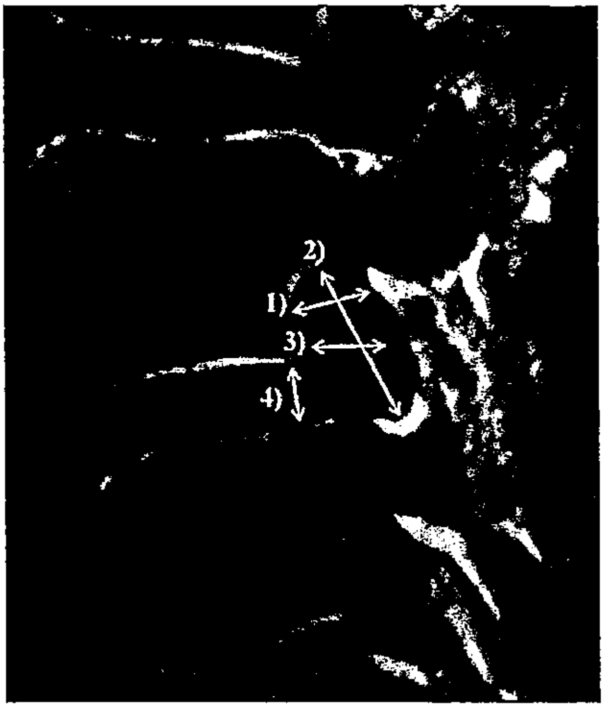

FIGURE 1. The vertical and sagittal dimensions of the lumbar foramen. (1) The distance between inferior cortex of the cranial pedicle and superior cortex of the caudal pedicle. (2) The distance between posterior margin of the superior vertebral body and superior articular facet. (3) The distance between posterior edge of the superior vertebral body and inferior articular facet. (4) The distance between posterior margins of the disc height.

postures were changed. Two different postures, include lumbar spine flexion and extension, were studied, and each posture was maintained for 10 seconds. The measurements were performed before and after L4-5 internal fixation. The pressure levels showed a waveform with respiratory pulsation and we estimated the average values to be the intermediate value of the wave. The changes in the ratio of the local pressure of the intervertebral foramen between lumbar spine flexion and extension was calculated as a percent pressure (%) = {(local pressure with extension − local pressure with neutral)/(local pressure with neutral)} × 100.

Institutional Review Board approval was granted and informed consent was obtained from all patients.

TABLE 1. The Average Values of Local Pressure of L4-5 Vertebral Foramen

	Neutral		Extension	% Pressure
Before fixation	33.82 ± 15.85	***	56.07 ± 23	79.66 ± 69.18 ***
After fixation	40.37 ± 19.21	NS	42.32 ± 18.72	7.07 ± 10.2

NS indicates not significant.
***$P < 0.001$.

TABLE 2. The Average Values of Local Pressure of L5-S Vertebral Foramen

	Neutral		Extension	% Pressure
Before fixation	25.41 ± 17.8	***	49.73 ± 28.05	138.05 ± 159.34
				NS
After fixation	25.07 ± 16.83	***	54.96 ± 34.24	153.82 ± 205.5

NS indicates not significant.
***$P < 0.001$.

Lumbar Spine Range of Motion (ROM)

Using functional plain radiographs in the sagittal plane, the sagittal angular motion from lumbar spine flexion to extension was measured with the Cobb technique (angle between superior and inferior vertebral endplate) at the L4-5 or L5-S segment.

Morphometric Measurement of the Lumbar Foramen

The vertical and sagittal dimensions of the lumbar foramen were measured with the preoperative parasagittal CT images at the middle of the pedicle. We conducted the following 4 measurement: the distance between the (1) inferior cortex of the cranial pedicle and superior cortex of the caudal pedicle, (2) posterosuperior margin of the superior vertebral body and superior articular facet, and (3) posteroinferior edge of the superior vertebral body and inferior articular facet; and the (4) intervertebral disc height at the posterior margin of the disc height (Fig. 1).

Statistical Analysis

The Mann-Whitney U test and Pearson correlation coefficient were used for statistical analyses. A P-value of <0.05 was considered statistically significant.

RESULTS

Local Pressure of the Intervertebral Foramen

The average local pressures of the intervertebral foramen (n = 56; including 26 L4-5 and 30 L5-S foramens) with lumbar spine flexion and extension before L4-5 PLF were 29.31 ± 17.3 mm Hg and 53.68 ± 25.8 mm Hg, respectively. The average local pressure significantly increased during lumbar spine extension ($P < 0.001$). The percent pressure was 110.94% ± 128.16%.

The average local pressures of the intervertebral foramen at the L4-5 segment are shown in Table 1. The local pressures of the intervertebral foramen significantly increased during lumbar spine extension before L4-5 PLF, but were nearly identical after PLF. The percent pressure before and after L4-5 PLF was significantly different.

The average local pressures of the intervertebral foramen at the L5-S segment are shown in Table 2. The local pressures of the intervertebral foramen, both before and after L4-5 PLF, significantly increased during lumbar spine extension. The percent pressure was not significantly different between before and after L4-5 PLF; however, the percent pressure after PLF tended to be higher than that obtained before PLF.

Lumbar Spine ROM

The average value of the sagittal angular motion from lumbar spine flexion to extension was 5.17 ± 4.11 degrees. There was no significant correlation between the percent pressure and lumbar ROM ($P = 0.42$, $r = 0.11$; Fig. 2).

Morphometric Analysis of the Lumbar Foramen

The average distance between the inferior cortex of the cranial pedicle and superior cortex of the caudal

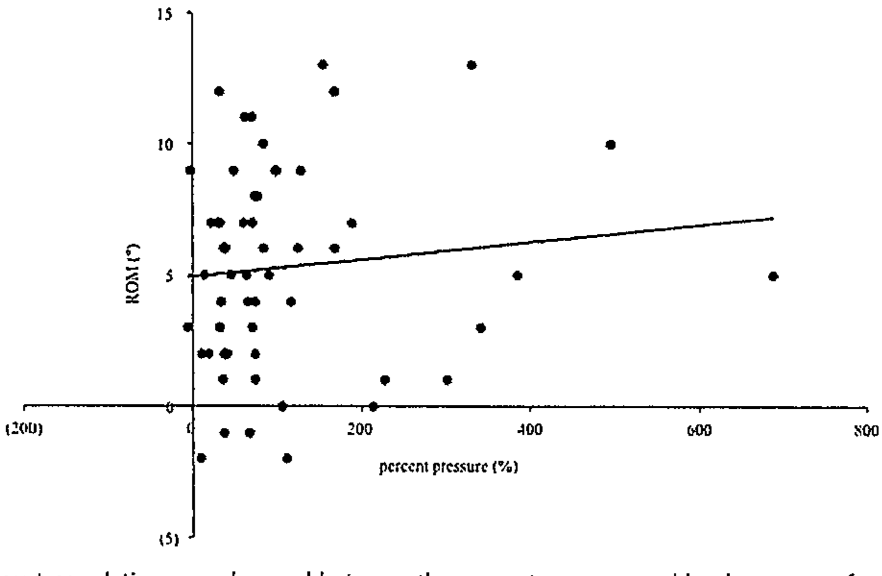

FIGURE 2. No significant correlation was observed between the percent pressure and lumbar range of motion. full color online

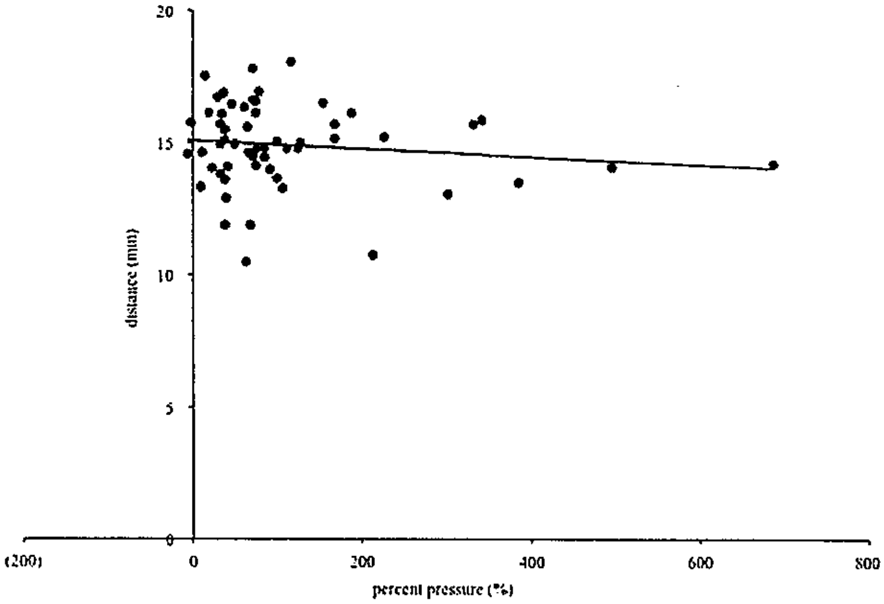

FIGURE 3. No significant correlation was observed between the percent pressure and the distance between inferior cortex of the cranial pedicle and superior cortex of the caudal pedicle. full color online

pedicle, posterosuperior margin of the superior vertebral body and superior articular facet, and posteroinferior edge of the superior vertebral body and inferior articular facet were 8.62 ± 1.89, 14.91 ± 1.59, and 7.98 ± 2.86 mm, respectively. The average value of intervertebral disc height was 3.84 ± 1.49 mm. There were no significant correlations between the percent pressure and each morphologic parameter of the lumbar foraminen ($P = 0.2$, $r = -0.17$; $P = 0.36$, $r = -0.13$; $P = 0.14$, $r = -0.2$; $P = 0.24$, $r = -0.16$; respectively; Figs. 3–6).

DISCUSSION

The foraminal height and width varies from 15.9 to 18.0 mm and from 5.0 to 7.2 mm, respectively,[11] and the

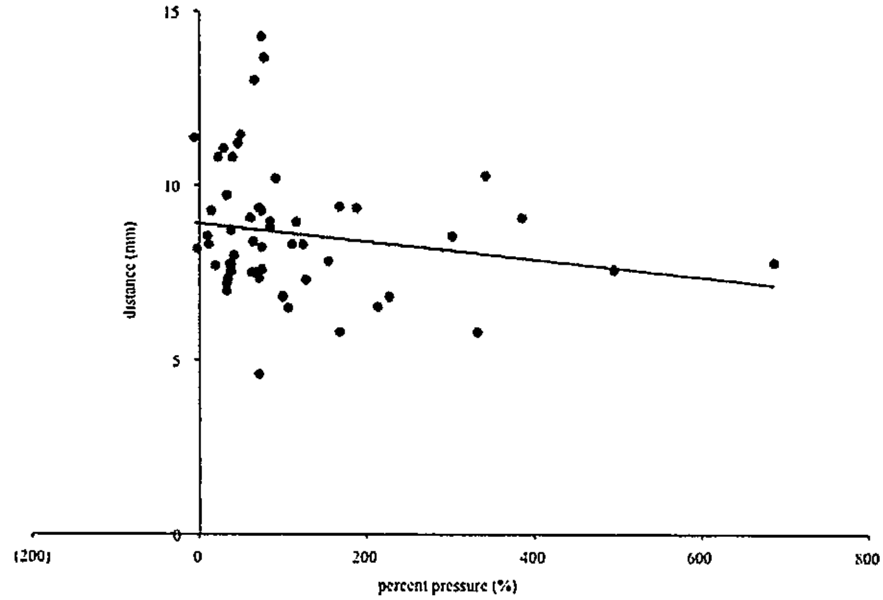

FIGURE 4. No significant correlation was observed between the percent pressure and the distance between posterior margin of the superior vertebral body and superior articular facet. full color online

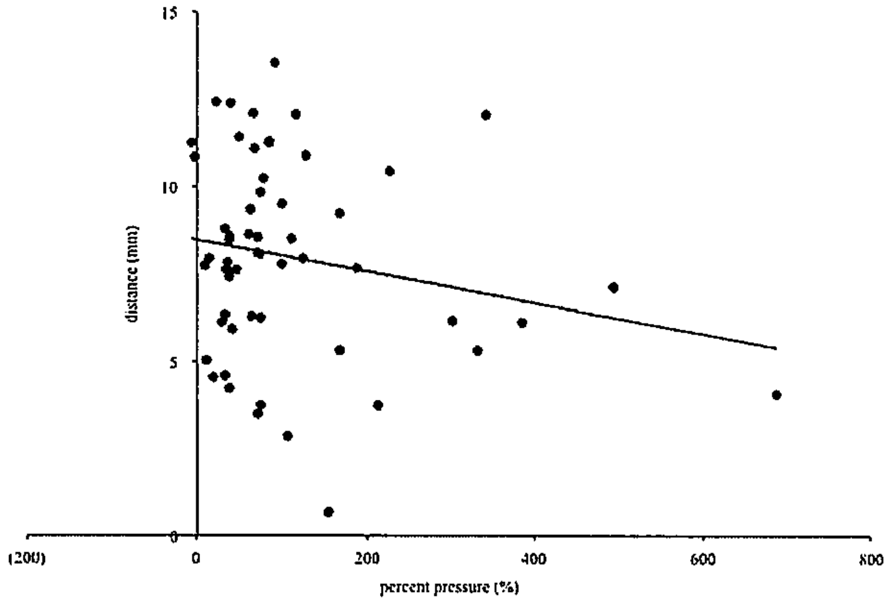

FIGURE 5. No significant correlation was observed between the percent pressure and the distance between posterior edge of the superior vertebral body and inferior articular facet. full color online

cross-sectional area vary from 40 to 160 mm^2.[4] The development of foraminal stenosis is related to the process of lumbar spondylosis. Hasegawa et al[12] reported that critical dimensions of foraminal stenosis are 4 mm or less for the posterior disc height and 15 mm or less for the foraminal height. However, in our results, posterior disc height was 3.84 ± 1.49 mm and foraminal height (distance between the inferior cortex of the cranial pedicle and superior cortex of the caudal pedicle) was 8.62 ± 1.89 mm; none of the subjects showed obvious foraminal stenosis on the images or responsible lesion in the intravertebral or extravertebral foramen. We presume that the bony foraminal stenosis on the images may not directly reflect the clinical symptomatology.

Mayoux-Benhamou et al[13] reported that all diameters of the lumbar vertebral foramens decreased as the spine moved from flexion to extension. Inufusa et al[14] also showed that the cross-sectional area of the vertebral foramen increased by 12% during flexion and decreased by 15% during extension. The lumbosacral nerve roots

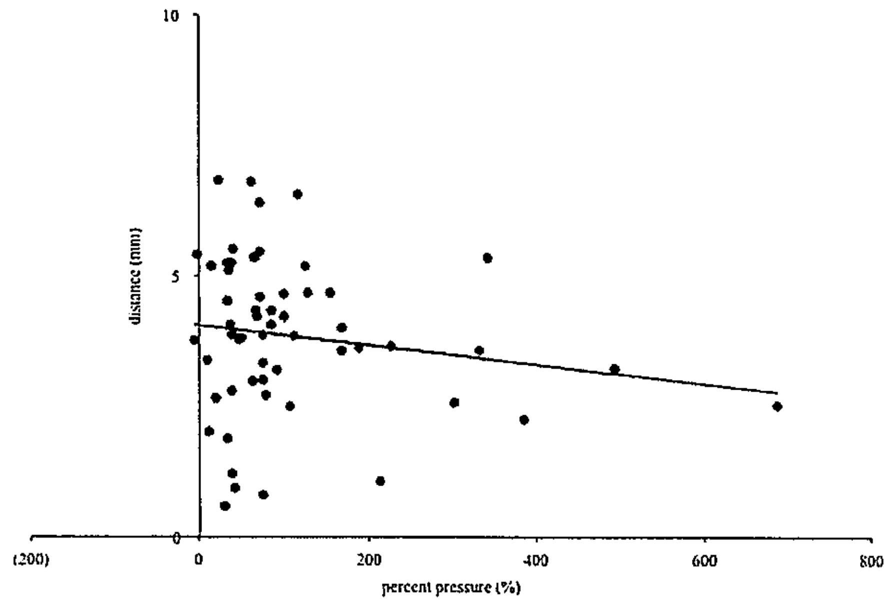

FIGURE 6. No significant correlation was observed between the percent pressure and the disc height. full color online

normally occupy ~30% of the available foraminal area.[15] According to our findings, the local pressure of the intervertebral foramen significantly increased during lumbar spine extension. Moreover, the local pressure of the intervertebral foramen reflected the electrophysiological values of the spinal nerve roots in the vertebral foramen in our previous published study.[8,9] According to these results, the spatial volume of the spinal nerve root in the vertebral foramen may increase relatively to the decreasing the capacity of the vertebral foramen during lumbar spine extension, and the external dynamic stresses on the spinal nerve root in the vertebral foramen may increase during lumbar spine extension.

The genesis of neurological intermittent claudication in lumbar spinal canal stenosis might be greatly affected by dynamic changes in the local pressure of the intervertebral foramen due to lumbar motion, rather than the static local pressure with each lumbar posture.[9] According to the current results, there were no significant relationships between the morphology of lumbar foramen and local pressure changes of the intervertebral foramen between lumbar spine flexion and extension, and the L4-5 vertebral foraminal pressure was not affected by the lumbar posture after L4-5 posterior fusion. Although the lumbar interbody fusion (posterior or transforaminal) may have advantages in postoperative bony union or certain decompression, abundant intraoperative or postoperative hemorrhage and postoperative infection may be suspected due to curettage of the intervertebral discs and insert the foreign substance in the intervertebral disc space. On the basis of the results, the external dynamic stresses on the nerve roots in the vertebral foramen might be improved by lumbar posterior fusion using instrumentation without direct decompression of the vertebral foramen.

Some issues remain unaddressed in the current study. Subjects with obvious foraminal stenosis based on the images or clinical symptoms were not discussed in the study. Therefore, the current investigation can be considered as a pilot study, and further research using a larger patient population may help to resolve several unclear issues in this study. Moreover, the physiological states of the pathologic condition of the lumbosacral nerve roots in the vertebral foramen should be clarified in more detail.

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Kinematic Effects of Cervical Laminoplasty for Cervical Spondylotic Myelopathy on the Occipitoatlantoaxial Junction

Asuka Desroches, MD, Yuichiro Morishita, MD, PhD,† Itaru Yugue, MD, PhD,† Takeshi Maeda, MD, PhD,† Charles-Henri Flouzat-Lachaniette, MD,* Philippe Hernigou, MD, PhD,* and Keiichiro Shiba, MD, PhD†*

Study Design: A retrospective evaluation of sagittal angular motion from cervical spinal flexion to extension.

Objective: To evaluate the kinematic effects of cervical laminoplasty for cervical spondylotic myelopathy (CSM) on the occipitoatlantoaxial junction.

Summary of Background Data: The kinematic effects of cervical laminoplasty for CSM on the occipitoatlantoaxial junction remain controversial.

Methods: A total of 65 CSM patients who were treated with cervical laminoplasty ranging from the C3 to C7 vertebrae were included in the study. After surgery, all patients wore a Philadelphia collar for the first week and began cervical range of motion exercises as soon as possible. Functional plain radiographs were obtained preoperatively and at 1 and 3 years postoperatively. Sagittal angular motion from cervical spinal flexion to extension was measured using the Cobb technique at 7 cervical segments (Oc–C1, C1–C2, C2–C3, C3–C4, C4–C5, C5–C6, and C6–C7). We defined the contribution of each segment's mobility to the total angular mobility of the cervical spine as percent segmental mobility.

Results: Total cervical angular mobility significantly decreased after cervical laminoplasty. There were no significant differences in Oc–C2 angular mobility; however, C2–C7 angular mobility had significantly decreased by 3 years postoperatively. No significant differences in percent segmental mobility were observed at 1 year postoperatively except at the C3–C4 segment. By 3 years postoperatively, percent mobility at the Oc–C1 and C1–C2 segments had significantly increased, whereas that at the C3–C4 and C5–C6 segments had significantly decreased.

Conclusions: Our results suggest that, although the contribution of occipitoatlantoaxial junctional mobility to total cervical mobility increases, dynamic mechanical stress to the occipitoatlantoaxial junction does not increase following laminoplasty, and no adjacent segmental disorder at the occipitoatlantoaxial junction was observed within 3 years postoperatively. We hypothesized that early removal of the cervical collar and early cervical range of motion exercises may contribute to these kinematic changes.

Key Words: cervical spondylotic myelopathy, cervical laminoplasty, cervical spine, occipitoatlantoaxial junction, sagittal angular motion, percent segmental mobility, functional plain radiographs, kinematic evaluation, Oc–C2, C2–C7

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Cervical spondylotic myelopathy (CSM) is the development of long-tract signs secondary to degenerative changes in the cervical spinal column. CSM is the most common cause of myelopathy in patients older than 50 years of age. A careful evaluation of the patient's history and physical examination allow early diagnosis and treatment and can prevent neurological deterioration, leading to optimal clinical outcomes.

There are many surgical procedures for addressing multilevel cervical compressive myelopathy. Posterior cervical decompression with laminectomy effectively decompresses the spinal cord in patients with multilevel spondylosis, ossification of the posterior longitudinal ligament, or developmental canal stenosis. However, complications of laminectomy, including postoperative segmental instability, progressive kyphotic deformity, formation of a postlaminectomy membrane, perineural adhesions, and late neurological deterioration have been identified.[1–6] Cervical laminoplasty is considered to be an alternative to laminectomy and is intended to decompress the spinal cord while preserving the posterior elements of the vertebra.

Numerous experimental studies have reported the kinematic effects of cervical laminoplasty.[4,7–13] However, to the best of our knowledge, few reports have thus far referred to the kinematic effects of cervical laminoplasty on the occipitoatlantoaxial junction. In the current study, we evaluated the kinematic changes in cervical mobility

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From the *Department of Orthopedic Surgery, Paris East University, Henri Mondor Hospital, Créteil, France; and †Department of Orthopedic Surgery, Spinal Injuries Center, Iizuka, Japan.
The authors declare no conflict of interest.
Reprints: Yuichiro Morishita, MD, PhD, Department of Orthopedic Surgery, Spinal Injuries Center, 550-4, Igisu, Iizuka 820-0053, Japan (e-mail: uchiro1968@mac.com).

following cervical laminoplasty at 1 and 3 years postoperatively. The purpose of this retrospective clinical study was to elucidate the kinematic effects of cervical laminoplasty on the occipitoatlantoaxial junction.

MATERIALS AND METHODS

Study Population

From January 2007 to December 2011, a total of 394 patients with CSM (266 males and 128 females) with an average age of 76.0 years (range, 34–89 y) underwent surgical posterior decompression by senior spine surgeons. All patients showed cervical cord intramedullary intensity changes on magnetic resonance T2-weighted images and demonstrated long-tract signs, such as finger fine motion disturbance, gait disturbance, and hyperreflexia of the deep tendons in the lower limbs. Exclusion criteria included the following: continuous ossification of the posterior longitudinal ligament at multiple segments, history of rheumatoid arthritis or cerebral palsy, and history of cervical surgery before or after the cervical laminoplasty. After exclusion, 65 patients (47 males and 18 females) with an average age of 69.2 years (range, 38–89 y) who were treated by means of cervical laminoplasty ranging from the C3 to the C7 vertebrae (including C7 dome osteotomy) were included in this study and were radiologically followed for 3 years postoperatively.

The study was approved by our Institutional Review Board, and informed consent was obtained from all patients.

Surgical Treatment: Cervical Laminoplasty and Postoperative Therapy

All patients underwent French-door cervical laminoplasty at the C3–C7 level.[14] The semispinalis cervicis muscles were preserved without detachment from the axis. A threadwire saw was used to perform the sagittal split in the spinous process, and hydroxyapatite blocks were placed as struts to maintain the patency of the hinged hemilaminae (Fig. 1).[15]

After surgery, all patients wore a Philadelphia collar for 1 week. Cervical range of motion (ROM) exercises were performed immediately after collar removal without causing any discomfort.

Measurement of Cervical Kinematics

For all patients, functional plain sagittal radiographs were obtained preoperatively and at 1 and 3 years postoperatively. Sagittal angular motion from cervical spinal flexion to extension was measured with the Cobb technique for each segment at 7 cervical segments: Oc–C1, the angle between the line from the basion to the opisthion (Oc) and the line from the anterior to the posterior tubercle of the inferior margin of C1 (C1); C1–C2, the angle between C1 and the inferior C2 endplate; and C2–C3, C3–C4, C4–C5, C5–C6, and C6–C7, the angle between the inferior vertebral endplate of the superior vertebral body and the superior vertebral endplate of the inferior vertebral body (Fig. 2). We defined the total sagittal motion of the cervical spine as the absolute total of the individual sagittal angular motions (Oc–C1 + C1–C2 + C2–C3 + C3–C4 + C4–C5 + C5–C6 + C6–C7) in degrees, and the contribution of each segment's mobility to the total angular mobility of the cervical spine was defined as the percent segmental mobility (%) [(sagittal angular motion of each segment in degrees)/(total sagittal angular motion in degrees) × 100].

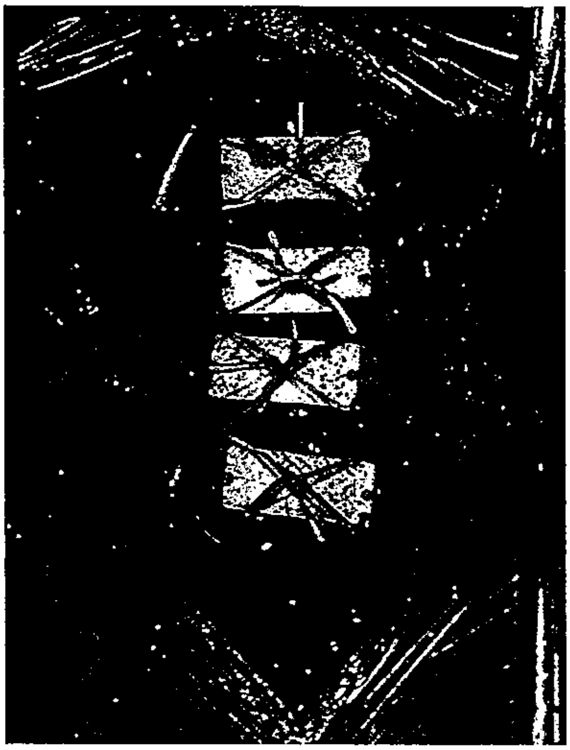

FIGURE 1. French-door cervical laminoplasty at C3–C6 and C7 dome osteotomy. The hydroxyapatite blocks were placed as a strut to maintain the patency of the hinged hemilaminae.

Statistical Analysis

The Mann-Whitney *U* test was used for all statistical analyses. A *P*-value of <0.05 was considered statistically significant.

RESULTS

Table 1 shows the mean total (Oc–C7), Oc–C2, and C2–C7 cervical angular mobility preoperatively and at 1 and 3 years postoperatively. The total cervical angular mobility significantly decreased after cervical laminoplasty. With respect to Oc–C2 angular mobility, there were no significant differences at 3 years postoperatively. In contrast, with respect to C2–C7 angular mobility, significant decreases were seen at 3 years postoperatively.

Table 2 shows the mean percent segmental mobility for each segment preoperatively and at 1 and 3 years postoperatively. There were no significant differences between preoperative values and those observed 1 year

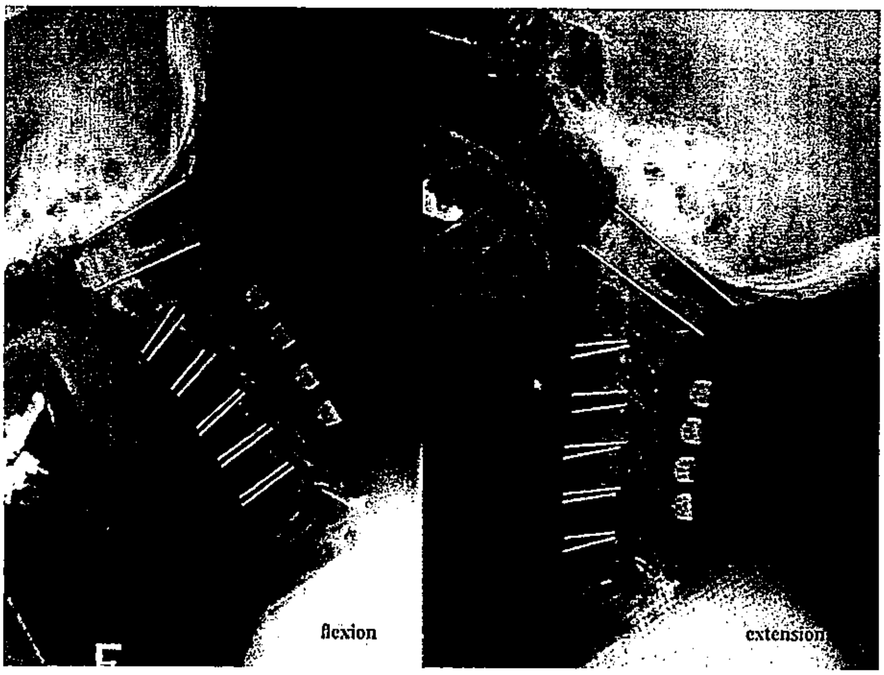

FIGURE 2. The sagittal angular motion through cervical spine flexion to extension was measured with the Cobb technique for each segment at seven cervical segments.

postoperatively, except for percent mobility at the C3–C4 segment. In a comparison of preoperative values and those at 3 years postoperatively, percent mobility at the Oc–C1 and C1–C2 segments significantly increased, whereas percent mobility at the C3–C4 and C5–C6 segments significantly decreased.

DISCUSSION

Cervical laminoplasty has been widely performed with good results in patients with multilevel cervical myeloradiculopathy.[7,16–18] Cervical laminoplasty ideally avoids postoperative instability or the need for fusion at multiple levels. Commonly used types of laminoplasty include the expansive open-door technique,[19,20] in which the arch is opened on one side and hinged on the contralateral side, and the French-door technique,[14] in which the laminae are opened in the midline and bilaterally hinged.

Several studies have described a reduction of cervical (C2–C7) sagittal mobility after cervical laminoplasty.[7–9,11] Loss of lordosis occurs after laminoplasty in 10%–50% of patients, and cervical ROM usually continues to diminish up to 18 months postoperatively.[21] Some authors have reported a relationship between cervical ROM and cervical posterior deep nuchal muscle atrophy after laminoplasty.[22–24] Fujishima and Nishi[22] reported that the volume of postoperative posterior deep nuchal muscle decreased to ≤60% of the preoperative muscle volume evaluated with computed tomography. Seichi et al[7] and Chiba et al[8] reported that the patients wore a cervical collar for 8–20 weeks after surgery, and postoperative cervical mobility at C2–C7 after laminoplasty was restricted to 22%–32% of preoperative cervical mobility. We believe that there is no absolute necessity of postoperative external fixation after cervical laminoplasty. We used cervical collar mainly for the

TABLE 1. The Average Values of Cervical Angular Mobility at Preoperatively, 1 Year, and 3 Years Postoperatively

	Angular Mobility (deg.)		
	Total	Oc–C2	C2–C7
Preoperative†	49.75 ± 10.57*	19.85 ± 7.05 (NS)	31.19 ± 9.84*
Postoperative 1 y‡	45.43 ± 11.5**	19.66 ± 7.25 (NS)	25.49 ± 10.09***
Postoperative 3 y	44.08 ± 12.17	21.37 ± 6.73	22.62 ± 11.26

The Mann-Whitney *U* test.
*$P < 0.05$.
**$P < 0.01$.
***$P < 0.001$.
†Compared with preoperative and postoperative 1 year.
‡Compared with preoperative and postoperative 3 years.

TABLE 2. The Average Values of Percent Segmental Mobility at Preoperatively, 1 Year, and 3 years Postoperatively

	Percent Segmental Mobility (%)						
	%Oc–C1	%C1–C2	%C2–C3	%C3–C4	%C4–C5	%C5–C6	%C6–C7
Preoperative†	22.46 ± 12.21 (NS)	17.5 ± 8.8 (NS)	10.77 ± 6.23 (NS)	14.99 ± 6.82*	11.67 ± 6.86 (NS)	12.23 ± 7.31 (NS)	10.38 ± 8.63 (NS)
Postoperative 1 y‡	24.4 ± 13.11**	19.65 ± 10.59*	10.05 ± 7.52 (NS)	12.08 ± 8.47***	13.43 ± 8.2 (NS)	10.08 ± 7.34**	10.31 ± 8.81 (NS)
Postoperative 3 y	28.74 ± 12.44	21.86 ± 10.25	11.07 ± 7.95	10.58 ± 8.01	10.19 ± 7.72	9.06 ± 7.95	8.5 ± 8.56

The Mann-Whitney *U* test.
*$P < 0.05$.
**$P < 0.01$.
***$P < 0.001$.
†Compared with preoperative and postoperative 1 year.
‡Compared with preoperative and postoperative 3 years.

management of postoperative neck pain for 1 week after surgery. In our study, the C2–C7 sagittal angular mobility significantly decreased within 3 years postoperatively; however, > 70% of the preoperative cervical mobility was preserved during the first 3 years postoperatively, and most patients did not complain of a limitation in activities of daily living accompanying reduced cervical mobility. We presume that early removal of the cervical collar and early cervical ROM exercises prevented contraction of the facet joint and postoperative atrophy and dysfunction of the extensor musculature of the cervical spine.

With respect to postoperative Oc–C2 mobility, Chiba et al[8] reported that the average sagittal mobility slightly increased from 22 to 28 degrees in patients with CSM. They discussed that the severe reduction (32%) of C2–C7 sagittal mobility due to laminar fusions were compensated to some degree by the increase in sagittal mobility of the upper cervical spine, resulting in only minor disturbances in activities of daily living. Hayashi et al[25] demonstrated that the Oc–C1 segment of the upper cervical spine plays an important role in compensating for decreased sagittal subaxial cervical spinal motion. In our study, preoperative Oc–C2 angular mobility was 19.85 degrees, which remained almost identical over the first 3 years postoperatively. We hypothesized that due to the relatively preserved C2–C7 sagittal mobility, compensatory mobility changes may not have occurred at the upper cervical spine.

The cervical angular mobility for each segment is unreliable for evaluating a patient's cervical kinematics because these values depend on the patient's condition, that is, axial pain, or a radiologist. Therefore, we believe that the contribution of each cervical segment's mobility to the total mobility of the cervical spine is the most reliable method for evaluating the patient's cervical kinematics. In our results, only percent segmental mobility at the C3–C4 segment significantly decreased during the first postoperative year. Cervical kinematics were not affected by cervical laminoplasty at 1 year postoperatively. However, at 3 years postoperatively, percent segmental mobility at the C3–C4 and C5–C6 segments had significantly decreased, and that at the Oc–C1 and C1–C2 segments had significantly increased. Therefore, there may be no compensatory mobility changes but rather compensatory kinematic changes that occur at the occipitoatlantoaxial junction. Our results suggest that although the contribution of occipitoatlantoaxial junctional mobility to total cervical mobility increases, dynamic mechanical stresses to the occipitoatlantoaxial junction do not increase, and no adjacent segmental disorder at the occipitoatlantoaxial junction was observed within 3 years postoperatively. We hypothesized that early removal of the cervical collar and early cervical ROM exercise may have contributed to these kinematic changes.

Certain issues remain unaddressed in the current study. Our study only addressed the radiographic factors during a mid-term postoperative period and did not address clinical symptoms. Therefore, using the current investigation as a pilot study, further research using a larger patient population and longer-term follow-up may resolve several remaining unclear issues. Moreover, the kinematic effects of cervical laminoplasty on the occipitoatlantoaxial junction need to be clarified in greater detail.

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RESEARCH ARTICLE

Experimental Mouse Model of Lumbar Ligamentum Flavum Hypertrophy

Takeyuki Saito[1,2], Kazuya Yokota[3], Kazu Kobayakawa[2], Masamitsu Hara[1,2], Kensuke Kubota[3], Katsumi Harimaya[2], Kenichi Kawaguchi[2], Mitsumasa Hayashida[2], Yoshihiro Matsumoto[2], Toshio Doi[4], Keiichiro Shiba[3], Yasuharu Nakashima[2], Seiji Okada[1,2¤]*

1 Department of Advanced Medical Initiatives, Graduate School of Medical Sciences, Kyushu University, Fukuoka, Japan, 2 Department of Orthopaedic Surgery, Graduate School of Medical Sciences, Kyushu University, Fukuoka, Japan, 3 Department of Orthopaedic Surgery, Spinal Injuries Center, Fukuoka, Japan, 4 Department of Orthopaedic Surgery, Kyushu University Beppu Hospital, Oita, Japan

¤ Current address: Departments of Advanced Medical Initiatives and Orthopaedic Surgery, Graduate School of Medical Sciences, Kyushu University, Maidashi, Higashi-ku, Fukuoka, Japan
* seokada@ortho.med.kyushu-u.ac.jp

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Abstract

Lumbar spinal canal stenosis (LSCS) is one of the most common spinal disorders in elderly people, with the number of LSCS patients increasing due to the aging of the population. The ligamentum flavum (LF) is a spinal ligament located in the interior of the vertebral canal, and hypertrophy of the LF, which causes the direct compression of the nerve roots and/or cauda equine, is a major cause of LSCS. Although there have been previous studies on LF hypertrophy, its pathomechanism remains unclear. The purpose of this study is to establish a relevant mouse model of LF hypertrophy and to examine disease-related factors. First, we focused on mechanical stress and developed a loading device for applying consecutive mechanical flexion-extension stress to the mouse LF. After 12 weeks of mechanical stress loading, we found that the LF thickness in the stress group was significantly increased in comparison to the control group. In addition, there were significant increases in the area of collagen fibers, the number of LF cells, and the gene expression of several fibrosis-related factors. However, in this mecnanical stress model, there was no macrophage infiltration, angiogenesis, or increase in the expression of transforming growth factor-β1 (TGF-β1), which are characteristic features of LF hypertrophy in LSCS patients. We therefore examined the influence of infiltrating macrophages on LF hypertrophy. After inducing macrophage infiltration by micro-injury to the mouse LF, we found excessive collagen synthesis in the injured site with the increased TGF-β1 expression at 2 weeks after injury, and further confirmed LF hypertrophy at 6 weeks after injury. Our findings demonstrate that mechanical stress is a causative factor for LF hypertrophy and strongly suggest the importance of macrophage infiltration in the progression of LF hypertrophy via the stimulation of collagen production.

Introduction

Lumbar spinal canal stenosis (LSCS) is a common spinal disorder in elder people. There are approximately 250,000 to 500,000 LSCS patients in the United States, with the number increasing due to the aging of the population [1]. LSCS causes lower back pain, leg pain, and claudication, leading to severe disability in the activities of daily living [2]. These symptoms primarily result from the hypertrophy of the ligamentum flavum (LF). The LF is a spinal ligament that covers most of the posterior and lateral parts of the spinal canal. Thus, hypertrophy of LF directly compresses the nerve roots and/or cauda equine, resulting in spinal disorders [3]. Although there have been several studies about LF hypertrophy, its pathomechanism remains unclear.

In previous studies, only human samples have been used due to the lack of a relevant animal model. A limitation of these studies was the difficulty in observing the gradual process of LF hypertrophy because the hypertrophied LF obtained from LSCS patients already showed advanced histological changes; the loss of elastic fibers and an excessive accumulation of collagen fibers [4,5]. Molecular expression changes were also observed in human hypertrophied LF, such as transforming growth factor-β1 (TGF-β1) [6], connective-tissue growth factor (CTGF) [7] and platelet-derived growth factor (PDGF) [8], which are related to collagen production [9–11]. However, whether such factors are causative or merely a consequence of LF hypertrophy remains unknown. Therefore, basic research using an experimental animal model is necessary to elucidate its etiology.

Various possible factors for LF hypertrophy have been considered, such as age, activity level, genetic components, and mechanical stress [12–14]. Among them, we focused on mechanical stress, which has been considered an influencing factor in previous studies. Indeed, Fukuyama et al. reported that the LF thickness of lumbar degenerative instability patients was larger than that of non-instability patients [12]. Furthermore, mechanical stretching force was reported to increase collagen synthesis in cultured human LF cells [15]. However, there are no *in vivo* studies directly demonstrating that mechanical stress induces LF hypertrophy.

In this study, we established a LF hypertrophy mouse model using a novel loading device and examined the influence of consecutive mechanical stress on LF hypertrophy. In addition, we induced macrophage infiltration into the mouse LF by applying micro-injury and examined the pathological role of macrophages in LF hypertrophy.

Materials and Methods

Animals

Eight-week-old female C57BL/6 wild-type mice and CAG-EGFP transgenic mice were used in this study (Japan SLC, Shizuoka, Japan). All mice were housed in a temperature- and humidity-controlled environment with a 12 h light–dark cycle. In all animal experiments, the mice were anesthetized intraperitoneally with an anesthetic mixture (medetomidine 0.3 mg/kg, midazolam 4 mg/kg, and butorphanol 5 mg/kg) every hour in consideration of the anesthetic duration [16]. The animal protocol was approved by the Committee of Ethics on Animal Experiment in Faculty of Medicine, Kyushu University (A-27-220-0) in accordance with the Guidelines for Animal Experimentation. All efforts were made to reduce the number of animals used and to minimize their suffering.

Histological analysis

After the mice were transcardially fixed with 4% paraformaldehyde, the lumbar spine was removed and immersed in the same fixative. The spine was decalcified in ethylenediaminetetraacetic acid solution and dehydrated in sucrose solution. The sample was then embedded into OCT compound, frozen in liquid nitrogen, and cut into 10-μm sections on a cryostat. The sections were subjected to hematoxylin-eosin (HE) and Elastica-van Gieson (EVG) staining. For immunostaining, the sections were stained with primary antibodies against Iba1 (1:200; macrophage marker; Wako, Osaka, Japan), laminin (1:200; basement membrane marker; Sigma-Aldrich, Saint Louise, MO), collagen type 1 alpha 1 (COL1A1; 1:200; Sigma-Aldrich), and 5-bromo-20-deoxyuridine (BrdU; 1:200; proliferating cell marker; Abcam, Cambridge, UK). Then, the sections were incubated with Alexa Fluor-conjugated secondary antibodies (1:200; Invitrogen, Carlsbad, USA). Nuclear counterstaining was performed using Hoechst 33342 (1:1000; Invitrogen). For BrdU detection, the sections were pre-treated with 2N-HCl for 30 min at 37°C.

Experimental procedures

To examine bone-marrow-derived cell (BMDC) infiltration into the LF under consecutive mechanical stress, 1×10^7 bone-marrow cells prepared from CAG-EGFP mice by flushing the femurs and tibias were transplanted into irradiated wild-type recipient mice as previously described [17]. After confirming the reconstitution of >90% EGFP-bone-marrow cells in the chimeric mice, we applied 12-week mechanical stress.

To quantify the number of proliferating cells by consecutive mechanical stress, BrdU (100 μg/g body weight) was intraperitoneally administered daily during the loading period in the two groups.

To induce macrophage infiltration, after peeling the lumbar paraspinal muscles and exposing the mouse LF, we applied micro-injury to the LF at the dorsal side with a sharp 30-gauge needle tip. At 1, 2, and 6 weeks after micro-injury, histological and gene expression analyses were performed. Sham surgery was performed on the controls.

Human LF samples

Human LF was obtained at surgery from 20 LSCS patients (mean age 68.6 years, range 65–78 years, as hypertrophied LF) and 10 lumbar disc herniation (LDH) patients (mean age 29.9 years, range 24–34 years, as non-hypertrophied LF). Hypertrophied LF from LSCS patients was then divided into two groups: mild (<4 mm) and severe (>4 mm) hypertrophy (n = 10 per group).Human LF sections were subjected to HE and EVG staining. All procedures were approved by the Kyushu University Institutional Review Board (25–126) and the analyses of the sample were performed after obtaining written informed consent from each patient.

Image acquisition and quantification

All radiographs of the mouse spine were scanned with micro-computed tomography (CT) (60 kV, 50 μm per pixel, Rigaku, Tokyo, Japan). For histological and immunohistochemical analyses, images were obtained using a BZ-9000 digital microscope (Keyence, Osaka, Japan). The thickness of human LF was measured at the facet joint level on axial T1-weighed magnetic resonance imaging (MRI) as previously described [18].The thickness of the mouse LF with/without mechanical stress (the mechanical stress group and the control group) was also measured at the facet joint level on the axial sections with EVG staining (n = 5 per group). To calculate the area of collagen and elastic fibers after EVG staining, we used the ImageJ software program (National Institutes of Health). The area was calculated 3 times and the average value was taken [5]. The number of LF cells in human samples was counted by HE staining of the sagittal sections in 5 random fields at 400× magnification as previously described (n = 10 per group) [19]. The number of LF cells, BMDCs, and proliferating cells in our mouse model was quantified by counting Hoechst, EGFP, and BrdU-immnunopositive cells in the axial sections at the L5-L6 facet joint level at 200× magnification (n = 5 per group). The algorithms for counting the cells were provided by the measurement software program Dynamic cell count BZ-H1c (Keyence).

Quantitative reverse transcription-polymerase chain reaction (qRT-PCR) Analysis

Total RNA was isolated from LF cells using the RNeasy Mini Kit (Qiagen, Hilden, Germany) and cDNA was synthesized from the total RNA using a PrimeScript reverse transcriptase (TaKaRa, Shiga, Japan) according to the manufacturer's instructions. Quantitative RT-PCR was performed using 20 μl reaction mixture with primers specific to the genes of interest (Table 1) and SYBR Premix Dimmer-Eraser (TaKaRa) [20]. The mRNA levels in each sample were normalized to those of glyceraldehyde-3-phosphate dehydrogenase mRNA (n = 5 per group).

Table 1. Primers used for quantitative reverse transcription polymerase chain reaction.

Gene (Accession Number)		5'- Primer -3'
COL1A1 (NM_007742.3)	Forward	AACCCTGGAAACAGACGAACAACC
	Reverse	TGGTCACGTTCAGTTGGTCAAAGG
COL1A2 (NM_007743.2)	Forward	ATCCAACTAAGTCTCCTCCCTTGG
	Reverse	CTCTGTGGAAGATAGTCAGAAGCC
COL3A1 (NM_009930.2)	Forward	TAAAGAAGTCTCTGAAGCTGATGG
	Reverse	ATCTATGATGGGTAGTCTCATTGC
TNF-α (NM_013693.2)	Forward	TTATGGCTCAGGGTCCAACTCTGT
	Reverse	TGGACATTCGAGGCTCCAGTGAAT
IL-1β (NM_013693.2)	Forward	GGGCTGGACTGTTTCTAATGCCTT
	Reverse	CCATCAGAGGCAAGGAGGAAAACA
IL-6 (NM_013693.2)	Forward	GCTCTCCTAACAGATAAGCTGGAG
	Reverse	CCACAGTGAGGAATGTCCACAAAC
CTGF (NM_010217.2)	Forward	GGCCATACAAGTAGTCTGTCAACC
	Reverse	CACTCCAAAAAGTAGGCACACTGC
PDGF-A (NM_008808.3)	Forward	AGACAGATGTGAGGTGAGATGAGC
	Reverse	ACGGAGGAGAACAAAGACCGCACG
TGF-β1 (NM_011577.1)	Forward	TGGACACACAGTACAGCAAGGTCC
	Reverse	ATCATGTTGGACAACTGCTCCACC
VEGF-A (NM_001025257.3)	Forward	CGGAGGCAGAGAAAAGAGAAAGTG
	Reverse	GGGAGAGAGAGATTGGAAACACAG
MMP-2 (NM_008610.2)	Forward	CCTGGTGACTTCAGATTTAAGAGG
	Reverse	GATGTTGAAGAACCAGAAGAGTGG
MMP-9 (NM_013599.3)	Forward	CTGGTGATCTCTTCTAGAGACTGG
	Reverse	ATGCATCTGCAACTACAGATAAGC
GAPDH (NM_004503)	Forward	GACTTCAACAGCAACTCCCACTCT
	Reverse	GGTTTCTTACTCCTTGGAGGCCAT

COL1A1 indicates collagen type 1 alpha 1; COL1A2, collagen type 1 alpha 2; COL3A1, collagen type 3 alpha 1; TNF-α, tumor necrosis factor-α; IL-1β, interleukin-1β; IL-6, interleukin-6; CTGF, connective tissue growth factor; PDGF-A, platelet-derived growth factor-A; TGF-β1, transforming growth factor-β1; VEGF-A, vascular endothelial cell growth factor-A; MMP-2, matrix metalloproteinase-2; MMP-9, matrix metalloproteinase-9; GAPDH, glyceraldehyde-3-phosphate dehydrogenase.

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Statistical analysis

Wilcoxon's rank sum test was used to compare the medians of the data between two groups for the area, width, and thickness of the LF, the area of the collagen and elastic fibers, the qRT-PCR results, and the cell count in the mouse LF. To analyze the differences among three groups in the ratio of elastic fibers to collagen fibers and the cell count in human LF, ANOVA with the Tukey-Kramer post hoc test was performed. Statistical significance was set at $p < 0.05$. The data were presented as the mean ± SEM. All statistical analyses were carried out using the JMP software program (version 11; SAS Institute, Cary, NC, USA).

Results

Consecutive mechanical stress loading to the mouse LF

First, to evaluate whether the mouse was a feasible experimental animal model for studying LF hypertrophy, we performed histological analyses of the mice lumbar spine. In the axial sections of the spine, HE staining showed that the mouse LF was located between the dural tube and facet joints (Fig 1A). In the sagittal sections, EVG staining demonstrated that the LF ran between adjacent laminas and mostly consisted of black-staining elastic fibers (Fig 1B). These histological features were very similar to those of human LF. Therefore, we decided to use mice to examine the pathomechanism underlying LF hypertrophy.

To establish a LF hypertrophy mouse model, we initially developed a loading device by which the mouse LF was subjected to consecutive mechanical stress for the present experiment (Fig 1C). The device consisted of a moving bed, straps, and motor driver (UNIQUE MEDICAL, Tokyo, Japan) (Fig 1D). During the loading, the limbs were firmly strapped onto the bed under anesthesia. When the upper half of the bed was constantly moving, the spine was bent and extended repeatedly at the rate of 20 cycles per minute by the motor. To determine the appropriate loading, we performed a preliminary experiment with 12 weeks of mechanical stress loading for 1.5, 3, and 4.5 h/day, and then decided on a 12-week loading period because an experimental period exceeding 12 weeks was not practical. During this period, some mice in the 4.5 h/day group showed weight and hair loss, whereas no adverse events were noted in the other groups. We therefore performed 3 h/day loading in subsequent experiments. The controls were under anesthesia alone. To apply mechanical stress consistently at the L5-L6 level, we used the iliac crest line as an anatomical land mark of the level (Fig 1E) and confirmed that mechanical stress was adequately loaded to the mouse LF at the level by CT images (Fig 1F).

Mechanical stress brought about LF hypertrophy

To examine whether mechanical stress indeed induced LF hypertrophy, we compared the axial cross-sectional area of the mouse LF with/without mechanical stress loading (the stress group vs. the control group, respectively). We found the sectional area in the stress group to be about 1.5-fold that in the control group on EVG staining after 12-week mechanical stress (Fig 2A and 2B). Although the width was comparable between the two groups, the thickness of the stress group was significantly higher than that of the control group (Fig 2B). These results indicated the successful establishment of a LF hypertrophy mouse model via mechanical stress.

We then investigated the effect of mechanical stress on the extracellular matrix (ECM). Previous observations in human samples demonstrated that the major ECM component was elastic fibers, while the minor component was collagen fibers in non-hypertrophied LF, whereas the ratio of collagen fibers was markedly increased in hypertrophied LF [4,5]. Similarly, in our mouse model, the area of collagen fibers was considerably higher in the stress group than in

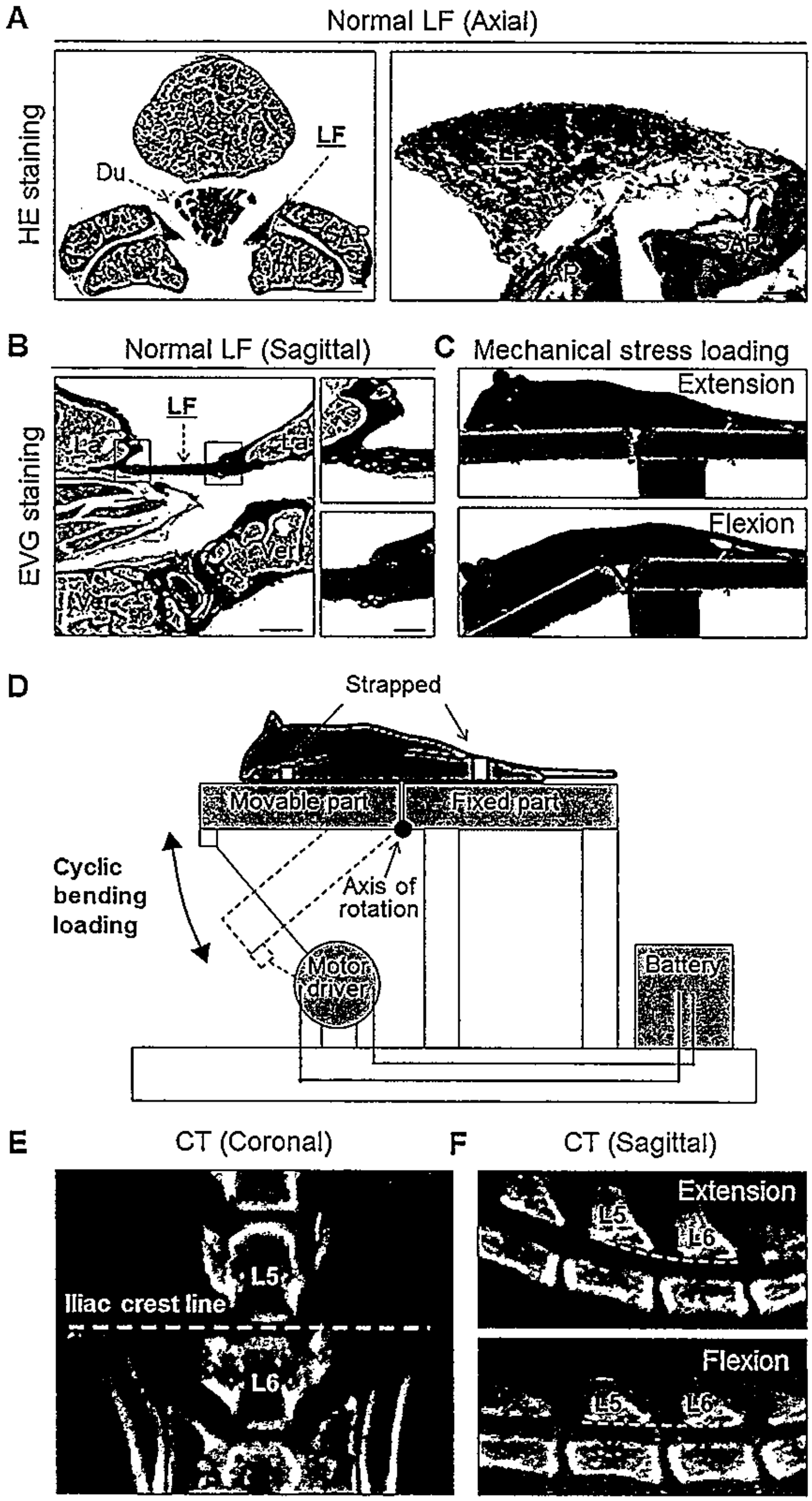
A
Normal LF (Axial)
HE staining
LF
Du
B
Normal LF (Sagittal)
EVG staining
LF
C
Mechanical stress loading
Extension
Flexion
D
Strapped
Movable part
Fixed part
Cyclic bending loading
Axis of rotation
Motor driver
Battery
E
CT (Coronal)
Iliac crest line
L5
L6
F
CT (Sagittal)
Extension
L5
L6
Flexion
L5
L6

Fig 1. Histological analyses of the mouse lumbar spine and a mechanical stress loading device. The application of mechanical stress to the mouse LF using a novel device. (A) HE and (B) EVG staining of the spine sections. (C) Photographs and (D) schematic illustrations of the device. (E) A coronal CT image showing that the iliac crest line corresponds to the L5-L6 disc level. (F) Sagittal CT images showing that mechanical stress was consistently applied at the L5-L6 level. Scale bars (A): 300 μm; insets: 50 μm; (B): 300 μm; insets: 100 μm. LF, ligamentum flavum; Ver, vertebral body; Du, dural tube; SAP, superior articular process; IAP, inferior articular process; La, lamina.

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the control group (Fig 2C). Although the area of elastic fibers also increased, the density of elastic fibers decreased compared to that of collagen fibers (Fig 2C–2F).

The histological comparison of the mouse and human LF

We next evaluated the severity of LF hypertrophy in the mouse model in comparison to human samples. Non-hypertrophied LF of human showed a dense and regular bundle of elastic fibers, whereas severely hypertrophied LF showed thin, irregular, and fragmented elastic fibers in EVG staining (Fig 3A). Additionally, the elastin-to-collagen ratio decreased in hypertrophied LF compared to non-hypertrophied LF (Fig 3B). In our mouse model, the elastic fibers in the control group were dense and aligned, whereas in the stress group, they were slightly degenerated, and a decreased elastin-to-collagen ratio was observed (Fig 3C and 3D). These results indicated that our mouse model by mechanical stress was histologically identical to mildly hypertrophied LF of human.

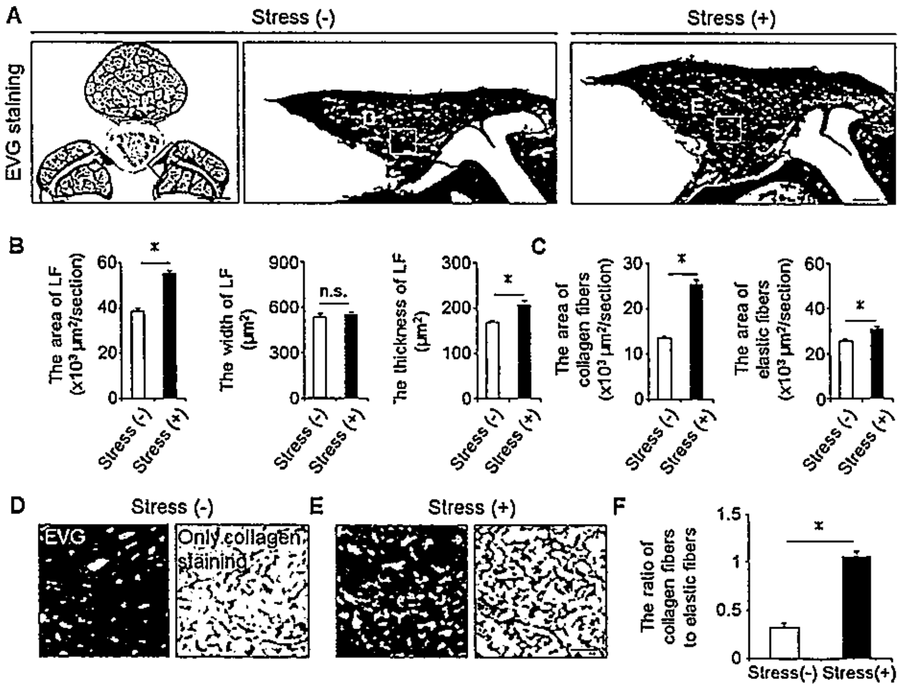

Fig 2. Mechanical stress induced LF hypertrophy. (A) Axial sections of the mouse LF with/without 12-week mechanical stress loading on EVG staining. (B and C) Bar graphs showing the cross-sectional area, width, thickness, and the area of collagen fibers and elastic fibers in the two groups. (D and E) High magnifications of (A). (F) Bar graph showing the ratio of collagen fibers to elastic fibers in the two groups. Scale bars (A): 500 μm; insets: 50 μm; (D and E): 10 μm. *$p < 0.05$, Wilcoxon's rank sum test, n.s. = not significant (n = 5/group).

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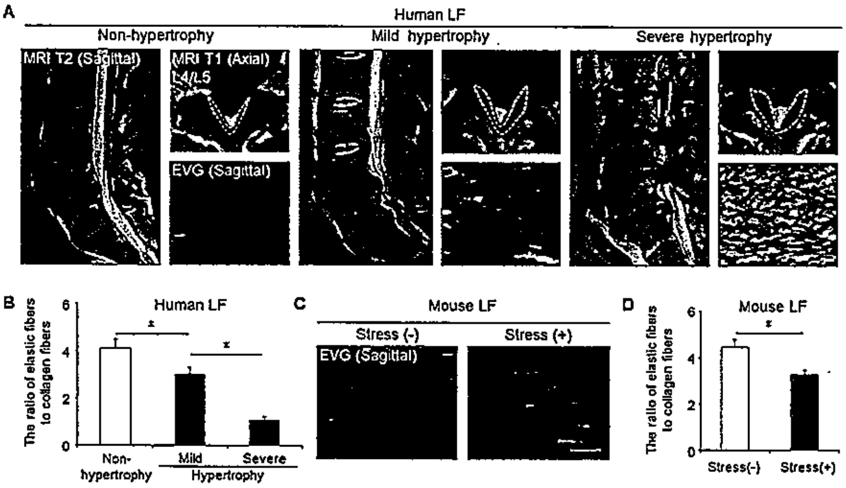

Fig 3. Our mouse model histologically reflected mildly hypertrophied LF in humans. (A) MRI and EVG staining of human samples: non-hypertrophy and mild and severe hypertrophy. The white broken lines indicate outlines of the LF. (B) Bar graph showing the ratio of elastic fibers to collagen fibers in the three groups. *$p < 0.05$, an ANOVA with the Tukey-Kramer post hoc test (n = 10/group). (C) EVG staining of the mouse LF with/without 12-week mechanical stress. (D) Bar graph showing the ratio of elastic fibers to collagen fibers in the two groups. *$p < 0.05$, Wilcoxon's rank sum test (n = 5/group). Scale bars (A): 100 μm; (C): 50 μm.

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Increased number of LF cells by mechanical stress

In addition to these ECM component changes, we examined the cellular distribution changes using human and our mouse samples. There were few cells in human non-hypertrophied LF, whereas a significantly increased number of cells was observed in human hypertrophied LF (Fig 4A and 4B). Also in our mouse model, the number of Hoechst-positive LF cells was significantly higher in the stress group than in the control group (Fig 4C and 4D). Furthermore, the number of BrdU-positive proliferating cells was significantly higher in the stress group (Fig 4E and 4F). We initially expected to observe BMDC infiltration by mechanical stress because macrophage infiltration was reported in human hypertrophied LF [21]. However, no EGFP-positive BMDC infiltration occurred in the bone-marrow-chimeric mouse LF with/without mechanical stress (Fig 4C).

Increased gene expression of fibrosis-related factors by mechanical stress

To examine the influence of mechanical stress on the activation of fibrosis-related factors in LF cells, we evaluated the gene expression of inflammatory cytokines, growth factors, and angiogenesis-related factors in the mouse model. Quantitative RT-PCR demonstrated that the gene expression of collagens, tumor necrosis factor-α, interleukin-1β, and interleukin-6 were significantly higher in the stress group than in the control group (Fig 5A and 5B). A significant increase in the CTGF and PDGF-A expression was also observed in the stress group (Fig 5C). Although an abundant TGF-β1 expression and angiogenic factors were reported in severely hypertrophied LF of humans [21], no significant differences were seen in the two mouse groups (Fig 5C and 5D).

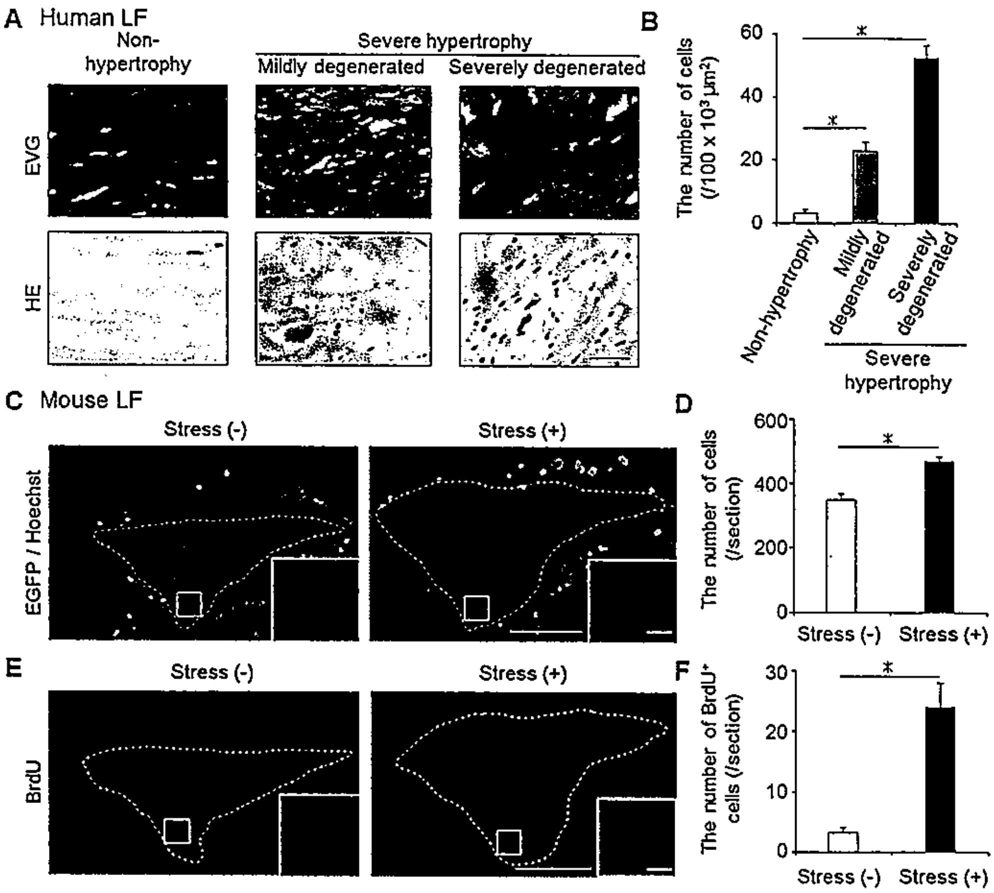

Fig 4. The changes in the cellular distribution in the hypertrophied LF of mice and humans. (A and B) The number of cells significantly increased with LF hypertrophy in humans. *$p < 0.05$, an ANOVA with the Tukey-Kramer post hoc test (n = 10/group). (C-F) The comparison of the number of cells (Hoechst, blue), infiltrating BMDCs (EGFP, green), and proliferating cells (BrdU, red) in the mouse LF with/without 12-week mechanical stress. To detect BMDCs, we generated bone-marrow-chimeric mice by transplanting from CAG-EGFP mice. The white broken lines indicate the outlines of the LF. *$p < 0.05$, Wilcoxon's rank sum test (n = 5/group). Scale bars (A): 100 µm; (C and E): 100 µm; insets: 10 µm.

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Micro-injury-induced macrophage infiltration and collagen accumulation in the injured area

In contrast to severely hypertrophied LF of LSCS patients, our mouse model by mechanical stress demonstrated no infiltrating macrophages, increase in TGF-β1 expression, or angiogenesis (Figs 4C, 5C and 5D). We therefore hypothesized that factors other than mechanical stress were involved in the progression of LF hypertrophy. To examine the pathological role of macrophages in LF hypertrophy, we induced macrophage infiltration by applying micro-injury to the normal mouse LF at the dorsal side. At 1 week after micro-injury, Iba1-positive macrophages had infiltrated around the injured lesion (Fig 6A). Notably, a qRT-PCR analysis revealed the gene expression of collagens and fibrosis-related growth factors, including TGF-β1, to be significantly higher in the micro-injured group than in the non-injured group (Fig 6B and 6C). Furthermore, laminin-positive micro-vessels and a significant increase in the levels of angiogenesis-related factors were also observed (Fig 6A and 6D). Indeed, excessive collagen

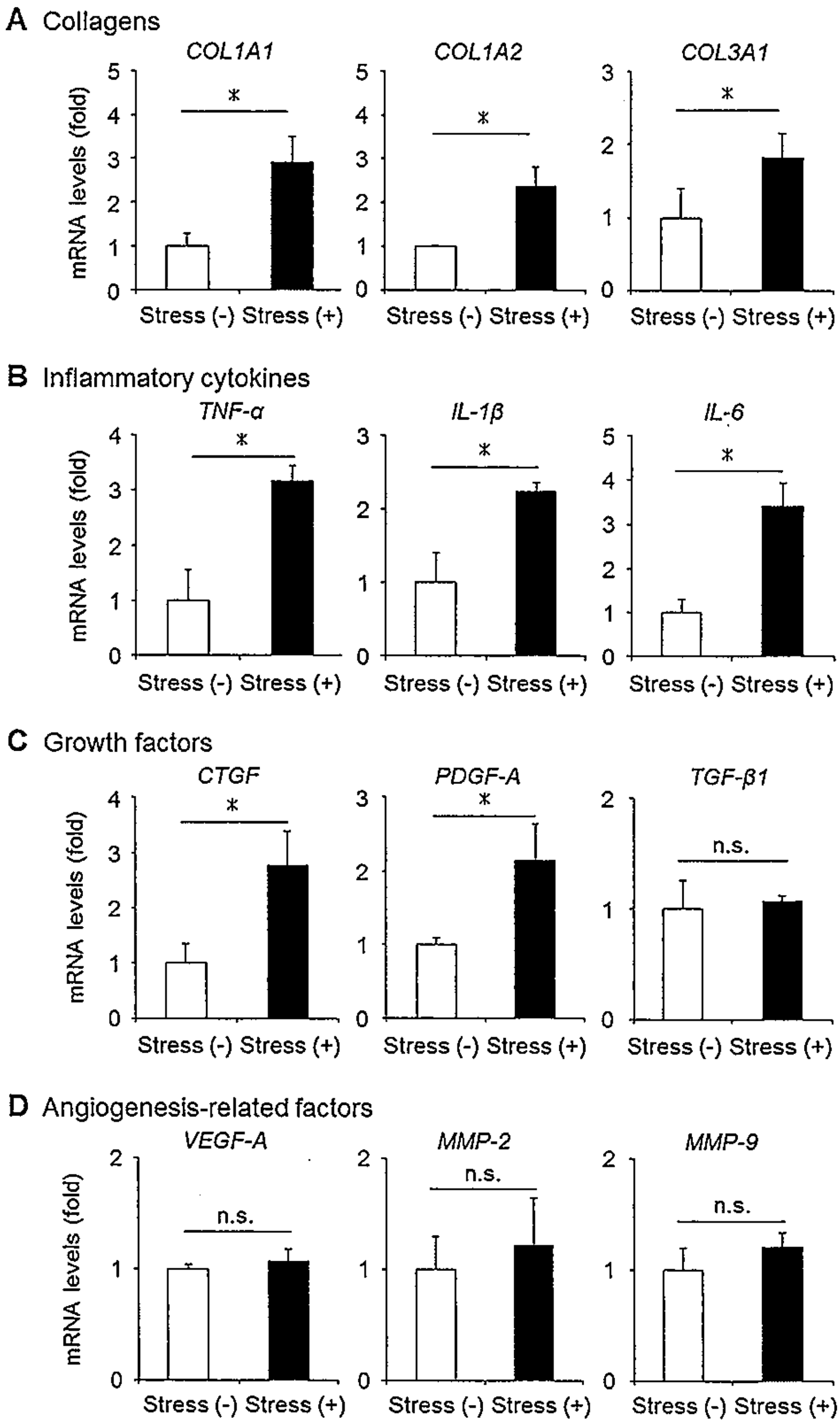
A Collagens
COL1A1
COL1A2
COL3A1
mRNA levels (fold)
*
Stress (-) Stress (+)
B Inflammatory cytokines
TNF-α
IL-1β
IL-6
C Growth factors
CTGF
PDGF-A
TGF-β1
n.s.
D Angiogenesis-related factors
VEGF-A
MMP-2
MMP-9

Fig 5. The mRNA expression of fibrosis-related factors in our mechanical stress mouse model. (A-D) The gene expression of collagens, inflammatory cytokines, growth factors, and angiogenesis-related factors evaluated in the mouse LF with/without mechanical stress loading by qRT-PCR (n = 5/group). *$p < 0.05$, Wilcoxon's rank sum test, n.s. = not significant. COL1A1, collagen type 1 alpha 1; TNF-α, tumor necrosis factor-α; IL, interleukin; CTGF, connective tissue growth factor; PDGF-A, platelet-derived growth factor-A; TGF-β1, transforming growth factor-β1; VEGF-A, vascular endothelial cell growth factor-A; MMP, matrix metalloproteinase.

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synthesis without elastic fibers was observed in the injured area at 2 weeks after micro-injury (Fig 6E), and LF hypertrophy was detected selectively in the micro-injury area at 6 weeks after injury (Fig 6F). These results strongly suggested that macrophage infiltration was a significant factor involved in the progression of LF hypertrophy by activating collagen production.

Discussion

In this study, by applying consecutive mechanical bending stress to the mouse LF, we demonstrated that mechanical stress was one of the direct causes of LF hypertrophy. In the mouse hypertrophied LF, increased collagen fibers, proliferating cells, and the gene expression of several fibrosis-related factors were found. In addition, macrophage infiltration with angiogenesis was induced by applying micro-injury to the mouse LF. In this macrophage infiltration model, LF hypertrophy was observed along with the excessive expression of collagen and the increased expression of TGF-β1. These findings suggest that long-term mechanical stress and macrophage infiltration significantly influence the progression of LF hypertrophy.

To date, previous studies have reported the common histological characteristics of human hypertrophied LF as follows: collagen deposition, elastic fiber fragmentation, and calcification [22,23]; inflammatory cell accumulation [21]; and an increased expression of fibrosis-related factors [6–8,24,25]. However, these pathological changes in human samples only indicated the advantaged stage of LF hypertrophy, and determining which factors contribute to the process of LF hypertrophy is difficult. Therefore, we established an experimental animal model to clarify its pathomechanisms. In our mechanical stress model, we confirmed the increases in collagen fibers, cell proliferation, and the fibrosis-related factors expression, in line with human LF pathology.

In fibrotic diseases of several organs, TGF-β1 has been reported to be an important disease-related factor for collagen production [26,27]. The main source of this cytokine was believed to be infiltrating macrophages in fibrosis [28,29]. For example, the number of infiltrating macrophages correlated with the TGF-β1 expression and the progression of collagen accumulation in liver fibrosis [28]. In addition, in severely hypertrophied LF of humans, macrophage infiltration was observed in the collagen deposition area with increased TGF-β1 expression [21]. In the development of a LF hypertrophy mouse model, we hypothesized that consecutive mechanical stress would induce macrophage infiltration and increased TGF-β1 expression. However, although the increased gene expression of several fibrosis-related factors was observed in our mechanical stress mouse model, there was no BMDC infiltration or increased TGF-β1 expression (Figs 4C and 5C). Therefore, we additionally induced macrophage infiltration by applying micro-injury, and found that macrophages were associated with the increased expression of collagens and TGF-β1 (Fig 6A–6C). Indeed, we found excessive collagen synthesis in the injured site at 2 weeks after micro-injury (Fig 6E) and confirmed LF hypertrophy at 6 weeks after micro-injury (Fig 6F). These results suggested that infiltrating macrophages may also play a significant role in the progression of LF hypertrophy via the increased expression of TGF-β1.

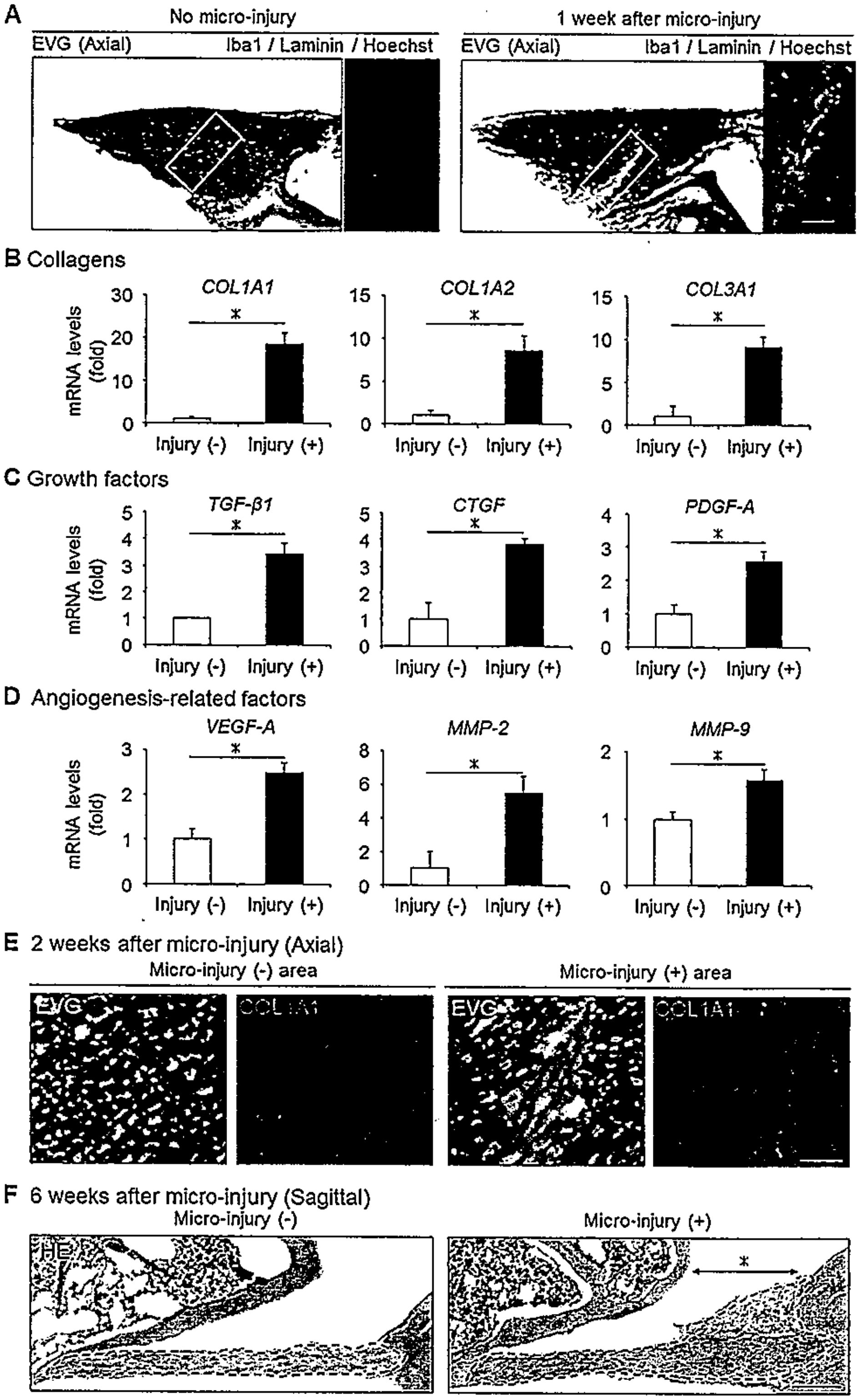
A
No micro-injury
EVG (Axial)
Iba1 / Laminin / Hoechst
1 week after micro-injury
EVG (Axial)
Iba1 / Laminin / Hoechst
B Collagens
COL1A1
COL1A2
COL3A1
mRNA levels (fold)
Injury (-)
Injury (+)
C Growth factors
TGF-β1
CTGF
PDGF-A
D Angiogenesis-related factors
VEGF-A
MMP-2
MMP-9
E 2 weeks after micro-injury (Axial)
Micro-injury (-) area
Micro-injury (+) area
EVG
COL1A1
F 6 weeks after micro-injury (Sagittal)
Micro-injury (-)
Micro-injury (+)
HE

Fig 6. The influence of macrophage infiltration following micro-injury on the mouse LF. (A) The presence of infiltrating macrophages (Iba1, green) and neovascular vessels (laminin, red) in the mouse LF with/without micro-injury. (B-D) Bar graphs showing the gene expression of collagens, fibrosis-related growth factors, and angiogenesis-related factors in the two groups. (E) The collagen synthesis in the injured area (COL1A1, green) at 2 weeks after micro-injury. (F) Sagittal sections of the mouse LF with/without micro-injury on HE staining at 6 weeks after micro-injury. The black broken lines indicate the outlines of the LF. The asterisk indicates the area to which micro-injury was applied. $*p < 0.05$, Wilcoxon's rank sum test (n = 5/group). Scale bars (A): 50 μm; insets: 20 μm; (E): 20 μm; (F) 200 μm. COL1A1, collagen type 1 alpha 1; TGF-β1, transforming growth factor-β1; CTGF, connective tissue growth factor; PDGF-A, platelet-derived growth factor-A; VEGF-A, vascular endothelial cell growth factor-A; MMP, matrix metalloproteinase.

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Another characteristic of human hypertrophied LF is angiogenesis. While the normal LF is non-vascularized, marked angiogenesis was observed in the area of collagen accumulation in the severely hypertrophied LF [21]. Several factors such as VEGF and MMPs are considered to be important for angiogenesis, and their actual expression has been mainly observed in fibrotic areas [30]. These angiogenic factors were reported to be derived from infiltrating macrophages, and neovascular vessels further promoted macrophage infiltration, resulting in the excessive expression of TGF-β1 as well as collagen production [31]. Therefore, the interplay between infiltrating macrophages and angiogenesis may also worsen the fibrotic pathology in LF hypertrophy progression. In our macrophage infiltration model, angiogenesis and the significantly increased expression of angiogenic factors were observed with infiltrating macrophages (Fig 6A and 6D). This macrophage infiltration model may help elucidate the effect of disrupting the cycle of macrophage infiltration and angiogenesis to prevent the progression to severe LF hypertrophy. Indeed, an angiogenesis inhibitor was reported to successfully suppress macrophage infiltration and subsequently prevent fibrotic collagen accumulation in renal fibrosis [32].

There are several limitations associated with the present study. We did not establish a LF hypertrophy mouse model showing advanced histological changes only by mechanical stress. Although we tried to investigate the influence of the combination of mechanical stress and micro-injury on LF hypertrophy, the combination unexpectedly caused an LF tear and the sample could not be analyzed. In addition to this limitation, our mechanical stress mouse model cannot be used to develop an LSCS model because the ratio of the LF to the dural tube was significantly smaller in mice than in humans. Nevertheless, we believe that each model we established in this study showed the pathological characteristics of human hypertrophied LF, at least in part, and is thus useful for a better understanding its pathogenesis.

In conclusion, we demonstrated for the first time that consecutive mechanical stress directly brought about LF hypertrophy in a mouse model. In addition, macrophage infiltration following micro-injury was found to be associated with severe LF hypertrophy by stimulating angiogenesis, collagen synthesis, and increased TGF-β1 production.

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Author Contributions

Conceptualization: TS SO.

Data curation: TS.

Formal analysis: TS KY K. Kobayakawa M. Hara K. Kubota KH K. Kawaguchi M. Hayashida YM TD KS YN SO.

Funding acquisition: SO.

Investigation: TS SO.

Methodology: TS.

Project administration: SO.

Resources: TS K. Kubota KH K. Kawaguchi M. Hayashida KS SO.

Supervision: SO.

Validation: SO.

Visualization: TS.

Writing – original draft: TS.

Writing – review & editing: SO.

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RESEARCH ARTICLE

Effects of Multilevel Facetectomy and Screw Density on Postoperative Changes in Spinal Rod Contour in Thoracic Adolescent Idiopathic Scoliosis Surgery

Terufumi Kokabu[1], Hideki Sudo[1]*, Yuichiro Abe[2], Manabu Ito[3], Yoichi M. Ito[4], Norimasa Iwasaki[1]

1 Department of Orthopaedic Surgery, Hokkaido University Hospital, Sapporo, Hokkaido, Japan, 2 Eniwa Hospital, Eniwa, Hokkaido, Japan, 3 Department of Spine and Spinal Cord Disorders, Hokkaido Medical Center, Sapporo, Hokkaido, Japan, 4 Department of Biostatistics, Hokkaido University Graduate School of Medicine, Sapporo, Hokkaido, Japan

* hidekisudo@yahoo.co.jp

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Abstract

Flattening of the preimplantation rod contour in the sagittal plane influences thoracic kyphosis (TK) restoration in adolescent idiopathic scoliosis (AIS) surgery. The effects of multilevel facetectomy and screw density on postoperative changes in spinal rod contour have not been documented. This study aimed to evaluate the effects of multilevel facetectomy and screw density on changes in spinal rod contour from before implantation to after surgical correction of thoracic curves in patients with AIS prospectively. The concave and convex rod shapes from patients with thoracic AIS ($n = 49$) were traced prior to insertion. Postoperative sagittal rod shape was determined by computed tomography. The angle of intersection of the tangents to the rod end points was measured. Multiple stepwise linear regression analysis was used to identify variables independently predictive of change in rod contour ($\Delta\theta$). Average $\Delta\theta$ at the concave and convex side were 13.6° ± 7.5° and 4.3° ± 4.8°, respectively. The $\Delta\theta$ at the concave side was significantly greater than that of the convex side ($P < 0.0001$) and significantly correlated with Risser sign ($P = 0.032$), the preoperative main thoracic Cobb angle ($P = 0.031$), the preoperative TK angle ($P = 0.012$), and the number of facetectomy levels ($P = 0.007$). Furthermore, a $\Delta\theta$ at the concave side $\geq 14°$ significantly correlated with the postoperative TK angle ($P = 0.003$), the number of facetectomy levels ($P = 0.021$), and screw density at the concave side ($P = 0.008$). Rod deformation at the concave side suggests that corrective forces acting on that side are greater than on the convex side. Multilevel facetectomy and/or screw density at the concave side have positive effects on reducing the rod deformation that can lead to a loss of TK angle postoperatively.

Introduction

Restoration and maintenance of the normal sagittal contour as well as coronal correction of the thoracic curve is an important surgical strategy in patients with thoracic adolescent idiopathic scoliosis (AIS), because these patients typically have a hypokyphotic thoracic spine compared with nonscoliosis patients [1]. Currently, posterior segmental pedicle screw (PS) instrumentation and fusion has become one of the most common surgical treatments. However, recent studies have reported that PS constructs to maximize scoliosis correction can cause further lordosis of the thoracic spine [2–4]. These patients exhibit a flat back, leading to progressive decompensation and sagittal imbalance [1,5]. Preservation of thoracic kyphosis (TK) is also critical to maintain lumbar lordosis after surgical treatment of AIS [1].

To overcome these issues, Ito et al. [6] and Sudo et al. [7–9] recently developed a very simple surgical technique called the simultaneous double-rod rotation technique (SDRRT) for correcting AIS. In this technique, two rods are connected to the screw heads and are simply rotated simultaneously to correct the scoliosis, while TK is maintained or improved. Moreover, hypokyphotic rod deformation is prevented with dual-rod derotation instead of single-rod derotation [6–9].

Some studies have investigated the correlation between AIS curve correction and destabilization procedures such as multilevel facetectomy [10] or the number of fixation anchors, such as PS density [11–14]. Implant rod curvature will also influence the postoperative TK. The initial shape of the rod could lead to a certain sagittal outcome. However, it has been recognized that rods bent by surgeons prior to implantation tend to flatten after surgery [15,16]. The postoperative implant rod deformation as a "spring-back" effect can alter the sagittal alignment of the spine and consequently the clinical outcome [17]. Until now, there has been no consensus on what possible factors can alter the shape of the rod. Based on the biomechanical point of view, the comprehensive effects of the surgical strategies on postoperative TK remain unknown. This study aimed to evaluate the effects of multilevel facetectomy and/or screw density on the change in the rod contour and TK in patients with thoracic AIS.

Materials and Methods

Patients

This study was an investigator-initiated observational cohort study conducted at a single medical center and approved by institutional review board of Hokkaido University Hospital (approval number: 014–0370). A written informed consent was obtained from all participants. Data from 49 patients (1 male, 48 female) with Lenke type 1 or type 2 AIS curves who underwent posterior thoracic curve correction between June 2009 and April 2016 were evaluated at our institution. Exclusion criteria included syndromic, neuromuscular, and congenital scoliosis and the presence of other double or triple major AIS curves, as well as thoracolumbar and lumbar AIS curves. The average age and Risser sign at surgery were 15.5 ± 2.2 years (range, 12–20) and 3.9 ± 1.1 (range, 1–5; Table 1), respectively.

Standing long-cassette posteroanterior and lateral radiographs were evaluated for multiple parameters before and at the 2-week follow-up. Coronal and sagittal Cobb angle measurements of the main thoracic (MT) curves were obtained. The end vertebrae levels were determined on preoperative radiographs and measured on subsequent radiographs to maintain consistency for statistical comparisons [7,8]. Sagittal measurements included the TK (T5–T12) angle [7,8]. The number of facetectomy levels was counted, and screw density was expressed as the number of screws per level instrumented for each patient. In this study, the number of hooks in the instrumented level was not counted.

Table 1. Disease characteristics and clinical features of the subjects.

	Mean ± standard deviation	Range
Body mass index (kg/m^2)	18.8 ± 2.4	12.4 to 24.2
Risser sign (grade)	3.9 ± 1.1	1 to 5
Preoperative main thoracic Cobb angle (°)	59.5 ± 10.2	46 to 88
Postoperative main thoracic Cobb angle (°)	13.3 ± 7.3	1 to 36
Preoperative thoracic kyphosis angle (°)	11.7 ± 7.8	-4 to 34
Postoperative thoracic kyphosis angle (°)	21.1 ± 6.3	7 to 33
Number of vertebrae in fusion (no.)	10.8 ± 1.6	7 to 14
Number of facetectomy levels (no.)	6.5 ± 3.4	0 to 12
Screw density at concave side (no. of screws / level instrumented)	0.89 ± 0.14	0.5 to 1
Screw density at convex side (no. of screws / level instrumented)	0.80 ± 0.16	0.4 to 1

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Surgical Technique

Six-millimeter diameter titanium-alloy implant rods and polyaxial PSs (USS II Polyaxial, DePuy Synthes, Raynham, MA, USA) were used to correct the scoliosis deformity. All rods were prebent only at a single plane. Rods and screws were surgically implanted via the double rod rotation technique [6–9]. In this technique, two implant rods were inserted into the polyaxial screw heads. The polyaxial screw heads remained unfastened until the completion of rod rotation, allowing the rods to rotate and translate freely inside the screw head. A torque was applied to the rod-rotating device to rotate the rods simultaneously, transferring the previous curvature of the rod at the coronal plane to the sagittal plane. Additional in situ bending or other reduction maneuvers were not performed in all cases. All polyaxial screws were carried upward and medially to the concave side of the curve by the rotation of the rods, which did not exert any downward force on the vertebral body [6–9]. Both polyaxial screw heads and simultaneous double-rod rotation were key to the current technique. Frictional force at the screw–rod interface was decreased, and there was little chance of screw cut-out laterally[9]. This technique provided derotation of the apical vertebra as well as restoration of TK, leading to rib hump correction without additional costoplasty [9].

Rod Analysis

The implant rod angle of curvature was used to evaluate implant rod deformation. Prior to implantation, following the intraoperative contouring of the rods, the surgeon traced the rod shapes on paper [15]. The angle between the proximal and distal tangential line was measured as the rod angle before implantation (θ1) as previously described [15]. Postoperative implant rod geometry was obtained a maximum of 2 weeks after the surgical operation using computed tomography (Aquilion 64 CT scan; Toshiba Medical Systems Corporation, Tokyo, Japan). Digital Imaging and Communications in Medicine (DICOM) data were obtained to reconstruct new images by DICOM viewer software (OsiriX Imaging Software; Pixmeo Labs., Geneva, Switzerland). The reconstructed sagittal images of the implanted rods were obtained, and the angle between the proximal tangential line and the distal tangential line was measured (θ2) (Fig 1). In cases in which the rod shape had both thoracic and lumbar curvature, the distal tangential line was determined based on the inflection point. The angle of rod deformation (Δθ) was defined as the difference between θ1 and θ2 (θ1−θ2). The angles θ1, θ2, and Δθ were obtained from the rods at both the concave and convex sides.

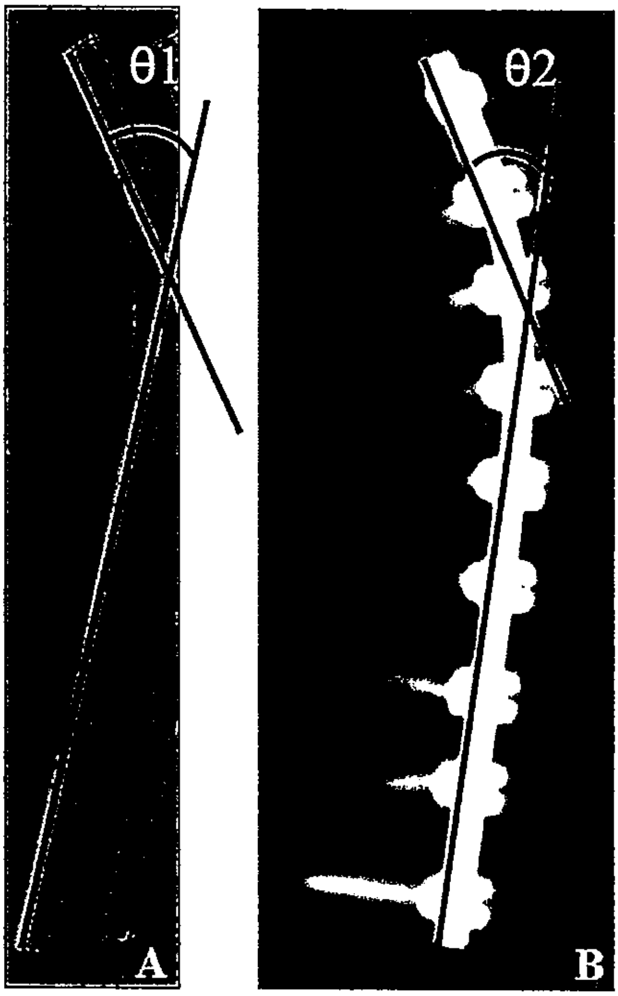

Fig 1. Rod angle before and after implantation. (A) Prior to implantation, the surgeon traced the rod shapes on paper. The angle between the proximal and distal tangential line was measured (θ1). (B) Postoperative implant rod geometry (θ2) was obtained after the surgical operation using computed tomography.

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Statistical Analysis

Bivariate statistical analysis was performed between the change in TK (postoperative TK–preoperative TK) and the Δθ at the concave or convex side using the Wilcoxon rank sum test. Pearson's correlation coefficient analysis was used to assess relationships between independent variables. Stepwise linear regression analysis was applied to control for possible confounding variables and to identify variables independently predictive of Δθ both at the concave and convex side. Patients' age and disease characteristics were included in the variables: age, body mass index [weight (kg)/height(m)^2], Risser sign, preoperative MT Cobb angle, postoperative MT Cobb angle, preoperative TK angle, postoperative TK angle, number of facetectomy levels, and screw density at both the concave and convex side. Significant multivariate predictors are reported with their respective predictive equations, including the intercept and regression coefficients (β). Model fit was assessed by using the goodness-of-fit F test and R^2 statistic. Data analyses were performed using JMP statistical software for Windows (version 12; SAS, Inc., Cary, NC, USA). $P < 0.05$ was considered statistically significant. All data are expressed as mean ± standard deviation.

Results

Disease characteristics are summarized in Table 1. On average, 10.8 ± 1.6 vertebrae were instrumented in the 49 patients. The average preoperative MT curve was 59.5° ± 10.2°. Postoperative radiographs showed an average MT curve of 13.3° ± 7.3°. Sagittal plane analysis revealed that the average preoperative TK was 11.7° ± 7.8°, which improved significantly to 21.1° ± 6.3° ($P < 0.0001$).

The preoperative θ1 and postoperative θ2 implant rod angle of curvatures at the concave and convex sides of the deformity are listed in Table 2.

The θ2 was significantly lower than the θ1 at the concave side ($P < 0.001$ at the concave side, $P = 0.019$ at the convex side, respectively). The Δθ at the concave side was significantly greater than that of the convex side ($P < 0.0001$) (Fig 2).

Postoperative TK was significantly correlated with the postoperative θ2 implant rod angle at both sides, particularly at the concave side (concave: $r = -0.415$, $P = 0.003$; convex: $r = -0.321$, $P = 0.025$, respectively) (Fig 3).

In multiple stepwise linear regression analysis, 4 variables were independent predictive factors for Δθ at the concave side: Risser sign ($P = 0.032$), the preoperative MT Cobb angle ($P = 0.031$), the preoperative TK angle ($P = 0.012$, and the number of facetectomy levels ($P = 0.007$). The model fit the data well (goodness-of-fit F test = 7.05, $R^2 = 0.50$, $P = 0.0001$) (Table 3).

Conversely, for Δθ at the convex side, 3 variables emerged as predictors: the number of vertebrae in fusion (standardized $\beta = -0.596$, $P = 0.0003$), the number of facetectomy levels (standardized $\beta = 0.578$, $P = 0.0006$), and the Risser sign (standardized $\beta = -0.292$, $P = 0.026$). However, R^2 was low (goodness-of-fit F test = 5.67, $R^2 = 0.34$, $P = 0.0009$), indicating that only 34% of the variation in Δθ was explained by these 3 predictors.

Subgroup Analysis

To determine whether Δθ affects postoperative TK, the total cohort was then divided into 2 groups on the basis of the mean Δθ at the concave side. The Δθ ≥ 14° group was defined by Δθ above the mean degree (13.6° ± 7.5°) at the concave side and further analyzed. The average age (n = 23) were 15.4 ± 2.1 years (range, 12–20). Disease characteristics and rod data in the group of ≥ 14° rod deformation are summarized in Table 4.

Pearson's correlation coefficient analysis showed that in the group of Δθ ≥ 14°, Δθ at the concave side had significant correlation with the postoperative TK angle ($r = -0.590$, $P = 0.003$),

Table 2. Implant rod angle of curvature at the concave and convex side of deformity.

	Mean ± standard deviation	Range
Preoperative rod angle (θ1) at concave side (°)	41.8 ± 7.1	22.3 to 66.5
Preoperative rod angle (θ1) at convex side (°)	38.4 ± 9.5	19.5 to 69.9
Postoperative rod angle (θ2) at concave side (°)	28.2 ± 9.1	9.2 to 48.5
Postoperative rod angle (θ2) at convex side (°)	34.1 ± 8.2	15.0 to 55.8
Rod deformation (Δθ) at concave side (°)	13.6 ± 7.5	-0.3 to 36.5
Rod deformation (Δθ) at convex side (°)	4.3 ±4.8	-6.8 to 17.8

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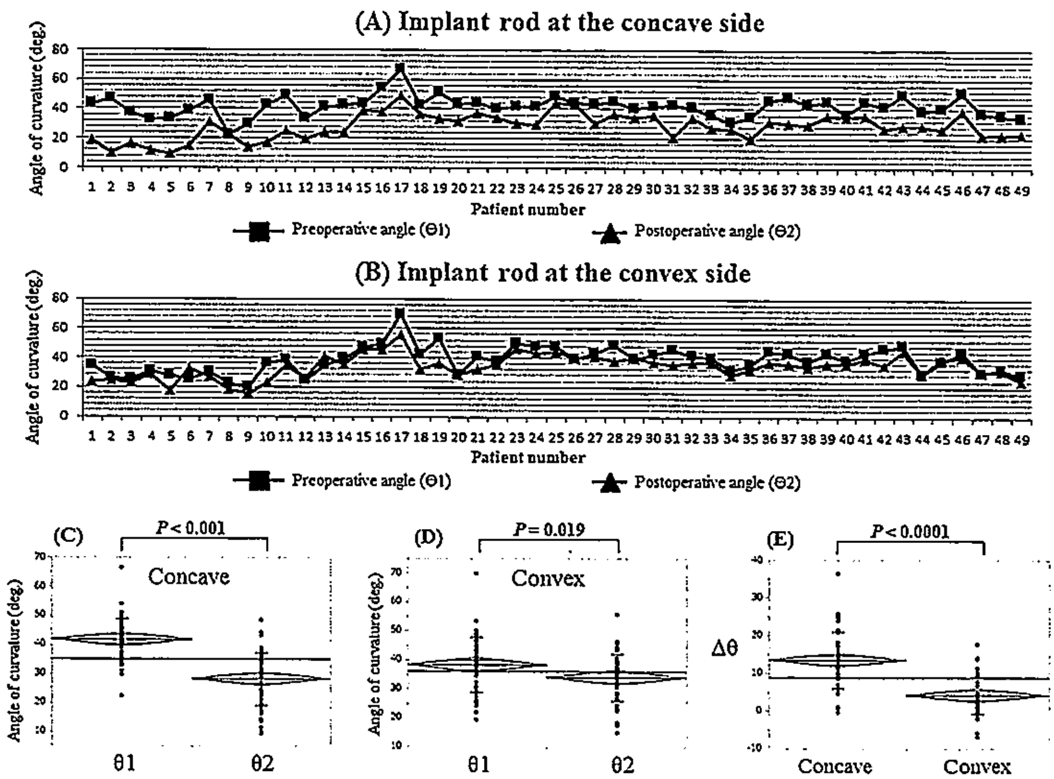

Fig 2. Implant rod angle of curvature at the concave and convex sides of the deformity. (A) θ1 and θ2 at the concave side of each patients. (B) θ1 and θ2 at the convex side of each patients. (C) Comparison between θ1 and θ2 at the concave side. (D) Comparison between θ1 and θ2 at the convex side. (E) Comparison between Δθ at the concave side and Δθ at the convex side.

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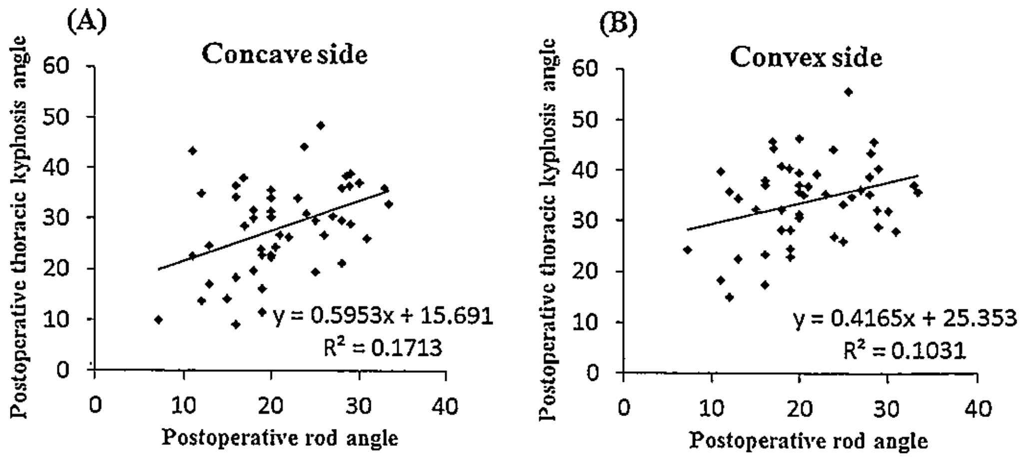

Fig 3. Correlation analysis between the postoperative rod angle and the thoracic kyphosis angle. (A) concave side. (B) convex side.

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Table 3. Associations between various factors and rod deformation at the concave side (°) using multiple stepwise linear regression analysis.

	Regression Coefficient	Standard Error	95% Confidence Interval	t	Standardized β	P
Constant	-10.787	8.57	(-28.081, 6.509)	-1.26	-	0.215
Risser sign (grade)	1.668	0.753	(0.148, 3.188)	2.21	0.249	0.032
Preoperative main thoracic Cobb angle (°)	0.265	0.085	(0.095, 0.436)	3.14	0.362	0.031
Preoperative thoracic kyphosis angle(°)	-0.279	0.106	(-0.494, -0.064)	-2.62	-0.292	0.012
Number of facetectomy levels (no.)	-0.716	0.253	(-1.225, -0.206)	-2.83	-0.325	0.007
Screw density at convex side (no. of screws / level instrumented)	10.372	5.205	(-0.133, 20.876)	1.99	0.223	0.053

$P < 0.05$ was considered statistically significant

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the number of facetectomy levels ($r = -0.479$, $P = 0.021$), and screw density at the concave side ($r = -0.537$, $P = 0.008$)(Table 5).

Discussion

Careful investigation of the changes in implant rod geometry is important to fully understand the biomechanics of scoliosis correction [16]. However, there have been few studies examining the relationship between rod deformation and sagittal alignment of the thoracic spine [15,16,18]. Cidambi et al. [15] documented that a significant difference was observed between pre- and postoperative rod contour, particularly for concave rods, and that the resulting deformations were likely associated with substantial *in vivo* deforming forces. Similarly, Salmingo et al. [16] reported that implant rods at the concave side were significantly deformed after surgery, whereas rods at the convex side had no significant deformation. Abe et al. [18] suggested that the corrective force during scoliosis surgery was 4 times greater at the concave side than at the convex side. The present study also showed that there was a significant positive relationship between postoperative TK and the postoperative implant rod angle of curvature, indicating

Table 4. Disease characteristics and rod data in the group of ≥ 14° rod deformation at the concave side.

	Mean ± standard deviation	Range
Body mass index (kg/m²)	18.6 ± 2.5	13.1 to 23.4
Risser sign (grade)	4.0 ± 0.9	1 to 5
Preoperative main thoracic Cobb angle (°)	61.7 ± 11.7	46 to 88
Postoperative main thoracic Cobb angle (°)	14.0 ± 6.3	1 to 27
Preoperative thoracic kyphosis angle (°)	7.6 ±5.5	-4 to 23
Postoperative thoracic kyphosis angle (°)	19.6 ± 6.0	7 to 33
Number of vertebrae in fusion (no.)	10.5 ± 1.6	7 to 13
Number of facetectomy levels (no.)	5.6 ± 3.4	0 to 11
Screw density at concave side (no. of screws / level instrumented)	0.89 ± 0.15	0.56 to 1
Screw density at convex side (no. of screws / level instrumented)	0.84 ± 0.15	0.5 to 1
Preoperative rod angle (θ1) at concave side (°)	43.4 ± 8.0	29.6 to 66.5
Preoperative rod angle (θ1) at convex side (°)	37.9 ± 11.3	19.5 to 69.9
Postoperative rod angle (θ2) at concave side (°)	23.7 ± 9.6	9.2 to 48.5
Postoperative rod angle (θ2) at convex side (°)	32.5 ± 9.3	15.0 to 55.8
Rod deformation (Δθ) at concave side (°)	19.7 ± 5.3	14.1 to 36.5
Rod deformation (Δθ) at convex side (°)	5.5 ± 6.0	-6.8 to 17.8

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Table 5. Correlation analysis between rod deformation and variable in patients with rod deformation ≥14 ° at the concave side.

Variable	Pearson's correlation coefficients		
	Correlation coefficient	95% CI	Statistical significance
Age at surgery (yrs)	$r = -0.017$	(-0.398, 0.427)	$P = 0.937$
Body mass index (kg/m^2)	$r = -0.207$	(-0.570, 0.225)	$P = 0.344$
Risser sign (grade)	$r = -0.084$	(-0.479, 0.340)	$P = 0.705$
Preoperative main thoracic Cobb angle (°)	$r = 0.142$	(-0.287, 0.524)	$P = 0.518$
Postoperative main thoracic Cobb angle (°)	$r = 0.396$	(-0.019, 0.695)	$P = 0.061$
Preoperative thoracic kyphosis angle (°)	$r = -0.286$	(-0.625, 0.143)	$P = 0.186$
Postoperative thoracic kyphosis angle (°)	$r = -0.590$	(-0.806, -0.235)	$P = 0.003$
Number of vertebrae in fusion (no.)	$r = -0.324$	(-0.649, 0.102)	$P = 0.132$
Number of facetectomy levels (no.)	$r = -0.479$	(-0.744, -0.083)	$P = 0.021$
Screw density at concave side (no. of screws / level instrumented)	$r = -0.537$	(-0.777, -0.160)	$P = 0.008$
Screw density at convex side (no. of screws / level instrumented)	$r = 0.350$	(-0.073, 0.666)	$P = 0.102$
Rod deformation (Δθ) at convex side (°)	$r = 0.014$	(-0.424, 0.400)	$P = 0.948$

$P < 0.05$ was considered statistically significant

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that implant rod curvature influences sagittal curve correction. In addition, rod deformation at the concave side was significantly greater than that of the convex side.

Removing the facets and soft tissues between the posterior elements has been shown to allow greater distraction abilities along the length of the posterior column [1]. Destabilization of the posterior spinal segment by releasing soft tissue or facet joints could be important to prevent implant breakage or pedicle fracture during maneuver in more severe curve corrections [18]. However, it is still unclear whether these posterior releases positively affect the TK, especially with a hyphokyphotic thoracic spine [1,9]. Recently, Sudo et al. [9] documented that in patients with a hypokyphotic thoracic spine < 15°, a significant correlation was found between the change in TK and the number of facetectomy levels, indicating that multilevel facetectomy is an important factor to restore TK in patients with hypokyphotic thoracic spines. In the present study, there was a significant negative correlation between preoperative TK and rod deformation, indicating that the rod deformation was greater in patients with preoperative hypokyphotic thoracic spines. In addition, the deformation could be decreased by increasing the number of facetectomy levels.

Screw density may be also a possible factor in optimizing restoration of TK. However, the effect of implant density on sagittal plane correction and TK restoration has been reported in only a few studies, and the results have been controversial [12,14,19]. Larson et al. [12] demonstrated that decreased TK was correlated with increased screw density for Lenke type 1 and 2 curves. Conversely, Liu et al. [14] documented that higher screw density provided better TK restoration than low screw density. Recently, Sudo et al. [9] also documented that in patients with preoperative TK < 15°, a significant positive correlation was found between the change in TK and screw density, whereas no correlation was found in patients with TK ≥15°, suggesting that screw density had a positive effect on TK restoration in patients with hypokyphotic thoracic spines. Their results indicate that screw density at the concave side has an impact not only on scoliosis correction but also on TK restoration.

In the present study, in patients with rod deformation at the concave side ≥ 14°, there were significant negative correlations between rod deformation at the concave side and postoperative TK or screw density at the concave side. These results suggest that rod deformation ≥ 14° at the concave side significantly decreases postoperative TK. However, this rod deformation could be decreased by increasing screw density at the concave side. Hence, the current results biomechanically supported the results presented by Sudo et al.[9], documenting that in patients with preoperative hypokyphotic thoracic spines, increasing screw density at the concave side is important for optimizing postoperative TK.

There were limitations to this study. First, we evaluated deformity surgery with the use of titanium rods. The module of elasticity of the titanium alloy is much less than either stainless steel or cobalt chrome implants [16]. Second, we did not analyze the effects of multilevel osteotomy on the *in vivo* flexibility of the thoracic spine. We are now measuring *in vivo* force acting at the vertebrae before and after multilevel osteotomies in order to investigate the biomechanical effects of spinal flexibility provided by multilevel facet osteotomies on rod deformation. Third, resisting forces from the deformed spine might be different between males and females and this would need to be addressed in our predominantly female cohort. However, there were no effects of gender on thoracic hypokyphosis postoperatively (data not shown). Last, the relationships between rod deformation and clinical symptoms remain unclear.

Conclusion

The present study showed that there was a significant relationship between postoperative TK and the postoperative implant rod angle of curvature. In addition, the rod at the concave side was significantly deformed after the surgical treatment. The rod deformation at the concave side suggests that corrective forces acting on that side are greater than on the convex side. Multilevel facetectomy and/or screw density at the concave side have positive effects on reducing the rod deformation that can lead to a loss of TK angle postoperatively.

Author Contributions

Conceptualization: HS.

Data curation: HS YA.

Formal analysis: TK HS YMI.

Investigation: TK HS.

Methodology: TK HS YA.

Project administration: HS.

Resources: HS MI.

Software: TK YMI.

Supervision: HS MI NI.

Validation: TK HS YMI.

Visualization: TK.

Writing – original draft: TK HS.

Writing – review & editing: HS.

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RESEARCH ARTICLE

In Vivo Mouse Intervertebral Disc Degeneration Model Based on a New Histological Classification

Takashi Ohnishi[1], Hideki Sudo[2]*, Koji Iwasaki[1], Takeru Tsujimoto[1], Yoichi M. Ito[3], Norimasa Iwasaki[1]

1 Department of Orthopaedic Surgery, Hokkaido University Graduate School of Medicine, Sapporo, Hokkaido, Japan, 2 Department of Advanced Medicine for Spine and Spinal Cord Disorders, Hokkaido University Graduate School of Medicine, Sapporo, Hokkaido, Japan, 3 Department of Biostatistics, Hokkaido University Graduate School of Medicine, Sapporo, Hokkaido, Japan

* hidekisudo@yahoo.co.jp

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Abstract

Although human intervertebral disc degeneration can lead to several spinal diseases, its pathogenesis remains unclear. This study aimed to create a new histological classification applicable to an *in vivo* mouse intervertebral disc degeneration model induced by needle puncture. One hundred six mice were operated and the L4/5 intervertebral disc was punctured with a 35- or 33-gauge needle. Micro-computed tomography scanning was performed, and the punctured region was confirmed. Evaluation was performed by using magnetic resonance imaging and histology by employing our classification scoring system. Our histological classification scores correlated well with the findings of magnetic resonance imaging and could detect degenerative progression, irrespective of the punctured region. However, the magnetic resonance imaging analysis revealed that there was no significant degenerative intervertebral disc change between the ventrally punctured and non-punctured control groups. To induce significant degeneration in the lumbar intervertebral discs, the central or dorsal region should be punctured instead of the ventral region.

Introduction

Human intervertebral disc (IVD) degeneration is a common cause of low back pain and it affects the daily activities [1–3]. It is the cause of spinal diseases such as spinal canal stenosis, disc herniation, and spinal deformity. Currently, there is no clinical treatment to prevent the development of IVD degeneration, and the present available therapeutic options for spinal complications, namely analgesics and surgical procedures, do not address the etiology [1].

The research focusing on IVD degeneration, from the gross anatomical to histological studies, has been conducted using various animal models: scalpel incision to annulus fibrosus (AF) in canines [4] and rats [5]; surface incision to AF in sheep [6]; full puncture to IVD using needle in mice[7] and rats [8]; and hemi-AF puncture using needle in mice [9], rats [10], and rabbits [11–13]. However, because of the animal size and the species-specific physiological variations, the level of IVD degeneration differs [10,14]. To establish an IVD degeneration model induced by needle puncture, a precise size and shape of the device and a detailed procedure for each of the species are necessary. In addition, although the number of reports describing IVD degeneration in terms of the genetic approaches is increasing [1,15–19], there has been no appropriate histological classification applicable to an *in vivo* mouse intervertebral disc degeneration model, which is also applicable to genetically modified mice. The aim of this study was to create a new histological classification applicable to an *in vivo* mouse intervertebral disc degeneration model induced by needle puncture.

Materials and Methods

All animal procedures in this study were conducted with the approval of the Institutional Animal Care and Use Committee of Hokkaido University (approval number: 13–0051). Moreover, all these procedures were carried out in accordance with the approved guidelines. Inbred C57BL/6 mice were obtained from Sankyo Labo Service Corporation (Tokyo, Japan). The mice were bred and housed under specific pathogen-free conditions before surgery, and housed under P2 conditions after surgery at Hokkaido University Creative Research Institution Platform for Research on Biofunctional Molecules. P2 means a level of isolation from natural environment, that keeps the room in sterilized and safe condition. They were kept in cages at room temperature (23°C ± 2 °C) and humidity of 50% ± 10%, under standard laboratory conditions with a 12 h light/dark cycle. They were allowed unrestricted cage activity and ad libitum access to food and water. Standard laboratory diet, Labo MR Stock (Nosan Corporation, Yokohama, Japan) and sterilized tap water were provided as sources of food and water, respectively. All the surgeries were performed under general anesthesia with ketamine 1.9 mg and xylazine 0.2 mg intraperitoneal injection, and all animal suffering was minimized. After surgery, the mice were monitored once in two days. During the experiment, five mice (which are not included in the total of 106 mice) died within one to two days after surgery, presumably with respiratory depression due to anesthesia or hemorrhage due to surgery. The protocol of early euthanasia/humane endpoints for mice that were severely ill or moribund, as indicated by shivering and respiratory distress with disability in walking suggestive of apparent distress, with no recovery expected, was intraperitoneal injection of 5 mg of pentobarbital sodium. However, none was applicable. Except for the five mice that died, all mice exhibited good health and well-being until the end of the experiment. They were euthanized with pentobarbital sodium intraperitoneal injection.

One hundred six C57BL/6 mice (male, 54; female, 52) were operated under general anesthesia. All the mice were 11 weeks old at the time of surgery. The lumbar spine was posterolaterally approached from the right side, and the L4/5 IVD was punctured with a 35-gauge (G) or 33G needle. Micro-CT scanning [3D micro X-ray CT R_mCT 2 (Rigaku, Tokyo, Japan)] was performed, and the punctured region was confirmed through multiplanar reconstruction views (Fig 1a). The regions in IVD were determined in order to identify the position of the needle, which are as follows. First, the mid-sagittal diameter was divided into three parts: a concentric ellipsoid that constituted the central region was described using boundary points. Second, the peripheral region was divided into the ventral and dorsal regions. Third, the ventral, central, and dorsal regions were defined (Fig 1b). The regions were space prescribed by the endplates. The outer layer of AF that bulged from the endplates was not counted as the intervertebral space. When the needle did not get punctured into the intervertebral space, the trial was repeated until the needle hit the intervertebral space. We determined the position of the needle by visually analyzing the multi-slice CT scan images. If the needle penetrated the central

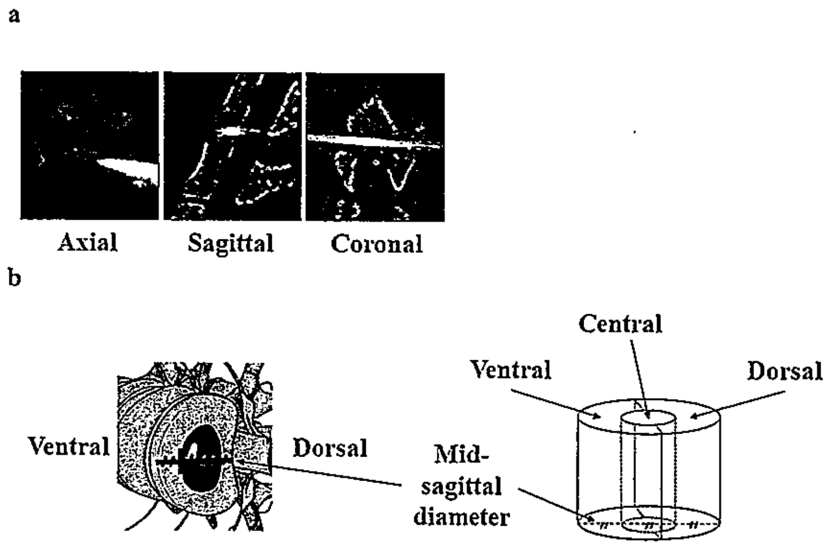

Fig 1. The location of a needle in the intervertebral disc was evaluated using micro-computed tomography scanning. (a) The punctured region was confirmed by multiplanar reconstruction views. (b) The punctured region was defined as the ventral (V), central (C), or dorsal (D) region.

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region, we designate the position of the needle as the 'central region', and in cases when the needle partially penetrated the dorsal or ventral region, consensus was obtained for the designation of the region. Before closing the wound, the needles were removed and the mice were euthanized one, two, four, eight, or 12 weeks after the surgery.

The mid-sagittal images of the punctured discs were qualitatively analyzed by using MRI to evidence the degenerative changes. More precisely, T2-weighed mid-sagittal images of the punctured discs were qualitatively analyzed by using a 7.0-Tesla MR scanner (Varian Unity Inova; Varian Medical Systems, Palo Alto, CA, USA) [1,17,20]. The degree of IVD was assessed by using the Pfirrmann classification [21]. A quantitative analysis of the sagittal image slices was also performed by using Analyze 10.0 software (AnalyzeDirect, Overland Park, KS, USA), as reported previously [1,17,20]. To quantify the alterations in the NP, the MRI index (the product of the NP area and the average signal intensity) was used [1,17,20]. Data were expressed as percentages of the results obtained when using untreated, non-punctured control discs [1,17,20]. The control was defined for the Pfirrmann grade as the value of L3/4 IVD and for the MRI index as the average value of both L3/4 and L5/6 IVDs. All the image assessments were performed by two independent blind observers, and the quantitative data were presented as means of three evaluations.

After the MRI examinations, each IVD was fixed in 10% neutral buffered formalin solution for 48 h, followed by decalcification with 10% EDTA for 2–4 weeks, and paraffin embedding. Mid-sagittal sections were obtained and stained with safranin O-fast green. For the histological analysis, four types of classification [for rabbits by Masuda et al. [11], for rats by Nishimura et al. [22], for mice by Yang et al. [9], and our group (Fig 2)] were used to evaluate the degeneration. For each classification type, the maximum points represent severe degeneration. The control was defined as the histological score of L3/4 IVD. All the histological assessments were performed by two independent blind observers, and the quantitative data were presented as the mean of three evaluations. Our internal studies of intra-/inter-rater reliability have shown excellent kappa statistics for all measures regarding MRI and histological examinations (0.85–1.0).

Intervertebral disc	Score	Findings
Annulus fibrosus (AF)	0	Normal
	1	Mildly serpentine (not bulge beyond endplate edge)
	2	Moderately serpentine (slightly bulge beyond endplate edge)
	3	Severely serpentine (obviously bulge beyond endplate edge)
	4	Severely serpentine and ruptured
	5	Indistinct
Nucleus pulposus (NP)	0	Normal
	1	Condensed
	2	Existence of chondrocyte-like cells, residual NP matrix
	3	Global existence of chondrocyte-like cells
	4	Mildly replaced by fibrous cartilaginous tissue
	5	Moderately or severely replaced by fibrous cartilaginous tissue

Degeneration score = AF score + NP score.

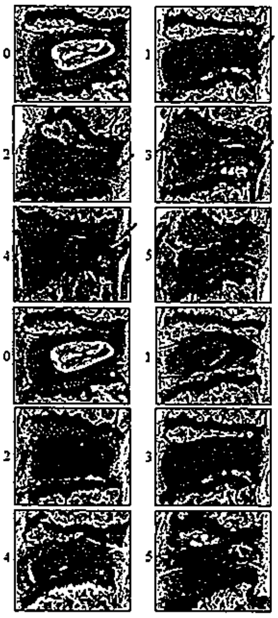

Fig 2. The novel proposed histological grading score. Arrows indicate the serpentine findings in the annulus fibrosus.

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The number of mice for each needle size and time point were as follows; ten for the 1-week, fourteen for the 2-week, eleven for the 4-week, ten for the 8-week, and ten for the 12-week time point for the 35G needle puncture; ten for the 1-week, ten for the 2-week, eleven for the 4-week, ten for the 8-week, and ten for the 12-week time point for the 33G needle puncture. A sham operation was defined as the posterolateral surgical approach without a needle puncture. The number of mice stratified according to sex in each time point of the 35G group were as follows: 1-week: female, 5; male, 5; 2 weeks: female, 10; male, 4; 4 weeks: female, 7; male, 4; 8 weeks: female, 5; male, 5; 12 weeks: female, 5; male, 5; for the 33G group: 1 week: female, 5; male, 5; 2 weeks: female, 1, male, 9; 4 weeks: female, 6; male, 5; 8 weeks: female, 5; male, 5; 12 weeks: female, 3; male, 7. For each time point there were four sham operations (female, 2; male, 2) (Fig 3).

Furthermore, statistical analyses were performed. A correlation analysis was used to evaluate the MRI index relationships with the histological classification scores. The multiple regression analysis was used to determine whether the postoperative time points and the punctured regions were significant variables. Kruskal-Wallis test was used for comparison of each subgroup of region with non-punctured control. Single regression analysis was used to determine whether the postoperative time point is a significant variable for NP score or AF score of punctured IVD. The Tukey HSD test was used for comparison of NP score at each time point. Single regression analysis was used to determine whether the postoperative time point is a significant variable for IVD height and width of punctured IVD. The Kruskal Wallis test was used to compare the 35G and the 33G needle for Pfirrmann grades, MRI indexes, or our histological classification scores.

Results

The comparison of four histological classification scores

We firstly analyzed the score distribution according to four histological classifications. Fig 4 shows the data distributions of the 35G puncture group based on the histological classification

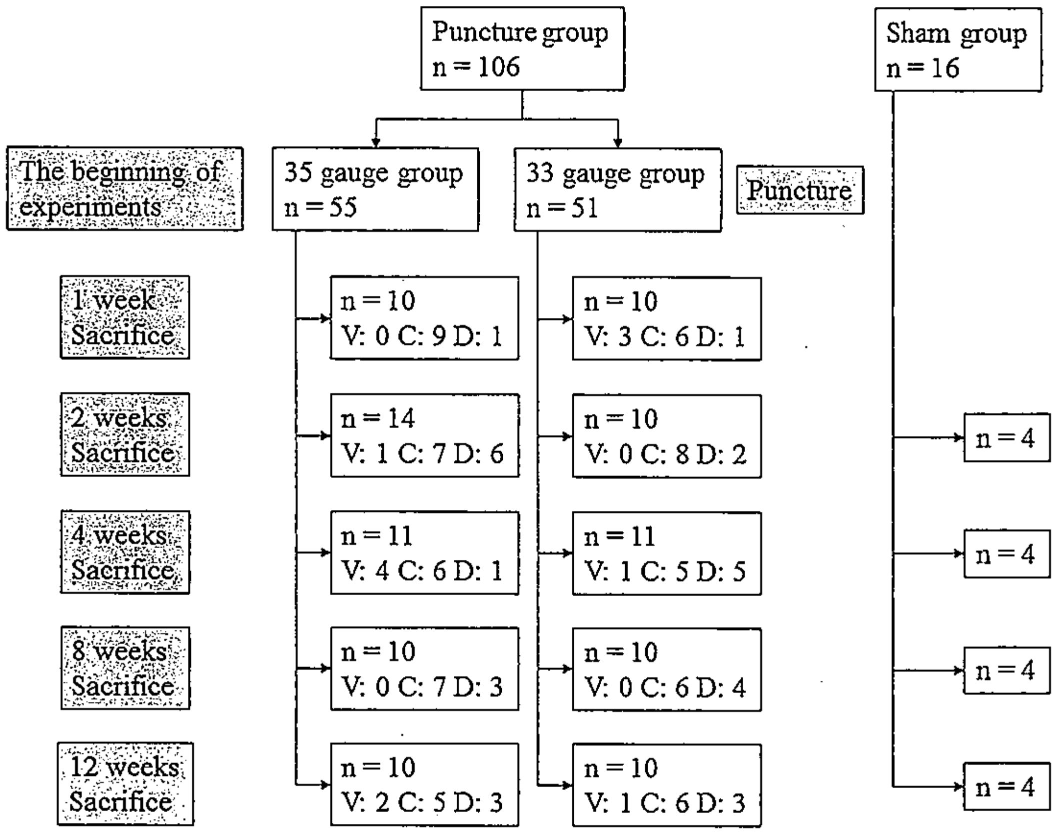

Fig 3. The flowchart of the experiment indicating the time course and the case number. V, ventral region; C, central region; D, dorsal region.

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scores. The score distribution of the classification by Masuda et al. [11] did not show normality, with a skewness (Sk) value of -1.27. Additionally, the score showed a ceiling effect, indicating that it was inappropriate for the present mice IVD degeneration model. In contrast, the distribution of the scores by Nishimura et al. [22]'s, Yang et al. [9]'s, and our classifications showed

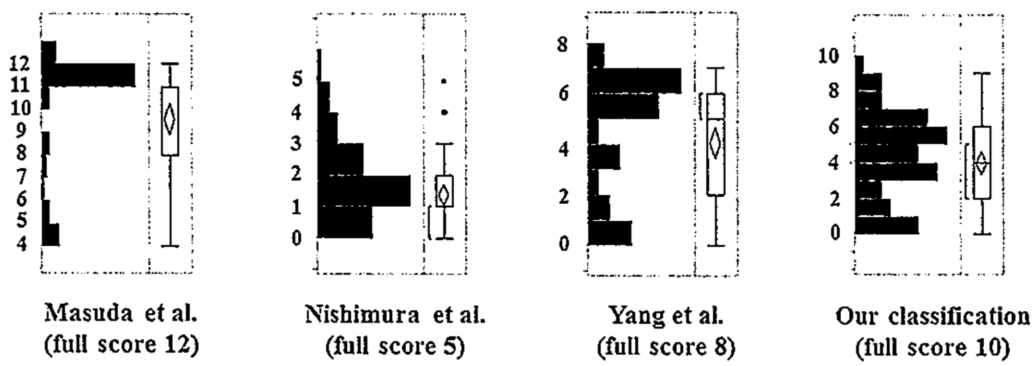

Fig 4. The comparison of the histological classifications. The distribution of scores in each classification. Red brackets indicate the minimum ranges that include 50% of the data. The red and black dots of the classification score of Nishimura et al.[22] indicate the outliers.

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normality, given that their Sk and kurtosis (Ku) were less than 1.00 (Sk = 0.97, Ku = 0.66 by Nishimura et al. [22], Sk = -0.69, Ku = -0.96 by Yang et al. [9], and Sk = -0.09, Ku = -0.72 by our classification). However, the Sk of Nishimura et al. [22]'s classification was higher than ours because their score had some outliers. In addition, compared to our classification, the Nishimura et al. [22] score showed a floor effect and the Yang et al. [9] score showed a ceiling effect. These results indicated that our classification could more precisely detect the gradual progression of the degenerative changes (Fig 4).

Correlation analysis relating MRI index

In the correlation and the simple linear regression analysis relating the MRI index with our classification, the results yielded $\rho = -0.66$ and $R^2 = 0.44$, showing that our classification yielded a good correlation and linear fit with the MRI index (Fig 5).

In a scatterplot and probability ellipse analysis, the 50% confidence probability ellipse for each punctured region were thin and well separated, indicating the good linear fit of our score. In addition, our score showed significant correlation with the MRI index in the central and dorsal regions with P values of 0.01 and 0.002, respectively (Fig 5).

Significant variable for inducing degenerative IVDs

Next, to identify the variables most predictive of degenerative IVDs, the following were tested in the multiple regression analysis: punctured region (including ventral, central, and dorsal regions) and time point. The results of the analysis revealed that not the "time point" but the "punctured region" was predictive of the degenerative outcomes (Table 1).

We further analyzed the whole data regarding punctured region. Compared with the non-punctured IVDs, those punctured through the central or the dorsal region showed significantly higher Pfirrmann grade and lower MRI index. Similarly, on using our classification, the IVDs punctured through the central or the dorsal region showed significantly higher histological scores. For the IVDs punctured through the ventral regions, our histological score was

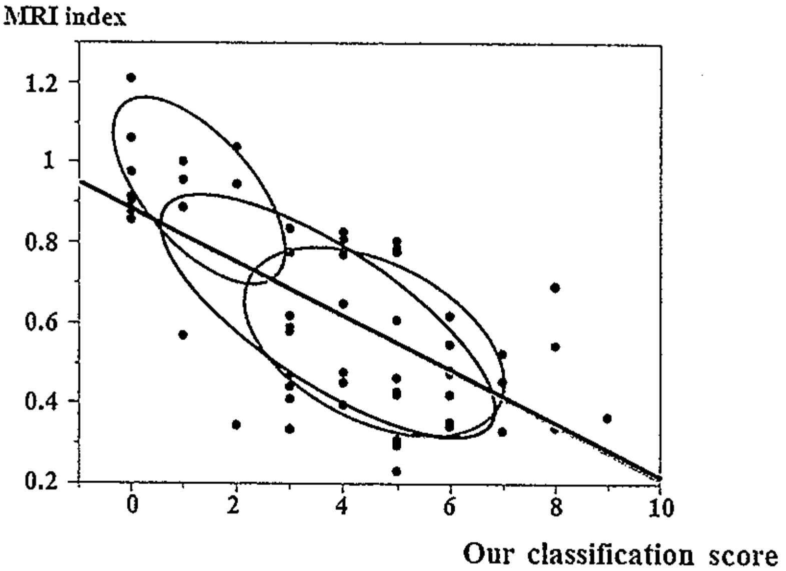

Fig 5. Correlation analysis between our histological score and MRI index. The blue, black, and red dots indicate the ventral, dorsal, and central region cases, respectively. Ovals indicate 50% confidence ellipse with bivariate normal distribution of each region.

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Table 1. Multiple regression analysis to identify significant variable for the degenerative intervertebral discs.

	Punctured region	Time point
35G		
Pfirrmann grade	< 0.01*	0.99
MRI index	< 0.01*	0.03**
Classification by us	0.04*	0.20
33G		
Pfirrmann grade	< 0.01*	0.34
MRI index	< 0.01*	0.13
Classification by us	< 0.01*	0.27

Numerical values indicate p values.
*Statistically significant.
**Not significant as a result of Tukey HSD test.

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significantly higher compared with that for the non-punctured IVDs. However, in the MRI analysis, no significant degenerative IVD difference was observed between the ventrally punctured and the non-punctured control groups (Table 2) (Fig 6).

In addition to the total score, AF and NP scores were separately analyzed. The single regression analysis was used to determine whether the postoperative time point was significant variable for NP score or AF score of punctured IVD excluding ventral puncture. For comparisons of NP score of each time point, Tukey HSD test was used. There was no significant change in the AF and NP scores, except that both 8- and 12-week NP scores were significantly higher compared to 1-week NP score in the 33G needle puncture group (data not shown). As for IVD height and width, the single regression analysis was also used to determine whether the postoperative time point is significant variable for IVD height and width of punctured IVD excluding ventral puncture. The L4/5 IVD punctured with either the 35G or the 33G needle showed an approximately 10% decrease in IVD height and approximately 20% (35G) or 30% (33G) increase in IVD width 1 week after the puncture compared to L3/4 non-punctured control IVD. However, there was no significant difference in IVD height and width among each time point (data not shown).

Center of the nucleus pulposus (NP) was deviated dorsally in IVD

From the anatomical point of view, we measured the deviation of the NP center relative to the IVD center in 77 intact mouse lumbar IVDs. To match the results of the punctured regions

Table 2. Punctured region and intervertebral disc degeneration compared to the control.

	Central region	Dorsal region	Ventral region
35G			
Pfirrmann grade	> Control*	> Control *	= Control
MRI index	< Control *	< Control *	< Control
Our classification score	> Control *	> Control *	> Control *
33G			
Pfirrmann grade	> Control *	> Control *	> Control
MRI index	< Control *	< Control *	< Control
Our classification score	> Control *	> Control *	> Control *

*p < 0.05.

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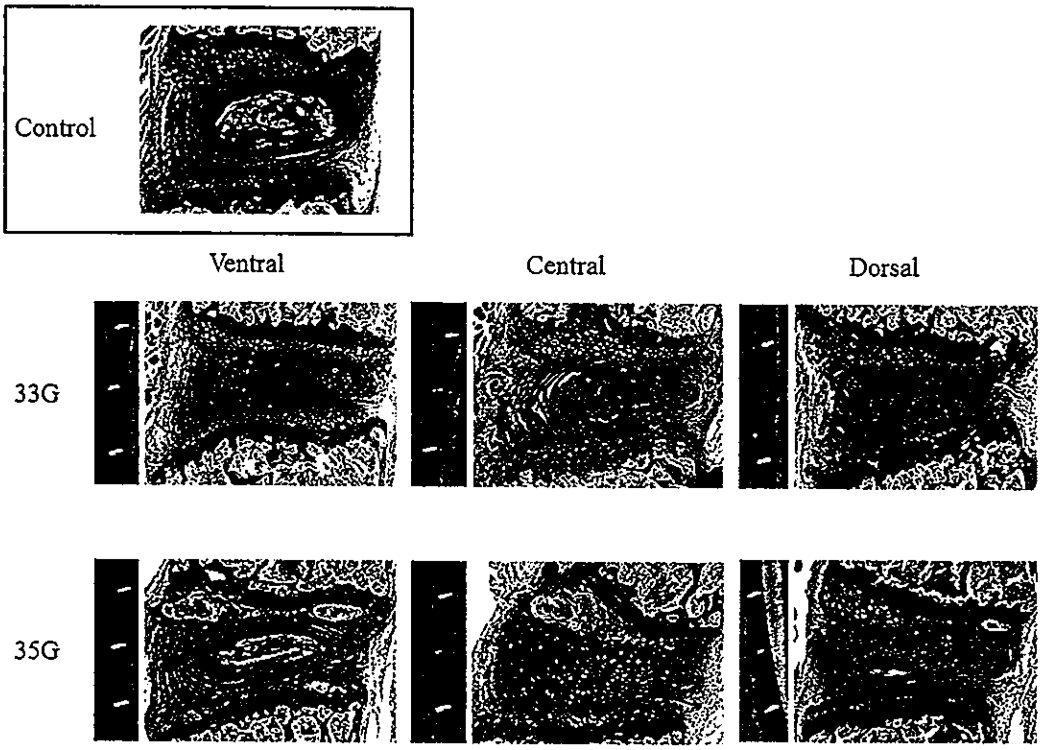

Fig 6. Punctured region and intervertebral disc degeneration. Representative magnetic resonance imaging and histological images at four weeks after puncturing with 35- and 33-gauge needles.

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based on the CT scan images and histological evaluations, the AF was measured on the space prescribed by the endplates. After the NP position was determined visually, the measurement was performed using Image J software (National Institutes of Health, Bethesda, Maryland, USA). The width of ventral AF, the dorsal deviation of the NP center relative to the IVD center, and the width of the dorsal AF were calculated as proportion relative to the major axis of the IVD. The average amount of the NP deviation (7%) corresponded to the difference in width between the average ventral (28%) and average dorsal AF (15%): the ventral site of AF is thicker compared to the dorsal site (Fig 7).

Intervertebral disc degeneration and needle size

Based on either the MRI (Table 3) or the histological analysis by our classification (Table 4), the IVD punctured with the 33G needle showed more degenerative changes compared with the IVDs punctured with the 35G needle. Regarding the vascularization and mineralization of the end plate, there was no certain findings in this puncture model (data not shown). In the sham group, both the MRI and histological findings were normal.

Discussion

Although it is ideal to use an age-related IVD degeneration mouse model to investigate the mechanisms of IVD degeneration, some genetically modified mice have short life spans [23,24]. To overcome this limitation, an *in vivo* mouse IVD degeneration model induced by needle puncture is needed. There may be a criticism that the IVD of a quadruped animal was

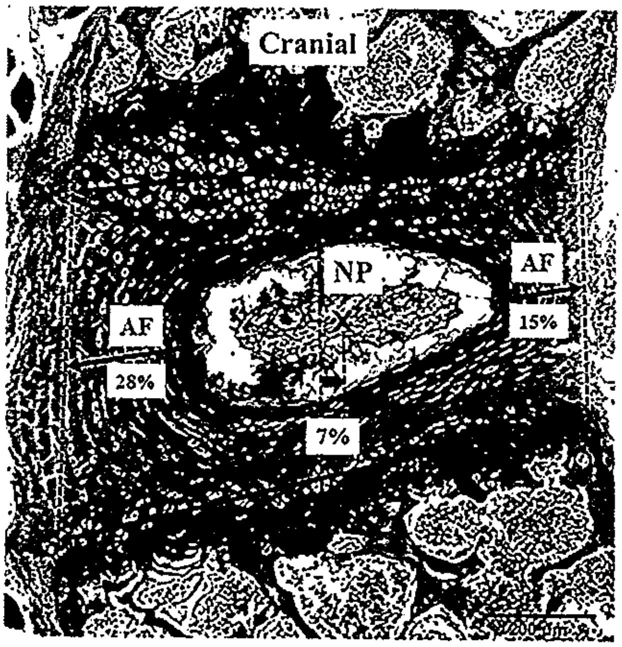

Fig 7. The mid-sagittal slice of the lumbar intervertebral disc (IVD). The nucleus pulposus (NP) center was deviated dorsally relative to the IVD center. In 77 intact mouse lumbar IVDs, the width of ventral annulus fibrosus (AF), the dorsal deviation of the NP center relative to the IVD center, and the width of dorsal AF were calculated as proportion relative to the major axis of the IVD. The average amount of NP deviation (7%) corresponded to the difference in width between the average ventral (28%) and the average dorsal AF (15%): the ventral site of AF is thicker compared to the dorsal site.

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used as an alternative to the bipedal human IVD. However, Elliott et al. [25] reported that the mouse discs, when normalized for geometry, they represented well the mechanical properties of the human lumbar spine. Their findings provided strong support for the use of the rodent model in the study of human disc function, disease, and degeneration. In addition, they found

Table 3. Intervertebral disc degeneration and needle size.

	35G	33G	P
Pfirrmann grade			
1-week	2.50 ± 0.71	3.71 ± 1.11	0.03*
2-week	2.54 ± 0.88	4.30 ± 0.82	< 0.01*
4-week	2.43 ± 1.13	4.50 ± 0.53	< 0.01*
8-week	2.50 ± 0.85	4.60 ± 0.70	< 0.01*
12-week	2.50 ± 0.93	4.22 ± 0.83	< 0.01*
MRI index			
1-week	0.71 ± 0.14	0.47 ± 0.11	< 0.01*
2-week	0.54 ± 0.23	0.34 ± 0.09	0.01*
4-week	0.62 ± 0.29	0.34 ± 0.09	0.04*
8-week	0.51 ± 0.17	0.34 ± 0.15	0.02*
12-week	0.49 ± 0.20	0.34 ± 0.10	0.08

Ventral puncture data were removed from groups.
*Statistically significant.

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Table 4. Intervertebral disc degeneration and needle size.

	35G	33G	P
Our classification score			
1-week	5.10 ± 1.91	4.86 ± 1.57	0.73
2-week	4.15 ± 1.82	6.30 ± 2.83	0.08
4-week	4.00 ± 3.00	6.70 ± 2.54	0.11
8-week	5.20 ± 2.66	7.30 ± 1.25	0.05*
12-week	2.88 ± 1.73	7.11 ± 1.69	< 0.01*

Ventral puncture data were removed from groups.

*Statistically significant.

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that some geometrical and mechanical properties correlated with the animal body weight in the lumbar spine but no parameter correlated in the tail spine, suggesting that the lumbar spine is a more appropriate model of the bipedal human spine than is the tail spine. [25,26] This is because the loading from the animal body weight may be transferred to the rodent lumbar spine.

To our knowledge, there is only one report of mouse lumbar IVD degeneration model induced by needle puncture [27]. However, there were some limitations to that study: short duration of follow-up, small number of cases, and subjective histological evaluation [27]. In addition, they punctured consecutive three discs in one mouse (L4/5, 5/6, 6/S1), and they evaluated the punctured status by using naked eye observation only [27]. In contrast, in our study, the number of mice was greater than 10 for each time point, and the follow-up periods were of up to 12 weeks. In addition, we used four histological classification scores. Only one lumbar IVD per mouse was punctured, and the punctured status was verified by CT scanning.

Masuda et al. [11] were the first to establish a rabbit model of disc degeneration based on puncturing the AF with a needle and evaluating the IVD degeneration by their original grading system for histology. Nishimura et al. [22] also evaluated IVD degeneration by their original grading system for rat IVD. Furthermore, Yang et al. [9] evaluated IVD degeneration by their original grading system for mice IVD. In the present study, the classification by Masuda et al. [11] showed a severe score even at early time points. In their classification, the AF grade received the maximum score when 30% of the AF fibers were serpentine, and the NP grade received the maximum score when NP was moderately condensed. In mice, those findings commonly appeared at the early stage or in mild degeneration. In the sections "border between the AF and NP" and "cellularity of the NP," the same problem appeared. In the classification by Nishimura et al. [22], scores were condensed to 0 to 2 points. In their classification, NP was not evaluated. With reference to the mice, the degenerative changes in NP were drastic even in the early stage, meaning that by excluding the NP from the evaluation of IVD degeneration leads to underestimation. In the classification by Yang et al. [9], scores were condensed to 5 to 6 points, indicating that the classification could not differentiate severe degeneration. Consequently, neither classification could detect the gradual progression of the IVD degeneration. In contrast, our classification could classify precisely the gradual degenerative changes for mouse AF and NP, and combine them as a total degeneration score.

In the present study, by using our histological score, the punctured IVD showed significant degeneration irrespective of the punctured region. However, in the MRI analysis, there was no significant degenerative IVD change between the ventrally punctured and the non-punctured control groups. We also found that the ventral site of AF is thicker than the dorsal site. Thus, the biomechanical effects of needle puncture on IVD degeneration is thought to be less severe.

Furthermore, the center of NP was deviated dorsally in IVD. NP plays central role in the biological reaction in the IVD [1,17]. Due to these anatomical characteristics and subsequent biomechanical/biological reasons, the degenerative change in the IVDs punctured through the ventral region was significantly milder compared to those of the IVDs punctured through the central or the dorsal region. To expand the versatility of the evaluation for IVD degenerative change to the MRI analysis, we recommend that the central or dorsal region be punctured.

Based on previous reports [14,27], we established the needle sizes as 35G and 33G. According to Elliot et al. [14], the ratio of the needle diameter to the punctured IVD height needed to exceed 0.4 to induce significant degeneration. Thus, in order to not destroy the IVD by a single puncture and induce subsequent degeneration, 35G (ratio 0.5) and 33G (ratio 0.87) were considered as reasonable diameters. Considering the severity of IVD degeneration, we recommend the use of the 35G model for the study of the IVD degeneration adjustment and the 33G model for the study of the IVD regeneration.

The present results also showed that the "time point" was not a predictive variable of the degenerative outcomes. Accordingly, the differences in Pfirrmann grades, the MRI indexes, and our histological classification scores among the 1-, 2-, 4-, 8-, and 12-week points were not significant. Therefore, we concluded that the mouse IVD degeneration induced by needle puncture progressed drastically in one week and then plateaued. This result suggests that one to two weeks of follow-up is sufficient for evaluating the degenerative outcome of the punctured IVD.

In conclusion, this study investigated the IVD region by puncturing with a needle with micro-CT scanning and the severity of the degeneration. Puncturing through the ventral region may not induce efficient degeneration. To induce significant degeneration in the lumbar IVD, the central or dorsal region should be punctured. In any case, our classification can detect the gradual progression of the degenerative changes. Based on the present results, researchers may replace the micro-CT scanning with high-resolution fluoroscopy for assistance in puncturing the central or dorsal region.

Author Contributions

Conceived and designed the experiments: TO HS.

Performed the experiments: TO HS.

Analyzed the data: TO HS KI TT YMI NI.

Contributed reagents/materials/analysis tools: HS.

Wrote the paper: TO HS.

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Clinical Study

Correlation analysis between change in thoracic kyphosis and multilevel facetectomy and screw density in main thoracic adolescent idiopathic scoliosis surgery

Hideki Sudo, MD[a,*], Yuichiro Abe, MD[b], Terufumi Kokabu, MD[a], Manabu Ito, MD[c], Kuniyoshi Abumi, MD[d], Yoichi M. Ito, PhD[e], Norimasa Iwasaki, MD[a]

[a]*Department of Orthopaedic Surgery, Hokkaido University Hospital, North-15, West-7, Kita-ku, Sapporo, Hokkaido 060-8638, Japan*
[b]*Department of Orthopaedic Surgery, Eniwa Hospital, Koganemachi 2-1, Eniwa, Hokkaido 061-1449, Japan*
[c]*Department of Spine and Spinal Cord Disorders, Hokkaido Medical Center, Yamanote 5-7, Sapporo, Hokkaido 063-0005, Japan*
[d]*Department of Orthopaedic Surgery, Sapporo Orthopaedic Hospital, Hassamu 13-4, Sapporo, Hokkaido 063-0833, Japan*
[e]*Department of Biostatistics, Hokkaido University Graduate School of Medicine, North-15, West-7, Kita-ku, Sapporo, Hokkaido 060-8638, Japan*

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Abstract

BACKGROUND CONTEXT: Controversy exists regarding the effects of multilevel facetectomy and screw density on deformity correction, especially thoracic kyphosis (TK) restoration in adolescent idiopathic scoliosis (AIS) surgery.

PURPOSE: This study aimed to evaluate the effects of multilevel facetectomy and screw density on sagittal plane correction in patients with main thoracic (MT) AIS curve.

STUDY DESIGN: A retrospective correlation and comparative analysis of prospectively collected, consecutive, non-randomized series of patients at a single institution was undertaken.

PATIENT SAMPLE: Sixty-four consecutive patients with Lenke type 1 AIS treated with posterior correction and fusion surgery using simultaneous double-rod rotation technique were included.

OUTCOME MEASURES: Patient demographics and preoperative and 2-year postoperative radiographic measurements were the outcome measures for this study.

METHODS: Multiple stepwise linear regression analysis was conducted between change in TK (T5–T12) and the following factors: age at surgery, Risser sign, number of facetectomy level, screw density, preoperative main thoracic curve, flexibility in main thoracic curve, coronal correction rate, preoperative TK, and preoperative lumbar lordosis. Patients were classified into two groups: TK<15° group defined by preoperative TK below the mean degree of TK for the entire cohort (<15°) and the TK≥15° group, defined by preoperative TK above the mean degree of kyphosis (≥15°). Independent sample *t* tests were used to compare demographic data as well as radiographic outcomes between the two groups. There were no study-specific biases related to conflicts of interest.

RESULTS: The average preoperative TK was 14.0°, which improved significantly to 23.1° (p<.0001) at the 2-year final follow-up. Greater change in TK was predicted by a low preoperative TK (p<.0001). The TK <15° group showed significant correlation between change in TK and number of facetectomy level (r=0.492, p=.002). Similarly, significant correlation was found between change in TK and screw density (r=0.333, p=.047). Conversely, in the TK ≥15° group, correlation was found neither between change in TK and number of facetectomy level (r=0.047, p=.812), nor with screw density (r=0.030, p=.880). Furthermore, in patients with preoperative TK<15°, change in TK was significantly correlated with screw density at the concave side (r=0.351, p=.036) but not at the convex side (r=0.144, p=.402).

FDA device/drug status: Approved (USS II Polyaxial).

Author disclosures: *HS:* Nothing to disclose. *YA:* Nothing to disclose. *TK:* Nothing to disclose. *MI:* Nothing to disclose. *KA:* Nothing to disclose. *YMI:* Nothing to disclose. *NI:* Nothing to disclose.

* Corresponding author. Department of Advanced Medicine for Spine and Spinal Cord Disorders, Hokkaido University Graduate School of Medicine, North-15, West-7, Kita-ku, Sapporo, Hokkaido 060-8638, Japan. Tel.: +81 11 706 5934; fax: +81 11 706 6054.

E-mail address: hidekisudo@yahoo.co.jp (H. Sudo)

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CONCLUSIONS: In patients with hypokyphotic thoracic spine, significant positive correlation was found between change in TK and multilevel facetectomy or screw density at the concave side. This indicates that in patients with AIS who have thoracic hypokyphosis as part of their deformity, the abovementioned factors must be considered in preoperative planning to correct hypokyphosis.

Keywords: Adolescent idiopathic scoliosis; Facetectomy; Lenke type 1 scoliosis; Posterior spinal correction and fusion; Screw density; Thoracic kyphosis

Introduction

Posterior spinal correction and fusion with segmental pedicle screw (PS) instrumentation is currently used for the correction of many types of scoliosis. Patients with a primary thoracic adolescent idiopathic scoliosis (AIS) are typically hypokyphotic relative to non-scoliosis patients [1]; therefore, restoration and maintenance of normal sagittal contour as well as satisfactory coronal correction of the main thoracic (MT) curve have been receiving increased attention of late [1–4]. Thoracic hypokyphosis of less than 20° has been correlated with decreased pulmonary function [5]. However, recent studies have reported that PS constructs to maximize scoliosis correction cause further lordosis of the thoracic spine [4,6,7]. These patients would not only demonstrate further decrease of pulmonary function but also show a flat back leading to progressive decompensation and sagittal imbalance [1,8]. Preservation of thoracic kyphosis (TK) is critical to maintain lumbar lordosis after surgical treatment of AIS [1]. To overcome these issues, Ito et al. [9] and Sudo et al. [10,11] recently developed a very simple surgical technique called the simultaneous double-rod rotation technique (SDRRT) for correcting AIS. In this technique, two rods are connected to the screw heads and are simply rotated simultaneously to correct the scoliosis, while TK is maintained or improved. Moreover, hypokyphotic rod deformation is prevented with dual-rod derotation compared with that with single-rod derotation [9–11].

Posterior distraction at each concave-side spinal segment is important for optimal correction in both coronal and sagittal planes [10,11]. In addition, some studies investigated the correlation between scoliosis curve correction and destabilization procedures, such as multilevel facetectomy [12], or scoliosis correction and the number of fixation anchors, such as PS density [13–16]. However, controversy exists regarding the effects of facetectomy and screw density on deformity correction, especially TK restoration in AIS surgery [16]. The purpose of this study is to evaluate the effects of multilevel facetectomy or screw density on sagittal plane correction in patients with MT AIS curve treated with SDRRT.

Materials and methods

After institutional review board approval, data from 64 consecutive patients (7 males, 57 females) with Lenke type 1 AIS curves were retrospectively evaluated; the patients underwent posterior MT curve correction using SDRRT with a minimum 2-year follow-up from June 2008 to September 2015 at our institution. Exclusion criteria included syndromic (n=14), neuromuscular (n=6), and congenital scoliosis (n=14), and the presence of other thoracic scoliosis curves such as Lenke type 2 double thoracic curves (n=25). No case was lost to follow-up. The average age and Risser sign at surgery were 14.8 (range, 10–20) and 3.6 (range, 0–5) years, respectively (Table 1).

Standing long-cassette posteroanterior and lateral radiographs were evaluated for multiple parameters before surgery and at the 2-year follow-up. Main thoracic curve flexibility was evaluated using preoperative supine bending radiographs. Coronal and sagittal Cobb measurements of MT curves were obtained. The end vertebrae levels were determined on preoperative radiographs and measured on subsequent radiographs to maintain consistency for statistical comparisons [10,11]. Sagittal measurements included TK (T5–T12) and lumbar lordosis (L1–S1) [10,11].

The number of facetectomy levels was counted, and screw density was expressed as the number of screws per level instrumented for each patient.

Surgical technique

Fusion level selection was based on both standing and bending films, and instrumentation levels were determined from end-to-end vertebrae on standing films in most cases. Vertebrae without rotation on bending films were selected as the lowest instrumented vertebra [10]. Surgeries were performed as described previously [9–11]. In brief, after exposure of the posterior spinal elements, side-loading polyaxial PSs (USS II Polyaxial, DePuy Synthes, Raynham, MA, USA) were placed. If PS placement was difficult at the most cephalad vertebra because of its narrowness, a transverse process hook was used. After a multilevel facetectomy, two rods measuring 6 mm in diameter were bent to the anticipated TK. After connecting the two rods to all screw heads, the rod on the concave side should be rotated gently with two rod holders. The convex rod will automatically rotate following the rotation of the concave rod in flexible curves. However, for rigid curves, the assisting surgeons should rotate the rod on the convex side simultaneously to make rod rotation smoother and safer. After 90° rod rotation, several screw heads were tightened to lock the rods. Distraction force was first applied

EVIDENCE & METHODS

Context
The authors sought to evaluate the effect of multilevel facetectomy and screw density on sagittal plane correction in 64 consecutive patients with main thoracic AIS curves.

Contribution
The authors performed a multivariable analysis evaluating a number of potential explanatory factors. When adjusting for other variables, multilevel facetectomy and screw density were found to be significantly correlated with correction.

Implications
This study has a limited number of patients in the sample, albeit consecutive in nature. Given the number of variables included in the model, the authors would have required about 200 patients to ensure the model is not overfit. Given that they have only 64, there is the potential for spurious statistical findings to be present. This along with differences in demographic composition between these patients and those treated at other centers should be considered prior to attempted translation of this study's findings to clinical practice. Given these limitations, the study presents Level IV evidence.

—*The Editors*

on each screw head on the concave side of the thoracic curve, such that not only scoliosis but also TK could be corrected more effectively by lengthening the posterior column. Then, compression force was applied segmentally on the convex curve. An in situ rod-bending maneuver was not conducted during the surgery. Local bone grafting followed decortication of the laminae. A brace was not required in any patient.

Table 1
Demographic characteristics and clinical features of the subjects

	Mean±standard deviation	Range
Age at surgery (y)	14.8±2.3	10 to 20
Risser sign (grade)	3.6±1.4	0 to 5
No. vertebrae in fusion	10.2±1.5	7 to 13
Screw density (no. of screws/level instrumented)	1.7±0.2	0.7 to 2
Preoperative main thoracic Cobb (°)	62.0±10.0	45 to 90
Flexibility in main thoracic curve (%)	61.3±13.8	31 to 93
Postoperative main thoracic Cobb (°)	17.2±6.2	4 to 31
Coronal correction rate (%)	72.3±9.0	55 to 92
Preoperative thoracic kyphosis (T5–T12) (°)	14.0±9.6	−4 to 55
Postoperative thoracic kyphosis (T5–T12) (°)	23.1±5.3	13 to 30
Change in thoracic kyphosis (T5–T12) (°)	9.1±8.9	−31 to 24
Preoperative lumbar lordosis (L1–S1) (°)	51.5±11.7	19 to 75
Postoperative lumbar lordosis (L1–S1) (°)	53.2±9.3	24 to 70
Change in lumbar lordosis (L1–S1) (°)	1.3±8.9	−20 to 32

Statistical analysis

All data are expressed as mean±standard deviation. Multiple stepwise linear regression analysis was applied to control possible confounding variables and to identify variables independently predictive of change in TK (at 2-year follow-up, preoperative measurements). The following covariates were tested in the multivariate regression analysis: age at surgery, Risser sign, number of facetectomy level, screw density, preoperative MT curve, flexibility in MT curve, coronal correction rate, preoperative TK, and preoperative lumbar lordosis. Significant multivariate predictors of change in TK are reported with their respective predictive equations, including the intercept and regression coefficients (β). Model fit was assessed by the goodness-of-fit F test and R^2 statistic. Independent sample *t* tests were used to compare between-group differences in demographic data. Pearson correlation coefficient and Spearman correlation coefficient analysis were used to assess relationships between change in TK and number of facetectomy level or screw density. Data analyses were performed using JMP statistical software for Windows (version 12; SAS, Inc., Cary, NC, USA). $p<.05$ was considered statistically significant.

Results

Demographic data are summarized in Table 1. On average, 10.2 vertebrae were instrumented in the 64 patients. The average screw density was 1.7. The average preoperative MT curve was 62.0°. The average preoperative MT curve flexibility on bending radiographs was 61.3% (range, 31%–93%). Postoperative radiographs showed an average MT curve of 17.2°. The average MT curve correction rate was 72.3% (range, 55%–92%). Sagittal plane analysis revealed that the average preoperative TK was 14.0° (range, from −4° to 55°), which improved significantly to 23.1° (range, 13°–30°; $p<.0001$) at the 2-year final follow-up. The average change in TK was 9.1° (range, from −31° to 24°). Other data regarding lumbar lordosis are also presented in Table 1.

Multiple stepwise linear regression analysis indicated that two variables were independently predictive of change in TK: number of facetectomy level and preoperative TK. The model fit the data well (goodness-of-fit F test=27.010, R^2=0.871, $p<.0001$), indicating that approximately 87% of the variation in change in TK was explained by the two significant independent predictors. Specifically, greater change in TK was predicted by a low preoperative TK ($p<.0001$) (Table 2).

Subgroup analysis

The cohort was then divided into two groups on the basis of preoperative TK. The preoperative TK<15° group was defined by preoperative TK below the mean degree of the kyphosis for the entire cohort (<15°). The preoperative TK≥15° group was defined by preoperative TK above the mean degree of the kyphosis (≥15°). The TK<15° group consisted of 36 patients, whereas the TK≥15° group had 28 patients. Both

Table 2
Associations between various factors and change in thoracic kyphosis (°) using multiple stepwise linear regression analysis

	Regression coefficient	Standard error	95% Confidence interval	t	Standardized β	p
Constant	17.431	12.550	(−7.933, 42.794)	1.39	—	.173
Age at surgery (y)	−0.104	0.509	(−1.132, 0.924)	−0.20	−0.023	.839
Risser sign (grade)	−0.193	0.676	(−1.560, 1.173)	−0.29	−0.028	.7763
Number of facetectomy level (no.)	0.668	0.212	(0.239, 1.097)	3.15	0.2116	.003
Screw density (no. of screws/level instrumented)	−2.120	3.349	(−8.888, 4.649)	−0.63	−0.043	.530
Preoperative main thoracic Cobb (°)	−0.067	0.071	(−0.2111, 0.077)	−0.94	−0.076	.351
Flexibility in main thoracic curve (%)	7.620	4.13	(−0.731, 15.971)	1.84	0.118	.073
Coronal correction rate (%)	0.033	0.025	(−0.018, 0.085)	1.32	0.087	.193
Preoperative thoracic kyphosis (T5–T12) (°)	−0.789	0.066	(−0.922, −0.656)	−12.00	−0.841	<.0001
Preoperative lumbar lordosis (L1–S1) (°)	−0.048	0.087	(−0.224, 0.128)	−0.55	−0.061	.586

groups were similar at baseline with respect to the following parameters: age, Risser sign, preoperative MT Cobb angle, flexibility of MT curve, and correction rate of MT Cobb angle. In addition, no difference was found between the groups regarding number of facetectomy level and screw density. Conversely, significant difference was observed between the groups regarding change in TK (p<.001) and preoperative lumbar lordosis (p=.018) (Table 3).

The TK<15° group showed significant correlation between change in TK and number of facetectomy level (Pearson: r=0.492, p=.002; Spearman: r_s=0.541, p=.007). Similarly, significant correlation was found between change in TK and screw density (Pearson: r=0.333, p=.047; Spearman: r_s=0.397, p=.016). Conversely, in the TK≥15° group, correlation was found neither between change in TK and number of facetectomy level (Pearson: r=0.047, p=.812; Spearman: r_s=0.155, p=.431), nor with screw density (Pearson: r=0.030, p=.880; Spearman: r_s=0.110, p=.576) (Table 4).

Finally, correlation analysis was conducted between change in TK and screw density in the TK<15° group. Change in TK was significantly correlated with screw density at the concave side (Pearson: r=0.351, p=.036; Spearman: r_s=0.318, p=.058), whereas no correlation was found between change in TK and screw density at the convex side (Pearson: r=0.144, p=.402; Spearman: r_s=0.122, p=.480) (Table 5).

Table 3
Comparison of two groups

	Preop thoracic kyphosis <15° (n=36)	Preop thoracic kyphosis ≥15° (n=28)	p
Age at surgery	14.9±2.2	14.7±2.5	.689
Risser sign	3.8±1.2	3.3±1.7	.182
Preoperative Cobb angle	60.3±8.9	64.1±11.0	.129
Flexibility of thoracic curve (%)	63.6±12.9	58.2±14.4	.119
Correction rate of Cobb angle (%)	73.2±9.7	71.1±8.1	.378
Change in thoracic kyphosis	13.7±6.1	3.3±8.5	<.001
Preoperative lumbar lordosis	48.4±11.4	55.4±11.3	.018
Postoperative lumbar lordosis	53.0±9.6	53.0±9.0	.998
Number of facetectomy level	5.0±2.9	5.3±2.8	.756
Screw density	1.8±0.3	1.7±0.2	.060

Discussion

Given that thoracic AIS is often associated with a preexisting reduction in TK, ideal surgical correction should address this deformity [1]. However, posterior spinal correction and fusion using segmental PS has decreased ability to restore kyphosis in hypokyphotic thoracic cases [4,6,17]. Lowenstein et al. [4] reported that the PS system decreased TK by an average of 10°, whereas Kim et al. [6] reported an average decrease of 9°. In addition, when using the direct vertebral rotation technique to decrease rotational deformity around the

Table 4
Correlation analysis between change in thoracic kyphosis (°) and variable

			Pearson correlation coefficients			Spearman correlation coefficient		
Variable	Mean±SD	Range	Correlation coefficient	95% CI	Statistical significance	Correlation coefficient	95% CI	Statistical significance
Preoperative thoracic kyphosis <15°								
Number of facetectomy level (no.)	5.0±2.9	3–11	r=0.492	(0.196, 0.707)	p=.002	r_s=0.541	(0.287, 0.752)	p=.007
Screw density (no. of screws/level instrumented)	1.8±0.3	0.7–2	r=0.333	(0.048, 0.596)	p=.047	r_s=0.397	(0.088, 0.647)	p=.016
Preoperative thoracic kyphosis ≥15°								
Number of facetectomy level (no.)	5.3±2.8	3–10	r=0.047	(−0.332, 0.413)	p=.812	r_s=0.155	(−0.194, 0.528)	p=.431
Screw density (no. of screws/level instrumented)	1.7±0.2	1.2–2	r=0.030	(−0.347, 0.399)	p=.880	r_s=0.110	(−0.336, 0.409)	p=.576

SD indicates standard deviation; CI, confidence interval.

Table 5
Correlation analysis between change in thoracic kyphosis (°) and screw density in patients with preoperative thoracic kyphosis <15°

			Pearson correlation coefficients			Spearman correlation coefficient		
Variable	Mean±SD	Range	Correlation coefficient	95% CI	Statistical significance	Correlation coefficient	95% CI	Statistical significance
Concave side screw density (no. of screws/level instrumented)	0.9±0.2	0.3–1	r=0.351	(0.026, 0.610)	p=.036	r_s=0.318	(0.049, 0.624)	p=.058
Convex side screw density (no. of screws/level instrumented)	0.9±0.1	0.5–1	r=0.144	(−0.193, 0.452)	p=.402	r_s=0.122	(−0.239, 0.413)	p=.480

SD, standard deviation; CI, confidence interval.

apex of the thoracic curve, the major applied force pushes the thoracic hump downward to decrease vertebral rotation deformity, which eventually causes dekyphosis of the thoracic spine [10].

Conversely, in SDRRT, once the two rods are connected to the screw heads, they are simply rotated simultaneously, resulting in correction of spinal deformity in the coronal and the sagittal planes without using the in situ rod-bending technique [9–11]. Two contoured rods carry the tips of the two screw heads upward and medially to the concave side of the curve, which does not exert any downward force on the vertebral body [9,10]. Both polyaxial screw head and simultaneous double-rod rotation are key to the current technique. Frictional force at the screw–rod interface is decreased, and there is little chance of screw cutout laterally. This technique provided derotation of the apical vertebra as well as restoration of thoracic kyphosis leading to rib hump correction without additional costoplasty. The present study showed that a preoperative TK of 14° increased significantly to 23° at the 2-year follow-up.

Removing the facets and soft tissues between the posterior elements has been indicated to allow greater distraction abilities along the length of the posterior column; however, it is still unclear whether these posterior releases positively affect the sagittal profile of a hyphokyphotic thoracic spine [1]. Halanski and Cassidy [12] documented that no significant difference was observed between multilevel facetectomy and coronal or sagittal correction in thoracic AIS surgery. However, they also indicated that under certain circumstances, such as an extremely stiff curve or kyphoscoliotic deformity, the osteotomy may prove to be very useful [12]. Using three-dimensional-finite element analysis, Abe et al. [18] also reported that mobilization of spinal segment by releasing soft tissue or facet joint could be more important than using a stronger correction maneuver with a rigid implant. In the present study, the number of facetectomy level was an independent predictor of change in TK. In addition, in patients with hypokyphotic thoracic spine <15°, significant correlation was found between change in TK and number of facetectomy level. The present results indicate that multilevel facetectomy is an important factor to restore TK in patients with hypokyphotic thoracic spine.

Another possible factor to optimize correction may be screw density. Larson et al. [14] documented that improved percentage correction of the major coronal curve was noted in the high-screw density cohort. Conversely, some authors have demonstrated successful results with low-density instrumentation for the treatment of scoliosis [13,19–21]. In addition, Clements et al. [22] reported an advantage in lumbar and thoracic coronal curves on using screws, compared with hooks, although the absolute number of screws used did not correlate with correction. In our study, there was significant correlation between MT coronal curve correction and screw density (r=0.296, p=.018). In addition, significant correlation was observed between MT coronal curve correction and screw density at the concave side (r=0.495, p<.001). However, no significant correlation was observed between MT coronal curve correction and screw density at the convex side (r=−0.150, p=.237). Recently, similar results were reported that only instrumentation at the concave side, particularly at the apical region, was associated with coronal curve correction [15].

As for TK, the effect of implant density on sagittal plane correction and TK restoration has been reported in only a few studies, and the results have been controversial [3,14,16]. Lonner et al. [3] reported that a greater percentage of screws in the construct was related to decreasing kyphosis at 2 years postoperatively (r=−0.18, p=.03). Larson et al. [14] also revealed that decreased TK was found with increased screw density for Lenke type 1 and 2 curves. Conversely, Liu et al. [16] documented that higher screw density provided better TK restoration than low screw density. In the present study, in patients with preoperative TK<15°, significant positive correlation was found between change in TK and screw density, whereas no correlation was found in patients with TK≥15°, suggesting that screw density had a positive effect on TK restoration in patients with hypokyphotic thoracic spine.

In the current study, in patients with preoperative TK<15°, change in TK was significantly correlated with screw density at the concave side, whereas no correlation was found with the screw density at the convex side. Liu et al. [16] also reported similar results although they did not perform correlation analysis between change in TK and screw density. Salmingo et al. [23] recently analyzed the changes of the implant rod's angle curvature during AIS surgery and showed that implant rod curvature greatly influences sagittal curve correction. In addition, they revealed that the implant rods at the concave side of deformity were significantly deformed after surgery, whereas rods at the convex side did not have significant deformation, suggesting that corrective forces acting on that side are greater than those on the convex side [23]. From a mechanical point of view, the translational and rotational displacement required for correction at the concave side is always greater than at the convex side, which also results to greater corrective forces at that side [23]. If this corrective force is stronger than the resistant force from the spine and greater than the pullout force from the screw–bone interaction, the spine would follow the shape of the rod [16]. Increased friction at the screw–rod interface that occurs with higher screw density at the concave side would prevent flattening of the contoured rod in the sagittal plane after rod rotation [16]. Due to the aforementioned reasons, the present study indicates that concave-side, rather than convex-side, screw density had an impact on not only scoliosis correction but also TK restoration.

There are some limitations to this study that should be addressed. First, we did not analyze the relationship between rod deformation during surgery and multilevel osteotomy and screw density. We are now collecting pre-bent and postoperative rod geometries from intraoperative tracing of the rod geometry and postoperative three dimensional-computed tomography images, respectively. Second, the relationships between multilevel osteotomy and screw density and clinical symptoms remain unclear.

Conclusions

In the patients with hypokyphotic thoracic spine, significant positive correlation was found between change in TK and multilevel facetectomy or screw density at the concave side. The results indicated that in patients with AIS who have thoracic hypokyphosis as part of their deformity, these factors must be taken into account in the preoperative planning to correct hypokyphosis.

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北海道における低侵襲脊椎外科 ー現状と課題ー

最小侵襲脊椎安定術（MISt）の現状と課題 〜mini-open TLIFの臨床成績から〜

小松　幹，須田　浩太

北海道せき損センター

は じ め に

高齢化が進行し，合併症を多く抱えるハイリスク患者が増加するなかで，脊椎外科領域も低侵襲手術の必要性が高まっている．脊椎外科においては鏡視下手術による腰椎椎間板ヘルニアや脊柱管狭窄症に対する手術を皮切りとして最小侵襲脊椎手術（Minimally invasive spine surgery：MISS）は普及してきたが，2009年にMISSの一分野として，最小侵襲脊椎安定術（Minimally invasive spine Stabilization：MISt）が提唱され，注目されている[1]（表１）．

当院では以前から不安定性のある症例に対し，transforaminal lumbar interbody fusion（TLIF）を行ってきたが，さらに2005年以降は，より低侵襲化を目指して傍脊柱筋間アプローチを併用したmini-open TLIF（以下，mini TLIF）を開発導入しており[7]，その有用性を検討した．

Mini TLIFの手術方法

L４／５単椎間固定を例に説明する．皮膚切開はL４棘突起上端からL５棘突起下端までの正中縦切開のみで全て行われる．L４棘突起から傍脊柱筋付着部をメスで切開し，コブエレベーターで症状優位側の椎間関節外側まで展開する．対側の脊柱管狭窄を合併して除圧が必要な場合には反対側も椎間関節部分まで展開しておく．

次に両側ともに筋間アプローチにて多裂筋の外側から椎間関節外側を展開する[3]．すなわち，傍脊柱筋の棘突起付着部にて腰筋膜と脊柱起立筋腱膜の間を外側に向かって剥離し，棘突起付着部から約３cm外側で脊柱起立筋腱膜をメスで縦割する．内側に多裂筋筋膜をみながら，多裂筋と最長筋の筋間を指で鈍的に分けて椎間関節外側からL４およびL５横突起まで展開する（図１）．このとき症状優位側のL４／５椎間関節は正中アプローチにてすでに展開されているためメルクマールとなる．適当な開創器にて外側開創部を保持する．筆者らは，頭尾側方向はトリムラインを，左右方向はゲルピー鉤を用いることが多い．

外側開創部から両側の椎弓根スクリューを刺入する．椎間関節外側，横突起，副突起を骨膜下に展開し，付着していた筋肉を除去すると，スクリュー刺入点でより正確になるが，侵襲は大きくなる．X線イメージを用いることで軟部組織の上からの刺入が可能となる．

続いて，脊柱管内から椎間孔部の除圧を正中アプローチにて行う．L４下関節突起ならびにL５上関節突起は基部より全切除し，椎間板上縁ならびに下縁を確認する．L４神経根は椎体後壁に沿って神経べらを椎弓根方向に滑らせると確認できる．必要に応じてL

表１

最少侵襲脊椎安定術（MISt）	
・MIS-TLIF/PLIF	・Mini-open TLIF/ PLIF
・MIS-long fixation	・XLIF, OLIF/DLIF
・Balloon kyphoplasty（BKP）	・Interspinous process motion-sparing implant（X-stop）
・Cortical bone trajectory（CBT）	・人工椎間関節
・最少侵襲腰仙椎腸骨固定術（S２AIなど）	・Cervical artificial disc
・腰仙椎関節安定術（SI）	・VATS, etc

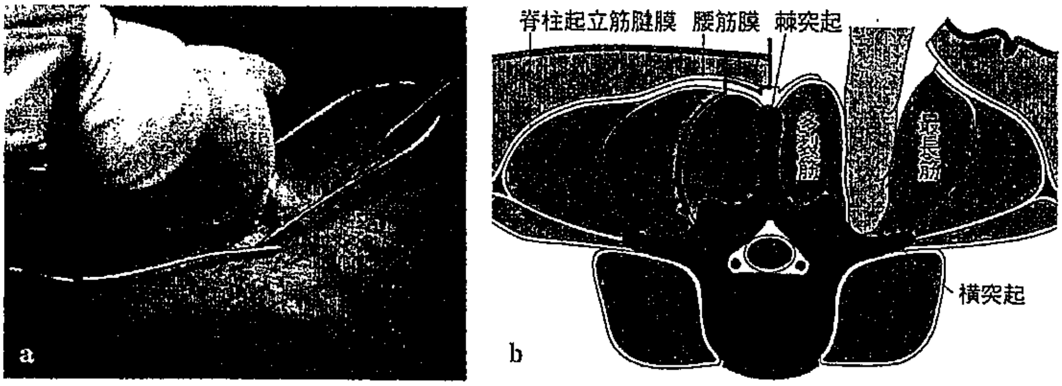

図1　傍脊柱筋間アプローチ（文献3より転載）
棘突起付着部から約3cm外側で，脊柱起立筋腱膜をメスで縦割し，内側に多裂筋筋膜をみながら，多裂筋と最長筋の筋間を指で鈍的に分けて，椎間関節外側に到達する

4下関節突起を椎弓根の方向に頭側に切除を加えて，脊柱管から椎間孔内外へのL4神経根走行を確認する．脊柱管狭窄合併例では，両側の内側椎間関節切除にて脊柱管内除圧を行い，L5神経根を確認する．

椎間関節全切除を行った症状優位側から片側進入TLIFを行う（図2）．L4ならびにL5神経根走行に干渉しない部位に椎間板操作のポータルを作成し，棘突起スプレッダーで椎間板腔を広げながらキュレットを用いて椎間板切除を行う．筆者らは，2個のボックス型の椎体間ケージを設置しているが，反対側のできるだけ遠い位置にケージを設置する際は外側開創部から，進入側手前に設置する際は正中アプローチからと，ケージの設置位置によって使い分けている．

その後，外側開創部から，両側のロッドを設置してインストゥルメンテーションを完成させる．椎間関節の残っている反対側に，必要に応じて後側方固定の追加が可能である．

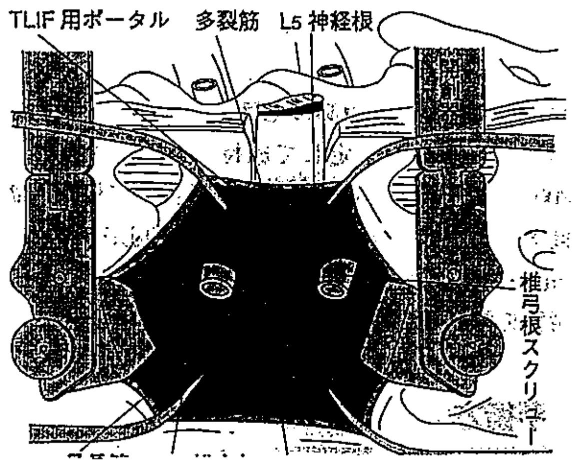

図2　傍脊柱筋間アプローチからの椎体間操作（文献3より転載）
外側開創部から椎弓根スクリューを刺入する．椎間関節全切除を行った症状側から片側進入TLIFを行う．

手術成績

1）対象と方法

2005年4月～2015年3月に，変性すべり症，分離すべり症，変性後側弯症などの不安定性を伴う腰椎疾患に対し，1椎間のmini TLIFを施行した32例（以下mini TLIF群）と従来型TLIFを施行した46例（以下TLIF群）を対象とした．mini TLIF群は男性15例，女性17例，平均年齢61.4歳で，TLIF群は男性30例，女性16例，平均年齢66.0歳であった．手術椎間は，mini TLIF群においてL3／4が6例，L4／5が18例，L5／Sが8例でTLIF群ではL2／3が1例，L3／4が5例，L4／5が36例，L5／Sが4例であった．平均経過観察期間はmini TLIF群が62.5ヶ月，TLIF群が41.7ヶ月であった（表2）．

手術時間，出血量，術前および術後6ヶ月，1年時のRoland Morris Questionnaire（RDQ），Oswestry Disability Index（ODI），骨癒合率，合併症，入院期間，隣接椎間障害に対する追加手術の有無を調査した．

表2

		mini TLIF群	TLIF群
年齢（歳）	平均	61.4	66.0
性別	男性	15	30
	女性	17	16
手術椎間	L2／3	0	1
	L3／4	6	5
	L4／5	18	36
	L5／S	8	4
入院期間（日）	平均	50.9	46.3
経過観察期間（月）	平均	62.5	41.7

2）結果

入院期間はmini TLIF群が50.9日，TLIF群が46.3日で有意差は無かった．手術時間はmini TLIF群が127－437分（平均249分），TLIF群が53－375分（平均123分）でmini TLIF群で優位に長く，それに比例して平均出血量はmini TLIF群が457ml，TLIF群が230mlとmini TLIF群で多かった（表3）．ODIはmini TLIF群が46％－26％－27％，TLIF群が47％－21％－22％で，術後はすべて術前より有意に改善したが両群間に有意差は無かった．一方でRDQの臨床成績はmini TLIF群が12.1－7.0－7.1，TLIF群が11.2－6.9－4.3であり，術後1年ではむしろTLIF群の方が経過良好であった．それぞれ1例の無症候性の偽関節を認め，骨癒合率はmini TLIF群が96.9％，TLIF群が97.8％であった．神経障害や深部感染などの重篤な合併症はなかった．隣接椎間障害に対し手術追加を要した症例はmini TLIF群で3例（9.1％），TLIF群で1例（2.2％）であった．

考　　察

mini TLIFでは手術手技が従来のTLIFと比べ手順が多いため，いかに術式に慣れようとも手術時間がより長くかかることが明らかとなった．それに比例して術中出血量も多くなる．また，これまでの報告[3]とは異なり臨床成績は術後1年の時点では従来式のTLIFの方が優れている可能性も示唆された．

近年経皮的椎弓根スクリューを用いたMIS－TLIFやMIS－long fixationが脚光を浴び，その低侵襲性[2,6]，低い術後感染率[4]，早期離床[5]などが注目されているが，従来式TLIFに将来完全にとって代わる術式であるかどうかは疑問である．従来式TLIFの適応がなかった全身状態の悪い患者や超高齢者においては一定の恩恵があるのは間違いないが，従来式TLIFの手術手技の重要性が失われることはないと感じている．若手脊椎外科医がMISSに傾倒しすぎるあまり，あるいは指導施設で従来式の手術手技に触れる機会が少ない為に，従来式手術手技の習熟度が全体として下がり，応用の効かない脊椎外科医が増えてしまうのではないかという危惧の念さえ抱く．MISSが発展することは患者にとって大いに喜ばしいことで，さらなる進化を期待もするが，今こそ基本的手術手技の重要性を再確認したい．

表3

	mini TLIF	TLIF
手術時間（分）	127－437（平均249）	53－375（平均123）
平均出血量（ml）	457	230

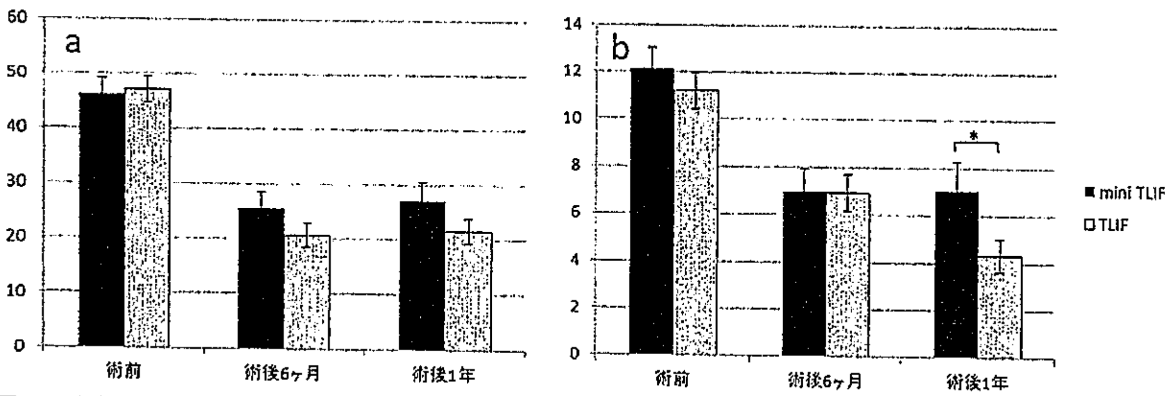

図3　臨床成績
A：ODI B：RDQ　＊：p<0.05

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手術困難なために遅発性麻痺を生じた びまん性特発性骨増殖症（DISH）脊椎骨折の１例

木田　博朗，須田　浩太，松本　聡子，小松　　幹，牛久智加良，
山根　淳一，遠藤　　努，東條　泰明，神谷　行宣，三浪　明男

北海道中央労災病院　せき損センター

要　　旨

遅発性麻痺を生じたDISH（Diffuse idiopathic skeletal hyperostosis）に伴う脊椎骨折の１例を経験した．

症例は86歳女性，転倒後に腰背部痛が出現し，Th12椎体高位でのReverse Chance型骨折と診断された．全身状態不良のため早期手術を断念し保存加療を行ったところ，受傷７日目にFrankel Cの対麻痺が出現した．CTでは骨折部の転位を認めた．手術可能な状態まで全身状態が回復したため後方固定術を施行したが，麻痺の改善は見られなかった．

DISHに伴う脊椎骨折では，骨折部に応力が集中し骨癒合が得られにくく，転位をきたしやすい．高齢者では全身状態が悪く骨脆弱性が著しい症例が多いため，手術困難例や術後合併症例が急増しておりこの傾向はますます強まるものと推察する．警鐘を鳴らす意味で本例を報告する．

緒　　言

DISHは脊椎を中心とした全身の骨格系における素因的な骨過形成症であり，高齢男性に比較的多い．DISHに伴う脊椎骨折は不安定性が強く，急速な麻痺の出現や偽関節がしばしば問題になる．高齢化が進むとともにDISHの脊椎骨折例は増加傾向にあるが，高齢者であるが故に手術限界例も散発しており，今後は全身状態や骨脆弱性のために手術不能な例も増加する可能性が高い．

上記の如く手術困難なため遅発性麻痺を生じたDISHを経験したため文献的考察を加えて報告する．

症　　例

86才女性

主訴：腰背部痛．

現病歴：自宅で転倒後，腰背部痛のため立位困難となり当院に救急搬送された．

初診時所見：高度な腰背部痛があったが，下肢痛や神経学的異常はなく介助歩行可能であった．単純X線写真，CTでは上位胸椎から腰椎にかけての連続した前縦靭帯骨化，椎体間骨性架橋，棘上・棘間靭帯骨化を認めた．さらにTh12椎体前壁から後方要素に至る骨折と椎体前方の開大を認め，リバースチャンス骨折（Reverse Chance型骨折）と診断した．MRIでは同部位での明らかな脊髄の圧迫を認めなかった（図１A–C）．

経過：早急な固定術が必要と判断したが，発熱，炎症反応高値，低栄養状態，胸水貯留など全身状態が不良であったため早期手術を断念した．

全身管理を行いながら，硬性装具を装着し床上安静による慎重な保存加療を行ったが，受傷７日目にFrankel Cの対麻痺（MMT：両腸腰筋以下２）と両L１領域以下の感覚鈍麻と膀胱直腸障害が発生した．CTでは骨折部上位が後方に転位し，同高位での脊髄圧迫を示唆し（図２A，B），翌日にはMMT：両腸腰筋以下０～１まで麻痺が進行した．

麻痺出現２日後において全身状態はわずかに改善傾向を示していたため，リスクを同意の上でTh９からL３までの後方固定術を施行した（図３A，B）．椎骨は紙のように柔らかく，椎弓根スクリュー刺入時の抵抗を感じなかった．また椎弓は指で触っているだけで折れてしまうほど脆弱であったため，ケーブルやフックの有効なアンカーを確保することを断念した．さらに本症例は低蛋白血症，低アルブミン血症を伴う低栄養状態であり，手術創治癒が得られない可能性が高く，インストゥルメンテーションは最小限にとどめるべきとの判断で頭尾側とも３椎体のみのアンカーとした．

術後麻痺の改善はみられなかった．手術創の治癒に

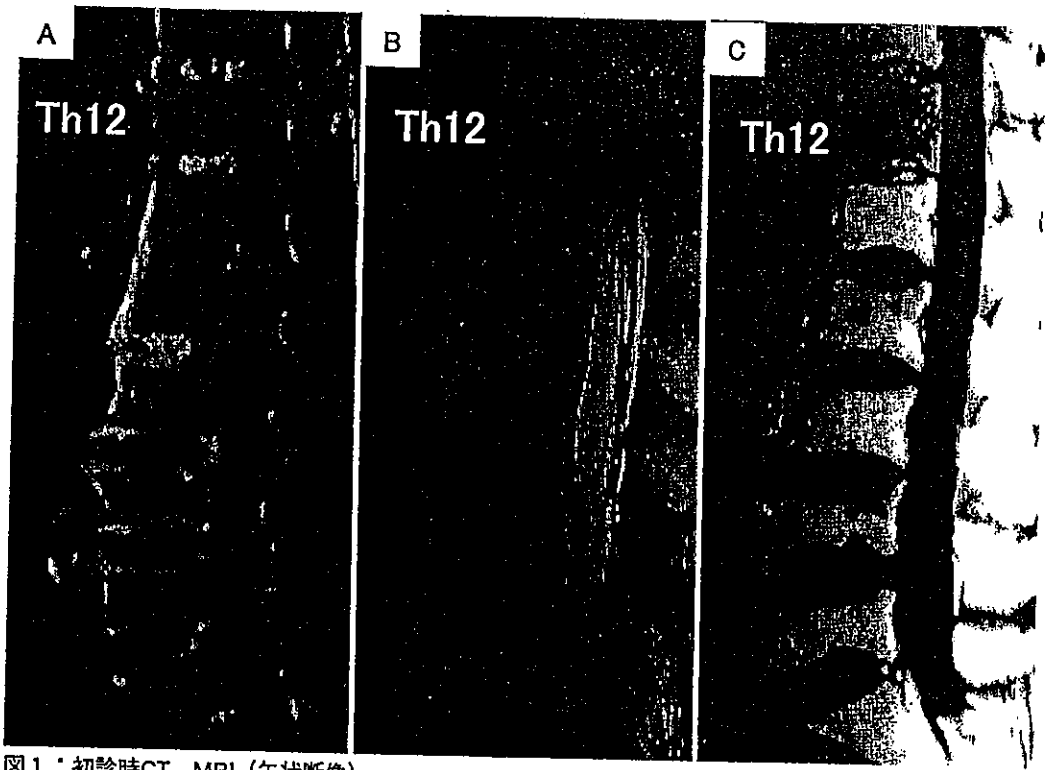

図1：初診時CT，MRI（矢状断像）
CT（A）ではTh12椎体前方はやや開大している．MRI（B：T2WI，C：T1WI）では同部位での明らかな脊髄の圧迫を認めない．

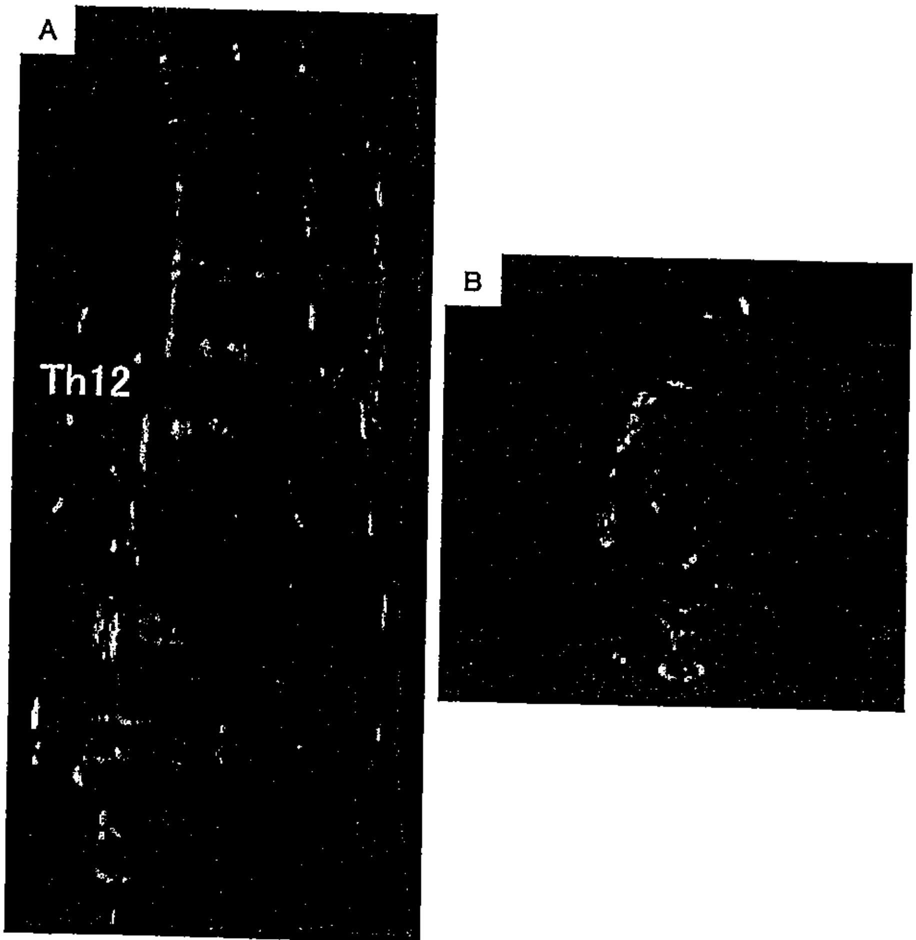

図2：受傷7日目CT（A：矢状断像，B：Th12高位横断像）
骨折部上位が後方に転位し，同高位での脊髄圧迫を示唆する．

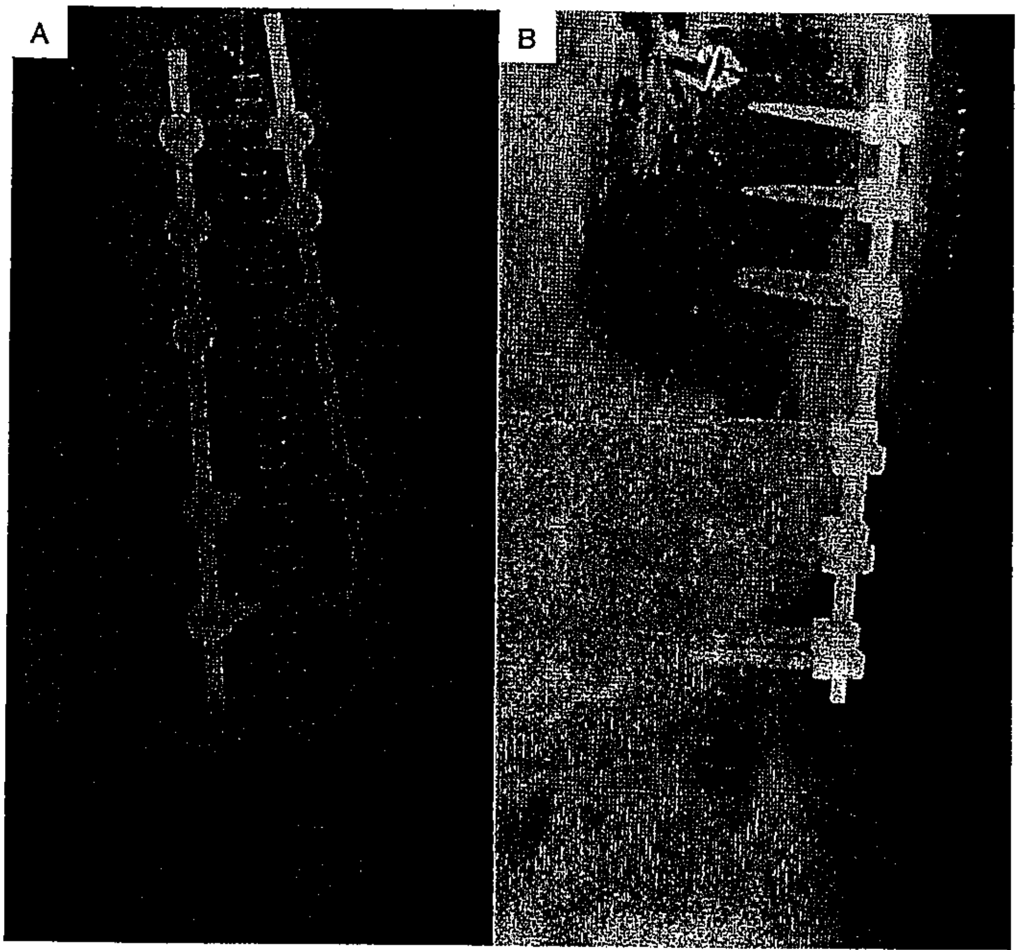

図3：T9－L3後方固定術後単純X線写真
A：正面像，B：側面像.

は8週間を要し，創嘴開を繰り返すたびに縫合を追加した．本例ではインストゥルメンテーションによる固定力には限界があったため，3カ月間を床上安静とした．

考　　察

DISHは脊椎を中心とした特徴的な骨増殖を呈する疾患で，主に60才以上の男性にみられる．

1950年にForestierが脊柱の前縦靭帯骨化を中心とする脊柱靭帯骨化により脊椎強直をきたす疾患を強直性脊椎骨増殖症（ASH）として報告し[2]，後にResnickら[3]によりDISHと提唱されるようになった．

de Perettiら[1]はDISHおよび強直性脊椎炎に伴う脊椎損傷を4つの型（①open－wedge anterior fracture；62.5%，②sawtooth fracture；8.4%，③occult or radiologically invisible fracture；16.6%，④non－specific fractures；12.5%）に分類し，椎体前方開大型の骨折が最も頻度が高いと報告した．この骨折はReverse Chance型骨折と呼ばれ，本症例もこのタイプに属していた．

DISHの患者では，椎間の骨性癒合により可動性が損なわれ，生理的荷重が加わらないため椎体は脆弱化する．また，多椎間にわたり癒合した脊椎は長管骨と同様であり可動性がない．すなわち，骨脆弱な長管骨と同じ状態であり軽度の外力でも骨折を起こしやすい．

また，ひとたび骨折するとレバーアームが長いために骨折部に応力が集中し転位や麻痺を生じやすい．

過去の報告では，DISHに伴う脊椎骨折に対し保存療法を行った28例中16例（57.1%）に遅発性麻痺が生じている[4]．特に骨粗鬆症が重度で骨脆弱性が強い症例では骨折部の破壊が進行しやすく，転位や遅発性麻痺のリスクが高まると考えられる．こういった症例では早期手術が重要となるが，超高齢者で全身状態が悪く手術が限界の症例は増加傾向にある．また，手術が可能だったとしても骨脆弱性のために十分な固定性を得られない場合も少なくないため，治療に難渋することが予想される．

転倒予防，骨粗鬆症治療，骨脆弱例に対する固定法など課題は山積している．

結　語

遅発性麻痺を生じたDISHに伴う脊椎骨折の1例を経験した.

本骨折は保存療法に抵抗性であり，特に高齢者で骨粗鬆症を伴う症例では骨折部の転位や遅発性麻痺のリスクが高く早期手術が望ましい．手術限界例が増加傾向にあり課題は多い.

キーワード：Diffuse idiopathic skeletal hyperostosis (DISH：びまん性特発性骨増殖症)，Chance fracture (Chance型骨折)，delayed paralysis (遅発性麻痺)

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2 [手術のバリエーション]

頚椎脱臼骨折の初期治療

私の治療戦略

須田浩太 Kota Suda
北海道せき損センター副院長
〒072-0015 北海道美唄市東4条南1丁目3-1

小松 幹 Miki Komatsu
北海道せき損センター整形外科部長

牛久智加良 Chikara Ushiku
北海道せき損センター整形外科部長

校條祐輔 Yusuke Menjo
北海道せき損センター整形外科副部長

松本聡子 Satoko Matsumoto
北海道せき損センター整形外科部長

初期治療におけるポイント

時間との勝負！ー完全麻痺でも回復することはある

完全麻痺でも歩行可能なレベルまで回復する例は存在する．脱臼骨折では①受傷時の初期脊髄損傷と②脱臼部位における脊髄絞扼＋不安定性による続発脊髄損傷によって麻痺が決定される．なかには完全横断損傷を免れている例があり，迅速な整復により麻痺が改善する．いかなる症例も麻痺回復の可能性があると考えて行動すべきである．

施設と術者

脊髄損傷では迅速かつ適切な初期治療が予後を左右する．一般病院で対応するのは困難であり脊損専門施設があれば手術を含めて依頼するのがベストである．脊損専門施設がない場合は脊椎外科医が常在する救急病院へ依頼する．誰が手術するかで患者の一生が左右されるため，然るべき術者が執刀するか，立ち会ってもらうこと．

移送・受け入れ

患部の固定をしっかりして搬送する．長距離移送ならば航空機やヘリコプターがベターであり麻痺増悪例が少ない．受け入れ施設では複数のスタッフで対応するが，頚椎保護の責任者を決め，その指示に全員が従う．多くの脱臼骨折では伸展位で脊髄絞扼が悪化するため，中間位から軽度屈曲位を保つ．特に胸椎後弯が強い症例では枕を高くする必要がある．

治療戦略

迅速で適格な診断をーまずCTから

短時間で病態を把握するためCTがベストである．バイタルチェック，神経チェック，採血が終わり次第，CTを撮像し損傷形態を把握する．AO分類やSLICスコアなど多くの分類があるが，著者はAllen分類を愛用しており，代表的な5つを紹介する（表1）[1]．またDF2（図1），CE4（図2），CF4（図3），VC3（図4）について症例を提示する．

整復が先？手術が先？ー時間を考えて臨機応変に

CTの次は短時間で整復できる方法を選ぶ．当センターは30～60分で手術室まで搬入できる体制が整っており，頭蓋直達牽引の準備や整復までの時間と同等である．MRIなど残りの検査を進め手術まで一気に仕上げる．しかし，通常の施設でこ

表1 Allen分類

Distractive-Flexion (DF) =伸延力+屈曲位	
DF1	後方靱帯複合体損傷．亜脱臼か自然整復されたものを含む
DF2	片側椎間関節脱臼．棘突起骨折や椎弓根骨折を伴うこともある
DF3	両側椎間関節脱臼．転位が50%まで
DF4	両側椎間関節脱臼．転位が50%以上．極めて不安定
Compressive-Extension (CE) =圧縮力+伸展位	
CE1	片側後方要素損傷
CE2	両側椎弓根骨折
CE3	CES2以外の両側後方要素損傷
CE4	不完全転位
CE5	完全転位
Compressive-Flexion (CF) =圧縮力+屈曲位	
CF1	軽度の椎体楔状圧迫骨折（椎体前縁の鈍化）
CF2	中程度の椎体楔状圧迫椎体（前方椎体高の減少）
CF3	明らかな椎体骨折（骨折線が生じ，遊離骨片を形成）
CF4	3mm未満の後方すべり
CF5	3mm以上の後方すべり
Vertical-Compression (VC) =圧縮力+中間位	
VC1	上下の椎体終板のうち片方のみの終板骨折
VC2	上下両側の椎体終板骨折（骨片転位が少ない）
VC3	上下両側の椎体終板骨折（骨片転位が明らか）
Distractive-Extension (DE) =伸延力+伸展位	
DE1	前方靱帯断裂・椎間板損傷・椎体横骨折
DE2	DES1に後方靱帯群損傷を合併（椎体は後方転位）

のスピードは困難であり，麻痺が明らかな症例では頭蓋直達牽引を優先したほうが良い．ただしCEは牽引を緩めると再脱臼する．CFやVCは整復できないと考えたほうが良い．DEやDF4は牽引で悪化する．整復が適しているのはDF2，DF3である．

椎骨動脈とWillis動脈輪

椎骨動脈とWillis動脈輪の後交通動脈（PcomA）によって脳幹部の血流は維持されている．頚椎脱臼骨折では約17％で椎骨動脈閉塞，健常人でも約15％に椎骨動脈低形成が存在する．また，Willis動脈輪が完全に保たれているのは健常人の約半数であり，椎骨動脈とPcomAの評価は必須である[2]（図5，図6）．椎骨動脈損傷の回避は当然であるが，致死的リスクがある側の椎弓根スクリューは勧めない．例えば両側PcomAが欠損し，右側椎骨動脈が閉塞している症例では左側椎骨動脈のみが脳幹部血流を維持している．この症例に対して左側に椎弓根スクリューを入れるのは良策とは言えない．

気管切開の要否

C5 AIS A以上の麻痺と脱臼骨折が混在した場合，呼吸障害により気切管理となる確率が高い．気管切開が予測される場合，感染を避けるため前方プレートやケージを使用しないほうが無難である．前方インプラントを使用する場合，1週間おいてから気管切開する[3]．

手術手技

椎体破裂型と関節脱臼型

頚椎脱臼骨折は椎体破裂型（CF，VC）と関節脱臼型（DF，CE，DE）に大別できる．椎体破裂型では前方再建を，関節脱臼型では後方再建を基本に考える．ただし，近年では椎弓根スクリューの登場により椎体破裂型でも後方単独再建が可能となった[4]．

椎体破裂型の手術（表2）

CF1，CF2，VC1は保存治療が基本．CF3，VC2は脊髄圧迫・後弯変形・不安定性により手術．CF4，CF5，VC3では前方除圧＋整復固定を行うのが基本．気管切開が予想される場合は術後感染を避ける意味で前方インプラントを避け，後方インストゥルメンテーションを追加する．破裂椎体

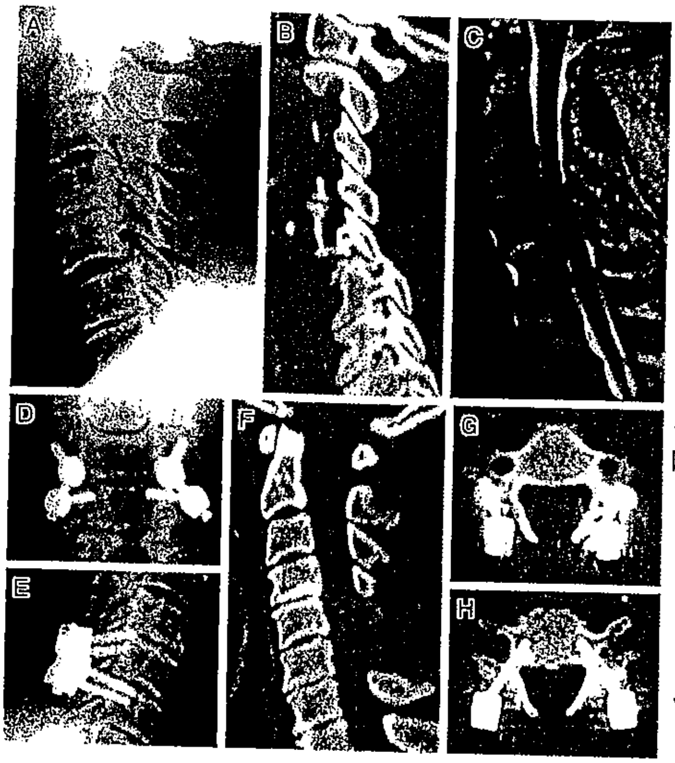

図1　Distractive-flexion injury stage II (DF2)の症例

- 整復時には屈曲損傷だからといって伸展させるのではなく，屈曲位にしなければ嵌合した関節を整復できないことがある．その場合イメージで安全を確認しながら行うべきである．
- 骨質が良好であれば外側塊スクリューでも十分な固定性が得られる．骨が脆弱な場合には片側の椎弓根スクリューを要するが，いずれにしても原則一椎間固定で十分である(D-H)．
- 通常，脱臼が整復されれば除圧の必要はなく椎弓は移植骨母床として利用できるが，椎間板ヘルニアを伴う場合には椎弓形成術を併用する．

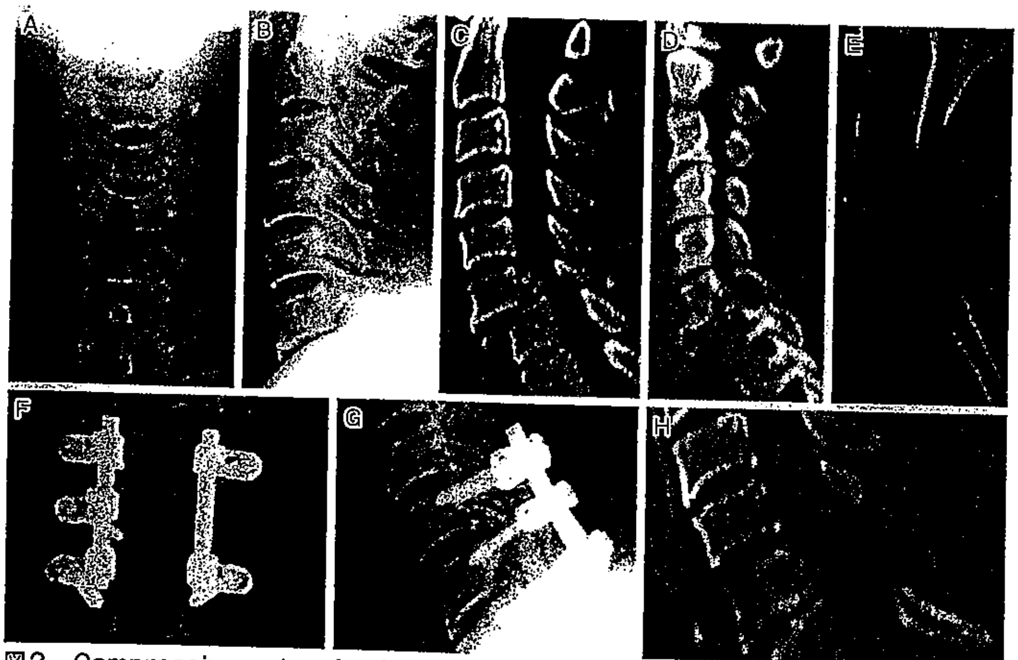

図2　Compressive-extension injury stage IV (CE4)の症例

- 下位頚椎に発症しやすく，単純X線のみでは見落とされやすい損傷の一つである (A-E)．
- 損傷2椎以上にまたがり多椎間固定を要する場合が少なくない (F-H)．
- 椎弓が完全にfloatingしている場合には椎弓を摘出する場合もあるが必須ではなく，移植骨母床として利用できる場合もある．
- 外側塊や棘突起が損傷されている場合が多く，外側塊スクリューやワイヤリングがアンカーとして選択できない場合も多い．

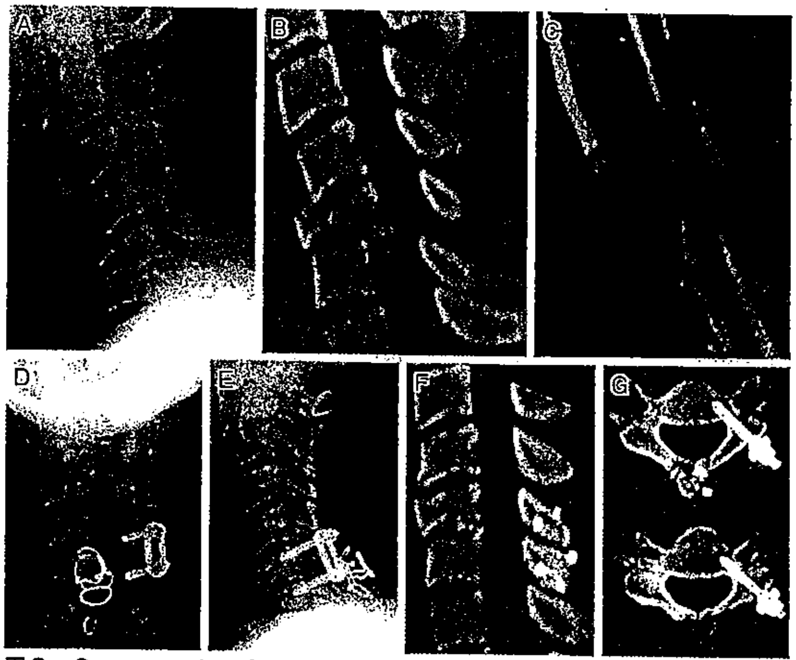

図3 Compressive-flexion injury stage Ⅳ（CF4）の症例

- 前方除圧＋整復固定術が基本である．
- 椎体破裂の程度が軽度の場合はコンストレインタイプの椎弓根スクリューを用いて後方1椎間固定のみで一期的に治療できる症例もある．

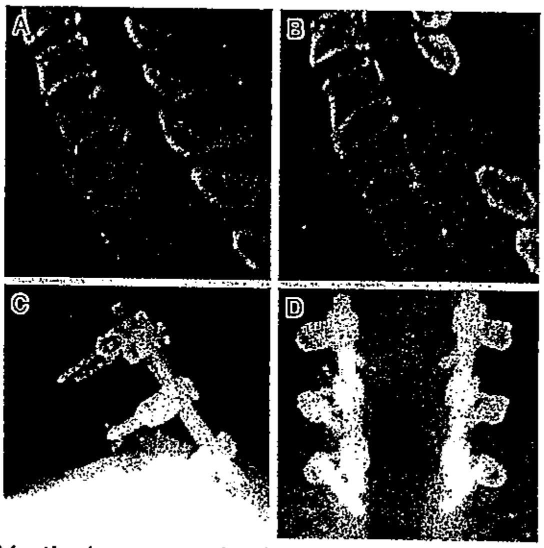

図4 Vertical-compression injury stage Ⅲ（VC3）の症例

- 椎体破壊が著しい場合には2椎間固定が必要となるが，これもコンストレインタイプの椎弓根スクリューであれば整復位を保持することが可能で一期的な後方整復固定術での治療が可能となった．

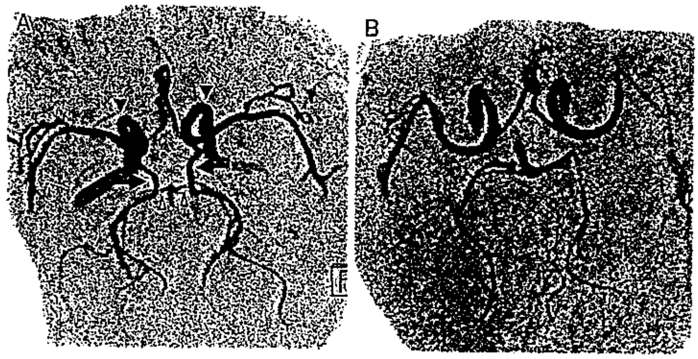

図5

A：MRAによる後交通動脈（PcomA）像（黒矢印）．左右の椎骨動脈は延髄上縁で合流し脳底動脈となった後，2本の後大脳動脈に分岐する（白矢頭）．PcomAは内頚動脈（黒矢頭）と椎骨動脈由来の血流を連絡する経路である．
B：PcomAの両側欠損例．椎弓根スクリュー刺入時には椎骨動脈開存の確認が必須である．

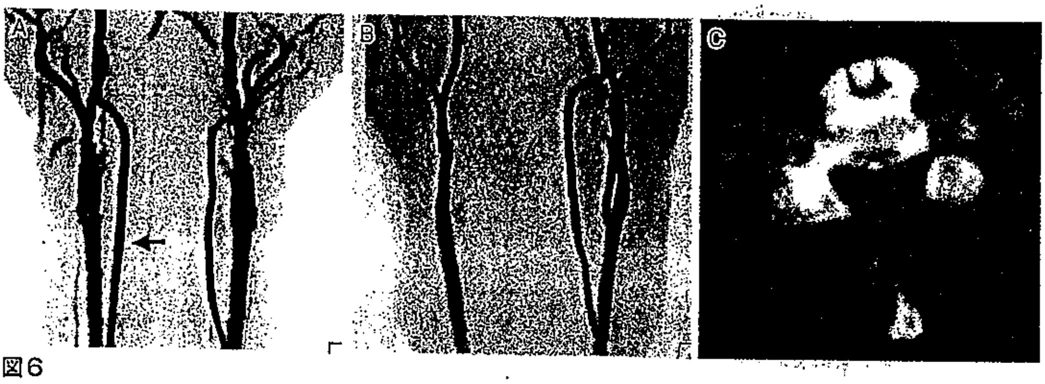

図6

A：MRAによる椎骨動脈像（矢印）．両側とも血流が保たれている．
B：右椎骨動脈は途絶している．
C：造影CT．右横突孔内で椎骨動脈が造影されず（矢印），血流の途絶または椎骨動脈低形成を疑う．PcomAが欠損していた場合，左側への椎弓根スクリュー刺入は良策とはいえない．

表2　椎体破裂型の手術

		前方 AF（Plate）	後方 Wiring	LMS	CPS
椎体骨折（+）	CF3	○*	×	×	○*
	CF4・5	○**	×	×	○**
	VC2	○*	×	×	○*
	VC3	○**	×	×	○**

＊不安定性や神経障害の程度による
＊＊症例に応じて前方か後方を追加

表3 関節脱臼型の手術

		前方 AF (Plate)	後方 Wiring	LMS	CPS
椎体骨折（−）	DF2・3	△	○*	○	○
	DF4	×	△	△	○
	CE1	○	○	○	○
	CE2・3	△	△	○	○
	CE4・5	×	×	△	○
	DE2	○	△	△	○

＊椎間板ヘルニアでは前方除圧固定

が椎弓根と外側塊に連続し第三骨片を伴わないことがある．このような症例では後方で整復固定が可能である．これらの骨折では通常は2椎間固定となるが，中間椎（骨折椎）にもスクリューを刺入し前方へ押して矯正力をかけると整復位を得られる[5]．逆に上下のスクリューに伸延力をかけすぎると弛みや破損につながる．

関節脱臼型の手術（表3）

DF1，DE1は神経障害がなければ保存治療とする．DF2，DF3で早期手術が不可能な場合は，頭蓋直達牽引による整復を行うが椎間板ヘルニアが生じることがあるので留意する．手術で整復する場合，上関節突起を切除すると脱臼椎を椎間板に対し平行に後方牽引して整復することになり，椎間板ヘルニアの危険性が増す．また，ワイヤリングの際は椎間圧縮力がかからない方法を選択する．ヘルニア合併例でも後方除圧で対応可能であるが，術後MRIで脊髄圧迫が顕著であれば前方除圧を即座に追加する．DF4は非常に不安定で，頭蓋直達牽引は適さない．椎弓根スクリュー，ワイヤー，外側塊スクリューを利用して固定性を担保する．固定性が悪ければ多椎間固定とする．

CE1の不安定性は軽度であり，後方ワイヤリング，前方プレートのどちらでも問題はない．まれに剪断損傷があり強固な固定を要する．CE2，CE3では両側後方要素損傷が伴っておりワイヤリングでは固定できない．外側塊スクリューか椎弓根スクリューを要するが椎弓根骨折や外側塊遊離骨折がある場合は2椎間固定となる．CE4，CE5では後方要素と椎体が分離しており椎弓根スクリューが適している．ワイヤリング・外側塊スクリューの場合は多椎間固定を要する．

DE2は前方固定でも後方固定でも良い．OPLLや脊柱管狭窄など多椎間除圧を必要とする場合は後方除圧固定が容易である．

後療法・予後

脱臼を強固に固定することによって，術直後から体動制限を減じ，体交，排痰措置，看護が容易となる．骨癒合が進む1〜3ヵ月間はカラー固定を行うが固定性が良ければ省略する．翌日から車椅子を許可し積極的な呼吸機能訓練，筋力増強訓練，関節可動域訓練，ADL訓練を開始する．初期には坐位によって窒息することがあり，スタッフが常に付き添う．血圧と酸素飽和度（サチュレーショ

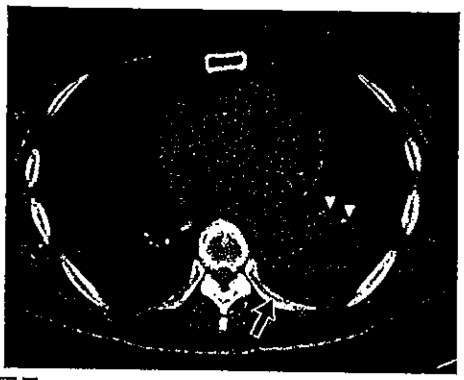

図7

胸水貯留（黒矢印）と無気肺（白矢頭）．特に高位頸損や高齢者では呼吸器合併症の発生が多い．術翌日の超早期から積極的に離床・車椅子移乗などリハビリテーションを行う．急激な酸素飽和度低下時には肺梗塞も疑い，造影CTを実施し評価する．

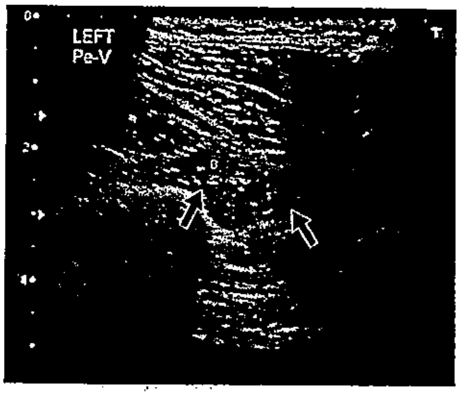

図8

下肢血管エコーによる深部静脈血栓像（黒矢印）．腓骨静脈，中央ヒラメ静脈に血栓が形成されている．麻痺高度例では，高率にかつ受傷超早期から血栓が形成される．検出にエコーが最適であるが，早期からの検出には検者の熟練度に影響される．膝窩部より中枢で血栓がある場合，MR Venographyや造影CTによる肺静脈血栓症の有無も評価する．

ン）をモニターしながら臥位や肺理学療法を行う．肺炎，無気肺（図7），尿路感染，膀胱炎，深部静脈血栓（図8），イレウス，消化管出血は頻発するので留意する．

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迅速な整復固定の重要性を示唆した頸椎脱臼骨折の１例
「例え運動完全麻痺であっても超早期手術により下肢筋力は完全回復する可能性がある」

福井　隆史[1)]，須田　浩太[1)]，遠藤　努[1)]，松本　聡子[1)]，小松　幹[1)]，牛久智加良[1)]，
山根　淳一[1)]，東條　泰明[1)]，神谷　行宣[1)]，三浪　明男[1)]，高畑　雅彦[2)]，岩崎　倫政[2)]

１）北海道中央労災病院せき損センター
２）北海道大学大学院医学研究科機能再生医学講座整形外科科学分野

要　　旨

今回我々は頸椎脱臼骨折後に四肢運動完全麻痺まで悪化したが，超早期手術により独歩可能まで回復した１例を経験した．症例は65歳男性，自動車運転中の事故にてC５／６レベルの頸椎脱臼骨折を受傷し，当院到着時は改良Frankel B１の完全運動麻痺であった．受傷後約６時間で観血的脱臼整復および頸椎後方固定（C５／６）を施行した．術直後から四肢の自動運動が可能となり，術後14日で独歩可能となった．さらに術後20日の時点で下肢筋力が完全回復した．

受傷後超急性期に観血的脱臼整復および一期的な内固定を施行したことが，下肢運動完全麻痺が完全回復にまで至った要因の一つと考えた．

緒　　言

脊髄損傷に対する急性期治療の目的は，１）神経機能回復の阻害因子（神経圧迫因子）の除，２）早期離床を可能とする脊椎安定性の獲得，３）脊髄二次損傷の予防の３点である．すなわち，脊髄麻痺を伴う頸椎脱臼骨折では可及的早期の整復固定が望ましい．しかしながら，運動完全麻痺例において早期脱臼整復固定による麻痺改善効果のエビデンスは乏しい．本稿では頸椎脱臼骨折後に徐々に麻痺が進行し，四肢運動完全麻痺（改良Frankel B１）[1)]まで悪化したが，超早期手術により手術直後に四肢自発運動が可能となり，術後14日で独歩可能までV字回復を示した症例を紹介し，脊髄損傷に対する急性期治療を一考する．

症　　例

症例：65歳男性，自動車運転中に自損事故にて受傷し前医へ救急搬送された．C５／６レベルにて脱臼骨折（Allen–Ferguson分類：Distractive–Flexion injury stage IV）を認めた．前医搬入時は改良Frankel Dの麻痺であったが，当院へ搬送前には改良Frankel Cまで悪化し，当院到着時は改良Frankel B１の完全運動麻痺となっていた．すなわち，四肢運動完全麻痺で肛門知覚のみが残存している状態まで悪化していた．

当院到着から54分で手術室へ入室し，到着から１時間20分（受傷から５時間54分）で手術を開始した．手術開始後，約10分で脱臼を整復し（受傷から約６時間５分），椎弓根スクリューシステムによりC５／６後方固定術を施行し55分で手術が終了した．麻酔覚醒直後に完全麻痺だった四肢の自動運動が可能となり翌日にかけて急速に回復した．手術後３時間30分の時点で触覚・痛覚は完全に改善していた．術後14日で独歩可能となり，術後20日では下肢筋力が完全回復した．

考　　察

頸髄損傷に対する早期手術の是非に関しては未だに結論を見ない．Vaccaroらによって受傷後72時間をカットオフ値とした比較研究がなされたが，これにおいては早期手術の有効性は示されなかった[2)]．上記を踏まえFehlingsらによって，脊髄損傷後24時間をカットオフとした多施設前向きコホート研究が行われ，早期手術群ではASIA機能障害スケールが２段階以上改善した症例が有意に多いことが証明された[3)]．さらにNewtonらによって，ラグビーによる頸椎脱臼に対し，受傷後４時間以内に非観血的脱臼整復を施行することで，初診時Frankel AとBの症例を合わせた12例中７例でFrankel E（下肢筋力完全回復）まで改善したことが報告された[4)]．一方で受傷後９時間以降の非観血的脱臼整復群では完全回復に至った例はなかった[3)]．またビーグル犬を用いたRabinowitzらの動物実験にお

図1A

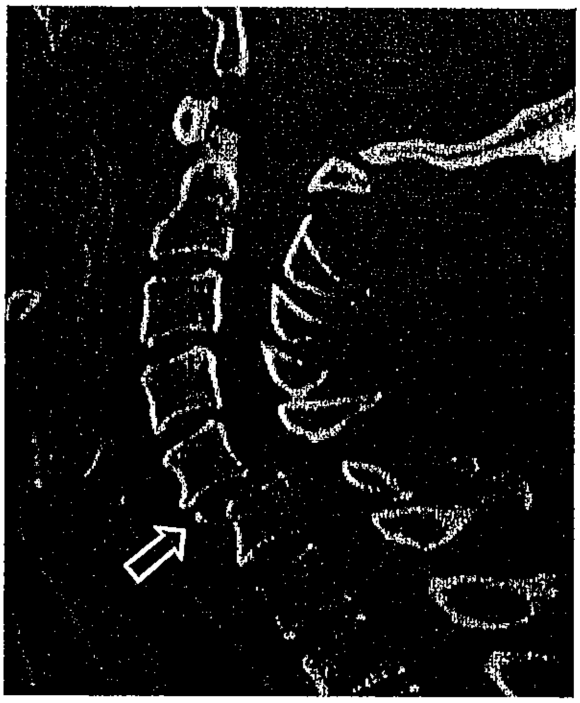


図1B

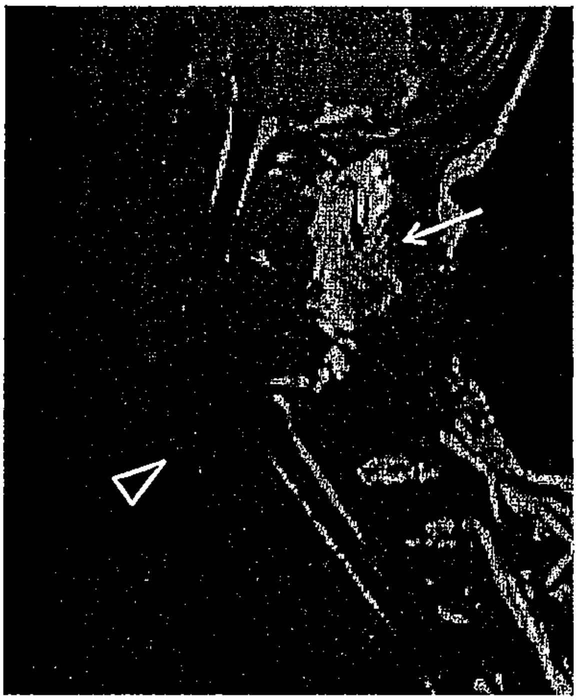
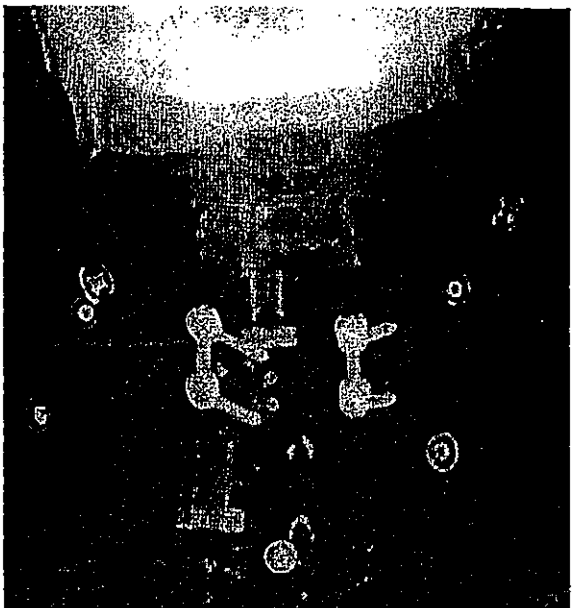


図1 当院搬送時CT画像と前医MRI画像.
(A) 頚椎脱臼（C5／6）とそれに伴う剥離骨片（⇦).
(B) 椎間板の破綻所見（◁）と後方要素の破綻所見（←).

図2



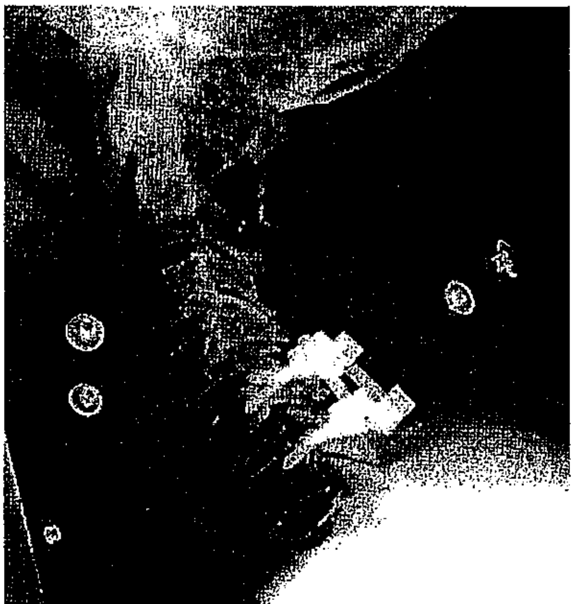


図2 術後単純X線画像
・手術開始後，約10分（受傷から約6時間5分）で観血的脱臼整復を施行した.
・C5／6頚椎後方固定術（S-shot）を施行した.
（右：椎弓根スクリュー，左：外側塊スクリュー，時間55分，出血102ml)
・術直後から両下肢の麻痺は改善した.

いては，脊髄損傷後6時間以内の観血的神経除圧により神経症状が改善したことが報告されており[5]，頚髄損傷が完治し得るタイムリミットは受傷後6－8時間ではないかと予想する．無論，仮にタイムリミットを過ぎていても，脊髄の減圧は早ければ早いほど望ましいことに変わりはない.

表１　初診時から術後経過における身体所見の経時的変化
徒手筋力テスト（MMT：(右／左)）を０－５で示した.

	前医 初診時	受傷後５H (搬送時)	術後 3H30M	術後 18H	術後 29H	術後 ４日	術後 ７日	術後 28日
肘関節屈曲	MMT 4/4	MMT 0/4	MMT 3/4	MMT 4/4	MMT 4/4	MMT 4/4	MMT 4/4	MMT 4/4
手関節伸展	MMT 4/4	MMT 0/2	MMT 2/2	MMT 4/3	MMT 4/3	MMT 4/4	MMT 4/4	MMT 4/4
肘関節伸展	MMT 4/4	MMT 0/1	MMT 1/2	MMT 2/3	MMT 3/3	MMT 4/3	MMT 4/3	MMT 4/3
手指屈曲	MMT 4/4	MMT 0/0	MMT 2/2	MMT 3/4	MMT 4/4	MMT 5/5	MMT 5/5	MMT 5/5
手指外転	MMT 4/4	MMT 0/0	MMT 2/2	MMT 2/3	MMT 4/4	MMT 4/4	MMT 4/4	MMT 4/4
股関節屈曲	MMT 4/5	MMT 0/0	MMT 1/2	MMT 4/5	MMT 4/5	MMT 5/5	MMT 5/5	MMT 5/5
膝関節伸展	MMT 4/5	MMT 0/0	MMT 1/3	MMT 4/5	MMT 4/5	MMT 5/5	MMT 5/5	MMT 5/5
足関節背屈	MMT 4/5	MMT 0/0	MMT 1/3	MMT 5/5	MMT 5/5	MMT 5/5	MMT 5/5	MMT 5/5
母趾伸展	MMT 4/5	MMT 0/0	MMT 1/3	MMT 5/5	MMT 5/5	MMT 5/5	MMT 5/5	MMT 5/5
足関節底屈	MMT 4/5	MMT 0/0	MMT 2/3	MMT 5/5	MMT 5/5	MMT 5/5	MMT 5/5	MMT 5/5

Newtonらの報告は，脱臼整復のタイミングのみならず脊髄損傷の不可逆性についても示唆している[4]．交通事故とは異なり，ラグビーのような低エネルギー外傷に伴う頚椎脱臼骨折では脊髄の不可逆的損傷を免れている可能性が高い．すなわち彼らの報告は，１）低エネルギーで生じた脱臼骨折では脊髄が不可逆性変化を免れている可能性が高いこと，２）短時間で整復されれば，二次損傷を回避し麻痺改善の可能性が高まることを示している．

本症例において特筆すべきは，超急性期に脱臼整復が可能だったという時間的要素のみならず，それが迅速な観血手術で施行され，更に一期的内固定までを完遂し得た点である．このことが，術後20日という速さで下肢運動麻痺が完全回復まで至った要因と考えてよいだろう．非観血的整復ではHalo ring等を用いた直達牽引により行うため，脱臼整復率は平均74％程度とされ[6]，整復不能例では麻痺を悪化させるリスクもある[6,7]．また整復後にHalo vestで外固定を施行する場合には脊椎安定性に不安が残る[8]．一方，観血的整復＋内固定術は確実に脱臼整復が可能であり，一期的に強固な内固定を行える利点がある．ただし，極めて迅速に検査から手術まで行える環境，迅速かつ確実な手術が必須条件となる．

低エネルギー外傷ではなくても，脊髄が不可逆損傷を免れている可能性は否定できない．どれほど検査技術が上がったとしても100％の鑑別は不可能である．すなわち，例え完全麻痺例であっても迅速な非観血的整復，あるいは観血的整復固定を旨とし，最善を尽くす姿勢が望まれる．逆に整復や手術が遅れることにより回復不能な状態，すなわち「手遅れ」にしてしまうことがあり得ることを肝に銘じるべきである．

結　語

今回，自動車事故に伴う頚髄損傷に対し，受傷後約６時間で手術を開始し，観血的整復および固定術を施行することにより，麻痺が術後14日で改良Frankel B１から下肢筋力完全回復まで改善した１例を経験した．完全運動麻痺であっても早期の減圧により神経機能回復の可能性がある．脊髄損傷の急性期医療は脊椎外科医や救急医だけでは不十分なことがあり，体制の整った施設への迅速な搬送が肝要である．

【キーワード】
脊髄損傷（spinal cord injury），運動完全麻痺（complete motor paralysis），超早期手術（super–urgent surgery），完全回復（complete recovery）

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Spinal Cord (2017) 55, 515–517

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ORIGINAL ARTICLE

A radiographic evaluation of facet sagittal angle in cervical spinal cord injury without major fracture or dislocation

T Takao[1], K Kubota[2], T Maeda[1], S Okada[2], Y Morishita[1], E Mori[1], I Yugue[1], O Kawano[1], H Sakai[1], T Ueta[1] and K Shiba[1]

Study Design: A retrospective radiographic study with a minimum 2-year follow-up.
Objective: To evaluate the relationships between the cervical articular facets' morphology and the incidence of traumatic cervical spinal cord injury (CSCI) without major fracture or dislocation.
Setting: Spinal Injuries Center, Japan.
Methods: This study included 113 patients with traumatic CSCI without major fracture or dislocation. Eighty-four healthy volunteers without neurological deficits or cervical cord pathology on magnetic resonance imaging (MRI) were defined as control subjects. We used a plain sagittal radiograph to measure the facet sagittal angles (FSA) at four cervical segments in all the CSCI patients and controls. We defined the FSA as the angle between the inferior margin of the superior cervical spinal body and the inferior articular process of the superior vertebra.
Results: Most frequent incidence of CSCI was seen at C3–4 segment (54%). With respect to CSCI at C3–4 segment, 55.7% of the subjects showed smallest FSA at C3–4 segment.
Conclusion: Most of the traumatic CSCI at C3–4 segment showed raised cervical articular facets at C3–4 segment. On the basis of our results, we hypothesized that the raised cervical articular facets might have an important role in the etiology of traumatic CSCI. The cervical spinal cord at the C3–4 segment might receive the highest load during acute hyperextension of the cervical spine because of the C3–4 articular facets' morphology.
Spinal Cord (2017) 55, 515–517; doi:10.1038/sc.2016.172; published online 20 December 2016

INTRODUCTION

The incidence of traumatic cervical spinal cord injury (CSCI) without major fracture or dislocation has increased in developed countries because of the increasing elderly population.[1] Most patients with CSCI are elderly and presented with spinal hyperextension predominantly at the C3–4 level.[2] Several studies have reported that the cervical spinal cord at the C3–4 segment might receive the highest load during acute hyperextension of the cervical spine.[3–5] We previously studied about the relationships between spinal canal diameter and pathophysiology of traumatic CSCI without major fracture or dislocation.[6,7] In the study, the narrow spinal canal might be an important risk factor for the incidence of traumatic CSCI. However, we could not find the exact etiology why most of traumatic CSCI occurred at the C3–4 segment. To our knowledge, few reports, included in our previous study, have described the biomechanical etiology of traumatic CSCI without major fracture or dislocation, and this remains unclear.

Through our previous studies, we hypothesized that the development of traumatic CSCI without major fracture or dislocation was associated with cervical articular facets' morphology. In the study, we measured the cervical facet sagittal angle by using a plane radiograph in the sagittal plane. The aim of the present study was to evaluate the relationships between the cervical articular facets' morphology and the incidence of traumatic CSCI without major fracture or dislocation.

MATERIALS AND METHODS

Study population

From 2005 to 2011, 194 patients with traumatic CSCI without major fracture or dislocation were treated in our facility. All these patients underwent functional plain radiography, computed tomography, magnetic resonance imaging (MRI) on the cervical spine and neurological examination by a senior spine surgeon at the time of admission. All the subjects were admitted to our facility within 2 days of trauma, and had evidence of CSCI with cervical intramedullary intensity change on T2-weighted MRI. The following subjects were excluded from this study: patients with multiple segmental cervical cord injuries, existing cervical myelopathy before trauma, apparent herniated disc at the injured segment, severe instability at the injured segment on functional radiography, or ankylosing spondylitis at cervical spine.

In this study, 113 patients (101 men and 12 women; mean age, 62 years (range, 22-88 years)) with traumatic CSCI without major fracture or dislocation were included. Of these, 3 subjects had an injury at the C2–3 segment, 61 subjects had an injury at the C3–4, 32 subjects had an injury at the C4–5, 13 subjects had an injury at the C5–6 and 4 subjects had an injury at the C6–7. Eighty-four healthy volunteers (HV) (51 men and 33 women; mean age, 51 years (range, 28–86 years)) without neurological deficits or cervical cord pathology on MRI were defined as control subjects. No significant difference in age was found between CSCI and HV groups. The summaries of traumatic CSCI patients and HV are shown in Table 1.

Institutional review board approval was granted and informed consent was obtained from all of the patients.

[1]Department of Orthopaedic Surgery, Spinal Injuries Center, Iizuka, Japan and [2]Department of Orthopaedic Surgery, Kyushu University, Fukuoka, Japan
Correspondence: Dr T Takao, Department of Orthopedic Surgery, Spinal Injuries Cente, 550-4 Igisu, Iizuka 820-0053, Japan.
E-mail: tsuneaki@iris.ocn.ne.jp
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Measurement of the facet sagittal angle in the sagittal plane

We used a plain radiograph in the sagittal plane to measure the facet sagittal angle (FSA) at four cervical segments (C3–4, C4–5, C5–6 and C6–7) in all of the CSCI patients and controls. We defined FSA as the angle between the inferior margin of the superior cervical spinal body and the inferior articular process of the superior vertebra (Figure 1).

Statistical analysis

The Mann–Whitney *U* test and Fisher's exact test were used for statistical analyses. A *P*-value of <0.05 was considered statistically significant.

RESULTS

In the present series, the incidence rates of traumatic CSCI without major fracture or dislocation at the C2–3, C3–4, C4–5, C5–6 and C6–7 segments were 2.7, 54, 28.3, 11.5 and 3.5%, respectively. Most frequent incidence of CSCI was seen at C3–4 segment.

The mean values of the FSA at the four cervical segments for the subjects with traumatic CSCI and HV are shown in Table 2. When compared with traumatic CSCI and HV, there were no significant differences at all of the segments. Among all the segments, except C6–7, the C3–4 segment had a significantly smaller FSA than the C4–5 and C5–6 segments in both groups. (Figures 2a and b).

The relationships between the incidence of traumatic CSCI without major fracture or dislocation and the morphology of cervical articular facets are shown in Table 3. 55.7% of the C3–4 SCI showed smallest FSA at the C3–4 segment. Moreover, with respect to C3–4 SCI, the C3–4 FSA was significantly smaller than those at the C4–5 and C5–6 segments ($P=0.0195$, Fisher's exact test).

Table 1 The patients with traumatic cervical spinal cord injury (CSCI) and healthy volunteers (HV)

	Traumatic CSCI	*HV*
No. (M:F)	113 (101:12)	84 (51:33)
Average age	62 (22–88)	51 (28–86)

Abbreviations: CSCI, cervical spinal cord injury; HV, healthy volunteers.

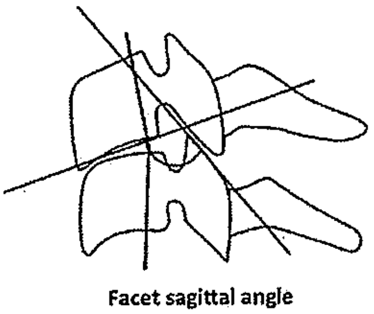

Figure 1 Facet sagittal angle (FSA). We defined the FSA as angle between the inferior margin of the superior cervical spinal body and the inferior articular process of the superior vertebrae.

Table 2 The average values of the FSA at the four cervical segments

	Facet sagittal angle (FSA) (°)			
	C3–4	*C4–5*	*C5–6*	*C6–7*
CSCI	133.4±6	136±5.7	135±6.2	128.4±6.5
	ns	ns	ns	ns
HV	130.6±5.9	134.1±5.9	132.4±5.6	124.8±6.2

Abbreviations: CSCI, cervical spinal cord injury; HV, healthy volunteers; ns, not significant. Mann–Whitney *U* test was used for this statistical analysis.

DISCUSSION

Several studies have reported the frequent incidence of traumatic CSCI at the level of C3–4 segment in the Japanese population.[8] We believe that morphological differences between the cervical segments may contribute to the mechanism of traumatic CSCI. Hayashi *et al.*,[9] reported that the cervical spine of the older subjects displayed narrowing of intervertebral discs and osteophytes at the levels of C5–6 and C6–7, where range of motion was decreased. Such degenerative changes resulted in retrolisthesis predominantly at the levels of C3–4 and C4–5, where intervertebral disc space was well maintained and mobility was well preserved. Moreover, Koyanagi *et al.*[10] hypothesized that the restricted intervertebral movement of the lower cervical segments due to degenerative changes might in fact protect the spinal cord at these segments from traumatic injury. Therefore, the upper segments (C3–4 or C4–5) rostral to the fixed segments might be damaged with cervical spinal hyperextension. However, through our experiences, not only elder patients but also many younger patients without degenerative changes in the lower cervical segments developed CSCI at the C3–4 segment. On the basis of this factor, we could not agree with their hypothesis. Imajo *et al.*[4] reported that the C3–4 finite element model with 60° facet was most susceptible to CSCI without radiological abnormality and that the bony pincers mechanism was dependent on facet joint inclination.

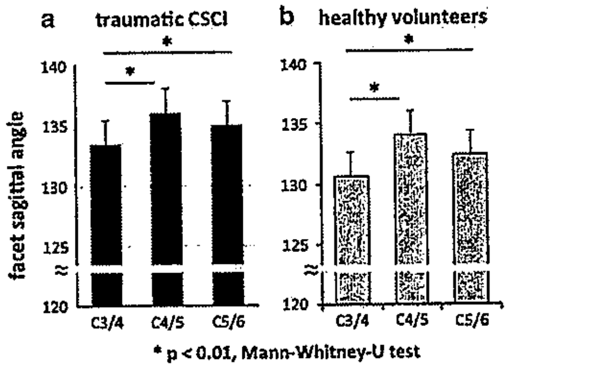

Figure 2 The FSA at the three cervical segments for the subjects with traumatic CSCI without major fracture or dislocation (a) and the healthy volunteers (b). Among all the segments, except C6-7, the C3–4 segment had a significantly smaller FSA than the C4–5 and C5-6 segments in both groups.

Table 3 The relationships between the incidence of traumatic CSCI without major fracture or dislocation and the morphology of cervical articular facets

Injured segment	*No.*	*Smallest FSA*		
		C3–4	*C4–5*	*C5–6*
C3–4	61	34 (55.7%)	11 (18%)	16 (26.3%)
C4–5	31	13 (41.9%)	8 (25.8%)	10 (32.3%)
C5–6	13	6 (41.1%)	2 (15.4%)	5 (38.5%)

Abbreviation: FSA, facet sagittal angle.

On the other hand, Morishita et al[5] reported that the cervical spinal cord at the C3–4 segment might receive the highest bony impingement load during acute hyperextension of the cervical spine. We previously studied about the relationships between cervical spinal canal diameter and the incidence of traumatic CSCI without major fracture or dislocation.[6,7] However, we could not find the significant relationships between cervical spinal canal diameter and the incidence of traumatic CSCI without major fracture or dislocation. Those published papers could not indicate the exact biomechanical etiology of traumatic CSCI without major fracture or dislocation.

The FSA at the C3–4 segment demonstrated significant smaller angle when compared with the C4–5 and C5–6 segments. Moreover, most of traumatic CSCI at the C3–4 segment showed smallest FSA at the C3–4 segment. On the basis of our results, we hypothesized that the raised cervical articular facets might have an important role in the etiology of traumatic CSCI without major fracture or dislocation. The cervical spinal cord at the C3–4 segment might receive the highest mechanical stress during acute hyperextension of the cervical spine because of the C3–4 articular facets' morphology.

Some issues remain unaddressed in this study. In the study, the C6–7 FSA was smallest among the cervical segments. However, we could not discuss the affects of C6–7 articular facets' morphology on the etiology of traumatic CSCI. Using the present investigation as the pilot study, further research that uses anatomical analysis of the cervical spinal column with a larger patient population may help shed light on these issues. Moreover, the biomechanical etiology of traumatic CSCI without major fracture or dislocation should be clarified in quite some detail.

DATA ARCHIVING

There were no data to deposit.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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ORIGINAL ARTICLE

Risk factors for severe dysphagia in acute cervical spinal cord injury

T Hayashi[1], Y Fujiwara[2], H Sakai[1], T Maeda[1], T Ueta[1] and K Shiba[1]

Study design: A retrospective, consecutive case series.

Objectives: The relationship between dysphagia and acute cervical spinal cord injury (CSCI) has been recently reported; however, the cause and mechanism of dysphagia are still not well understood. No definitive factors have yet been established according to multivariate analysis. The objective is to elucidate the incidence and risk factors of dysphagia in patients with acute CSCI.

Setting: Spinal Injuries Center, Fukuoka, Japan.

Methods: A total of 298 patients with acute CSCI, who were evaluated for neurological impairment within 3 days after injury, were reviewed. CSCI patients with tube dependence due to obvious aspiration after injury were defined as having dysphagia. The factors postulated to increase the risk for dysphagia, including the patient's age, sex, American Spinal Injury Association (ASIA) impairment scale at 3 days after injury, level of injury, tracheostomy and operative treatment, were analyzed using a multiple logistic regression model.

Results: Of 298 patients, 21 were suffering from severe dysphagia after acute CSCI (7.0%). Of these 21 patients, 12 (57%) had CSCI at the C3–C4 level. Multivariable logistic regression analysis revealed that old age (>72 years), severe ASIA impairment scale (A or B) and presence of tracheostomy were significant risk factors of dysphagia. Level of injury ⩾C3–C4 was not a significant risk factor after adjustment for several potential confounders.

Conclusion: The incidence of severe dysphagia associated with aspiration was 7%. Old age, severe paralysis and presence of tracheostomy may be the risk factors for dysphagia. The risk for dysphagia should be evaluated to prevent aspiration pneumonia.

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INTRODUCTION

Dysphagia following cervical spinal cord injury (CSCI) in the acute phase can increase the risk of pulmonary complications, which may cause life-threatening conditions.[1] Diseases of the respiratory system are the first leading primary cause of death in patients with spinal cord injury.[2] In the USA, 67.4% of these are cases of pneumonia.[2] Especially, aspiration pneumonia remains a major cause of further morbidity and mortality.[3,4]

The relationship between dysphagia and CSCI has been recently reported;[4–7] however, the cause and mechanism of dysphagia are not well understood. Although several risk factors for dysphagia such as age, tracheostomy and anterior surgery have been postulated in patients with CSCI,[4–8] no definitive factors have yet been established according to a multivariate analysis. We conducted the analysis in order to identify the risk factors of dysphagia using larger number of patients and multivariate model. The purpose of this study was to elucidate the incidence and risk factors of dysphagia in patients with acute CSCI.

PATIENTS AND METHODS

Patients

A total of 464 consecutive patients with traumatic cervical spinal injury with and without spinal cord damage were treated at our institute and were registered in our database system from January 2007 to December 2014. All patients underwent computed tomography, magnetic resonance imaging and neurological examination at admission. We retrospectively selected 298 patients based on the following criteria:[1] admission within 3 days following injury,[2] patients with paresis or paralysis,[3] patients without brain injury[4] and patients without premorbid history of swallowing disorder before trauma. Neurological impairment scale was evaluated according to American Spinal Injury Association (ASIA) impairment scale[9] by surgeons and physiotherapists. Level of injury was determined by two surgeons using computed tomography and magnetic resonance imaging. All surgeons were expert board members of the Japanese Society for Spine Surgery and Related Research, who determined the level of injury and neurological impairment by using the ASIA classification.

Medical records were individually reviewed retrospectively to evaluate condition of eating, tracheostomy due to respiratory complication and operation of CSCI. We extracted patients with tube dependence due to obvious aspiration after injury. The functional oral intake scale (FOIS)[10] was used to evaluate oral intake function (FOIS items—Level 1: Nothing by mouth, Level 2: Tube-dependent with minimal attempts of food or liquid, Level 3: Tube-dependent with consistent oral intake of food or liquid, Level 4: Total oral diet of a single consistency, Level 5: Total oral diet with multiple consistencies, but requiring special preparation or compensations, Level 6: Total oral diet with multiple consistencies without special preparation, but with specific food limitations and Level 7: Total oral diet with no restrictions). Levels 1 through 3 relate to varying degrees of non-oral feeding; levels 4 to 7 relate to varying

[1]Department of Orthopaedic Surgery, Japan Organization of Occupational Health and Safety, Spinal Injuries Center, Fukuoka, Japan and [2]Department of Nursing, Japan Organization of Occupational Health and Safety, Spinal Injuries Center, Fukuoka, Japan

Correspondence: Dr T Hayashi, Department of Orthopaedic Surgery, Japan Organization of Occupational Health and Safety, Spinal Injuries Center, 550-4 Igisu, Iizuka city, Fukuoka 820-8508, Japan.

E-mail: tetsuo884hayashi@yahoo.co.jp

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degrees of oral feeding without non-oral supplementation. In this study, FOIS levels 1 through 3, whose patients were tube-dependent for nutrition due to obvious aspiration, were defined as having severe dysphagia.

This study was approved by our Institutional Review Board of Spinal Injuries Center. Some of the patients in this study were included in our previous paper, which examined the risk factors of tracheostomy between 1996 and 2010.[11]

Data analysis

We analyzed the factors postulated to increase the risk for dysphagia, including the patient's age, ASIA impairment scale (AIS) at 3 days after injury, level of injury, tracheostomy and operative treatment. Patients with dysphagia were compared with those without dysphagia. χ^2-test was used after the variables were categorized. A logistic regression model was used to compute odds ratios (ORs) and 95% confidence intervals (95% CIs) for an increased risk for dysphagia. Age was categorized into the following two groups: 72 years or less and >72 years. The cutoff value of 72 years was analyzed and selected using receiver operating characteristic curve. AIS at 3 days after injury was categorized into severe (A or B) and mild (C or D). Level of injury was categorized into the following two groups: C3–C4 or more cephalic and C4–C5 or more caudal. Treatment method was categorized into conservative treatment and operative treatment. Whether the patients received tracheotomy within a month after trauma was also categorized. The logistic regression model was adjusted for age, sex, AIS, level of injury, treatment and tracheostomy. All statistical analyses were performed using the JMP 10 statistical software package (SAS Institute Inc., Cary, NC, USA). A *P*-value of less than 0.05 was considered statistically significant.

RESULTS

Table 1 shows the patient demographics of this study. Of the 298 patients, 21 appeared to be suffering from severe dysphagia after acute traumatic CSCI (7.0%). All of these patients experienced evident aspiration, had to stop oral intake due to aspiration and were tube-dependent temporarily for nutrition. The neurological status of each patient with dysphagia revealed that 13 of those patients were AIS A, 6 patients were AIS B and 2 patients were AIS C. Of the 21 patients, 12 (57.1%) received tracheostomy.

Of 21 patients who had severe dysphagia, 12 patients (57%) had spinal cord injury at C3–C4, 4 patients (19%) at C4–C5, 4 patients (19%) at C5–C6 and 1 patient (5%) had spinal cord injury at C6–C7.

CSCI patients with and without dysphagia were compared in Table 2. Those with dysphagia showed significantly greater age, more severe AIS, higher level of injury and presence of tracheostomy by both χ^2-tests and simple logistic regression analyses. After adjustment for potential confounding factors, multivariable logistic regression analysis revealed that age >72 years (OR: 3.71, 95% CI: 1.21–12.3, $P=0.02$), AIS A or B (OR: 8.98, 95% CI: 2.06–63.60, $P=0.008$) and presence of tracheostomy (OR: 16.41, 95% CI: 5.14–58.26, $P<0.001$) were significant risk factors for dysphagia.

Table 1 Summary of demographic data of 298 patients with cervical spinal cord injury

	Severe dysphagia[a] *(+)*	*Severe dysphagia*[a] *(−)*	*Total*
Cases (*n*)	21	277	298
Age (median (range))	73 (32–84)	63 (14–91)	64 (14–91)
Sex (male) (*n* (%))	20 (95)	236 (85)	256 (86)
Operative treatment (*n* (%))	7 (33)	92 (33)	99 (33)
Tracheostomy (*n* (%))	12 (57)	14 (5)	26 (9)
ASIA impairment scale (n (%))			
A	13 (62)	85 (31)	98 (33)
B	6 (29)	32 (12)	38 (13)
C	2 (10)	125 (45)	127 (43)
D	0 (0)	35 (13)	35 (12)

Abbreviations: ASIA, American Spinal Injury Association; FOIS, functional oral intake scale.
[a]Severe dysphagia: FOIS ⩽ 3.

DISCUSSION

Several previous studies[6–8] have reported that the incidence of dysphagia after CSCI was between 8.3 and 41%. Shin *et al.*[4] reported that 10 of 121 (8.3%) tetraplegic patients showed evidence of aspiration on a videofluoroscopic swallowing study. Shem *et al.*[6] reported that dysphagia was present in 12 of 29 (41%) individuals with acute tetraplegia who underwent a prospective bedside swallow evaluation. In our study, which included the greatest number of patients with acute CSCI compared with previous studies, the rate of incidence was lower than in previous reports. The reason for this is that patients with CSCI often present with varying degrees of dysphagia, which makes it difficult to set a definition for dysphagia. Our criteria for dysphagia, which was defined as patients with tube dependence for nutrition due to obvious aspiration (FOIS levels 1–3), may signify a more severe swallowing disorder than seen in other studies.

Old age was significantly related to the higher incidence of dysphagia in our study. Previous studies[6,8] also identified age as a significant risk factor. Aging itself, independent of CSCI, can increase

Table 2 Risk factors for dysphagia in acute cervical spinal cord injury

	Severe dysphagia[a] *(+)* n=21	*Severe dysphagia*[a] *(−)* n=277	P-*value*[b]	*Crude OR (95% CI)*	*Adjusted OR (95% CI)*
Age (yr), n (%)					
⩽72	10 (48)	210 (76)		Reference	Reference
>72	11 (52)	67 (24)	0.004	3.44 (1.39–8.62)[c]	3.71 (1.21–12.3)[c]
ASIA impairment scale, n (%)					
C, D	2 (10)	168 (56)		Reference	Reference
A, B	19 (90)	117 (44)	<0.001	12.9 (3.67–82.52)[c]	8.98 (2.06–63.60)[c]
Level of injury, n (%)					
⩽C4/5	9 (43)	189 (63)		Reference	Reference
⩾C3/4	12 (57)	109 (37)	0.04	2.47 (1.01–6.26)[c]	2.57 (0.71–10.43)
Treatment, n (%)					
Conservative treatment	14 (67)	185 (62)		Reference	Reference
Operative treatment	7 (33)	92 (38)	0.991	1.01 (0.37–2.50)	0.78 (0.18–3.43)
Tracheostomy, n (%)					
Negative	9 (43)	263 (88)		Reference	Reference
Positive	12 (57)	14 (12)	<0.001	25.05 (9.19–71.71)[c]	16.41 (5.14–58.26)[c]

Abbreviations: ASIA, American Spinal Injury Association; CI, confidence interval; FOIS, functional oral intake scale; OR, odds ratio.
The logistic regression model was adjusted for age, sex, AIS, level of injury, treatment and tracheostomy.
[a]Severe dysphagia: FOIS ⩽ 3.
[b]*P*-value was calculated by the χ^2-test.
[c]$P<0.05$ by univariate or multivariate logistic analysis.

the risk for dysphagia, because changes in physiology with aging are seen in the upper esophageal sphincter and pharyngeal region, whose sensation is blunted with age.[12]

Tracheostomy was a significant risk factor for dysphagia in this study. As tracheostomy accompanied with acute respiratory failure was reported to be correlated with severe neurological impairment scale, they may be confounding factors of dysphagia.[11] Previous studies[6,8] also supported this correlation. Gross *et al.*[13] reported that the reduction of respiratory volume and subglottic pressure due to a tracheostomy tube or a thorax trauma raised the risk of aspiration. The reduction of subglottic pressure and stimulation of a tracheal cannula to larynx and esophagus may cause dysphagia of patients with tracheostomy.[14] The OR of tracheostomy was highest among significant risk factors demonstrated in this study; thus, we need to pay special attention to aspiration of patients with tracheostomy.

Our study demonstrated that severe paralysis (AIS A or B) was a significant risk factor for dysphagia. Maeda *et al.*[15] reported that the area of prevertebral hyperintensity on T2-weighted magnetic resonance imaging had a significant negative correlation with the ASIA motor score, indicating that patients who had larger prevertebral hyperintensity tended to show more severe paralysis. Therefore, swelling at the retropharyngeal space due to vertebral fracture or soft tissue damage may affect swallowing dysfunction.

Multiple logistic regression analysis revealed that level of injury ≥C3–C4 was not a significant risk factor, whereas both χ^2-test and simple logistic regression model showed a significant difference. More than half the patients with dysphagia had a spinal injury at C3–C4 level, whereas no patient had dysphagia at C2–C3 level in our study. Seidl *et al.*[5] also showed that the number of swallowing disorders increased as the level of tetraplegia lowered with the peak of the C4 level. On the other hand, Shem *et al.*[6] reported that no relationship between dysphagia and level of injury was found to exist. Buchholz and Neumann[16] postulated changes in pharyngeal wall sensitivity as a result of separation of the rear wall of pharynx as a result of trauma and surgery. Most of the CSCI in old patients are spinal cord injury without major bone injury, and they often occur at the C3–C4 level.[17,18] Confounding factors, such as age and level of injury, should be considered although injury at C3–C4 may affect a cause of dysphagia because larynx is located just in front of C3–C4 vertebrae.

Our study showed that operation was not a significant risk factor for dysphagia. Anterior surgical approach of cervical spine has been reported to cause dysphagia.[19,20] Andrew and Sidhu[19] reported that the greatest level of swelling or change in the prevertebral soft tissues after anterior cervical surgery occurred at the mid-body of C4 with an average change of 10.7 mm. Because only 1 of 7 patients who underwent surgery underwent anterior approach for CSCI, operation might not be identified as a risk factor for dysphagia in this study.

Limitations to this study should be acknowledged. Patients with dysphagia present with varying degrees of swallowing disorders. Difficulty with food transmission through pharynx and problem of mastication, which were other symptoms of dysphagia, were not evaluated in this study, because we focused on aspiration. Also, as tube dependence due to aspiration is a very important line between life and death in clinical practice, we aimed to examine the risk factors for severe dysphagia. Because our criteria for dysphagia was FOIS levels 1–3 due to obvious aspiration, only severe swallowing disorder was defined as severe dysphagia and examined in this study. Moreover, detailed examination using videofluoroscopic examination of swallowing or videoendoscopic evaluation of swallowing would provide more accurate diagnosis of aspiration.

When we treat acute CSCI patients with these risk factors, caution is necessary to avoid aspiration. In addition to these risk factors, patients with a past history of stroke, aspiration pneumonia or chronic pulmonary disease may also require close attention and screening tests in clinical practice. Diet with special preparation, oral care, avoidance of unnecessary tracheostomy and screening for dysphagia should be performed to prevent pulmonary complications associated with dysphagia and maintain better nutritive condition. Therefore, the risk for dysphagia should be evaluated.

CONCLUSION

A total of 298 patients were retrospectively reviewed to detect risk factors for dysphagia using a multiple logistic regression model. The incidence of severe dysphagia associated with aspiration was 7%. Old age, severe paralysis and tracheostomy may be at risk for dysphagia. Risk for dysphagia should be evaluated to prevent aspiration pneumonia.

DATA ARCHIVING

There were no data to deposit.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Effects of orthotic therapeutic electrical stimulation in the treatment of patients with paresis associated with acute cervical spinal cord injury: a randomized control trial.

Iwahashi K[1], Hayashi T[1,2], Watanabe R[1], Nishimura A[1], Ueta T[1,2], Maeda T[2], Shiba K[2].

Author information

Abstract

STUDY DESIGN: A randomized controlled trial.

OBJECTIVES: To determine the effects of orthotic therapeutic electrical stimulation (TES) on the hand in patients with paresis associated with acute cervical spinal cord injury.

SETTING: Spinal Injuries Center, Fukuoka, Japan.

METHODS: The study included patients treated for spinal cord injuries (Frankel classification, grades B and C) at our institution within 1 week post injury between May 2011 and December 2014. The patients were allocated randomly to TES and control groups at the time of admission and underwent TES+conventional training or conventional training alone, respectively. Both hands of each patient were treated in the same way. The primary outcome was total passive motion (TPM) of the fingers (degrees). The secondary outcomes were edema (cm) and the upper-extremity motor scores of the International Standards for the Neurological Classification of Spinal Cord Injury (ISNCSCI). After randomization, outcomes were assessed at 1 week, 1 month and 3 months post injury in both groups.

RESULTS: Twenty-nine individuals were assessed at 3 months (15, TES; 14, control). There were no significant between-group differences for TPM of the fingers, edema and upper-extremity motor scores at 1 week, 1 month and 3 months after injury, although TPM of the fingers tended to be lower in the control group.

CONCLUSIONS: It is unclear from the results of this study whether TES has a therapeutic effect on TPM, edema or the upper-extremity motor score of the ISNCSCI. The results of this study provide useful data for future meta-analyses.Spinal Cord advance online publication, 27 June 2017; doi:10.1038/sc.2017.74.

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ISCoS

ARTICLE

Sensitivity and specificity of the 'knee-up test' for estimation of the American Spinal Injury Association Impairment Scale in patients with acute motor incomplete cervical spinal cord injury

Itaru Yugué[1] · Seiji Okada[2] · Takeshi Maeda[1] · Takayoshi Ueta[1] · Keiichiro Shiba[1]

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Abstract

Study design A retrospective study.

Objective Precise classification of the neurological state of patients with acute cervical spinal cord injury (CSCI) can be challenging. This study proposed a useful and simple clinical method to help classify patients with incomplete CSCI.

Setting Spinal Injuries Centre, Japan.

Methods The sensitivity and specificity of the 'knee-up test' were evaluated in patients with acute CSCI classified as American Spinal Injury Association Impairment Scale (AIS) C or D. The result is positive if the patient can lift the knee in one or both legs to an upright position, whereas the result is negative if the patient is unable to lift the knee in either leg to an upright position. The AIS of these patients was classified according to a strict computerised algorithm designed by Walden et al., and the knee-up test was tested by non-expert examiners.

Results Among the 200 patients, 95 and 105 were classified as AIS C and AIS D, respectively. Overall, 126 and 74 patients demonstrated positive and negative results, respectively, when evaluated using the knee-up test. A total of 104 patients with positive results and 73 patients with negative results were classified as AIS D and AIS C, respectively. The sensitivity, specificity, positive predictive and negative predictive values of this test for all patients were 99.1, 76.8, 82.5 and 98.7, respectively.

Conclusions The knee-up test may allow easy and highly accurate estimation, without the need for special skills, of AIS classification for patients with incomplete CSCI.

Introduction

Precise classification of the neurological state of patients with acute spinal cord injury (SCI) is essential in determining the prognosis, therapeutic strategy and outcomes/benefits from the interventions [1–10]. The American Spinal Injury Association (ASIA) published standards for neurological and functional classification of SCI in 1982 [11]. The International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI) was accepted and recommended by the International Medical Society of Paraplegia (IMSOP) in 1992, and the ASIA Impairment Scale (AIS) based on the revised version of ISNCSCI [12, 13] is now used worldwide to determine motor and sensory impairments in patients with SCI. In order to accurately assess AIS, it is mandatory to determine the sensory level, sensory scores, motor level and strength of the key muscles using the ISNCSCI classification [14]. The ISNCSCI method was tested for its inter- and intra-rater reliabilities [15–26]. This method is slightly complicated, and several studies illustrated that training and experience may be required for accurate agreement [15, 20, 21, 25, 26]. Importantly, some studies reported that the reliability of sensory and motor components of ISNCSCI in patients with incomplete SCI was lower than that in patients with complete SCI [15, 19, 20, 22, 26]. In the patients with motor incomplete SCI, the most complicated task even after training was to distinguish AIS B from AIS C/D based on the motor sparing of more than three segments below the motor level [20, 24, 27]. Moreover, in the patients classified

✉ Itaru Yugué
iyugue@orange.ocn.ne.jp

[1] Department of Orthopaedic Surgery, Spinal Injuries Centre, Iizuka, Fukuoka, Japan

[2] Department of Orthopaedic Surgery, Kyushu University, Fukuoka, Japan

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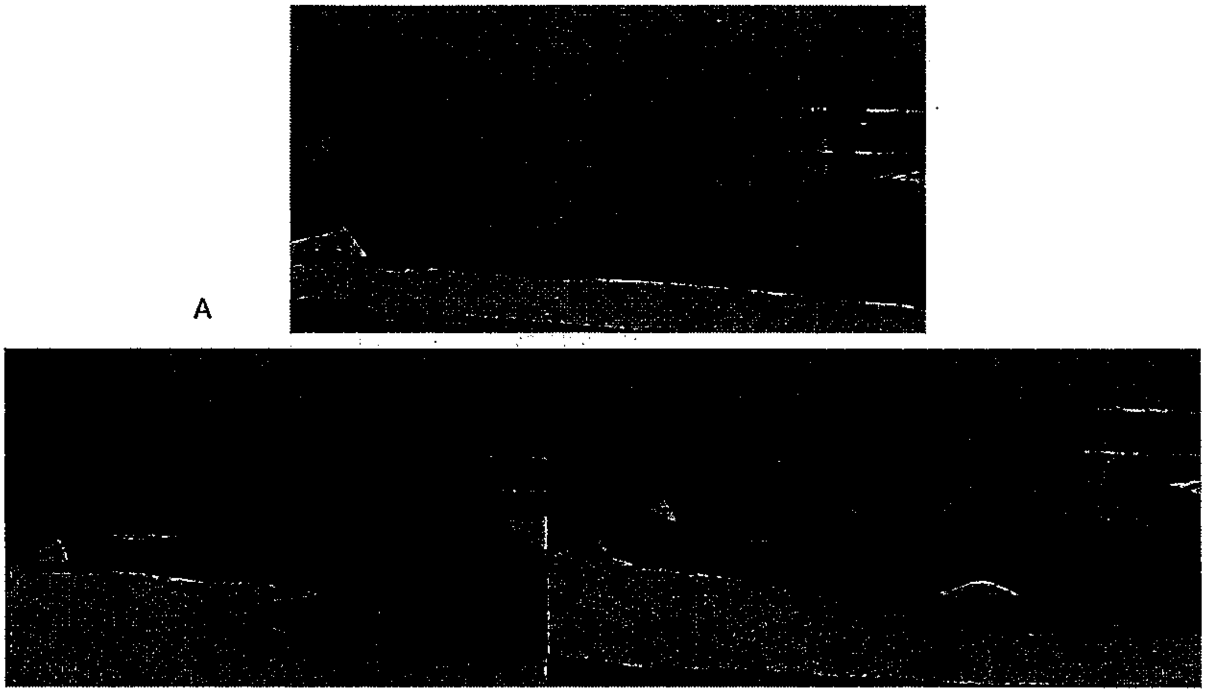

Fig. 1 a In the knee-up test, the patient was placed in the supine position. b Clinicians ask patients to lift up their knees off the bed. If patient was able to lift their knees to an upright position, then the patient had a positive knee-up test result (left leg). c If the patient was unable to lift the knees up to the upright position, then the patient had a negative knee-up test result (left leg)

as AIS D after training, ~15% of those was misclassified [20, 27]. These results indicate that a very careful evaluation was mandatory to correctly assess AIS in patients with incomplete SCI. These patients often exhibit spontaneous motor function recovery; hence, an easy and quick to perform screening tool needs to be developed because a complete ISNCSCI examination in these patients might reach up to an hour, and frequent evaluation using the full ISNCSCI method is not practical in the early stage of injury.

We previously reported that the knee-up test was useful for the early detection of postoperative motor deficit [28] as well as hysterical paralysis [29]. This test is also thought to have a possibility to easily estimate the severity of paralysis. The purpose of this study is to verify the usefulness of estimating paralysis severity using the 'knee-up test' in patients with incomplete SCI, especially in distinguishing AIS C from D.

Methods

Study population

A total of 675 patients with cervical SCI (CSCI) were treated at the Department of Orthopaedic Surgery of the Spinal Injuries Centre from June 2005 to June 2016. The inclusion criteria were the following: (1) patients with traumatic CSCI verified using magnetic resonance imaging, (2) patients with motor incomplete CSCI determined according to the ISNSCI classification at the time of admission and (3) ability to adequately communicate. The medical records of 215 consecutive patients with acute motor incomplete CSCI, who were treated within 2 days after injury, were reviewed. Fifteen patients were excluded because some motor functions were not testable due to fracture and/or hypersensitivity of the extremities. The medical records of the remaining 200 patients were then analysed.

Informed consent was obtained from all individual participants included in the study.

Manoeuvre of the knee-up test

Patients were placed in the supine position, and the clinicians asked them to lift up their knees off the bed (Fig. 1a). If patients were able to lift their knees to an upright position, they were considered to have a positive knee-up test result (Fig. 1b). If patients were unable to do so, then the knee-up test had a negative result (Fig. 1c). Patient had a positive single knee-up test if he/she was able to lift at least one of his/her knees, whereas the patient was considered to have a negative single knee-up test if he/she was not able to lift either of his/her legs.

Patients were independently examined at the time of admission by two expert orthopaedic surgeons (I.Y. and T. U.), who had >5 years of experience in using the ISNCSCI method. At the same time, two non-expert residents who had <1 year of experience in using the ISNCSCI method performed the knee-up tests. They were blinded to the results obtained by the other observers.

Key muscles for knee-up positive and relation between the key muscles and upper and lower extremities' muscle functions

Considering that the physiologic continuity of the spinal cord long tract fibres is broken into CSCI, paralysis of one muscle is often linked to paralysis of the other muscles in the upper and lower extremities. Therefore, we analysed the key leg muscles that contributed positively to the knee-up test and the relationship between the motor scores of all key muscles and key leg muscles associated with the knee-up test.

AIS classification

Regarding AIS, data to be filled into the neurological worksheet were: sensory scores including light touch and pin prick, motor score for each segment, presence of voluntary anal contraction, and results of the knee-up test. Since 1980, non-key muscles, such as shoulder elevation, shoulder abductors, wrist flexors, finger extensors, hip adductors, hip abductors and long toe flexors, were examined and graded using the Manual Muscle Test. All data were collected prospectively. Given that the ISNCSCI methods were improved during our study period, to update the AIS classification, every parameter, including sensory score, motor score for each segment and presence of voluntary anal contraction of each patient, was entered into a personal computer, and the AIS of each patient was evaluated and verified by the computerised algorithm designed by Walden et al. [30]. after completing the data entry.

When a disagreement existed between the results of the single knee-up test and the results of AIS obtained by the two observers, the results were classified as single knee-up test negative and as AIS C.

Statistical analysis

The association between the result of the single knee-up test of a patient and the results of AIS was investigated. Fisher's exact test was used to compare categorical data. Odds ratio (OR), and 95% confidence interval (CI), sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) were calculated. The kappa statistic was used to assess the inter-observer agreement on the knee-up test.

To clarify the importance of the key leg muscles in maintaining the knee in its lifted position, the relationship between the result of the knee-up test and the strength of each key leg muscle was analysed using a multiple logistic regression model. Correlations between the motor scores of the significant key muscles and those of the other key muscles were analysed using Pearson's correlation coefficient. The correlation coefficient (r) was interpreted as follows: value of r between −1.0 and −0.7 or 1.0 and 0.7: a strong linear relationship; between −0.7 and −0.5 or 0.5 and 0.7: a moderate linear relationship; and between −0.5 and −0.3 or 0.3 and 0.5: a weak linear relationship [31]. All statistical analyses were performed using the JMP 11 statistical software package (SAS Institute Inc., Cary, NC, USA). A value of $p < 0.05$ was considered to be statistically significant.

Results

Two hundred eligible patients (166 males, 34 females) were selected for inclusion in the final sample. All injuries were the result of blunt trauma. Mean patients' age was 62.4 ± 15.6 years (mean ± SD) (range, 16–91 years). The consciousness level of all patients was normal. The mean interval between the day of injury and the day of evaluation was 0.8 ± 0.75 day (mean ± SD) (range, 0–2 days). The neurological status of each patient was evaluated at the time of admission. Neurological level of injury was C2 in 4 patients, C3 in 15, C4 in 104, C5 in 45, C6 in 25, C7 in 6 and C8 in 1 patient. Ninety-five of the 200 patients were classified as AIS C. The mean total upper motor score (TUEMS) was 11.95 ± 1.14 (mean ± SD) and mean total lower motor score (TLEMS) was 14.26 ± 1.08 (mean ± SD). According to Pouw et al. [32], traumatic central cord syndrome (TCCS) was defined as a TUEMS of 10 points less than the TLEMS; 30 in 95 patients (31.58%) had TCCS. One hundred and five of the 200 patients were classified as AIS D. The mean TUEMS was 30.10 ± 1.07 (mean ± SD) and mean TLEMS was 41.78 ± 1.02 (mean ± SD). Fifty-five in the 105 patients (52.38%) had TCCS. Both mean TUEMS and TLEMS in the AIS D group were statistically significantly higher than those in the AIS C group (TUEMS: $p < 0.0001$, TLEMS: $p < 0.0001$) and the percentage of TCCS in the AIS C group was statistically significantly higher than that in the AIS D group ($p = 0.0041$) (Table 1). The kappa coefficient for the AIS between two expert orthopaedic surgeons was 0.99 ($p <$

Table 1 Demographic characteristics according to the American Spinal Injury Association impairment scale

Patients	C 95 patients	D 105 patients	p
Sex	Male: 77; female: 18	Male: 89; female: 16	0.572
Age (years)	64.1 ± 1.59 (mean ± SD)	60.8 ± 1.52 (mean ± SD)	0.145
TUEMS	11.95 ± 1.14 (mean ± SD)	30.10 ± 1.07 (mean ± SD)	<0.0001*
TUEMS: 0–10	53 patients	7 patients	
TUEMS: 11–20	27 patients	20 patients	
TUEMS: 21–30	11 patients	26 patients	
TUEMS: 31–40	4 patients	23 patients	
TUEMS: 41–50	No patient	29 patients	
TLEMS	14.26 ± 1.08 (mean ± SD)	41.78 ± 1.02 (mean ± SD)	<0.0001*
TLEMS: 0–10	41 patients	1 patient	
TLEMS: 11–20	25 patients	2 patients	
TLEMS: 21–30	22 patients	15 patients	
TLEMS: 31–40	6 patients	20 patients	
TLEMS: 41–50	2 patients	67 patients	
TCCS	TCCS: 30; non-TCCS: 65	TCCS: 55; non-TCCS: 50	0.0041**

TUEMS total upper motor scores, *TLEMS* total lower motor scores, *TCCS* traumatic central cord syndrome

* Unpaired *t* test: $p < 0.05$

** Fisher's exact test: $p < 0.05$

0.0001). There was no difference in the knee-up test derived by the two non-expert examiners.

One hundred and twenty-six patients exhibited positive results when evaluated using the single knee-up test, whereas 74 patients exhibited negative results. The mean TUEMS was 27.03 ± 1.10 (mean ± SD) and the mean TLEMS was 39.16 ± 0.94 (mean ± SD) in the knee-up positive group, whereas the mean TUEMS was 12.04 ± 1.44 (mean ± SD) and the mean TLEMS was 10.91 ± 1.24 (mean ± SD) in the knee-up negative group. Seventy-one in 126 patients (56.35%) had TCCS in the positive group and 14 in 74 patients (18.92%) had TCCS in the negative group. Both mean TUEMS and TLEMS in the knee-up positive group were statistically significantly higher than those in the knee-up negative group (TUEMS: $p < 0.0001$, TLEMS: $p < 0.0001$) and the percentage of TCCS in the negative group was statistically significantly higher than that in the positive group ($p < 0.0001$) (Table 2). One hundred and four of the patients with positive results were classified as AIS D. Seventy-three patients with negative single knee-up test were classified as AIS C (Fisher's exact $p < 0.0001$; OR, 345.1; 95% CI, 45.5–2617.7) (Table 3). The sensitivity, specificity, PPV and NPV of this test for all cases were 99.1, 76.8, 82.5 and 98.7, respectively. Concerning the relationship between the knee-up test and TCCS (Table 4), the sensitivity, specificity, PPV and NPV of this test were 83.5, 52.17, 56.35 and 81.03, respectively.

Multiple logistic regression demonstrated that hip flexors ($p < 0.0001$; OR, 5.87; 95% CI, 2.94–13.6), hip adductors ($p = 0.0352$; OR, 2.11; 95% CI, 1.04–4.29) and hip abductors ($p = 0.0291$; OR, 1.86; 95% CI, 1.06–3.49) were statistically significant for the key leg muscles that contributed positively to the knee-up test (Table 5). When the muscles were restricted only to the ASIA key muscles, multiple logistic regression demonstrated that hip flexors ($p < 0.0001$; OR, 10.9; 95% CI, 5.9–23.4) and ankle dorsiflexors ($p = 0.0255$; OR, 1.6; 95% CI, 1.1–2.6) were statistically significant for the key leg muscles that contributed positively to the knee-up test (Table 6).

The motor score of both hip flexors (Table 7) and ankle dorsiflexors (Table 8) showed significantly strong correlations with that of the other key muscles in the lower extremities, and significantly moderate correlations with that of the elbow extensors, finger flexors and finger abductors. The motor scores of hip flexors and ankle dorsiflexors showed a significantly weak correlation compared to those of the elbow flexors and wrist extensors.

Discussion

In the present study, we demonstrated the usefulness of the knee-up test for AIS assessment in patients with motor incomplete CSCI. To correctly assess AIS, several complicated examination steps are required. First, sensory (ie, light touch and pin prick sensation) and motor examinations for the right and left extremities are determined according to the ISNCSCI method. Second, NLI, which is the most caudal segment of the cord with intact sensation and antigravity muscle function strength, should be determined. Third, AIS is evaluated using these sensory and motor findings in a comprehensive manner. Mastery of skills needed for each step in the ISNCSCI method is required for clinicians as described above, indicating that examination skills might influence the result of AIS grading. Both AIS C and D indicate that motor function is preserved below the NLI; however, the distinction between them is not always easy. The function of more than half of the key muscles below the single NLI have a grade of <3 (grades 0–2) is classified as AIS C, whereas the case wherein at least half (half or more) of the key muscles below the NLI have a grade greater or equal to 3 (grades 3–5) is classified as AIS D [14].

Table 2 Demographic characteristics according to the result of knee-up test

Patients	Positive 126 patients	Negative 74 patients	p
Sex	Male: 107; female: 19	Male: 59; female: 15	0.436
Age (years)	61.06 ± 1.39 (mean ± SD)	64.58 ± 1.80 (mean ± SD)	0.123
TUEMS	27.03 ± 1.10 (mean ± SD)	12.04 ± 1.44 (mean ± SD)	<0.0001*
TLEMS	39.16 ± 0.94 (mean ± SD)	10.91 ± 1.24 (mean ± SD)	<0.0001*
TCCS	TCCS: 71; non-TCCS: 55	TCCS: 14; non-TCCS: 60	<0.0001**

TUEMS total upper motor scores, *TLEMS* total lower motor scores, *TCCS* traumatic central cord syndrome

* Unpaired t test: $p < 0.05$

** Fisher's exact test: $p < 0.05$

Table 3 Relationship between the American Spinal Injury Association impairment scale and the knee-up sign findings

	The ASIA impairment scale		
	C (n)	D (n)	Total (n)
Knee-up test positive	22	104	126
Knee-up test negative	73	1	74
Total	95	105	200

Table 4 Relationship between the traumatic central cord syndrome and knee-up test findings

	TCCS (n)	Non-TCCS (n)	Total (n)
Knee-up test positive	71	55	126
Knee-up test negative	14	60	74
Total	85	115	200

TCCS traumatic central cord syndrome

Table 5 Multiple logistic regression by combined muscle functions for the positive knee-up test (with the non-key muscles)

Combined muscle functions	p	Odds ratio	95% confidence interval
Hip flexors	<0.0001*	5.88	2.94–13.6
Hip adductors	0.0353*	2.10	1.05–4.29
Hip abductors	0.0292*	1.85	1.06–3.49
Knee extensors	0.3549	0.78	0.45–1.30
Ankle dorsiflexors	0.1745	1.35	0.87–2.15
Long toe extensors	0.9054	1.03	0.59–1.77
Ankle plantar flexors	0.7574	1.09	0.63–1.86

* $P < 0.05$

Table 6 Multiple logistic regression by combined muscle functions for the positive knee-up test

Combined muscle functions	p	Odds ratio	95% confidence interval
Hip flexors	<0.0001*	10.85	5.9–23.4
Knee extensors	0.7918	0.93	0.57–1.52
Ankle dorsiflexors	0.0255*	1.64	1.07–2.59
Long toe extensors	0.8930	0.96	0.57–1.62
Ankle plantar flexors	0.3503	1.26	0.77–2.07

* $P < 0.05$

Table 7 Correlation between the motor score of hip flexors and those of the other key muscles

Key muscle	p	Correlation coefficient
Elbow flexors	<0.0001*	0.357
Wrist extensors	<0.0001*	0.459
Elbow extensors	<0.0001*	0.566
Finger flexors	<0.0001*	0.564
Small finger abductors	<0.0001*	0.509
Knee extensors	<0.0001*	0.857
Ankle dorsiflexors	<0.0001*	0.844
Long toe extensors	<0.0001*	0.807
Ankle plantar flexors	<0.0001*	0.836

* $P < 0.05$

In patients with acute CSCI, some merits exist for accurate distinction between AIS C and D. For example, AIS C is a more appropriate neurological condition in validating the efficacy of treatment for neurological improvement [1–4]. In addition, acute complications were found to develop more frequently in patients with AIS C than in those with AIS D [5, 6]. Therefore, early distinction between AIS C and D is important to evaluate treatment outcomes and complication risk during the early stage of injury, especially the need for tracheostomy [5] in patients with incomplete CSCI.

Several studies reported the inter-rater and intra-rater reliability of ISNCSCI [15–26]. Generally, intra-rater and inter-rater agreements among trained or experienced raters were acceptable; [17, 21–23] however, even for trained examiners, the agreements of sensory and/or motor examination were less reliable in patients with an incomplete SCI than in those with a complete SCI [19, 22]. In addition,

Table 8 Correlation between the motor score of ankle dorsiflexors and those of the other key muscles

Key muscle	*p*	Correlation coefficient
Elbow flexors	<0.0001*	0.270
Wrist extensors	<0.0001*	0.410
Elbow extensors	<0.0001*	0.520
Finger flexors	<0.0001*	0.534
Small finger abductors	<0.0001*	0.508
Hip flexors	<0.0001*	0.845
Knee extensors	<0.0001*	0.837
Long toe extensors	<0.0001*	0.896
Ankle plantar flexors	<0.0001*	0.858

* $P < 0.05$

although several studies have reported that training improved accuracy of agreement [15, 16, 18, 20, 24–26], efficacy was significantly lower in incomplete than in complete SCI [15, 16, 20, 24–26]. For example, Chafetz et al. [20] reported that training improved correct classification of patients with AIS C from 29 to 54% and of those with AIS D from 37 to 84%, and stated clearly that accurate classification of AIS designation remained unacceptably low even after training. These reports suggested that non-experts should receive proper training before using the ISNCSCI in clinical practice [20, 25]. In this study, inter-rater agreements among two expert orthopaedic surgeons who had 5 years or more of experience in using the ISNCSCI method in >400 SCI cases were high enough. This means that to be able to correctly classify patients with motor incomplete CSCI, proper training and greater level of experience are needed.

In contrast, the knee-up test presented in this study does not require special skills when performing. We previously reported that the knee-up test was useful for the early detection of postoperative motor deficit [28] as well as hysterical paralysis [29]. In the current study, no patient data overlapped with the previous studies [28, 29]. In a previous study [28], hip adductors and abductors were important muscles in lifting the knees up (knee-up test positive) and in keeping the knee in this position. However, these muscles were not used to analyse their correlations with the key muscles in the current study, because they were not key muscles of the ISNSCI classification. The knee-up test also provides easy distinction between AIS C and D in patients with motor incomplete CSIC. If the patient could not lift his/her knees in either legs to an upright position (single knee-up test negative), this patient was classified as AIS C with 98.6% probability; on the other hand, if the patient was able to lift his/her knee in at least one leg (single knee-up test positive) to an upright position, this patient was classified as AIC D with 82.5% probability. Although the knee-up test was useful to estimate AIS C or D, the purpose of this test was not to promote shortcuts for clinical evaluations but to screen the severity of motor incomplete CSCI for non-expert examiners using an easy clinical tool. The knee-up test is thought to be useful to estimate TCCS. However, with regard to the relationship between the knee-up test and TCCS, the sensitivity, specificity, PPV and NPV of this test were 83.5, 50.89, 56.35 and 80.26, respectively. These results suggest that the knee-up test is more useful for the distinction between AIS C and D in patients with incomplete CSCI than for the distinction of TCCS.

Even though the single knee-up test was positive in 126 patients, only 22 were classified as AIS C. This might explain the relatively low specificity of the knee-up test. Among these patients, 15 (68%) had a one side positive test result. When a single positive test is divided into two categories: both side positive (73 of 80 cases (91%) were AIS D) and one side positive (31 of 46 cases (67%) were AIS D), the percentage of correctly identified cases with AIS D increased; however, the sensitivity and specificity of the test could not be calculated. Regardless of its relatively low specificity, these correction rates of classification (98.6% and 82.5%) are high enough to be compared to the results of the trained raters [15, 20, 24, 27].

In this study, we analysed the motor score of the key muscles necessary for lifting the knee using a multiple logistic regression model and found that the hip flexors and ankle dorsiflexors were the statistically significantly associated with the knee-up test (Table 2). Notably, the motor score of these muscles had a strongly positive correlation with the score of the key muscles in the lower limbs and a moderately positive correlation with that of the key muscles of upper limbs. These results suggest that a simple examination using the knee-up test yields general information of paralysis in extremities, especially in the legs, with great accuracy. Alternatively, the lower-limb muscles, besides the hip flexors and ankle dorsiflexors, had a moderate correlation with the upper-limb muscles. These results indicate that patients with a positive knee-up test most likely had a substantial motor function in the upper and lower limbs. Given that the distinction between AIS C and D is that whether at least half of the key muscle functions below the NLI have a muscle grade of >3 (5–3) or <3 (2–0), there is a high possibility that patients with positive knee-up test are classified as AIS D. For this reason, this test could estimate the AIS classification with high probability in patients with incomplete CSCI.

There are several possible limitations associated with this study. First, the sample size was relatively small. Second, the knee-up test was evaluated at a single institution. Third, this test is not applicable to patients with pelvic fracture and/or lower-limb fracture who are unable to lift up their knees. Fourth, because only patients in a very acute stage were examined, the results of this study cannot be transferred to patients in the chronic stage because of severe spasticity, joint contractures, pain and heterotopic ossifications. Finally, the knee-up test is not useful for the patient with CSCI who has absent motor function of the lower extremities but sacral sensory sparing with sparing of motor function more than three levels below the motor level for that side of the body; the patient is then classified as AIS C. When the patient had no leg motor function but who has sacral sensory sparing, adequate ISNCSCI examination is mandatory to precisely classify AIS. Despite these limitations, we believe that this test is useful at bedside for non-trained clinicians who are not familiar with the ISNCSCI method. In addition, this test is applicable for the patients who have difficulties with precise communication and neurological evaluation.

In conclusion, the sensitivity, specificity, PPV and NPV of this test for distinction between AIS C and D in patients with motor incomplete CSCI were 99.1, 76.8, 82.5 and 98.7, respectively.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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A Safe Surgical Procedure for Old Distractive Flexion Injuries of the Subaxial Cervical Spine

Osamu Kawano, Takeshi Maeda, Eiji Mori, Itaru Yugue, Takayoshi Ueta, Keiichiro Shiba

Department of Orthopaedic Surgery, Spinal Injuries Center, Fukuoka, Japan

Study Design: Retrospective review.

Purpose: To describe a safe and effective surgical procedure for old distractive flexion (DF) injuries of the subaxial cervical spine.

Overview of Literature: Surgical treatment is required in old cases when a progression of the kyphotic deformity and/or persistent neck pain and/or the appearance of new neurological symptoms are observed. Since surgical treatment is more complicated and dangerous in old cases than in acute distractive-flexion cases, the indications for surgery and the selection of the surgical procedure must be carefully conducted.

Methods: To identify a safe and effective surgical procedure, the procedure selected, reason(s) for its selection, and associated neurological complications were investigated in 13 patients with old cervical DF injuries.

Results: No neurological complications were observed in nine patients (DF stage 2 or 3) who underwent the anterior-posterior-anterior (A-P-A) method and two patients (DF stage 1) who underwent the posterior method. It was initially planned that two patients (DF stage 2) who underwent the P-A method would be treated using the Posterior method alone; however, anterior discectomy was added to the procedure after the development of a severe spinal cord disorder.

Conclusions: The A-P-A method (anterior discectomy, posterior release and/or partial facetectomy, reduction and instrumentation, anterior bone grafting) is considered to be a suitable surgical procedure for old cervical DF injuries.

Keywords: Old cervical spine injuries; Distractive flexion injuries; Post-traumatic deformity; Circumferential release; Delayed presentation

Introduction

Distractive flexion (DF) injuries [1] are often observed among patients with subaxial cervical spine injuries. The treatment generally selected for patients with such injuries is closed or open reduction and internal fixation with the purpose of spinal reconstruction, ensuring protection of the spinal cord. Reduction is usually performed during the acute phase, and good alignment can usually be obtained. However, the surgical treatment of patients with old injuries, where the injury was overlooked at the initial assessment, can be complicated and dangerous in terms of spinal alignment and spinal cord safety [2,3]. Surgical treatment is required in patients with old injuries when there is progression of the kyphotic deformity and/or persistent neck pain and/or the appearance of new

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Corresponding author: Osamu Kawano

Department of Orthopaedic Surgery, Spinal Injuries Center, 550-4 Igisu, Iizuka, Fukuoka 820-8508, Japan

Tel: +81-948-24-7500, Fax: 81-948-29-1065, E-mail: orthosic@orange.ocn.ne.jp

neurological symptoms [4]. Because surgical treatment is more complicated and dangerous in patients with old injuries than in those with acute DF injuries, indications for surgery and the selection of an appropriate surgical procedure must be carefully conducted.

The purpose of this study was to clarify which surgical procedure was the safest and most effective for treating patients with old DF injuries of the subaxial cervical spine. We also investigated the reasons why this type of injury is sometimes overlooked at the initial assessment and discuss the initial diagnostic methods that can be used to avoid overlooking such injuries in the future.

Materials and Methods

The medical records of all 1,208 patients with subaxial cervical spinal injuries who were surgically treated at our institute between 1990 and 2015 were retrospectively reviewed. Of these patients, only 13 were surgically treated and had old trauma injuries, which were all classified as DF injuries [1]. All patients were male and ranged in age from 23 years to 73 years. The mean duration of follow-up was 2.8 years (range, 2–5 years).

To investigate the reasons why DF injuries were overlooked at the initial assessment, eventually resulting in old fracture dislocation or post-traumatic kyphotic deformities requiring treatment, the following four items were obtained from the records of the 13 patients: (1) the affected intervertebral segment, (2) the presence of neck pain and neurological symptoms at the initial assessment, (3) the use of radiography at the initial assessment and the detection of any abnormalities on available radiographs, and (4) the time between injury and surgery and the symptoms that led to the correct diagnosis. To investigate the suitability of the surgical procedure, the following items were investigated: (5) the surgical procedure and the reason(s) for its selection and (6) neurological and any other complications associated with surgery.

Results

1. Affected segment of the cervical spine

Among the 13 patients, the C4/5 segment was affected in three, the C5/6 segment in four, and the C6/7 segment in six (Table 1). Many of the injuries affected the lower cervical spine, where injuries are prone to being overlooked during radiography because of overlap with the shoulder. One patient with a C4/5 injury was diagnosed with a DF injury at the initial assessment at another hospital; however, the patient was conservatively treated using a halo vest to obtain reduction and fibrous fusion. Another patient with a C4/5 injury had a complication of a dislocated larynx; treatment for this delayed the treatment for cervical spine dislocation. A third patient with a C4/5 injury had subluxation that spontaneously repositioned in the supine

Table 1. Case summary: primary assessment

Case	Level	Neck pain	Neurological symptom	Radiographic examination	Radiographic abnormality
1	C6/7	+	Arm pain	+	None
2	C4/5	-	-	+	+ (Halo vest)
3	C5/6	+	-	+	None
4	C5/6	+	-	–	-
5	C6/7		-	+	None
6	C5/6	+	-	–	-
7	C6/7	-	-	–	-
8	C6/7	+	-	+	None
9	C5/6	+	Arm pain	+	None
10	C6/7	+	Quadriplegia	+	None
11	C4/5	+	-	+	+ (Dislocation of the larynx)
12	C4/5	+	-	+	None
13	C6/7	+	-	+	CT: C7 fracture

CT, computed tomography.

position at the initial assessment.

2. Symptoms immediately following injury

Neck pain was observed at the initial assessment in 10 patients, with some type of neurological symptoms observed in three patients (two with arm pain and one with incomplete quadriplegia) (Table 1).

3. Radiography at the initial assessment

Radiography was not performed at the initial assessment in three patients (Table 1). Of the 10 patients examined by radiography, abnormal findings were observed in only two: the patient treated with a halo vest and the patient with the laryngeal injury, described above. A patient was diagnosed as having a C7 vertebral body fracture by a computed tomography (CT) scan. No abnormalities were observed in seven patients who were radiographically ex-

Table 2. Case summary: primary and new symptoms

Case	Primary symptoms (persistance or aggravation)	New symptoms
1	Neck pain	-
2	Neck pain (halo vest)	-
3	Neck pain	ROM limitation of the neck
4	Neck pain	Numbness of the arm
5	-	Neck and arm pain
6	-	Numbness of the fingers
7	-	Neck pain and palsy of U/E
8	Neck pain	Palsy of U/E
9	Neck pain and arm pain	-
10	-	Quadriplegia
11	Neck pain (dislocation of larynx case)	-
12	Neck pain	Lt. C5 palsy
13	Neck pain	Lt. arm pain

ROM, range of motion; U/E, upper extremity; Lt., left.

Table 3. Case summary: diagnosis, treatment, and complications

Case	Time between injury and surgery (mo)	Reduction prior to surgery	Surgical method	Neurological deterioration
1	1	+	P	-
2	5	-	A-P-A	-
3	4.5	-	A-P-A	-
4	1.5	+	P	-
5	1.5	-	A-P-A	-
6	3	-	A-P-A	-
7	3	-	A-P-A	-
8	2	-	P-A	AIS E→A→D
9	2	-	A-P-A	-
10	3.5	-	P-A	AIS D→A→C
11	1.5	-	A-P-A	-
12	1	-	A-P-A	-
13	2	-	A-P-A	-

P, posterior; A anterior; P-A, posterior-anterior; AIS, American Spinal Injury Association Impairment Scale.

amined. It was thought that these cases included patients in whom the subluxation became spontaneously repositioned or the affected segment was hidden by the shoulder and could not be diagnosed.

4. Time between injury and surgery and key symptoms that led to the correct diagnosis

Table 2 lists the patients' primary and new symptoms, and Table 3 summarizes their diagnoses and treatment. The time interval between injury and surgery was one to five months (mean, 2.4 months). Nine patients were diagnosed on the basis of other radiological examinations investigating new symptoms, and two patients were diagnosed upon reinvestigation because of symptoms that had persisted since the initial assessment.

5. Surgical procedures

The anterior-posterior-anterior (A-P-A) method (anterior discectomy, posterior release and/or partial facetectomy, reduction and instrumentation, and anterior bone grafting) (Fig. 1) was performed for nine patients (five at DF stage 2 and four at DF stage 3); the posterior-anterior (P-A) method (posterior release and/or partial facetectomy reduction and instrumentation, anterior discectomy, and bone grafting) was performed for two patients, both at DF stage 2; and the posterior (P) method (posterior release, reduction, and fusion) was performed for two patients, both at DF stage 1 (Table 3). Either spinous process wiring or the lateral mass screw and rod system was used for posterior instrumentation. Lateral flexion–extension radiography using X-ray images obtained prior to surgery

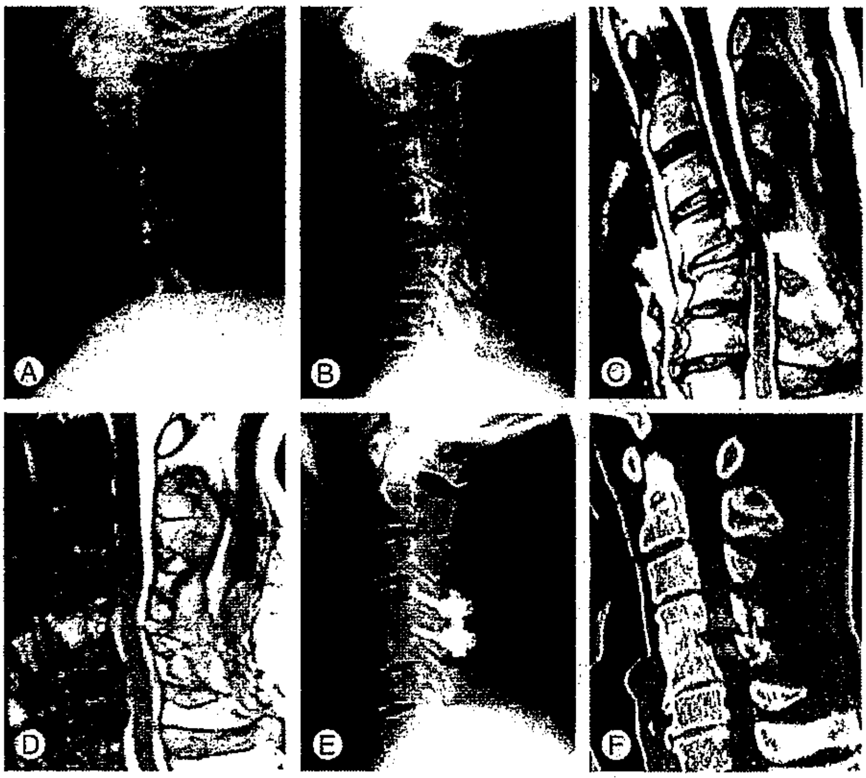


Fig. 1. (A) Lateral X-ray obtained immediately after the injury (supine position). The distractive flexion (DF) injury was not clear. (B) Lateral X-ray obtained after three weeks (sitting position). C4/5 subluxation due to the DF injury has been cleared. The patient's neck pain persisted and left C5 palsy subsequently developed. (C) Magnetic resonance imaging (MRI): T2 sagittal image. The C4/5 disc migrated to the spinal canal. (D) MRI: T2 sagittal image. Disc herniation was removed with sufficient spinal cord decompression. (E) Lateral X-ray obtained after surgical treatment with the anterior-posterior-anterior method using the lateral mass screw system and anterior iliac bone grafting. Good alignment was obtained. (F) Multi planar reconstruction-computed tomography (one year after surgery). Good bony fusion was obtained at the C4/5 intervertebral body.

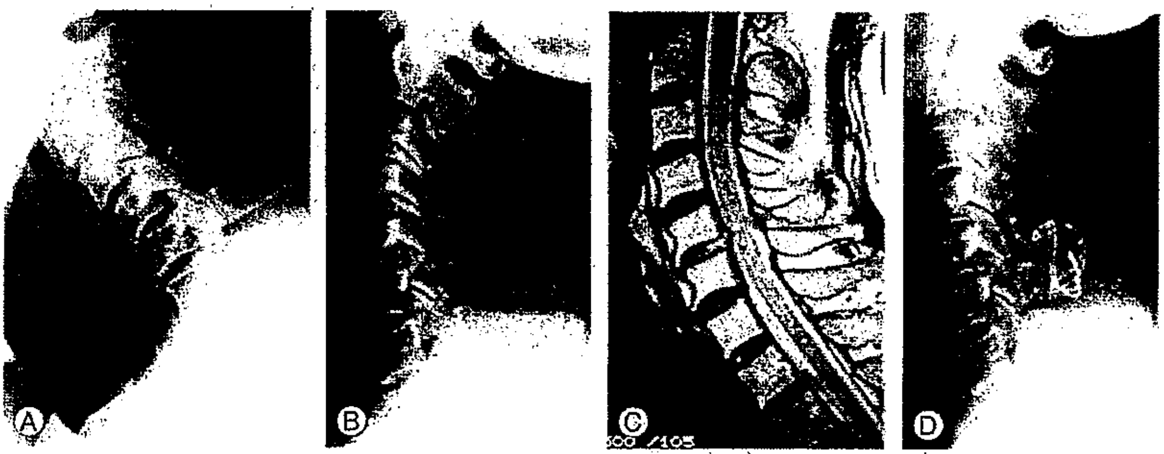


Fig. 2. (A) Lateral flexion X-ray: C5/6 distractive flexion injury. C5 subluxation (DFS1). (B) Lateral extension X-ray: a reduction position was obtained with no neurological deterioration. (C) Magnetic resonance imaging (MRI): T2 sagittal image. No neurological complications occurred despite C5/6 disc bulging. (D) Lateral X-ray obtained after surgical treatment: posterior reduction and fixation with spinous process wiring and bone grafting were performed.

confirmed that both patients treated with the P method alone had obtained a reduction. Radiography had been performed with the assistance of a spine surgeon while the patient was conscious, and the lack of any new neurological symptoms (spinal cord disorder or radiculopathy) was confirmed at that time (Fig. 2).

It was initially planned that the two patients who underwent the P-A method would be treated using the P method alone; however, these patients developed severe spinal cord disorders. Therefore, anterior decompression with discectomy and bone grafting were also performed. Neither patient achieved reduction, as indicated by lateral flexion–extension radiography using X-ray images prior to surgery.

6. Outcomes and complications

There were no intraoperative or postoperative complications among the nine patients treated using the A-P-A method or the two patients treated using the P method. These patients obtained good bony fusion. As described above, the anterior method was added to the treatment regimen of two patients because of the development of severe spinal cord disorders. In both patients, aggravation of the spinal cord disorder was caused by increased spinal cord compression due to intervertebral disc herniation. In one of these patients, the neurological status deteriorated from American Spinal Injury Association Impairment Scale (AIS) E to AIS A immediately after posterior surgery. However, one year after undergoing immediate anterior decompression surgery, the patient's neurological status had recovered to AIS D (Fig. 3). The other patient's neurological status was AIS D before surgery. Because neurological deterioration from AIS D to AIS A was noted immediately after posterior surgery, emergency anterior decompression surgery was subsequently performed. At the final follow-up visit two years after presentation, the patient's neurological status was found to have recovered to only AIS C.

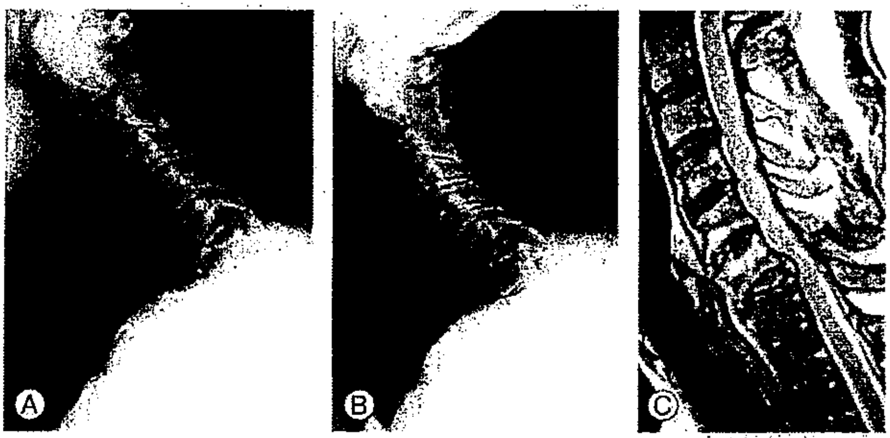
The mean surgical time was 229.3 minutes (range, 160–325 minutes) for the A-P-A method, 64.0 minutes (range, 60–68 minutes) for the P method, and 201.5 minutes (range, 178–225 minutes) for the P-A method. The mean blood loss was 269.2 g (range, 89–538 g) for the A-P-A method, 99.5 g (range, 80–119 g) for the P method, and 152.5 g (range, 108–197 g) for the P-A method.

7. Compliance with ethical standards

This article does not contain any studies with human participants or animals performed by any of the authors. Informed consent was obtained from all individual participants included in the study.

Discussion

Two problems can arise regarding old cervical DF injuries. The first relates to the initial assessment, and the second



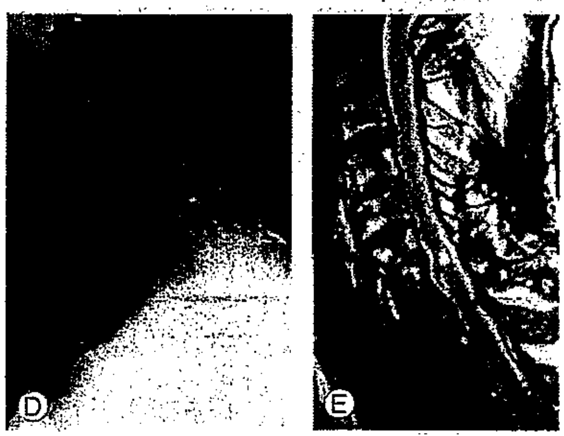


Fig. 3. (A) Lateral neutral X-ray: C6/7 distractive flexion injury. (B) Lateral extension X-ray: a reduction position could not be obtained. (C) Magnetic resonance imaging (MRI): T2 sagittal image. C6/7 disc protrusion. (D) Lateral X-ray after surgical treatment: anterior decompression and bone grafting were added to the treatment regimen immediately following posterior surgery with release, reduction, and fixation because of the development of neurological deterioration as a result of disc herniation after surgery. (E) MRI: T2 sagittal image obtained after surgery. A high-intensity area remained in the spinal cord.

relates to the surgical procedure. The initial diagnosis and treatment are performed as emergency medical services, where it is difficult to sufficiently evaluate the lower cervical spine because it is hidden by the shoulder [5,6]. CT scanning has become simplified in recent years, allowing the evaluation of bone fractures in the lower cervical spine. However, spontaneous reduction of anterior dislocation or subluxation without fractures in the lower cervical spine can sometimes occur in association with DF injuries, but these cannot be accurately evaluated using CT [7]. When a cervical spine injury is suspected based on the circumstances under which the injury occurred or because of the presence of symptoms such as severe neck pain, it is necessary to carefully apply lateral flexion–extension radiography using X-ray images, with the assistance of a spine surgeon, in addition to radiography and CT scans.

In patients in whom the affected segment of the cervical spine is hidden by the shoulder, it is worth evaluating using swimmer's lateral view flexion–extension radiography or a CT scan in the flexion position. At our institute, lateral flexion–extension radiography or CT scans in the flexion position are performed during the initial assessment and the degree of instability due to soft tissue injury is evaluated [8]. These investigations should be carefully performed such that the patient's neurological symptoms are not aggravated. Recently, many surgeons have been using magnetic resonance imaging (MRI) to detect soft tissue injuries. The frequency of performing stress radiography is therefore expected to decrease in the future.

Our patients were surgically treated because of the persistence of neck and arm pain or the deterioration of neurological symptoms [4]. These symptoms were caused by progression of the kyphotic deformity and/or persistent instability of the cervical spine. Accordingly, when selecting the surgical procedure, the goal should be to achieve both good alignment and bony fusion to reconstruct the injured cervical spine and avoid worsening any neurological symptoms.

Previous reports have discussed surgical procedures for old (or delayed presentation) DF injuries, with apparent advantages and disadvantages for each of these methods [2,9-11]. Bartels and Donk [2] concluded that the A-P-A method should be performed for patients with non-acute bilateral cervical facet dislocations. Hassan [10] reported a method involving five steps, with traction in between; however, the method is very complicated and leads to a long treatment course. Liu et al. [11] reported that anatomical reduction can be successfully achieved with the P-A method, primarily including posterior release, anterior release, reduction, intervertebral bone grafting, and anterior plating. However, we are concerned about the possibility of the failure of reduction via the anterior method and the low stability provided by anterior plating for circumferential soft tissue release to the cervical spine. Basu et al. [12] reported that preoperative traction is a safe and effective initial treatment for patients with neglected cervical facet dislocation. Traction may be effective for acute and subacute patients; however, the patients in that study were treated at 7 to 21 days (mean, 14 days) after injury, whereas our patients were treated more than one month after the injury. Goni et al. [13] suggested that there was no role for skull traction in neglected DF injuries to the cervical spine after a delay of more than three weeks. They recommended the Posterior method followed by the anterior method.

Based on our experience, surgery can be safely performed without worsening the patient's neurological symptoms using the A-P-A method (anterior discectomy, posterior release and/or partial facetectomy, reduction and instrumentation, and anterior bone grafting), and we believe that this method should therefore be recommended, even though it is rather complex to perform. Based on their experience, Liu et al. [11] recommended either the P-A method (posterior release, anterior release, reduction, intervertebral grafting, and anterior plating) or the P-A-P method (posterior release, anterior reduction and plate fixation, and posterior instrumentation). However, the Posterior method has advantages in terms of safety and strength for instrumentation during the reduction and for arranging spinal alignment. We therefore consider the A-P-A method to be more reasonable and to able to provide better outcomes than the P-A and P-A-P methods. In any case, circumferential release, fixation, and bone grafting are likely to be necessary in patients with old DF injuries

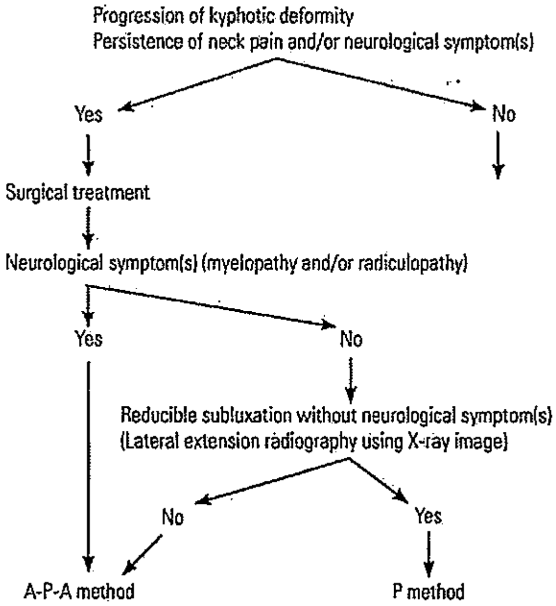


Fig. 4. Flowchart for selecting the surgical method for treating patients with old distractive flexion injuries. A-P-A, anterior-posterior-anterior; P, posterior.

associated with neurological symptoms and/or kyphotic deformities.

The P method can be applied in patients at DF stage 1; using this method, good reduction is achieved on lateral extension radiography using X-ray images prior to surgery, without worsening the patient's neurological symptoms or disc herniation on MRI (Fig. 4).

Our experience of patients with old cervical DF injuries in which one or more months have passed since the trauma has shown that forcible reduction via posterior release alone results in an excess load to the anterior element (intervertebral disc) during the process of scar formation, bringing the risk of deterioration of the patient's neurological symptoms due to herniation of the intervertebral discs [14]. The optimal type of surgical management should be determined not only by the label of "old" but also based on whether there is an irreducible condition due to scar formation resulting from the microinstability of an old DF injury. The A-P-A method is considered to be a reasonable, safe, and reliable procedure that can be applied for patients with old DF injuries of the subaxial cervical spine. The P method can be applied, such as in patients at DF stage 1, in whom good reduction is achieved on lateral extension radiography using X-ray images prior to surgery, without a deterioration in the patient's neurological symptoms or disc herniation on MRI.

A limitation of the present study was the small population size (only 13 patients). However, this was inevitable, as this kind of lesion is infrequent. We nevertheless hope that our clinical experience can help spine surgeons safely treat patients with old DF injuries.

Conclusions

Because surgical treatment is more complicated and dangerous for patients with old DF injuries than for those with acute DF injuries, the surgical method must be carefully considered. Circumferential release, fixation, and bone grafting of the spinal column are likely to be necessary in patients with old cervical DF injuries associated with neurological symptoms and/or kyphotic deformities. The A-P-A method (anterior discectomy, posterior release and/or partial facetectomy, reduction and instrumentation, and anterior bone grafting) is considered to be a reasonable, safe and effective surgical procedure for treating patients with old cervical DF injuries.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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REVIEW ARTICLE

Physiological basis and practice of rehabilitation medicine in the management of individuals with spinal cord injury

Fumihiro Tajima,[1] Yoshi-ichiro Kamijo,[1] Tadashi Sumiya,[1] Yukihide Nishimura,[1] Hideki Arakawa,[1] Takeshi Nakamura[2] and Kazunari Furusawa[3]

[1]Department of Rehabilitation Medicine, School of Medicine, Wakayama Medical University, Wakayama, [2]Department of Rehabilitation Medicine, School of Medicine, Yokohama City University, Yokohama, [3]Department of Rehabilitation Medicine, Kibikogen Rehabilitation Center for Employment Injuries, Okayama, Japan

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Correspondence
Fumihiro Tajima, MD, PhD, Department of Rehabilitation Medicine, Wakayama Medical University, School of Medicine, 811-1 Kimiidera, Wakayama city, Wakayama 641-8509, Japan.
Tel: +81-73-446-6475
Fax: +81-73-441-0664
Email: fumi@wakayama-med.ac.jp

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Abstract

Rehabilitation medicine has made dramatic and successful progress in recent years, and neurologists and physiatrists have faced greater challenges in coordinating the clinical management of patients with spinal cord injuries (SCI). To ensure the best clinical outcome in SCI, physiatrist need to comprehend the dysfunctions of various body systems and the physiological aspects of the central nervous, musculoskeletal and autonomic nervous system, as well as the social support system. Furthermore, the rehabilitation team, including physiatrists, nurses, physical therapists, social workers and peer supporters, should provide surgical treatment, clinical management, drug therapy and optimal assistance for SCI. We believe that the first important task in the management of SCI patients is precise diagnosis of the site of the spinal cord lesion. This should be followed as soon as possible by spinal surgery to stabilize the vertebral column. The day after surgery, the patient should be handled by the rehabilitation team. Orthostatic loads should be applied, and exercise of the remaining muscles should begin in order to ensure early mobilization and satisfactory repair. Our group has carried out extensive research into the pathophysiology of the cardiovascular, respiratory, endocrine and autonomic nervous systems and exercise responses in SCI, and reported the benefits and improvements of early mobilization and exercise, and the safety of physical medicine and rehabilitation. The rehabilitation team should follow these individuals closely to provide long-term clinical care, and deal with social issues arising during the chronic phase. Participation in sports activities (para-sports) could work well to improve the physical condition of these individuals.

Introduction

Rehabilitation medicine was established after World War II after political pressure to care for injured war veterans, with the aim of improving the daily living and quality of life of individuals with war-related disabilities.[1] Subsequently, the scope of rehabilitation medicine extended to otherwise healthy individuals who suffered traumatic spinal cord injury (SCI). During the past five decades, rehabilitation medicine has become a recognized clinical specialty in many countries, including the USA, UK, Australia and Japan. Today, physiatrists (i.e. a physician who specializes in physical medicine and rehabilitation) face several challenges in the management of rehabilitation wards in addition to the coordination of clinical care of patients with SCI with physicians of other specialties. To achieve optimal clinical outcomes, physiatrists have to understand both the physiological/clinical/social issues of clinical care plus manage the entire rehabilitation team including nurses, physiotherapists, occupational therapists and case managers to deliver optimal medical and social support for SCI patients.[1]

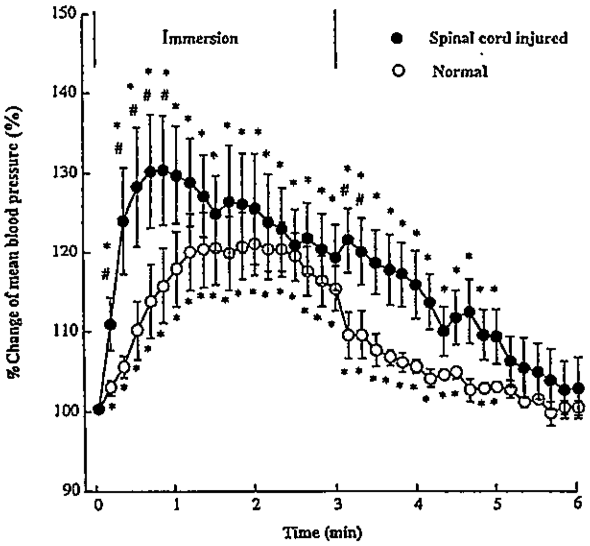

Figure 1 Percent change in mean blood pressure in control ($n = 6$) and spinal cord injury subjects ($n = 8$) during 3 min of cold pressor test (foot immersion in 0°C water) and 3 min of recovery. Data are mean ± SEM. *$P < 0.05$, compared with the control period. #$P < 0.05$ control versus spinal cord injury subjects.

complications. In a study that compared patients with chronic thoracic SCI and healthy subjects, our group evaluated the vessel diameter, blood flow velocity, and flow volume in the left and right carotid arteries using high-resolution B-mode ultrasonography.[7] The results showed lower flow volume and flow velocity in the common carotid arteries of SCI than healthy subjects.

Isometric muscle contraction (static exercise) induces a major circulatory response, and increases in blood pressure and heart rate in normal subjects.[8] In this regard, some researchers raised concerns about excess pressure response during static exercise in SCI.[4] Our group investigated static exercise-induced pressor response and blood redistribution in non-exercising muscles during static exercise in SCI individuals and normal subjects.[9] In the study, we non-invasively measured the mean blood pressure, heart rate, cardiac output, total peripheral resistance, leg skin blood flow and leg muscle blood flow during 2 min of arm static exercise at 35% maximal voluntary contraction. All of the aforementioned parameters increased in both the SCI and normal subjects during maximal voluntary contraction, and the amounts of the increases were similar. The results also showed that sympathetic vasoconstriction in the resting leg area did not contribute to the pressor reflex during 35% maximal voluntary contraction of arm static exercise. These findings suggest that static exercise in SCI was not worse compared with normal subjects.

In another study, we also compared the pressor response with static exercise in patients with cervical SCI (CSCI, spinal lesion at C6–C8 level) and normal subjects. Static exercise significantly increased blood pressure in both CSCI and normal subjects (Fig. 2).[4] In contrast, the same exercise increased the heart rate in normal subjects, but not in CSCI patients. The significant increase in blood pressure observed in the study indicates the presence of a peripheral control loop from muscle receptors, which evoked pressor response during static exercise in SCI subjects.

Pressure sores in SCI

Pressure ulcers remain a major problem in SCI, as the condition compromises quality of life for financial, physical and psychological reasons. Pressure ulcers occur almost exclusively over bony prominences that are subjected to excessive pressure for a length of time, and inevitably resolve once such pressure is avoided. Therefore, it is likely that ischemia as a result of supracapillary pressure is the main

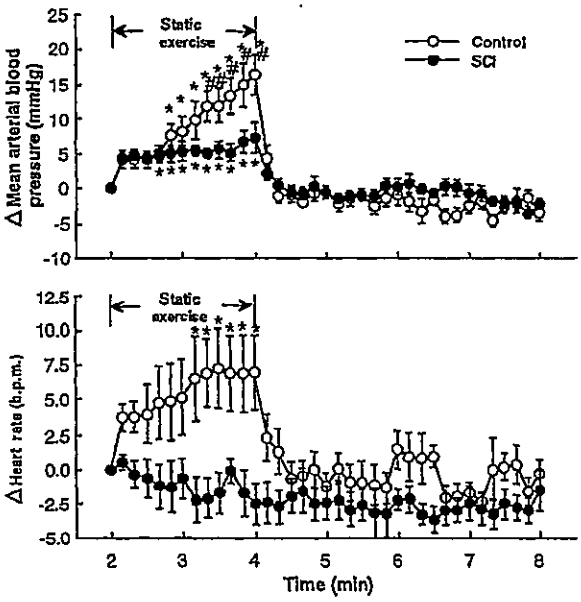

Figure 2 Changes (Δ) in (a) mean blood pressure and (b) heart rate in control ($n = 7$) and spinal cord injury (SCI) subjects ($n = 7$) during 2 min of static exercise (35% maximal voluntary contraction) and 4 min of recovery. Data are mean ± SEM. *$P < 0.05$, compared with the pre-exercise period. #$P < 0.05$, compared with SCI subjects.

century. Dr Nakamura provided clinical care for a large number of SCI patients, and his effort resulted in the stabilization of their medical conditions. However, most of these patients had to stay in hospitals for the remainder of their lives. Sir Goodman established the basis of rehabilitation medicine for SCI, and Dr Nakamura started his clinical training in rehabilitation medicine in 1960 with Dr Goodman at the Stoke Mandeville Hospital, Aylesbury, UK. After completing the training and returning to Japan, Dr Nakamura established Japan Sun Industries in 1965 at Oita Prefecture. The purpose of that project was to provide jobs for individuals with physical disabilities. However, the project offered only small handicraft jobs, with much disappointment to Dr Nakamura. Consequently, he popularized the slogan, "No charity, but a chance" for individuals with disabilities, and hired the firm to complete his dream. In 1972, Japan Sun Industries grew dramatically after establishing joint ventures with modern industrial enterprises: Sony, Honda, Mitsubishi, Denso and Omron. These large companies decided to join the project, and constructed subsidies at Oita. Before his death in 1984, Sun Industries had established several branches at Aichi, Kyoto and Ohga. Since then, the Japanese government legislated several regulations regarding employment of individuals with disabilities; persons with disabilities must form at least 1.8% of the work force in most Japanese corporations.

Age-related problems in SCI

At the time of the establishment of Sun Industries, all employees were young individuals; and the majority were aged <30 years. When the Author started working with Sun Industries in 1984, aging of individuals with disabilities was not an issue and was never discussed, as most physicians believed that the majority of such individuals would die within 20 years of the injury. At present, however, most individuals with disabilities can live more than 30 years after the injury, particularly as they are provided with optimal medical support and look after their own condition.

Although individuals with chronic SCI suffer from many of the same medical disorders of their able-bodied counterparts, the clinical manifestations of these medical conditions might be atypical because of the complex physiological changes associated with spinal cord transection, as described previously.[3,4,14] However, there is very little information at present regarding age-related clinical problems in individuals with disabilities.

Age-related changes in maximum oxygen consumption and sports activities in SCI

The first physiological age-related change is a decline in cardiovascular function and physical fitness. Sadly, this issue has rarely been investigated in SCI. Approximately 20 years ago, we measured the maximum oxygen consumption (VO_2max) of Japanese wheelchair sports athletes with SCI.[15] Later, we invited some of the individuals who participated in the aforementioned study to join a follow-up study, and examined age-related changes in VO_2max, as well provided information on their daily physical activities and training that could have influenced physical capacities. Seven athletes with SCI who participated in the 4th, 5th and 6th Oita International Wheelchair Marathon Race were examined approximately 20 years ago, and re-examined for VO_2max to determine the longitudinal changes in physical capacity. First, as expected, there was a large interindividual variability (Fig. 3);[15] the VO_2max of participants A–F, who had continued participation in marathon racing, was almost maintained or increased over the 20-year period. Second, the VO_2max markedly increased in participants B and F, who had undertaken regular exhaustive training. Third, in participant G, who had not carried out any sports activity during the same period, the VO_2max was decreased by 53%. These results suggest that vigorous physical capacity reflected the sports activities in individuals with SCI.

In the past, it was thought that excessive exercise in SCI individuals could add insult to the neuromuscular and skeletal system as a result of altered physiology; however, our results showed that one of the highest load exercise, the wheelchair full marathon race, increased physical capacity. Therefore, we recommend the participation in sports activities to SCI individuals, and that the workload under medical observation can be more than moderate exercise.

Mechanical ventilation for high-level CSCI

Most patients with high-level CSCI; that is, above C3, are dependent on long-term ventilatory support, and frequently suffer ventilatory insufficiency. Wicks and Menter reported that the level of SCI was a major determinant of ventilator independence; 85% of C1 patients, 72% of C2 and 40% of C3 were dependent on mechanical ventilation.[16] During the acute phase of CSCI, the mechanical ventilator with the cuffed tracheostomy tubes should be set at low

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〈Regular Article〉

Assessment of chest movements in tetraplegic patients using a three-dimensional motion analysis system

Takefumi SUGIYAMA[1)], Kozo HANAYAMA[1)], Hiromichi METANI[1)], Sosuke SEKI[1)], Akio TSUBAHARA[1)], Kazunari FURUSAWA[2)], Masaki HYODO[3)]

1) Department of Rehabilitation Medicine, Kawasaki Medical School
2) Kibikogen Rehabilitation Center for Employment Injuries
3) Department of Rehabilitation Medicine, Isehara Kyodo Hospital

ABSTRACT We used optoelectronic plethysmography (OEP) to evaluate the effects of posture on chest and abdominal movements during respiration in patients with chronic-stage complete spinal cord injuries. The subjects were five cervical injury patients (male, C4-C8 injury, American Spinal Injury Association Impairment Scale grade A) and five healthy people matched to each of the cervical injury patients for age, height, and weight. The chest wall movement each of the subjects was recorded using OEP during six quiet breathing and three deep breathing periods in each of the following positions: supine, with the trunk elevated to 30°, and with the trunk elevated to 60°. Data on the chest wall volume and compartment volumes (upper thorax, lower thorax, abdomen) were then compared among the postures. During quiet breathing in the tetraplegic patients, the change in upper thorax volume was smaller at the end of inhalation than at the end of exhalation, presenting as a paradoxical breathing pattern. During deep breathing in the tetraplegic patients, abdominal volume accounted for a large portion of the change in total chest wall volume. Posture affected the recorded abdominal volume; volume was greatest in the supine position and decreased as the posture became more upright.

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Key words : Spinal cord injury, Optoelectronic plethysmography, Respiration, Paradoxical breathing, Three-dimensional motion analysis system

INTRODUCTION

In 1963, Stone and Keltz[1)] published the first detailed report on the pulmonary functions of patients with cervical and thoracic spinal cord injuries. Since then, there have been reports on how respiratory dysfunction due to spinal cord injury relates to injury level[2-4)] and lung complications[5-7)]. In patients with complete cervical spinal cord injuries, even if the diaphragm is spared, the main respiratory muscles (such as

Corresponding author
Takefumi Sugiyama
Department of Rehabilitation Medicine, Kawasaki Medical School, 577 Matsushima, Kurashiki, 701-0192, Japan

Phone : 81 86 462 1111
Fax : 81 86 464 1044
E-mail: t.sugiyama@med.kawasaki-m.ac.jp

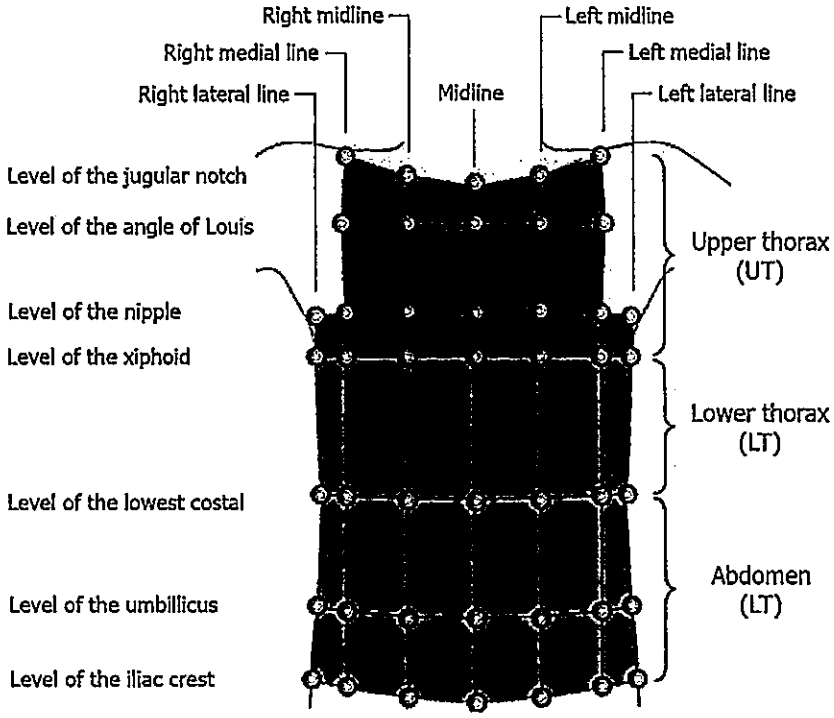

Fig. 1. Positions of the reflective markers on the chest wall.

would not be covered by the subject's body. The subject's shoulders were slightly abducted so the markers on the chest wall could be photographed using the cameras. The respiratory movements were recorded using an optoelectronic motion analysis system (VICON MX, Motion Capture Systems, Oxford, UK), with six infrared cameras placed around the subject. It was confirmed that all the markers could be photographed with the infrared cameras and checked on a PC so that the 3D coordinates would be obtained without loss.

Next, the subjects were given sufficient time to breathe naturally and instructed to perform a period of quiet breathing followed by a period of deep breathing, and to repeat this several times. For deep breathing, the procedure for measuring vital capacity with spirometry was as follows: the subjects were instructed to perform a series of at least three maximum inhalations and maximum exhalations. After data were recorded in the supine position, the trunk was raised to 30°, followed by 60° the same assessment being performed in each posture. The coordinate data were saved at 120-Hz sampling.

The suspension criteria were: (1) subject asked to stop, (2) subject complained of severe fatigue, and (3) an adverse event occurred.

Estimation of chest wall volumes

We placed 45 infrared reflective markers on the anterior and lateral surfaces of the chest and abdominal walls. Next, virtual markers were defined at points where lines dropped perpendicular to the bed from each marker on the chest wall intersected with a reference plane created by the four markers on the bed (Fig. 2). The volume of the total chest wall (V_{CW}) and the volume of each compartment were calculated from the markers' 3D coordinates using the methods of Ferrigno and Carnevali *et al.*[26] and Wang *et al.*[27]. V_{CW} was divided into compartments as follows: volume of the upper thorax (V_{UT}), volume of the lower thorax (V_{LT}), and

Table 1. Characteristics of the tetraplegic patients and the control group

Study Group	Age (years)	Height (cm)	Weight (kg)	Neurological level
tetraplegics (n = 5)	42.0 ± 14.1	170.8 ± 5.2	61.8 ± 13.6	C4/C4/C5/C5/C8
control (n = 5)	44.0 ± 10.7	167.8 ± 1.9	68.1 ± 11.3	
p-Value	0.807	0.262	0.445	

All the presented values are means ± standard deviation. In the last line, the p-values of the comparison between tetraplegics and controls are shown. All the tetraplegic patients were classified as American Spinal Injury Association Impairment Scale (AIS) A. The sex of all the subjects in both groups was male.

five patients (age, 18–54 years; height, 164–178 cm; body weight, 47.3–81 kg; time from injury, 327–4,364 days) (Table. 1) and the control group of five healthy subjects (age, 29–55 years; height, 165–170 cm; weight, 53–75 kg) completed all the procedures. The final analysis was performed on all these subjects.

Effects of posture on volume changes of the total chest wall during quiet breathing

We compared volume changes of the total chest wall during quiet breathing [ΔV_{CW} (QB)] at each posture between the control and tetraplegic groups (Fig. 3).

The mean ΔV_{CW} (QB) in each posture differed significantly between the control and tetraplegic groups. Additionally, ΔV_{CW} (QB) increased in the control group as the posture became more upright; however, the differences were not significant. In the tetraplegic group, ΔV_{CW} (QB) was significantly greater at 30° than at 60°.

Effects of posture on volume changes of the total chest wall during deep breathing

The mean value of ΔV_{CW} (DB) at each posture differed significantly between the control and tetraplegic groups. Significant changes in ΔV_{CW} (DB) due to posture were not observed in the control group. In the tetraplegic group, however, ΔV_{CW} (DB) tended to decrease as the posture became more upright and was significantly greater at 0° than at 60° (Fig. 4).

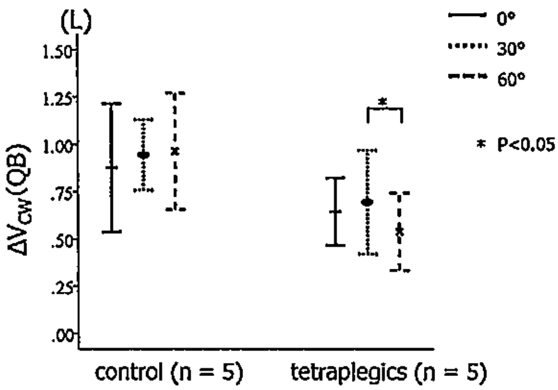

Fig. 3. Comparison of ΔV_{CW} (QB) due to posture between the control and tetraplegic groups.
Each bar indicates the standard deviation, and the center of bar indicates the mean. ΔV_{CW} (QB) expresses the change in chest wall volume during a period of quiet breathing that is equivalent to tidal volume by spirometry. The ΔV_{CW} (QB) value tended to increase in the control group as the trunk was raised, but the differences were not significant. In the tetraplegic group, ΔV_{CW} (QB) was significantly greater at 30° than at 60°. In the same posture, ΔV_{CW} (QB) was significantly lower in the tetraplegic group than in the control group.

Effects of posture on ΔV_{CW} (ERV)/ΔV_{CW} (DB)

We compared ΔV_{CW} (ERV)/ΔV_{CW} (DB) at each posture between the control and tetraplegic groups (Fig. 5). At the same postures, ΔV_{CW} (ERV)/ΔV_{CW} (DB) tended to be lower in the tetraplegic group than in the control group, however no significant differences were observed. ΔV_{CW} (ERV)/ΔV_{CW} (DB) tended to increase as the trunk was raised in both the control and tetraplegic groups, but the differences were not significant.

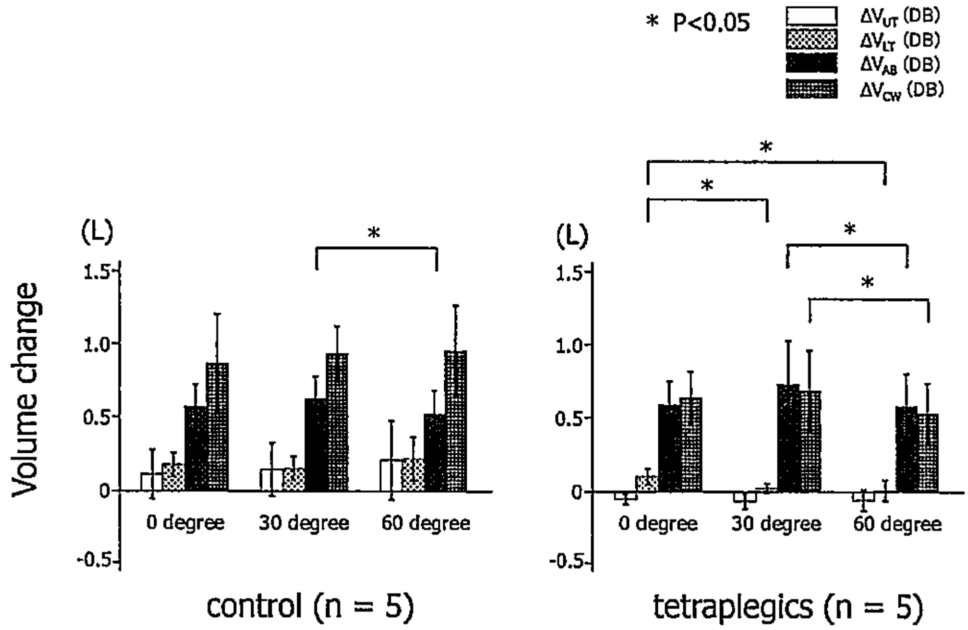

Fig. 6. ΔV_{CW} (QB) and changes in each compartment volume.
Volume change of the upper thorax during quiet breathing [ΔV_{UT} (QB)], volume change of the lower thorax during quiet breathing [ΔV_{LT} (QB)], volume change of the abdomen during quiet breathing [ΔV_{AB} (QB)], volume change of the total chest wall during quiet breathing [ΔV_{CW} (QB)]. In the control group, a significant difference was only observed for ΔV_{AB} (QB) between 30° and 60°. In the tetraplegic group, ΔV_{LT} (QB) at 0° was significantly different than at 30° and 60°, and ΔV_{AB} (QB) and ΔV_{CW} (QB) were significantly greater at 30° than at 60°.

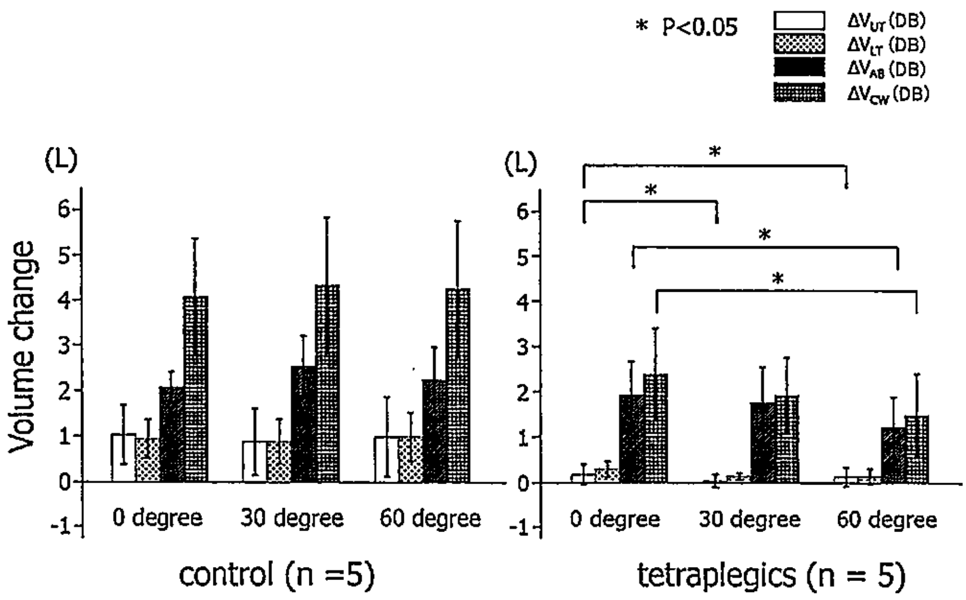

Fig. 7. ΔV_{CW} (DB) and changes in each compartment volume.
Volume change of the upper thorax during deep breathing [ΔV_{UT} (DB)], volume change of the lower thorax during deep breathing [ΔV_{LT} (DB)], volume change of the abdomen during deep breathing [ΔV_{AB} (DB)], volume change of the total chest wall during deep breathing [ΔV_{CW} (QB)]. No significant differences in ΔV_{CW} (DB) due to posture were observed in the control group. In the tetraplegic group, ΔV_{UT} (DB) at 0° was significantly different than at 30° and at 60°; ΔV_{AB} (DB) at 0° was significantly different than at 60°; and ΔV_{CW} (DB) at 0° was significantly different than at 60°. Both ΔV_{AB} (DB) and ΔV_{CW} (DB) decreased as trunk angle increased.

expiratory reserve volume (ERV) and increased residual volume (RV) due to lower forced expiratory capacity. ΔV_{CW} (ERV)/ ΔV_{CW} (DB) served as an indicator of the percentage that expiratory effort occupied among the factors causing decreased vital capacity. In the present study as well, ΔV_{CW} was lower in spinal cord injury patients than in healthy people, and ΔV_{CW} (ERV)/ ΔV_{CW} (DB) was also lower but not significant. It was expected that ΔV_{CW} (ERV)/ ΔV_{CW} would decrease because abdominal and intercostal muscle paralysis in tetraplegics makes effort expiration difficult. However, because there is a considerable difference in the average value, it seems possible that the number of cases was insufficient, and further study is necessary.

Effects of posture

The results of the current study show that the volume change was larger both in the chest and abdomen in supine position. It seemed that, considering the possibility that the difference in posture affects the load amount in respiratory muscle strengthening and exercise loading, we should pay attention to exercise posture when we plan exercise protocol in such patients.

A previous study by Miccinilli *et al.*[24] assessed subjects in two positions (supine and sitting in a wheelchair), whereas the present study evaluated three trunk angles (0°, 30°, 60°). Another study by Romei *et al.*[30] found that when the trunk angle of healthy women was increased from supine to a reclining sitting position, the proportion of the abdomen that comprised the ventilatory volume of a breath decreased significantly, although no significant difference was observed in healthy men. They also found that respiration in the sitting position was influenced by the presence or absence of a backrest. In the present study, all assessments were performed using a backrest.

Past studies found that, in healthy people, chest movements comprise a relatively large percentage during respiration in the standing and sitting positions compared with the supine position, while the abdomen makes up a relatively small percentage[15, 16].

In tetraplegic patients, volume change of the lower thorax during quiet breathing [ΔV_{LT} (QB)] decreased as the posture became upright, although ΔV_{UT} (QB) was a negative value consistently and was not influenced by posture. Abdominal content creates pressure on the diaphragm in the supine position; however, in the upright position it does not, making the diaphragm work more efficiently. This phenomenon makes the rib cage be pulled up to the cranial direction, so it is considered that there is little movement in the supine position in tetraplegics.

During deep breathing, the accessory breathing muscles seemed to work because ΔV_{UT} (DB) no longer had a negative value. In this situation, it seems that movement of the diaphragm directly affected ΔV_{CW} (DB).

A study by Agostoni *et al.*[19] reported that abdominal compliance increased in the supine position even in healthy people. Goldman *et al.*[29] reported that, in the supine position, abdominal wall compliance was 77% higher in spinal cord injury patients than in healthy people. These findings help substantiate the increase in volume change of the abdomen (ΔV_{AB}) that we observed in the supine position.

CONCLUSION

In the present study, we performed a motion analysis using OEP to evaluate the effects of posture on the breathing pattern of patients with complete spinal cord injuries. During quiet breathing, spinal cord injury patients exhibited paradoxical movements of the upper thorax and abdominal movements made up the greatest percentage of respiratory movement. During deep breathing, tetraplegic also exhibited a breathing pattern that

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ORIGINAL ARTICLE

Efficacy and safety of osteoporosis medications in a rat model of late-stage chronic kidney disease accompanied by secondary hyperparathyroidism and hyperphosphatemia

M. Ota[1] · M. Takahata[1] · T. Shimizu[1] · Y. Kanehira[2] · H. Kimura-Suda[2] · Y. Kameda[1] · H. Hamano[1] · S. Hiratsuka[1] · D. Sato[1] · N. Iwasaki[1]

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Abstract
Summary This study showed that bisphosphonate was safe and effective for the treatment of bone disorders in stage 4 chronic kidney disease (CKD) rats. Intermittent teriparatide therapy showed an anabolic action on bone even under secondary hyperparathyroidism conditions without having an adverse effect on mineral metabolism in late-stage CKD.
Introduction Patients with late-stage CKD are at high risk for fragility fractures. However, there are no consensus on the efficacy and safety of osteoporosis medications for patients with late-stage CKD. In the present study, we aimed to examine the efficacy and safety of alendronate (ALN) and teriparatide (TPD) for treating bone disorder in late-stage CKD with pre-existing secondary hyperparathyroidism using a rat model of CKD.
Methods Male 10-week-old Sprague-Dawley rats were subjected to a 5/6 nephrectomy or sham surgery and randomized into the following four groups: sham, vehicle (saline subcutaneous (sc) daily), ALN (50 μg/kg sc daily), and TPD (40 μg/kg sc daily). Medications commenced at 24 weeks of age and continued for 4 weeks. Micro-computed tomography, histological analysis, infrared spectroscopic imaging, and serum assays were performed.
Results Nephrectomized rats developed hyperphosphatemia, secondary hyperparathyroidism (SHPT), and high creatinine, equivalent to CKD stage 4 in humans. ALN suppressed the bone turnover and increased the degree of mineralization in cortical bone, resulting in an improvement in the mechanical properties. TPD further increased the bone turnover and significantly increased the degree of mineralization, micro-geometry, and bone volume, resulting in a significant improvement in the mechanical properties. Both ALN and TPD had no adverse effect on renal function and mineral metabolism.
Conclusions BP is safe and effective for the treatment of bone disorders in stage 4 CKD rats. Intermittent TPD therapy showed an anabolic action on bone even under SHPT conditions without having an adverse effect on mineral metabolism in late-stage CKD.

Keywords Bone quality · Chronic kidney disease · Hyperphosphatemia · Osteoporosis medication · Secondary hyperparathyroidism

✉ M. Takahata
takamasa@med.hokudai.ac.jp

1 Department of Orthopedic Surgery, Hokkaido University Graduate School of Medicine, Kita-15 Nishi-7, Kita-ku, Sapporo 060-8638, Japan

2 Chitose Institute of Science and Technology, Chitose, Japan

Introduction

Patients with chronic kidney disease (CKD) have a 2- to 14-fold higher fracture risk than that of the general population [1, 2], and the incidence of fracture increases as the CKD stage increases [3, 4]. Because patients with CKD experience fractures more frequently than expected from bone mineral density-based predictions [5–7], the increased fracture risk in patients with CKD is attributable to bone quality abnormalities in addition to bone loss. Previous studies demonstrated that the abnormal mineral metabolism caused by CKD, termed CKD-related mineral and bone disorder (CKD-MBD) [8], leads to secondary hyperparathyroidism (SHPT) with vitamin D insufficiency, increased fibroblast growth factor 23 (FGF-23), and hyperphosphatemia, resulting in abnormal bone turnover and mineralization.

A problem in the management of osteoporosis in CKD is that the information regarding the safety and efficacy of osteoporosis medications is lacking, especially for patients with CKD stages 4 and 5 (late stage) who are more susceptible than patients with CKD stages 1–3 to fragility fractures. Although anti-osteoporotic agents, such as bisphosphonate (BP) or teriparatide (TPD), reduce the fragility fracture risk among patients with mild CKD [9], the safety and efficacy of BP and TPD for late-stage CKD (stages 4 and 5) patients are not entirely clear because clinical trials have not been performed on patients with CKD stages 4 and 5 due to safety concerns. Therefore, the data obtained from an animal study examining the effects of these medications on CKD-MBD should provide important information that will help establish a treatment strategy for osteoporosis in patients with late-stage CKD.

In the current study, we investigated the efficacy and safety of BP and TPD for the treatment of hyperparathyroid bone disease in late-stage CKD using a rat 5/6 nephrectomy model and focused on how BP and TPD improve bone quality, including material properties and structural properties, and on whether intermittent TPD therapy shows an anabolic effect on bone under SHPT conditions.

Materials and methods

Animal model and experimental design

All animal studies were performed in accordance with protocols approved by the Hokkaido University Committee on Animal Resources. Male Sprague-Dawley rats ($n = 24$; 8 weeks of age; CLEA Japan Inc., Tokyo, Japan) were maintained at 20 °C on a 12-h light/dark cycle with free access to water and rat food containing 0.98% calcium (Ca) and 0.80% inorganic phosphorus (IP) (Labo MR Stock; Nosan Corporation Life-Tech Department, Yokohama, Japan). Following a 1-week adaptation period to the new environment, all rats were stratified according to body weight and underwent a two-third left nephrectomy. Two weeks after the first surgery, a right nephrectomy or sham operation (sham) was performed [10]. After the two-stage 5/6 nephrectomy surgeries, all rats were randomized into three groups within each stratum according to the following treatments: vehicle control group ($n = 6$), alendronate (ALN) group ($n = 6$), and TPD group ($n = 6$) (Fig. 1). ALN (LKT Laboratories Inc., MN) at a dosage of 50 μg/kg/day was administered to the animals by daily subcutaneous injection. Recombinant human TPD (Forteo®; Eli Lilly Ltd., Kobe, Japan) at a dosage of 20 μg/kg/day was administered to the animals by twice-daily subcutaneous injections (total 40 μg/kg/day). These doses were selected based on previous studies [11, 12]. Sham-operated controls also received vehicle treatment.

Serum chemistry tests

Serum chemistry tests were performed using the blood collected at 24 weeks of age (the onset of treatment) and at 28 weeks of age (the time of sacrifice). Serum was separated from the blood taken from fasted animals via centrifugation (30 min, 3000 rpm) at 4 °C and stored in single-use aliquots at −80 °C until analysis. Blood urea nitrogen (BUN), creatinine (CRE), and IP levels were measured using enzymatic methods. Ca levels were measured by the o-cresolphthalein complexone method. FGF-23 and intact-parathyroid hormone (i-PTH) levels were measured using an enzyme-linked immunosorbent assay (ELISA) kit.

Biomechanical testing

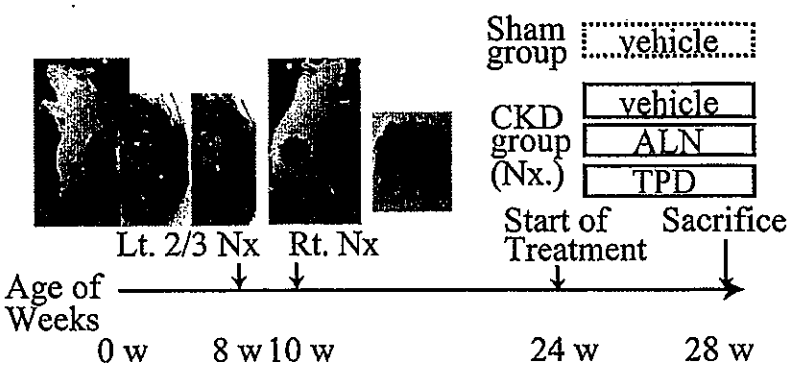
A three-point bending breakdown test was performed on the femoral shaft using a load mechanical universal testing machine (RTC-1310, AND Corp., Tokyo, Japan). The femur was placed with its anterior surface facing upward on the two lower support bars that were 14 mm apart. The load was applied at a rate of 0.2 mm/min until breakage. The ultimate load (N) and stiffness (N/mm) were calculated from the load-deformation curve. The load-displacement data were normalized to obtain intrinsic material properties, such as ultimate stress and elastic modulus, which are independent of cross-sectional size and shape [13, 14].

Micro-computed tomography analysis

The right femur and fifth lumbar vertebral body were scanned individually by micro-computed tomography (CT) (R_mCT2; Rigaku, Tokyo, Japan) at a 20-μm isotropic resolution. For the femur, a 2000-μm area of interest of 100 slices that encompassed the distal metaphysis, starting from 500-μm proximal to the growth plate, was used to assess the bone morphology. For the lumbar vertebral body, an area from the upper growth plate to the lower growth plate was used to assess the trabecular bone morphology.

Trabecular bone parameters of the distal femur and vertebral body, including the volumetric bone mineral density (vBMD), trabecular bone volume fraction (BV/TV), trabecular number (TbN), and trabecular thickness (TbTh), were determined using TRI/3D–BON software (Ratoc System Engineering Co., Tokyo, Japan) in accordance with the guidelines described by Bouxsein et al. For cortical bone analysis of the distal femur, the cortical thickness (CtTh) and polar moment of inertia (J) were determined [15].

Fig. 1 Experimental model and design. A schematic diagram of two-stage rat 5/6 nephrectomy (Nx) surgery and the treatment schedules for the osteoporosis medications are shown



Histology and histomorphometry

For dynamic bone formation analysis, calcein (20 mg/kg; Dojindo Laboratories, Kumamoto, Japan) was injected subcutaneously at 10 and 3 days before the rat was killed. The femora were fixed in 70% ethanol and stained with Villanueva bone stain. These specimens were then subjected to undecalcified tissue processing. The specimens were embedded in methyl methacrylate (MMA; Wako Chemicals, Kanagawa, Japan) and sectioned at 5 μm in the coronal plane. The distal femur was examined by fluorescence microscopy (BX53, Olympus, Tokyo, Japan) to evaluate the dynamic parameters of bone formation. Histomorphometric analysis was performed using ImageJ (NIH, Bethesda, MD). The measured parameters for trabecular bone of distal femur included total tissue volume (T. Ar), bone volume (B. Ar), osteoid volume (O. Ar), bone surface (B. Pm), osteoblast surface, eroded surface, single- and double-labeled surfaces (sL. Pm and dL. Pm, respectively), and inter-label width. These data were used to calculate the percent bone volume (B. Ar/T. Ar), percent osteoid volume (O. Ar/B. Ar), osteoblast number, osteoblast surface (Ob. Pm/B. Pm), eroded surface (E. Pm/B. Pm), mineral apposition rate (MAR), and bone formation rate (BFR/B. Pm) in accordance with the standard nomenclature proposed by Dempster et al. [16].

Fourier transform infrared spectroscopic imaging

The femora were fixed in 70% ethanol and were then subjected to undecalcified tissue processing. The specimens were embedded in MMA (Wako Chemicals, Kanagawa, Japan) and sectioned at 3 μm in the coronal plane. The sections were mounted on 1-mm thickness BaF_2 window (Pier Optics, Japan) to assess bone quality by Fourier transform infrared spectroscopic (FTIR) imaging. Spectra were acquired with a Spectrum Spotlight 400 Imaging System (PerkinElmer, MA, USA), consisting of a FTIR spectrometer (Spectrum 400) and infrared (IR) microscope with a linear array mercury-cadmium-telluride (MCT) focal plane array detector. FTIR images were collected in the transmission mode at a spectral resolution of 4 cm^{-1} and 1 scan/pixel in the frequency region from 4000 to 680 cm^{-1} with an IR detector pixel size of 25 × 25 μm.

FTIR spectra were extracted from the FTIR images. After subtraction of a linear baseline and MMA spectrum, the FTIR spectrum was used to characterize the bone quality. A number of metrics related to bone biochemistry were calculated, including the mineral-to-matrix ratio [MTMR; PO_4^{3-} (1183–985 cm^{-1})/amide I (1707–1599 cm^{-1})], which describes the degree of phosphate mineralization, and the carbonate-to-phosphate ratio [CTPR; CO_3^{2-} (895–849 cm^{-1})/PO_4^{3-} (1183–985 cm^{-1})], which describes the amount of carbonate substitution in the apatite crystal lattice [17].

Statistical analysis

Comparisons of data among the sham and CKD vehicle groups were performed using a Student's *t* test. Comparisons of data among the CKD groups were performed using a one-way analysis of variance and Newman-Keuls tests. A significance level of *P* less than 0.05 was used for all comparisons. Data are represented as the mean ± standard deviation (SD). All statistical analyses were performed using GraphPad Prism version 5 (GraphPad Software, San Diego, CA, USA).

Results

Rat 5/6 nephrectomy led to CKD stage 4 in rats

When treatment commenced at 14 weeks after 5/6 nephrectomy, the serum BUN and CRE levels were significantly elevated in the CKD rats compared with the rats in the sham group. Although the serum Ca levels did not change in the CKD rats, the serum levels of IP, FGF-23, and i-PTH were significantly elevated among CKD rats compared with the rats in the sham group (Fig. 2a). These serologic data suggested that the 5/6 nephrectomized rats developed a condition equivalent to CKD stage 4 in humans in terms of renal function and mineral metabolism.

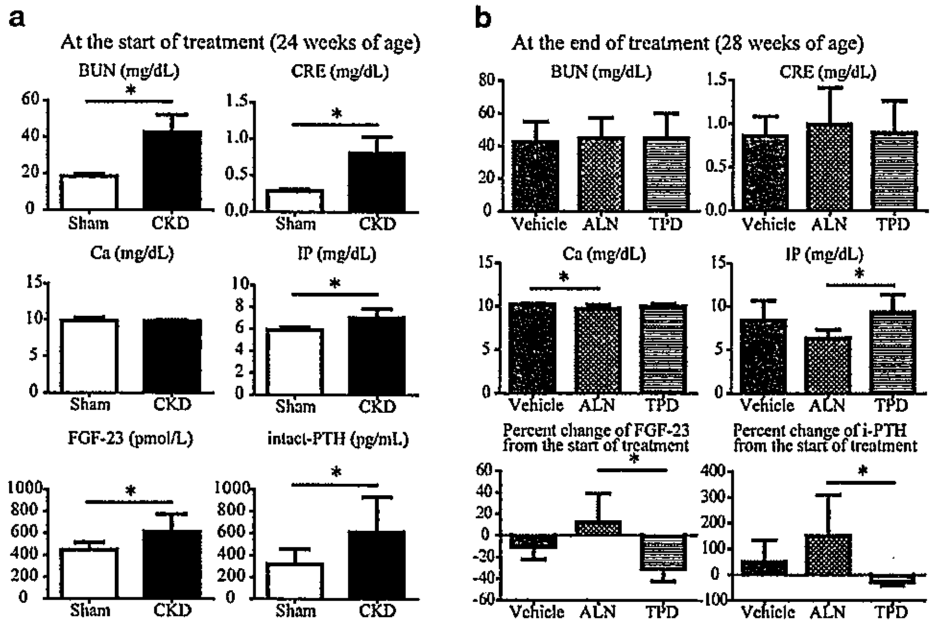


Fig. 2 Effects of ALN and TPD treatments on renal function and mineral metabolism in 5/6 nephrectomized rats. **a** Serum chemistry tests for renal function (BUN, CRE) and mineral metabolism (Ca, IP, FGF-23, and i-PTH) 14 weeks after 5/6 nephrectomy showed that the nephrectomized rats developed CKD stage 4 at the start of treatment with the osteoporosis medication. **b** The effects of 4 weeks of treatment with ALN or TPD on renal function and mineral metabolism are shown. The ALN and TPD treatments did not worsen renal function. The ALN treatment normalized hyperphosphatemia and increased the serum levels of FGF-23 and i-PTH, albeit not in a statistically significant manner. TPD treatment showed a tendency to increase the IP levels and decrease the serum levels of FGF-23 and i-PTH, albeit not in a statistically significant manner. Values shown are the mean ± SD. $*P < 0.05$

Effects of BP and TPD on renal function and mineral metabolism in rats with CKD stage 4

Serum chemistry tests were performed 4 weeks after treatment with ALN or TPD to assess the effect of these medications on renal function and mineral metabolism (Fig. 2b). Neither ALN nor TPD further elevated the serum levels of BUN and CRE in the CKD rats, indicating that 4 weeks of treatment with BP or TPD did not worsen renal function. Regarding the mineral metabolism, the rats in the ALN group had decreased serum levels of Ca and IP compared with those in the vehicle group. The decrease in IP levels in the ALN group was not significant; however, the serum levels of IP in the ALN group were equivalent to those of the rats in the sham group, indicating that ALN normalized the serum IP levels. TPD did not significantly change the serum levels of Ca and IP. The FGF-23 levels tended to be increased by ALN treatment but decreased by TPD therapy (mean change of FGF-23 4 weeks after the treatment from the baseline −10.4 ± 10.6% in the vehicle group, 12.3 ± 24.3% in the ALN group, and −30.9 ± 10.5% in the TPD group). The i-PTH levels tended to increase in the ALN group but tended to decrease in the TPD group, albeit the changes were not statistically significant (mean change of i-PTH 4 weeks after the treatment from the baseline 49.3 ± 76.6% in the vehicle group, 150.2 ± 145.6% in the ALN group, and −28.6 ± 10.9% in the TPD group).

Effects of BP and TPD on biomechanical properties in rats with CKD stage 4

The biomechanical properties of the femoral shaft were evaluated by a three-point bending test (Fig. 3). The femora from the rats in the sham and vehicle groups did not exhibit any significant changes in ultimate load and in stiffness; in contrast, after the 5/6 nephrectomy, the intrinsic material properties of the femoral shaft deteriorated. Compared with the femora from the rats in the sham group, the femora from vehicle-treated CKD rats exhibited a significant decrease in elastic modulus and bending strength ($P < 0.05$). Treatment of the CKD rats with ALN tended to restore the intrinsic material properties, as well as the ultimate load and stiffness, albeit the improvement was not statistically significant. TPD therapy significantly increased the ultimate load, elastic modulus, and bending strength compared with those of the vehicle-treated CKD rats.

Effects of BP and TPD on bone volume and micro-structural properties in rats with CKD stage 4

We next evaluated the changes in bone volume and microstructure of the distal femur and of the fifth lumber vertebral body (Fig. 4). Compared with the rats in the sham group, the nephrectomized rats had a statistically significant change in

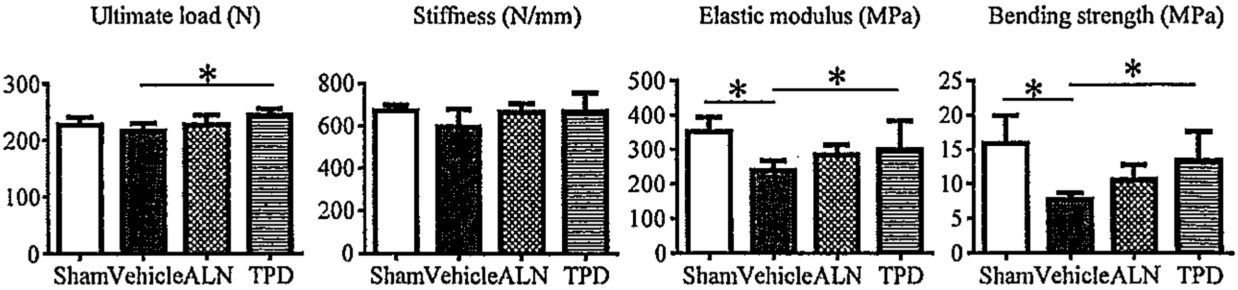


Fig. 3 Effects of ALN and TPD treatments on the biomechanical properties of the femora in rats with CKD. Although nephrectomy did not have a significant negative impact on the ultimate load and stiffness, the intrinsic material properties, including elastic modulus and bending strength, worsened in the rats of the vehicle group compared with the rats of the sham group. Although BP showed only a tendency to increase biomechanical parameters, TPD caused a significant increase in the biomechanical parameters of CKD rats. Values shown are the mean ± SD. $^{*}P < 0.05$

the BV/TV in the distal femur; however, there were no changes in the BV/TV in the L5 vertebral body and the vBMD and structural parameters of the trabecular and cortical bones in both the distal femur and L5 vertebral body. Compared with the rats in the vehicle group, the rats in the ALN treatment group had significantly higher BV/TV in the distal femur but did not have statistically significant changes in other bone volume and structural parameters. TPD treatment exerted a significant effect on the bone volume and structure in both the distal femur and L5 vertebral body. The rats in the TPD

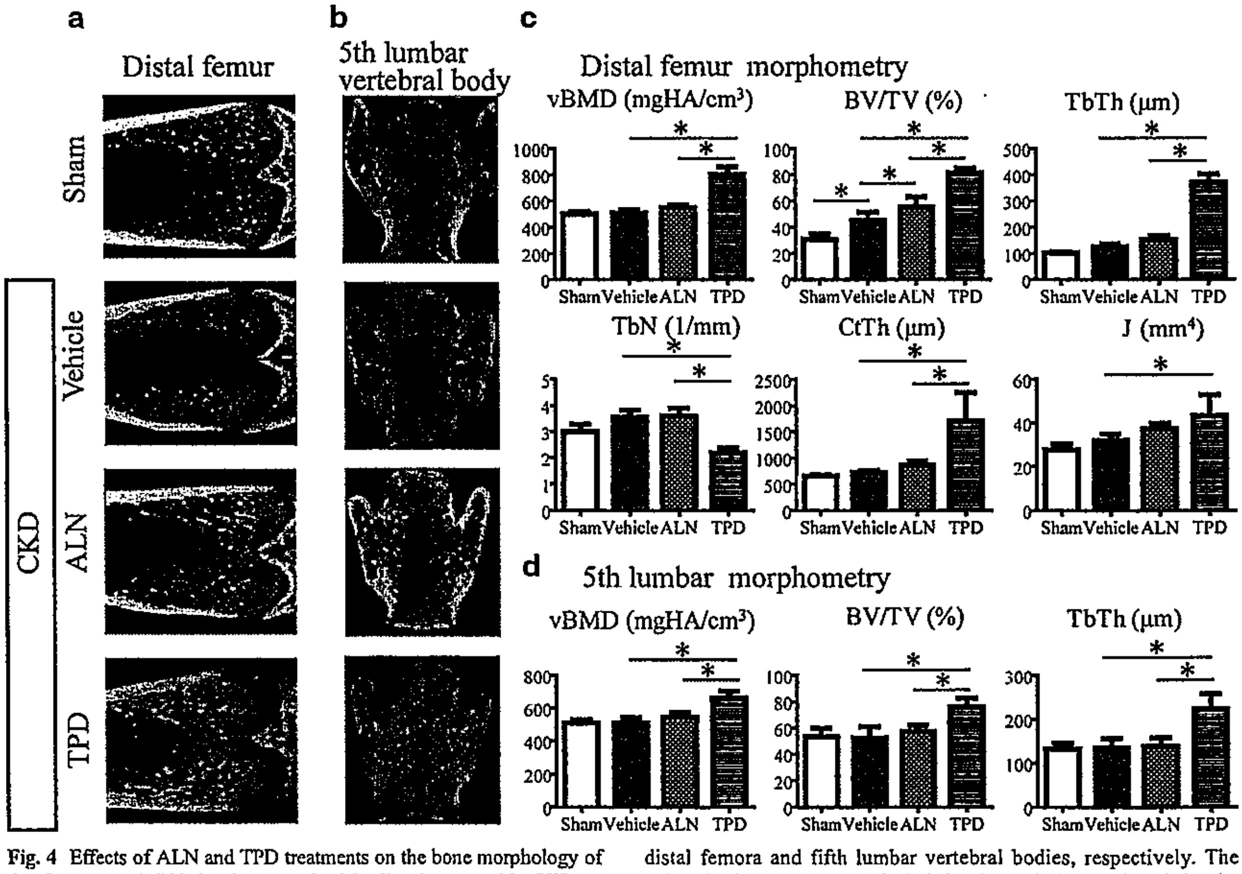


Fig. 4 Effects of ALN and TPD treatments on the bone morphology of the femora and fifth lumbar vertebral bodies in rats with CKD. **a** Representative coronal cross-sectional views of micro-CT images of the distal femora 4 weeks after the treatments. **b** Representative coronal cross-sectional views of micro-CT images of the fifth lumbar vertebral bodies 4 weeks after the treatments. **c, d** The quantitative micro-CT morphometrical data of the trabecular bone and cortical bone in the distal femora and fifth lumbar vertebral bodies, respectively. The trabecular bone parameters included volumetric bone mineral density (vBMD), the trabecular bone volume fraction (BV/TV), trabecular number (TbN), and trabecular thickness (TbTh), and the cortical bone parameters included the cortical thickness (CtTh) and polar moment of inertia (J). Values shown are the mean ± SD. $^{*}P < 0.05$

group had significantly higher bone density (vBMD), bone volume (BV/TV), trabecular structure (i.e., Tb. Th and Tb. N), and cortical bone structure (i.e., Ct. Th and J).

Effects of BP and TPD on bone metabolism in rats with CKD stage 4

To better understand the drug effects on bone metabolism in CKD rats, we performed dynamic bone histomorphometry using calcein-labeled undecalcified histological sections of the distal femur (Fig. 5). Compared with the sham rats, CKD rats did not have a significant change in B. Ar/T. Ar. ALN did not change the B. Ar/T. Ar in histology, whereas the rats in the TPD group had significantly increased B. Ar/T. Ar compared with that of the rats in the vehicle group. The osteoid, which is unmineralized bone matrix that becomes stained red-purple with Villanueva staining, was abundant in CKD rats in the vehicle group, suggesting high bone turnover in CKD rats. Although the rats in the TPD group did not have a significant change in O. Ar/B. Ar, the rats in the ALN group had significantly decreased O. Ar/B. Ar compared with the rats in the vehicle group. Analysis of bone formation and resorption parameters revealed that CKD tended to increase bone formation (i.e., Ob. Pm/B. Pm, MAR, and BFR/B. Pm) and significantly increased bone resorption (E. Pm/B. Pm) compared with the values in the sham group, indicating that CKD induces high bone turnover. Compared with the CKD rats in the vehicle group, the rats in the ALN group had significantly decreased bone formation (i.e., Ob. Pm/B. Pm, MAR, and BFR/B. Pm) and bone resorption (E. Pm/B. Pm). In contrast, the rats in the TPD group had further increased bone formation (i.e., Ob. Pm/B. Pm, MAR, and BFR/B. Pm) and decreased bone resorption (E. Pm/B. Pm) compared with those of the rats in the vehicle group.

Effects of BP and TPD on bone material properties in rats with CKD stage 4

To further investigate the drug effects on bone quality, we evaluated the material properties of bone using FTIR imaging (Fig. 6). CKD significantly decreased the MTMR of the center of the cortical bone in the distal femur, which indicates a reduction in the mineralization of cortical bone, and CKD decreased the CTPR of both the cortical and trabecular bone in the distal femur, which indicates the amount of carbonate substitution for phosphate or hydroxide in the mineral crystals. The decrease in the amount of carbonate substitution in the bone matrix indicates metabolic acidosis [18, 19]. The ALN treatment significantly increased the MTMR of the endosteal and periosteal regions of cortical bone. Compared with the rats in the vehicle group, the rats in the ALN group had a significantly increased CTPR of both trabecular and cortical bone, which indicates improvement of the metabolic acidosis in the rats treated with ALN. The TPD treatment significantly increased the MTMR of the cortical bone. Although the TPD treatment increased the CTPR of the trabecular bone, it did not have a significant effect on the CTPR of the cortical bone.

Discussion

The primary aim of this study was to elucidate the efficacy and safety of osteoporosis medications in late-stage CKD, which has not been tested in clinical trials due to safety concerns [20, 21]. In general, dietary phosphorus restriction and calcium binders are used as the initial treatments of CKD-MBD in stage 3 and 4 CKD, which were accompanied by moderately to severely reduced kidney function [22–24]. If these treatments fail to decrease i-PTH levels, active vitamin D analogs can be used as a second line of therapy [25]. Cinacalcet should be effective but is not approved for the treatment of SHPT in stage 3 and 4 CKD [26]. The problem is the uncertainty in the efficacy of these treatments for fracture prevention. In contrast, osteoporosis medications, including BP and TPD, are expected to be effective among patients with CKD stage 4 based on their proven effectiveness in fracture prevention for patients with CKD stages 1–3. If osteoporosis medications can safely be used by patients with late-stage CKD, then these should be effective treatment options, especially for the patients who have a high risk for fragility fracture due to coexisting illnesses, such as postmenopausal osteoporosis and glucocorticoid-induced osteoporosis [27].

Our data suggest that BP, which is a first-line therapy for most osteoporosis cases [28], is safe and effective for the treatment of osteoporosis in patients with CKD stage 4. Although 4 weeks of treatment with ALN only showed a tendency to have a positive impact on bone strength, FTIR imaging and micro-CT analyses demonstrated that ALN improved the material properties of cortical bone and increased the bone volume of the distal femur in the CKD rats. We believe that this improvement in bone quantity and quality reduces the fracture risk in patients with CKD and that longer-term treatment with BP may significantly increase bone strength. Regarding the safety of BP therapy, ALN did not worsen renal function to any extent. In contrast, hyperphosphatemia was improved by the ALN treatment. Furthermore, the rats in the ALN group had significantly increased CTPR of both trabecular and cortical bone compared with that of the rats in the vehicle group; thus, ALN might improve the metabolic acidosis in CKD. These results are consistent with the findings in some clinical studies showing that BP effectively reduces fracture risk without worsening renal function in patients with CKD stage 4 [29, 30].

A particularly important question addressed in this study is whether TPD therapy shows anabolic action on bone metabolism even under SHPT conditions. Our data demonstrated that intermittent TPD therapy did show an anabolic action

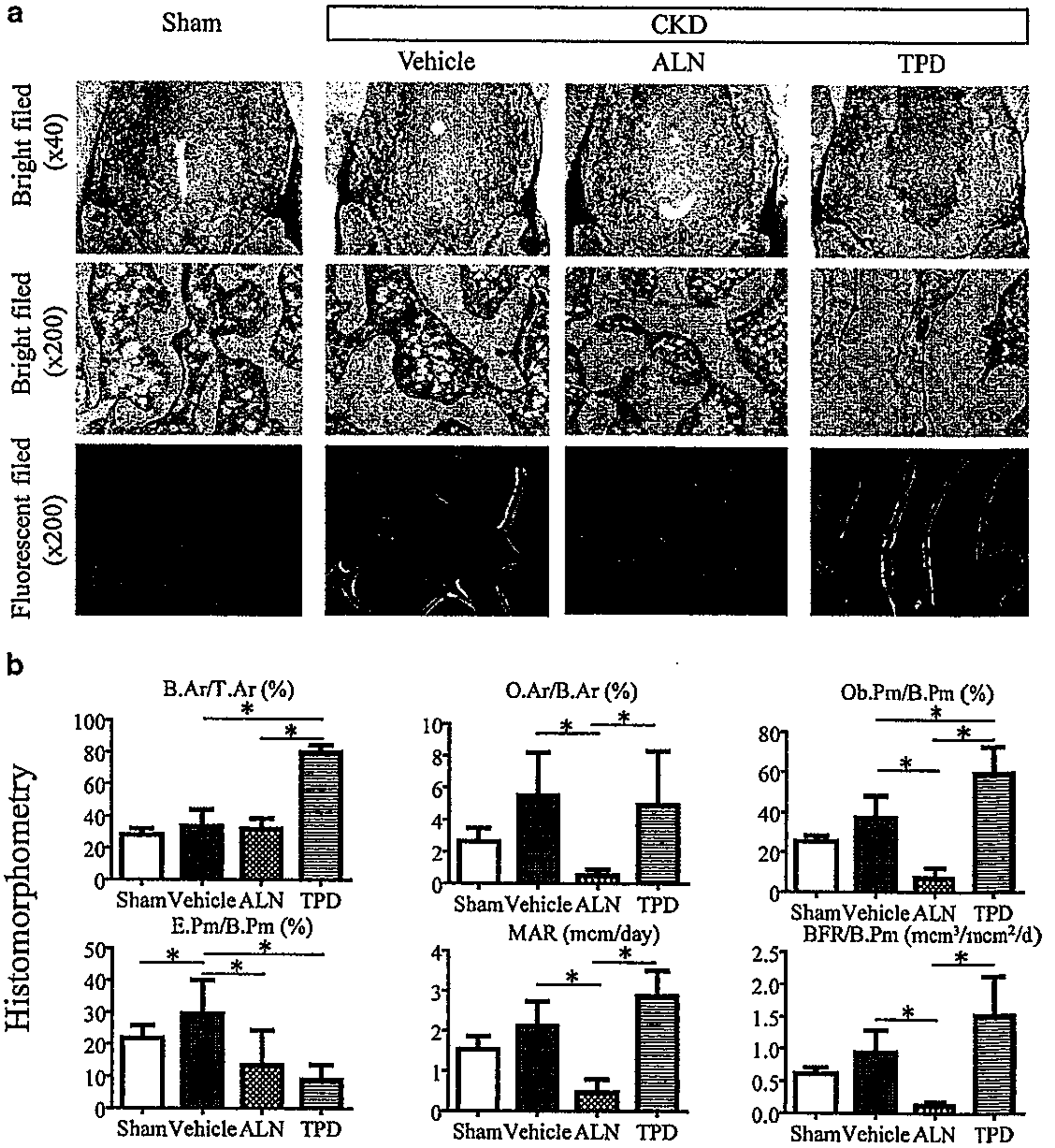


Fig. 5 Effects of ALN and TPD treatments on the bone metabolism in rats with CKD. a Micro-graphs showing representative coronal sections of the distal femora with Villanueva bone staining. Representative bright field micro-photographs (*upper panels*) and higher-magnification views (*middle panels*) show that osteoids, which are shown in the red-purple region, are abundant in the rats of the vehicle group. Representative fluorescence micro-graphs (*lower panels*) of trabecular bone obtained at 5-day intervals for double labeling with calcein green show that the rats in the vehicle group had more bone formation than the rats in the sham group; additionally, that TPD further promoted bone formation, while ALN attenuated it. b Bone histomorphometry data, including the bone volume of tissue volume (B. Ar/T. Ar), osteoid volume of bone volume (O. Ar/B. Ar), osteoblast surface (Ob. Pm/B. Pm), eroded surface (E. Pm/B. Pm), mineral apposition rate (MAR), and bone formation rate of bone surface (BFR/B. Pm), are shown. *Bars* = 100 μm. Values shown are the mean ± SD. $^{*}P < 0.05$

on systemic bone metabolism even under SHPT conditions. Previous clinical studies reported that TPD therapy was effective for postmenopausal osteoporosis among patients with mild or moderate renal impairment (CKD stages 1–3) [31]; however, this is the first study to provide clear evidence of the anabolic action of TPD therapy in CKD stage 4 and under SHPT conditions. In addition to the remarkable increases in bone volume, the degree of mineralization, and microstructure, the dynamic bone histomorphometric data support this idea.

Regarding the safety of TPD therapy, the serologic data obtained in this study showed that TPD therapy had neither a positive nor a negative effect on mineral metabolism as well as renal functions in late-stage CKD. Note, however, that 4 weeks of treatment with TPD tended to decrease serum FGF-23 levels, which may reduce phosphorus excretion, leading to

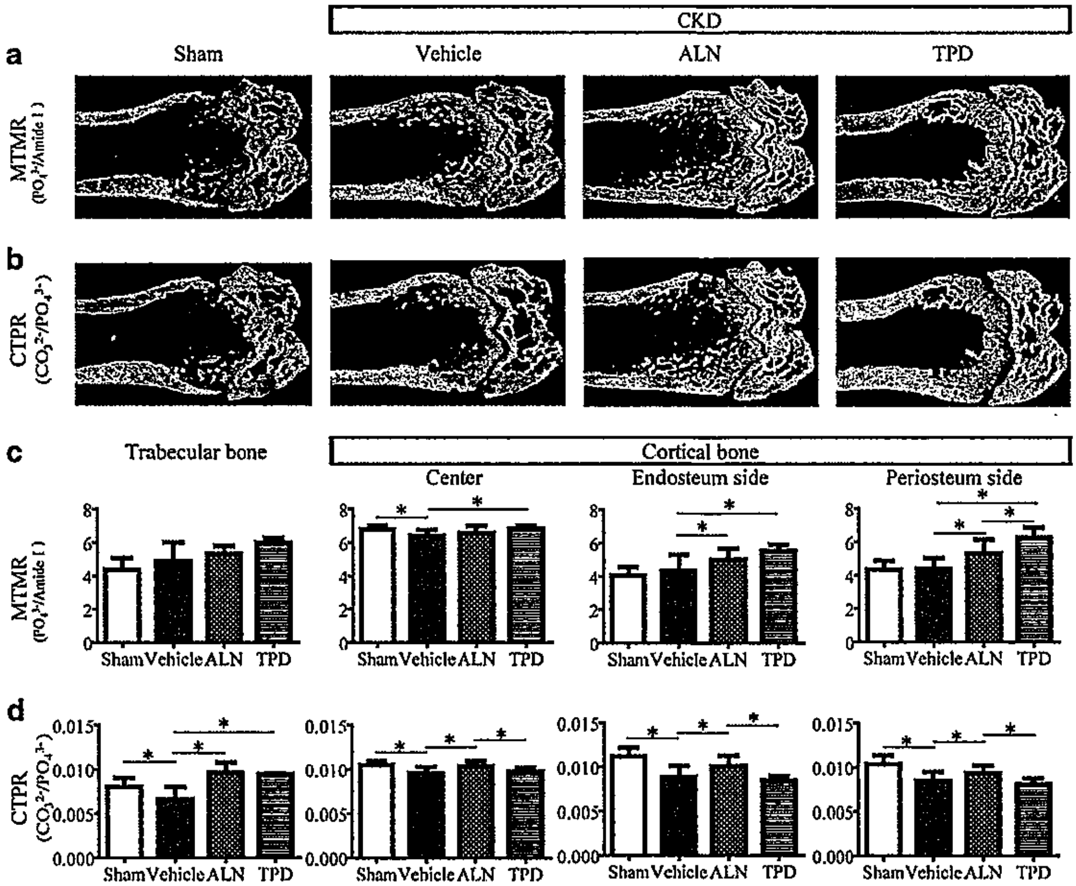


Fig. 6 Effects of ALN and TPD treatments on the bone matrix quality in rats with CKD. Representative FTIR color mapping images of MTMR (PO_4^{3-}/amide I) (a) and CTPR (CO_3^{2-}/PO_4^{3-}) (b) of the distal femur in the sham, vehicle, ALN, and TPD groups 4 weeks after the treatments. Comparisons of the values of MTMR (c) and CTPR (d) at the distal metaphysis of the femur are shown. The values of MTMR and CTPR were calculated separately according to the anatomical sites from the FTIR spectrum. The measured anatomical sites included the trabecular bone, center of the cortical bone, endosteal side of the cortical bone, and periosteal side of the cortical bone. Values shown are the mean ± SD. $^*P < 0.05$

exacerbation of hyperphosphatemia. As for the response of FGF-23 production to intermittent TPD therapy, however, it is inconclusive whether TPD therapy decreases serum FGF-23 levels or not. Sridharan M. et al. showed that FGF-23 increased after intermittent TPD therapy in 27 elderly women with postmenopausal osteoporosis and that there was a positive correlation between changes in bone formation maker procollagen-type 1 N-terminal propeptide (P1NP) and FGF-23 [32]. In contrast, it was demonstrated that increased bone formation down-regulates FGF-23 possibly through dentin matrix protein 1 (DMP-1) using mouse models manifesting differing degrees of coupled and uncoupled bone turnover [33]. Furthermore, transgenic expression of DMP-1 was demonstrated to reduce FGF-23 levels and to rescue the DMP-1-null animals from hypophosphatemia, suggesting that DMP-1 is likely to act as an inhibitor of FGF-23 expression [34].

There are several limitations of this study. First, we could not monitor the serum levels of vitamin D (1,25-dihydroxyvitamin D) and sclerostin, which are associated with CKD-MBD, because the amount of serum obtained from the living rats was limited. Serum concentrations of vitamin D should be decreased due to suppressed 1α-hydroxylase activity in a 5/6 nephrectomy rat model of CKD. However, changes in serum levels of vitamin D and sclerostin in response to BP or TPD treatment under the condition of CKD stages 4 and 5 should be investigated in the future study to better understand therapeutic action of these drugs on bone in patients with late-stage CKD. Second, the TPD dosage used in this study corresponds to tens or hundreds of multiples of the FDA-approved dosage of 20 μg/day for the treatment of osteoporosis. We selected the dosage of 40-μg/kg body weight TPD per day because a larger TPD dose is needed to observe significant effects in rodents, possibly due to the species difference. Finally, we did not evaluate the heterotopic mineralization of the vasculature although hyperphosphatemia induces it. It is of interest whether BP or TPD affects this mineralization. Therefore, how osteoporosis medications affect cardiovascular tissues in patients with CKD stage 4 must be evaluated in a future study.

It should be noted, however, that findings obtained in this study can be applicable to hyperparathyroid bone disease but not to other bone disorders induced by CKD-MBD. It is known that various pathologic patterns of bone remodeling are expressed in CKD including hyperparathyroid bone disease (high-turnover disease), adynamic bone disease and osteomalacia (low-turnover bone disease), and mixed uremic osteodystrophy (high-turnover plus a mineralization defect). However, a 5/6 nephrectomy rat model used in this study does simulate SHPT leading to high bone turnover condition but does not simulate other bone disorders induced by CKD-MBD. Very recently, Iwasaki et al. demonstrated that partial nephrectomy does not develop ABD but combination of partial nephrectomy and thyroparathyroidectomy induces ABD [35]. However, it is uncertain whether this model really mimics ABD or not because ABD is believed to be attributable to skeletal resistance to PTH and the pathogenesis of ABD has not been fully elucidated.

In conclusion, BP is safe and effective for the treatment of osteoporosis in stage 4 CKD rats. BP not only suppresses bone turnover but also may improve hyperphosphatemia and metabolic acidosis in CKD rats. Intermittent TPD therapy showed an anabolic action on bone even under SHPT conditions, thus resulting in remarkable increases in bone volume, the degree of calcification, and micro-geometry. Despite the excellent therapeutic efficacy of TPD in bone, the use of TPD in late-stage CKD might require careful attention because it possibly exacerbates hyperphosphatemia.

Compliance with ethical standards

Conflicts of interest None.

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ORIGINAL ARTICLE

Osseointegration improves bone–implant interface of pedicle screws in the growing spine: a biomechanical and histological study using an in vivo immature porcine model

Kanako Shiba[1] · Hiroshi Taneichi[1] · Takashi Namikawa[1] · Satoshi Inami[1] · Daisaku Takeuchi[1] · Yutaka Nohara[1]

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Abstract
Purpose Implant failure is a frequent complication in corrective surgery for early onset scoliosis, since considerable forces are acting on small and fragile vertebrae. Osseointegration showing biomechanical and histological improvement in bone–implant interface (BII) after dental implant placement has been well investigated. However, there are no studies regarding osseointegration in immature vertebral bone. The purpose was to evaluate the timecourse of biomechanical and histological changes at BII after pedicle screw placement using in vivo immature porcine model.
Methods Ten immature porcine were instrumented with titanium pedicle screws in the thoracic spine. After a 0-, 2-, 4-, and 6-month survival periods, the spines were harvested at the age of 12 months. Histological evaluation of BII was conducted by bone volume/tissue volume (BV/TV) and bone surface/implant surface (BS/IS) measurements. Bone mineral density (BMD) measurement and biomechanical testing of BII were done.
Results Contact surface and bone volume around the screw threads were significantly increased over the time. BV/TV and BS/IS were improved with statistically significant differences between 0- and ≥4-month ($p \leq 0.001$) periods. BMD in all subjects was determined to be the same ($p \geq 0.350$). Pullout strength was also increased over time with significant differences between 0- and ≥2-month ($p \leq 0.011$) periods.
Conclusion Improved stability at BII caused by osseointegration was confirmed by in vivo immature porcine model. A two-stage operation is proposed based on the osseointegration theory, in which an implant is installed in advance in the vertebrae at the first stage and deformity correction surgery is performed after sufficient stability is obtained by osseointegration at a later stage.

Keywords Osseointegration · Early onset scoliosis · Growing rod · Osteotomy · Porcine model

✉ Hiroshi Taneichi
htane@sea.plala.or.jp

[1] Department of Orthopaedic Surgery, Dokkyo Medical University, 880 Kitakobayashi, Mibu-machi, Shimotsuga-gun, Tochigi 321-0293, Japan

Introduction

Spinal instrumentation has been developed for the purposes of correction of spinal deformity and spinal reconstruction after trauma, tumor resection, or degenerative conditions. As techniques evolved, spinal instrumentation surgery has been increasingly applied to not only adolescent but also preadolescent patients. Instrumentation has been used in young children after spinal osteotomy for congenital scoliosis, growth modulation surgery such as growing rods for early onset scoliosis, and reduction and fusion for fracture dislocation [1–5]. Spinal instrumentation comprises anchors such as pedicle screws, hooks, and the others [6] and longitudinal members such as rods and plates for rigid fixation of the spinal column. At least two concerns exist regarding the use of instrumentation in young children and they are (1) the considerable growth potential of the spinal column in which implants are set [1, 7–10] and (2) the vulnerability of the anchor sites due to small and immature configuration of the vertebrae to which strong correction and in vivo forces are applied [2, 3, 5, 11]. In the former case, the typical problem is that spinal fixation by instrumentation surgery interferes with growth of the spinal column in the longitudinal direction. A variety of growth friendly treatment strategies have been developed so far [2, 5, 12–14]. In the latter case, however, anchor dislodgement with growing rods [5, 13] and instrumentation failures during deformity correction and hemivertebra resection for congenital scoliosis [2, 3, 11] are currently unsolved problems.

In the area of dental implants, a method that has been widely used consists of a process in which a titanium implant is inserted into the alveolar bone in advance as a foundation of an artificial tooth, and a secondary process in which a prosthesis is installed after the implant is mechanically stabilized for a certain time period [15–18]. This method is based on the principle of osseointegration described by Brånemark [18]. In osseointegration, histological changes occurring around the implant are similar to the bone healing process following fractures. In principle, woven bone formed at the micro-fractures around the implant is gradually replaced by lamellar bone that matures after the process of bone remodeling, so that lamellar bone forms in close contact with the titanium implant to dynamically stabilize the implant. The osseointegration in which mechanical properties of bone–implant interface (BII) improve over time may be expected to provide better mechanical strength at the anchor site when corrective surgery is performed in young children with spinal deformities. However, there has been neither basic science nor clinical study regarding the application of osseointegration in the field of spinal surgery. The purpose of this study was to evaluate whether the osseointegration occurs or not after standalone placement of pedicle screws into vertebrae in an in vivo experimental study using an immature porcine model.

Methods

The study was conducted with the approval of the Animal Experiment Committee at our institution (Experiment No. 0532). Ten male Clawn miniature pigs at ages ranging from 6 to 12 months were used, because pig spine has a large similarity with human spine in terms of geometry, material, or biomechanical properties [19]. For each animal, the length of the trunk (the distance between external acoustic pores and the base of the tail) and bodyweight was measured once a month. The bodyweight at 6 months after birth was an average of 20.7 kg (18.5–21.7 kg) and the length of the trunk was an average of 66.0 cm (65.0–67.0 cm).

Surgical procedures

After ensuring an adequate level of anesthesia, the thoracic spine was subperiosteally exposed via a midline posterior approach. The point of insertion and trajectory of pedicle screws were determined with reference to the vertebral bone specimens obtained from cubs of the same species. Monoaxial pedicle screws made of titanium alloy (Ti-6Al-4V, Showa Ika, Co Ltd., Toyohashi, Japan) with 3.5 mm diameter and 20 mm length were placed at T10 through T14. To avoid influence of screw loosening on the BII, all pedicle screws were placed independently in each vertebra and not interconnected with rods. Postoperative X-rays were taken to verify the positions of pedicle screws.

Operations were performed on three animals at the age of 6 months, three at 8 months, two at 10 months, and two at 12 months. The animals that had undergone surgery between the ages of 6–10 months were fed up to the age of 12 months and then euthanized. Two animals operated on at the age of 12 months were euthanized immediately after surgery. The animals were divided into 6M Group for those operated at the age of 6 months, 4M Group for those operated at the age of 8 months, 2M Group for those operated at the age of 10 months, and 0M Group for those operated at the age of 12 months, denoting the time for osseointegration prior to analysis. To standardize condition of the specimens such as anatomical size and bone maturity at the time of biomechanical testing, histological analysis, and bone mineral density measurement, all animals were killed at the age of 12 months.

After harvest of the thoracic spine, each vertebra was split vertically along a line connecting the center of the spinous process and the center of the vertebral body using an oscillating saw. From T10 to T14, we have obtained total of 90 vertically split specimens. Of these, 19 specimens that sustained damage such as pedicle fractures and visible breach of pedicle screws were excluded from evaluation. Two specimens to be used for histological investigation were selected randomly from each animal and fixed with 10% formalin. Other specimens were frozen at −25 °C and stored immediately after harvest of the spine.

Biomechanical testing

The frozen specimens were defrosted to room temperature. Using metallic rods and resin, each specimen was fastened to a jig, such that the screws were perpendicular. The pullout test jig was installed on the testing machine via a universal joint, so that the pullout direction would be always in line with the pedicle screw. The pullout test was performed using a hydraulic universal tester (EHF-LB5kN-4LA, Shimazu Co, Kyoto, Japan) at a pullout rate of 1 mm/min with a maximum displacement of 10 mm. From the load–displacement curves determined experimentally, the maximum load was calculated and determined as the pullout strength.

Histological analysis

On the cross-sectional surface passing the longitudinal axis of pedicle screw, a hard tissue polishing sample was prepared. After cutting the specimen and embedded with methyl methacrylate resin, the observation surface was polished with a micro-grinding machine (MG-4000, EXAKT GmbH, Hamburg, Germany) for mirror polishing. The slices with 30–40 μm thickness were stained with hematoxylin/eosin (HE) and toluidine blue (TB) stains.

Histological evaluation of BII was carried out qualitatively and quantitatively. Qualitative evaluation was done on the TB stained sample in which woven bone was deeply stained [16]. For the quantitative evaluation of osseointegration around the pedicle screws, rectangular areas (1.0 mm × 1.1 mm) covering a valley and the adjacent threads were selected as a region of interest (ROI). Bone volume/tissue volume (BV/TV) and bone surface/implant surface (BS/IS) were measured in each ROI [16] (Fig. 1). For measurement of BV/TV, image processing software, Image J (NIH, MD, USA), was used, and for measurement of BS/IS, image analysis software, Win ROOF (MITANI Co, Fukui, Japan), was used.

Measurement of bone mineral density

Five specimens with no screw placement in each animal were selected randomly and fixed with 70% ethanol. The bone mineral density (BMD) was measured using the peripheral quantitative computed tomography (pQCT) (XCT, Stratec GmbH, Pforzheim, Germany). The analytical region was an area of 4 × 6 mm in the central potion of the vertebral body. The average bone density in this area (mg/cm^3) was determined.

Statistical analysis

For statistical analysis, ANOVA and the Tukey–Kramer HSD test were used. The level of significance in cases with "significant differences among the groups" was defined as $p < 0.05$. On the other hand, the level of significance in cases with "no significant differences among the groups" was defined as $p > 0.20$.

Results

Operation and complications

All except two animals were euthanized immediately after surgery survived and returned to normal activities. No postoperative motor deficits occurred. One animal in 4M Group that survived until 12 months encountered a deep surgical site infection and was excluded. Therefore, subjects for biomechanical testing, histological analysis, and BMD measurements constituted a total of nine animals: two animals in 0M Group, two in 2M Group, two in 4M Group, and three in 6M Group.

Growth of experimental animals

A mean length of the trunk and bodyweight at 12 months of age was 82.8 cm (80.0–86.0) and 34.7 kg (32.8–37.0), respectively. Length of the trunk increased an average of 25.5% and bodyweight increased 67.6% during the period between 6 and 12 months of age.

Biomechanical testing

A total of 57 specimens were used for biomechanical testing and details were listed in Table 1. There were no significant differences in the transverse diameters of the pedicles between T10 thru T12 and T13 thru T14; however, compared to T10 thru T12, the transverse diameter of the pedicles of T13 and T14 was significantly larger (Fig. 2). The pullout strength increased significantly over time from 825.1 ± 200.5 N in the 0M Group to 2048.3 ± 311.1 N in the 6M Group (Fig. 3). However, a mean pullout strength at each level was similar without any significant differences (Fig. 4).

Histological analysis

Qualitative analysis

In 0M Group, trabecular bone around the screw thread was disrupted and fragmented, indicating micro-fractures caused by screw insertion (Fig. 5a). In 2M Group, newly developed lamellar bone partially combined with woven bone was observed at the BII in micro-fracture site at the time of screw insertion (Fig. 5b). In 4M Group, the lamellar bone volume and the contact surface between the screw and bone were increased. Woven bone was no longer observed (Fig. 5c). In 6M Group, bone volume around the screw was drastically increased and the remodeling process was further advanced (Fig. 5d).

Quantitative analysis

Bone volume/tissue volume was 19.6 ± 8.5% in 0M Group, 29.6 ± 7.5% in 2M Group, 43.4 ± 8.9% in 4M Group, and 53.3 ± 12.2% in 6M Group, which increased over time. There were significant increases of BV/TV in all except two combinations with marginal significance (0M–2M, $p = 0.082$ and 4M–6M, $p = 0.078$) (Figs. 6, 7). In addition, BS/IS increased significantly at 2 months and

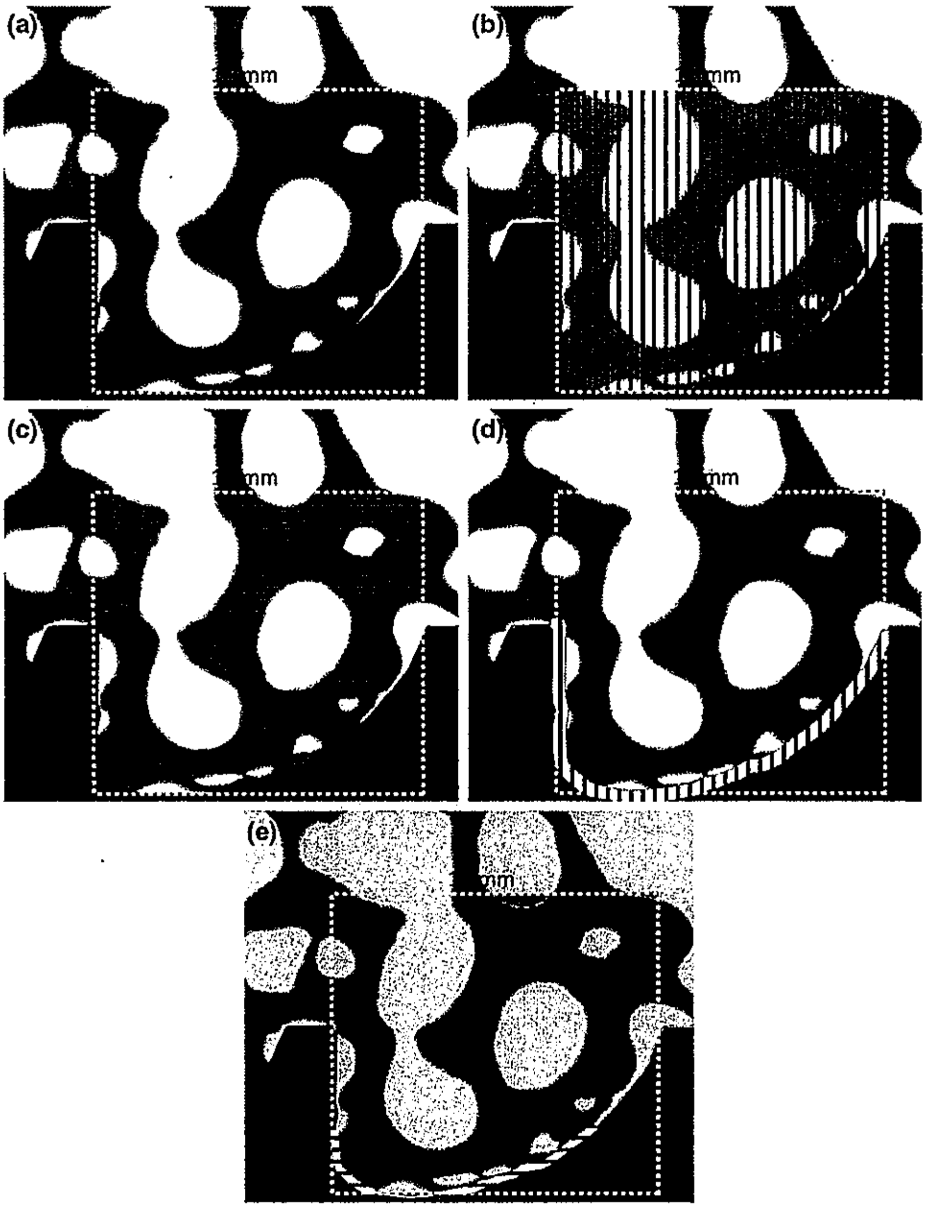

Fig. 1 Histological evaluation. a Region of interest (ROI) (1.0 mm × 1.1 mm). b Tissue volume (TV): the area except screw thread (*vertical line*). c Bone volume (BV): the area of the bone (*horizontal line*). d Implant surface (IS): the total length of the implant (band with *vertical line*). e Bone surface (BS): the length of bone in contact with the implant (band with *horizontal line*)

later after screw implantation: 0M Group, 6.6 ± 4.5%; 2M Group, 5.9 ± 6.6%; 4M Group, 24.2 ± 1.7%; and 6M Group, 43.8 ± 13.8%, respectively. There were significant increases of BS/IS in all except the combination of 0M and 2M Groups (Figs. 6, 8).

Measurement of bone mineral density

The average BMD with respect to individual animals is shown in Table 2. With all subjects combined, BMD among the subjects in this study was determined to be the same ($p \geq 0.350$).

Discussion

According to this study, fragmentation of the trabecular bone due to micro-fractures caused by screw insertion was found immediately after surgery. The fragmented trabecular bone was then gradually repaired by bone remodeling.

Table 1 Level and number of the specimens in the biomechanical testing

Group level	0M	2M	4M	6M	Total
T10	3	2	3	3	11
T11	0	3	2	2	7
T12	1	2	4	3	10
T13	4	3	3	2	12
T14	4	4	4	5	17
Total	12	14	16	15	57

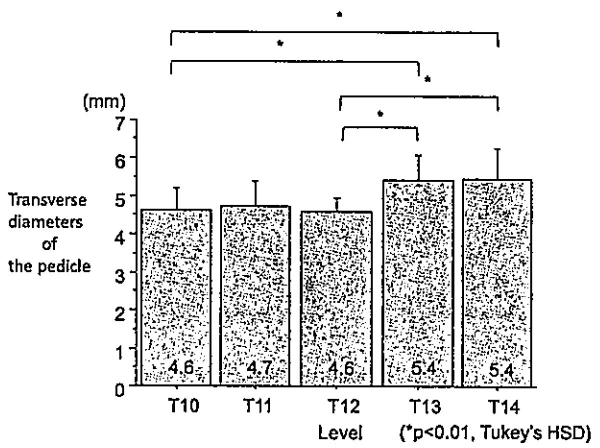

Fig. 2 Transverse diameters of the pedicles according to level. There were no significant differences in the transverse diameters of the pedicles between T10 thru T12 and T13 thru T14. However, compared to T10 thru T12, the diameter of the pedicles of T13 and T14 was significantly larger

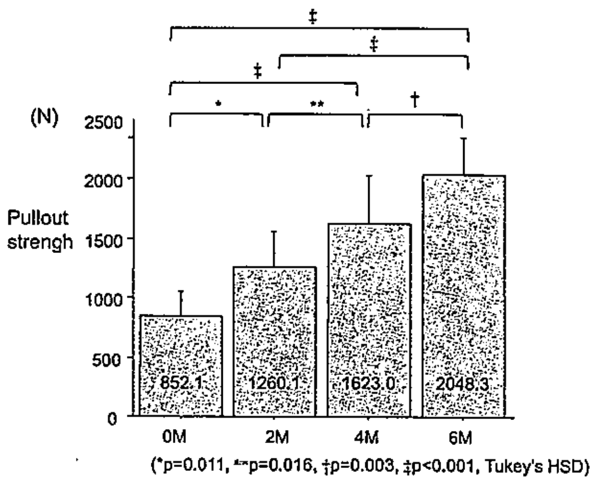

Fig. 3 Comparison of the pullout strength between 0M-, 2M-, 4M-, and 6M Groups. There were significant differences between all combinations. The pullout strength increased over time after implantation

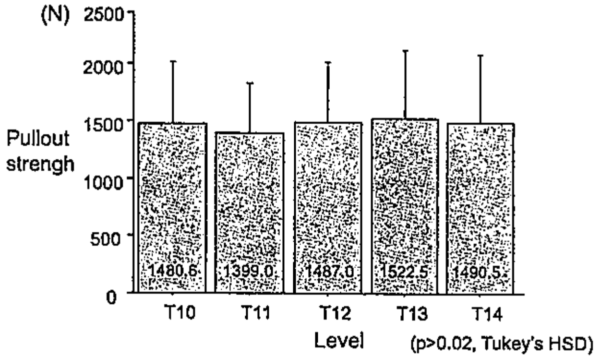

Fig. 4 Comparison of the pullout strength with respect to levels. The pullout strengths with respect to levels were equal without any significant differences

Mechanical properties of the woven bone with irregularly aligned collagen fibers were inferior to those of lamellar bone [20, 21]. At 2 months postoperatively, when woven bone was still present at the BII, bone volume around the implant increased but the pullout strength of the screws was not strong enough. In the later phases, the pullout strength improved over time, because there was an increase of bone volume with rich lamellar bone contents and expansion of the contact surface between the implant and the host bone. A typical feature of osseointegration that was observed with dental implants [15–18] was reproduced in the immature vertebral bone in this study.

Since histological and biomechanical studies were performed at the same age among the animals and all had the same bone mineral density, differences found in the mechanical stability at the BII would be directly dependent on the bone morphology around the implants. The same results were previously demonstrated in experimental study using implants in long bones of adult animals. Wu et al. [22] demonstrated that pullout strength of titanium screws which were placed in the tibia increased over time in their in vivo study using rats. Furthermore, Brånemark et al. [23] reported that when titanium screws were inserted into the tibia in rats, the bone volume in contact with the screw increased over time from 0 to 16 weeks. According to an in vivo study by Grizon et al. [24], when a titanium screw was placed into the femur in sheep at 5–6 years of age, the bone volume around the implants tended to increase over time for 3–18 months postoperatively.

Since patients needing dental implant treatments are typically elderly who have lost teeth, basic science and clinical studies have been conducted predominantly in adults and little has been reported for pediatrics before adolescence. The rate of bodyweight gain of mini-pigs used in this study from 6 to 12 months of age was 68%, and the increase rate in body length was 26%. Humans from 12 to 17 years (middle-to-late adolescence) have a rate of

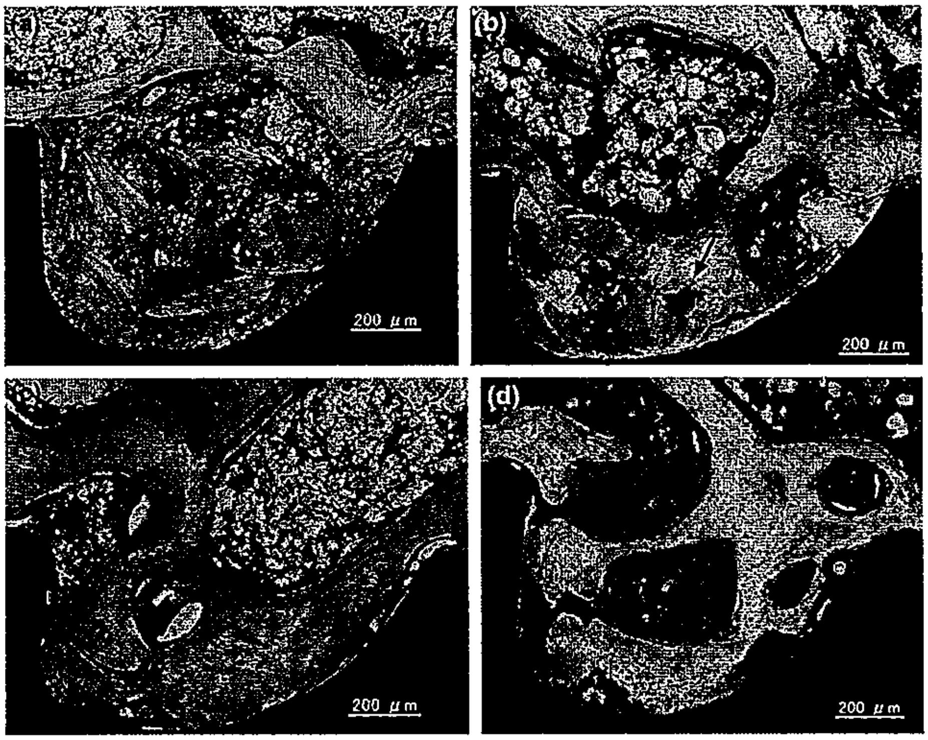

Fig. 5 Qualitative analysis of bone–implant interface (TB staining). **a** 0M Group: the trabecular bone around the screw thread was disrupted and fragmented, indicating micro-fractures caused by screw insertion. **b** 2M Group: newly developed lamellar bone partially combined with immature woven bone (*arrows*) was observed at the BII, where fragmented trabecular bone had been observed around the screw threads at the time of screw insertion. **c** 4M Group: the amount of newly developed lamellar bone increased and the contact surface between the screw and the bone also increased. Woven bone was no longer observed at this stage. **d** 6M Group: bone volume around the screw was drastically increased and the remodeling process was more advanced

bodyweight gain of 41% in males and 21% in females, and their sitting height increases by 12% in males and 4% in females. In contrast, humans from 6 to 11 years (before adolescence-to-early adolescence) experience bodyweight gain of 77% in males and 89% in females, and sitting height increases by 19% in males and 23% in females [25]. Based on the data above, the mini-pigs used in this study can be considered approximately comparable to the pediatric period before adolescence in humans. Thus, this study demonstrated that osseointegration occurs in the same way during the pediatric period before adolescence, and contributes to improved mechanical stability of implants.

It has been pointed out that in spinal deformity correction surgery for preadolescent children, huge correction forces that are loaded onto anchors such as pedicle screws installed in small, fragile vertebrae can result in anchor site failure during surgery or early in the postoperative period [2, 3, 5, 11, 13]. Whereas, deformity correction with insufficient correction forces to prevent such complications leads to unsatisfactory clinical results [2, 3, 5, 11, 13]. To avoid these problems, a two-stage operation is proposed based on the osseointegration theory, in which an implant is installed in advance in the vertebrae at the first stage and deformity correction surgery is performed after sufficient stability is obtained by osseointegration at a later stage. The merits of such an approach would be that sufficient correction forces can be applied and postoperative bracing can also be avoided. According to Ranade et al., pedicle screws are more suitable for anchors of growing rod constructs than hooks which can frequently dislodge [1]. However, unlike a hook, a pedicle screw has the potential risk of spinal cord injury due to its dislodgement. The risk of spinal cord injury can be reduced when a two-stage operation based on the osseointegration theory is carried out for growing rod constructs using pedicle screws. Pedicle screws are generally used as anchors in hemivertebra resection or vertebral column resection for pediatric patients with congenital scoliosis. Hedequist et al. pointed out that pedicle screws placed in the small and fragile vertebrae in young children cannot tolerate considerable forces applied during deformity correction [11]. In such situations, a two-stage operation employing the osseointegration theory has great advantages in prevention of perioperative anchor failure. There is some concern, but controversy, over pedicle screws violate the neurocentral synchondrosis which may result in developmental spinal

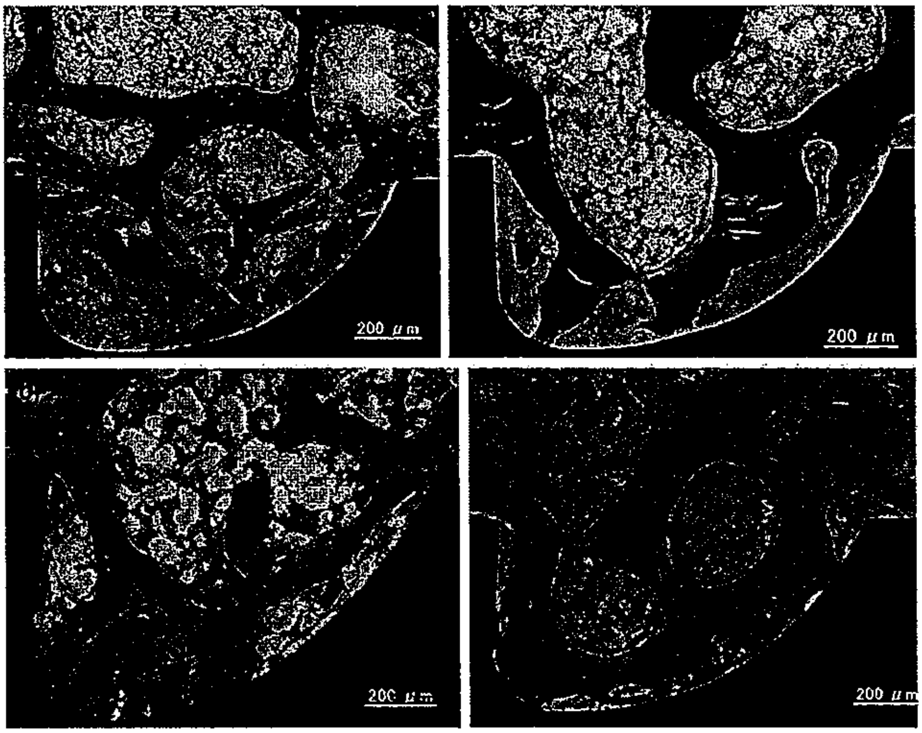

Fig. 6 Qualitative analysis of bone–implant interface (HE staining). a 0M Group, b 2M Group, c 4M Group, and d 6M Group

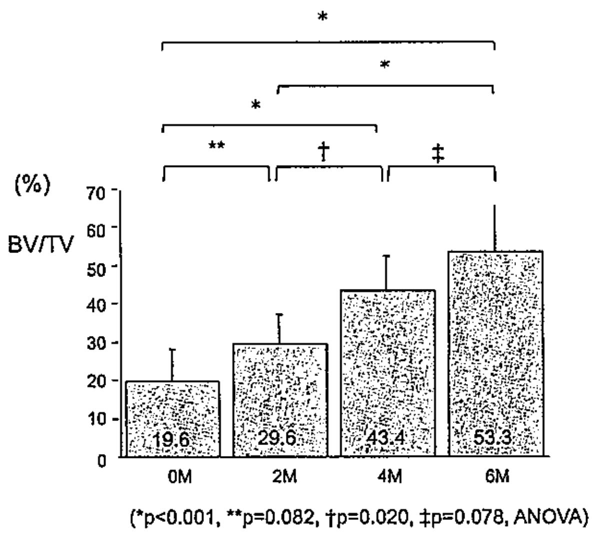

Fig. 7 Comparison of BV/TV between 0M-, 2M-, 4M-, and 6M Groups. BV/TV increased over time. Although the differences barely reached significant levels between the 0M Group and the 2M Group ($p = 0.082$) and the 4M Group and the 6M Group ($p = 0.078$), a trend of increased bone volume over time was observed and there were significant increases in all other combinations

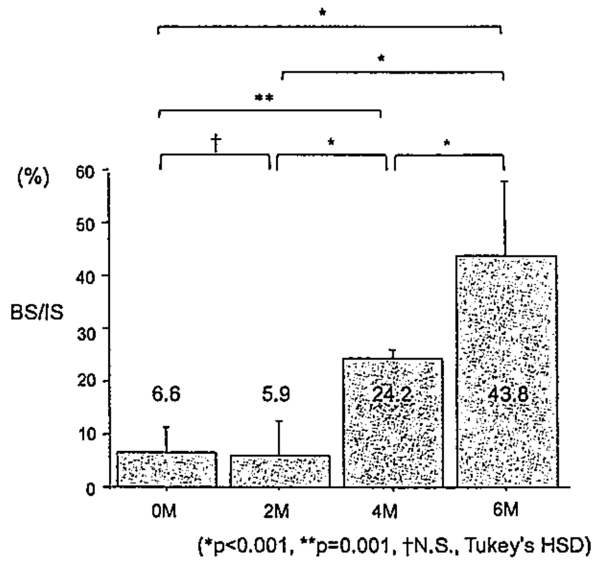

Fig. 8 Comparison of BS/IS between 0M-, 2M-, 4M-, and 6M Groups. BS/IS increased significantly at 2 months and thereafter after screw implantation

canal stenosis [1–3, 9]. Another issue of concern is that, in pediatric patients, autofusion can occur at the surgical site, where subperiosteal exposure is performed for screw placement as a first-stage procedure of two-stage corrective surgery. The autofusion may adversely affect the corrective surgery itself. To prevent this, percutaneous screw placement with or without navigation that avoids subperiosteal exposure may be considered.

Table 2 Average bone mineral density (BMD) with respect to individual animals

Group BMD (mg/cm^3)	0M-1	0M-2	2M-1	2M-2	4M-1	4M-2	6M-1	6M-2	6M-3
0M-1 348.3	–	1.000	0.350	0.696	0.808	0.930	0.587	0.954	0.999
0M-2 351.2		–	0.391	0.696	0.796	0.924	0.630	0.946	0.997
2M-1 313.0			–	0.997	1.000	0.940	0.999	0.916	0.773
2M-2 324.5				–	1.000	1.000	1.000	0.999	0.978
4M-1 321.1					–	0.999	1.000	0.999	0.983
4M-2 331.7						–	0.999	1.000	1.000
6M-1 322.9							–	0.997	0.959
6M-2 332.9								–	1.000
6M-3 338.9									–

With all subjects combined, the *p* value was 0.350 or greater, so that the bone density among the subjects in the present study was determined to be the same

Study limitations

In the present study, both osteogenesis around the implant and mechanical stability of the implant continuously increased while under observation for a period of 6 months, but we could not determine at which point a plateau would be achieved. Verification of the plateau point would require a more extended screw retention period. In addition, considering differences in bone remodeling and strength between species, we think that an investigation based on clinical observation in humans is necessary prior to recommending an appropriate time interval between the anchor installation and the deformity correction surgery.

Baseline conditions of animals at the time of surgery were not standardized for the purpose of performing biomechanical testing, histological analysis, and BMD measurement at a same age. This limitation may influence the biological course of osseointegration in the animals with growing age.

Conclusion

Improved stability at the BII caused by osseointegration was confirmed by in vivo immature porcine model assumed comparable to pediatric humans undergoing rapid growth. Placement of pedicle screws in advance in small and fragile vertebrae can be effective in preventing implant failure in corrective surgery for young children with spinal deformities.

Compliance with ethical standards

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Conflict of interest The authors declare that they have no competing interests.

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Original Article

Multiple concave rib head resection improved correction rate of posterior spine fusion in treatment of adolescent idiopathic scoliosis

Takashi Namikawa [a, b, 1], Hiroshi Taneichi [a, *], Satoshi Inami [a], Hiroshi Moridaira [a], Daisaku Takeuchi [a], Yo Shiba [a], Yutaka Nohara [a]

[a] Department of Orthopaedic Surgery, Dokkyo Medical University, Tochigi, Japan
[b] Department of Orthopaedic Surgery, Osaka City General Hospital, Osaka, Japan

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ABSTRACT

Background: Hybrid constructs have been widely used to surgically correct thoracic adolescent idiopathic scoliosis (AIS). To enhance the correction obtained with hybrid constructs, we perform concave rib head resection and convex costovertebral release as posterior release procedures. The objective of the study was to evaluate coronal and sagittal curve correction in patients with adolescent idiopathic scoliosis (AIS) treated with hybrid constructs combined with concave rib head resection and convex transverse process resection as posterior release procedures.
Methods: The records of 24 patients with Lenke type 1 or 2 AIS treated with hybrid constructs combined with posterior release procedures were retrospectively reviewed. The mean age at surgery was 14.3 years. The mean follow-up period was 33.0 months (range, 24–60 months). Radiographs were evaluated before surgery, immediately postoperatively, and at latest follow-up.
Results: The average preoperative Cobb angle of the main thoracic (MT) curve was 58.1 ± 12.6° (range, 45–88°). The MT curve was corrected to 12.8 ± 9.0° (range, 0–38°) immediately after surgery. At the latest follow-up, the average Cobb angle was 13.6 ± 9.9° (range, 0–44°; correction, 77.5 ± 14.0%). The average loss of coronal correction was 0.8°. The average preoperative flexibility of the MT curve was 54.6 ± 17.4%. The average Cincinnati correction index was 1.53 ± 0.48 at the latest follow-up. The average preoperative thoracic kyphosis (TK) was 13.7 ± 12.0° (range, −12–34°). Immediately after surgery, TK was corrected to 18.6 ± 5.9° (range, 10–29°). At the latest follow-up, TK measured 18.1 ± 6.5° (range, 6–32°).
Conclusions: Hybrid instrumentation combined with concave rib head resection and convex transverse process resection as posterior release procedures achieved satisfactory coronal and sagittal curve correction with little loss of correction at 2-year follow-up.

1. Introduction

Sublaminar wiring as segmental spinal instrumentation has been widely used in the surgical correction of spinal deformity since the development of the technique by Luque in the 1980s [1]. Hybrid constructs for the treatment of scoliosis, such as ISOLA instrumentation, include sublaminar wires, hooks and pedicle screws (PS) as segmental instrumentation [2]. The mechanism of correction using hybrid constructs is the sequential tightening of mutisegmentally placed sublaminar wires fastened to a rod contoured to the ideal shape of the thoracic spine. Meanwhile, segmental PS constructs have been widely used in recent years in surgery for thoracic adolescent idiopathic scoliosis (AIS). There are several reports that segmental PS constructs provide better coronal correction than hybrid constructs [3–6].

We use hybrid constructs as our preferred method for the correction of thoracic AIS at our institution. To enhance the correction obtained with hybrid constructs, we routinely perform concave rib head resection (CRR) and convex costovertebral release for radical posterior release. The CRR includes releasing the radiate ligament on the apical portion of the concave side, which connects the rib head to both the upper and lower thoracic vertebrae. The

* Corresponding author. Department of Orthopaedic Surgery, Dokkyo Medical University, 880 Kitakobayashi, Mibu-machi, Shimotsuga-gun, Tochigi, 321-0293, Japan. Fax: +81 282 86 5422.
E-mail address: tane@dokkyomed.ac.jp (H. Taneichi).
[1] Address for reprints: Department of Orthopaedic Surgery, Osaka City General Hospital, 2-13-22 Miyakojimahondoori, Miyakojima-ku, Osaka-city, 534-0021, Japan.

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purpose of this study was to evaluate coronal and sagittal curve correction in patients with AIS treated with hybrid constructs in conjunction with CRR as a posterior release procedure.

2. Materials and methods

2.1. Patients

We retrospectively reviewed the records of 24 patients (20 females, four males) with Lenke type 1 or 2 AIS who underwent posterior selective thoracic fusion at our institution between 2008 and 2011. A minimum 2-year follow-up was required for inclusion in the study. The mean patient age at surgery was 14.3 years (range, 12–17 years). Patients were radiographically evaluated before surgery, immediately after surgery and at the latest follow-up.

2.2. Surgical procedures

All patients underwent surgery with hybrid constructs combined with CRR. The CRR was performed as a posterior release procedure on three to five ribs around the apical vertebra on the concave side. After exposure of the proximal portion of the ribs to be released, the transverse process was resected and the rib removed approximately 3 cm lateral to the tip of the transverse process. The ventral side of the proximal rib was exposed subperiosteally. The radiate ligament, which connects the rib head to both the upper and lower thoracic vertebrae, was loosened to allow full manipulation of the costovertebral joint. The resected rib heads and transverse processes were then used as bone grafts. Additionally, the transverse processes were resected from the vertebrae around the apex of the convex side, except for the transverse process of the apical vertebra, on which the transverse hook was placed. A Cobb elevator was inserted into the costovertebral joint and pushed laterally to release the radiate ligament on the convex side.

As for hybrid constructs, conventional transverse process and pedicle hook-claw constructs were used as proximal anchors and apex anchors on the convex side. Pedicle screws were used as distal anchors. Ultra-high molecular weight polyethylene (UHMWPE) cables were used as a sublaminar anchoring device. Sublaminar cables were multisegmentally placed on the concave side of the main thoracic curve.

The correction maneuver was a combination of cantilever, translational force through sublaminar cables and in-situ contouring technique. We typically used a titanium alloy rod 6.0 mm in diameter.

The fusion area was selected based on whole-spine erect posteroanterior (PA), supine side-bending and traction radiographs. For patients with Lenke 2 curves, the proximal thoracic curves were included in the fusion area. For those with Lenke 1 curves, the proximal thoracic curves were not included in the fusion area. For patients with lumbar modifier A pattern, the lower instrumented vertebra was selected as the stable vertebra according to traction radiographs, which was one or two levels proximal to the stable vertebra according to erect PA radiographs. For patients with lumbar modifier B or C pattern, the lower instrumented vertebra was selected as the stable vertebra according to erect PA radiographs.

2.3. Radiographic evaluation

Preoperative radiographic evaluation included whole-spine erect, erect lateral, and supine side-bending radiographs. Cobb angles of the proximal thoracic, main thoracic (MT) and thoracolumbar/lumbar curves were measured from erect PA radiographs as coronal parameters. Flexibility of the curves was evaluated on the side-bending radiographs. TK, defined as T5–T12 kyphosis, was measured on erect lateral radiographs. Postoperative radiographic evaluation included erect PA and lateral radiographs. The proximal thoracic, MT, and thoracolumbar/lumbar curves and TK were also measured on the postoperative radiographs.

As described by Vora et al. [7], the following ratios were determined:

Preoperative flexibility (%) = [(Preoperative erect Cobb angle − Supine bending Cobb angle)/Preoperative erect Cobb angle] * 100.

Postoperative correction (%) = [(Preoperative erect Cobb angle − Postoperative erect Cobb angle)/Preoperative erect Cobb angle] * 100.

Cincinnati Correction Index = Postoperative correction %/ Preoperative flexibility %

2.4. Statistical analysis

A paired t-test was used to assess differences between the magnitude of the curves at preoperative examination and at latest follow-up. Statistical significance was defined as $P < 0.05$.

This study has been approved by the ethics committee of our institution (approval number 28082).

3. Results

The mean follow-up period was 33.0 months (range, 24–60 months). The average preoperative Cobb angle of the MT curve was 58.1° (range, 45–88°). The MT curve was corrected to 12.8° (range, 0–38°) immediately after surgery. At the latest follow-up, the mean Cobb angle was 13.6° (range, 0–44°) and the average final correction percentage was 77.5% (range, 44–100%) (Fig. 1). The average loss of coronal correction was 0.8° (range, −2–6°). Changes in coronal parameters are shown in Table 1. The mean preoperative flexibility of the MT curve was 54.6% (range, 24–91%). The mean Cincinnati Correction Index was 1.53 (range, 1.03–3.16) at the latest follow-up.

The average preoperative TK was 13.7° (range, −12–34°). Immediately after surgery, TK had increased to 18.6° (range, 10–29°). At the latest follow-up, TK measured 18.1° (range, 6–32°) (Fig. 2).

The average operative time was 324.1 min (range, 228–414 min). The average intraoperative blood loss was 739.9 mL (range, 207–1687 mL). One patient had pleural injury related to CRR and underwent pleural repair with the use of a polyglycolic acid sheet and fibrin glue; chest tube placement was not required. Three patients had slight pleural effusion on the concave side but none required chest tube placement. There were no other intraoperative or perioperative complications, including neurological complications, implant breakage or laminar fractures.

4. Discussion

The development of Cotrel-Dubousset multisegmental instrumentation enabled not only coronal correction but also sagittal plane correction of spinal deformity [8]. The instrumentation solved the problem of "iatrogenic flatback" seen with the use of Harrington instrumentation. The hybrid construct is a segmental instrumentation technique using sublaminar wires, pedicle screws and hooks. Multisegmentally placed sublaminar wires generate

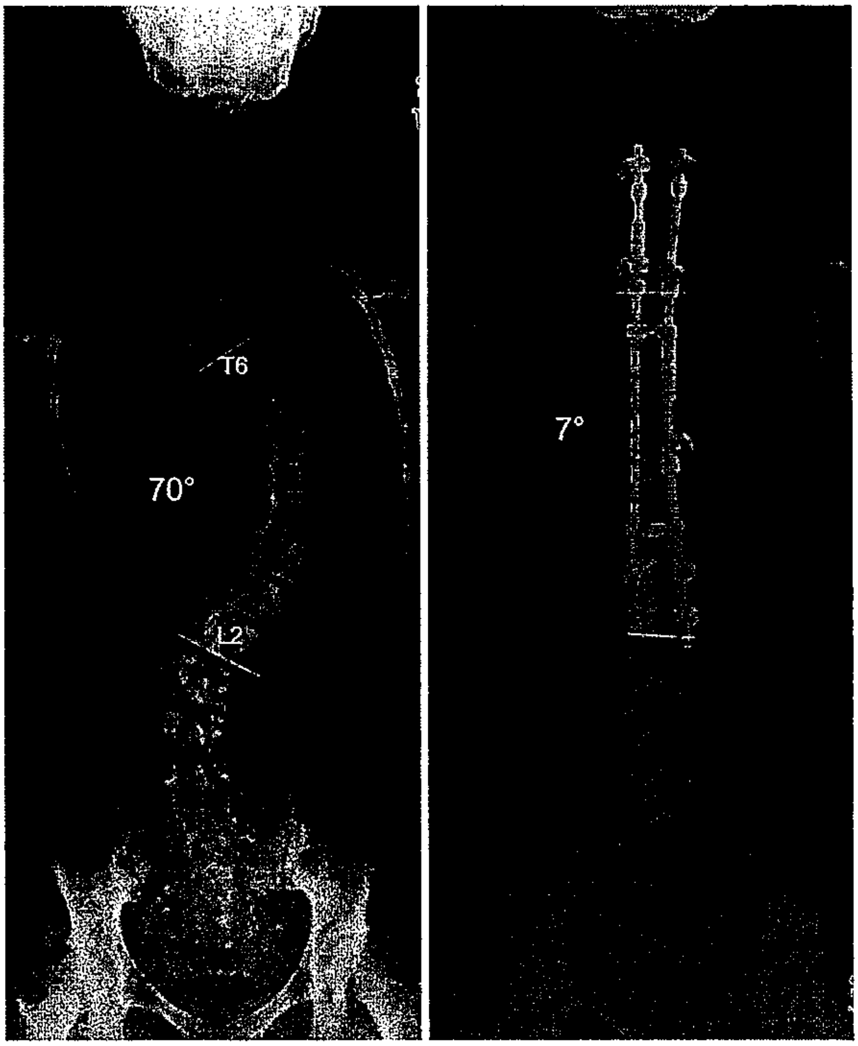

Fig. 1. Preoperative and 3-year follow up postero-anterior radiograph of a 14 years old girl with AIS, Lenke type 2A-. T6-L2 main thoracic curve was corrected from 70 to 7° (90% correction). Six sublaminar UHMWPE cables were used from Th6 to Th11 laminae. CRR was undergone from left 8th to 10th ribs, and right transverse process resection with costovertebral joint release was undergone Th8 and 9 vertebrae.

Table 1
Summary of the pre- and postoperative radiographic parameters.

	Preoperative	Immediately postop.	Latest follow-up	P-value (Preop. vs Latest f/u)
Main thoracic curve (°)	58.1 ± 12.6	12.8 ± 9.0	13.6 ± 9.9	<0.0001
Preoperative flexibility (%)	54.6 ± 17.4	n/a	n/a	n/a
Postoperative correction (%)	n/a	78.9 ± 12.7	77.5 ± 14.0	n/a
Cincinnati correction index	n/a	1.57 ± 0.50	1.53 ± 0.48	n/a
Proximal thoracic curve (°)	31.6 ± 9.7	16.9 ± 9.1	16.4 ± 9.6	<0.0001
Thoracolumbar/lumbar curve (°)	31.5 ± 9.2	8.8 ± 7.1	7.9 ± 9.1	<0.0001
Thoracic kyphosis (°)	13.7 ± 12.0	18.6 ± 5.9	18.1 ± 6.5	0.02

posterior and medial translational force on the spine, ensuring both coronal and sagittal correction of the spinal deformity.

In this study we used hybrid constructs for the surgical correction of scoliosis with modifications for better correction of coronal and sagittal deformity. First, we used 5-mm-wide UHMWPE cables as sublaminar anchorage devices. This reduces the risk of laminar fracture during deformity correction because the width of the UHMWPE cables is larger than that of stainless steel wires. The increased width enables greater translational force to be applied to the lamina [9]. Second, we performed CRR and convex costovertebral joint release to enhance the flexibility of the deformity. El Masry et al. reported that concave rib osteotomy was a safe and reliable alternative to anterior release in posterior surgery of severe and rigid curves in patients with AIS [10]. Our method includes not only

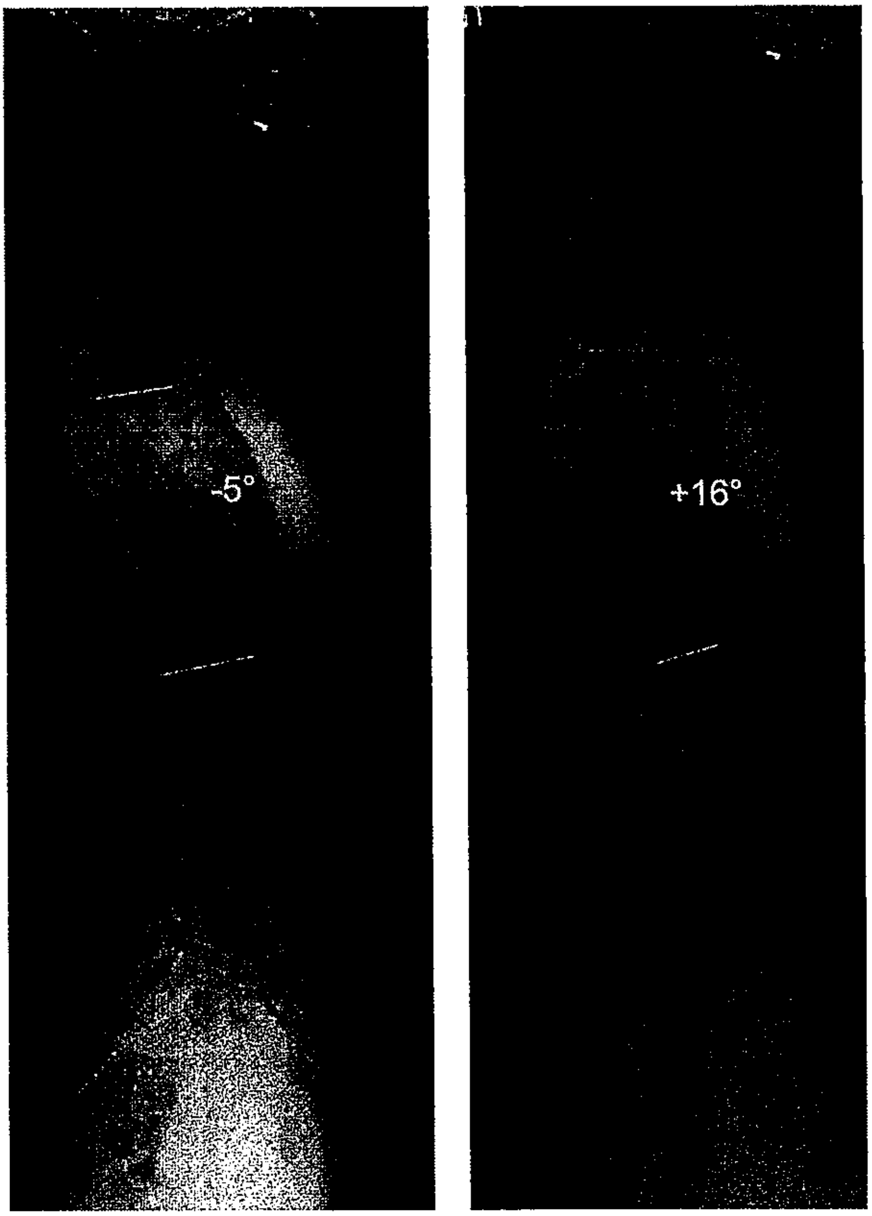

Fig. 2. Preoperative and 3-year follow up lateral radiograph of a same patient with Fig. 1. Thoracic kyphosis was improved from −5 to +16° after surgery.

concave rib osteotomy but also rib head resection with costovertebral joint manipulation. This combination results in costotransverse ligament resection and costovertebral ligament (radiate ligament) release. Yao et al. reported that costotransverse ligament and costovertebral joint release resulted in decreased force required for axial rotation and lateral bending in a cadaveric biomechanical study [11]. Their results suggest that release of those ligaments in posterior scoliosis surgery would contribute to better curve correction. An additional benefit was that the resected rib heads were used as bone graft, which helped to avoid bone graft procurement from the ilium. In this study, there was no patient in whom iliac bone harvesting was necessary. However, CRR is associated with some risk of pulmonary complications, such as pleural injury, which sometimes requires chest tube placement for hemothorax. However, in our experience, chest tube placement is not necessary if pleural injuries are repaired with a polyglycolic acid sheet and fibrin glue.

Since Suk's report [12] of thoracic pedicle screws as segmental anchors for deformity correction, many surgeons have become interested in segmental PS constructs. Some authors have reported that pedicle screws, which are theoretically the strongest anchors for correction, provide a better correction rate and less loss of curve correction than other methods [3–6]. Although several reports have described the advantages of hybrid constructs in maintaining thoracic kyphosis compared with segmental PS constructs [4,6,7,13], the use of hybrid constructs for scoliosis surgery is currently viewed as outdated.

In this study, average MT curve correction was 77.5% with hybrid constructs with CRR as a posterior release procedure. The sagittal thoracic alignment was corrected from 13.7° preoperatively to 18.6° postoperatively, and maintained at 18.1° at latest follow-up. MT curve correction is reported to be 54.0–63.0% with the use of conventional hybrid constructs [2,3,6,9,13] and 63–79.6% with the use of segmental PS constructs [3,4,6,12–17]. Our results suggest that hybrid constructs combined with posterior release procedures are not only better than conventional hybrid constructs but comparable to segmental PS constructs in coronal curve correction. Thus, hybrid constructs remain a useful option for the surgical correction of scoliosis when combined with posterior release procedures. We emphasize that hybrid constructs avoid the potential risks of thoracic pedicle screws, including neurological and vascular complications.

In conclusion, hybrid constructs combined with posterior release procedures including CRR and convex costovertebral release achieved satisfactory coronal and sagittal curve correction with little loss of correction at minimum 2-year follow-up. The coronal curve correction obtained with hybrid constructs with posterior release procedures was better than that obtained with conventional hybrid constructs alone.

Conflict of interest

The authors declare that they have no conflict of interest.

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特集　高齢者の脊髄損傷

高齢者脊髄損傷の疫学

松本聡子* 須田浩太*
小松　幹* 三浪明男*

要旨：脊髄損傷の大規模全国発生調査からから約30年が経過し，脊髄損傷の疫学は当時と様相を違えてきた。日本は超高齢社会を迎え高齢者特有の脊椎変性変化，強直脊椎（DISH），骨粗鬆症など脊髄損傷の潜在リスクを有しつつも，活動性の高い高齢者の増加などが背景となり，日本における高齢者脊髄損傷の発生は増加傾向にある。世界の動向は，経済的背景により地域間格差が大きいものの，北米，ヨーロッパ諸国など高齢化が進む地域では，日本同様発生年齢が高齢化している。日本では，平地転倒など軽微な外傷が主な受傷原因であり，回避可能なケースが多いと推察する。政策としての「高齢者の社会参加活動の促進」を安全に遂行するためにも，医学界からの高齢者脊損予防の啓発を積極的に行う必要がある。

はじめに

世界保健機関（World Health Organization；WHO）の定義では65歳以上が総人口の21%以上を超えた社会を「超高齢社会」という。日本は2007年に21.5%となり超高齢時代を迎え今年で10年となり，2025年には30.3%，2060年に39.9%に達すると予想されている（図1）。2016年現在，超高齢社会は，日本，イタリア，ギリシャ，ドイツ，ポルトガル，フィンランドの6カ国である[1)2)]。

特に日本の高齢化は世界に例をみない速度で進行している。世界のどの国も経験したことのない「長寿大国」日本における脊髄損傷（以下，脊損）の疫学の特徴分析は人口分布に対する脊損発生トレンドを推測する上で有益である。増え続ける高齢者脊損にどう対応していくべきかを提言するためにも，継続的な全国疫学調査の重要性がいっそう高まっている。

I．日　本

本邦における全国疫学調査はこれまでに2回実施されているが，登録患者数およびアンケート回収率から，第1回実施の調査が脊損発生の現状を推定するのに適切なものと考えられている[3)～5)]。1990年から1992年にかけて行われ，登録患者数9,752名の大規模なものである。発生率は40.2人/100万人/年，発生時年齢のピークは59歳で次に20歳の二峰性だった。頚髄損傷（以下，頚損）は全体の75%で平均年齢51歳，それより尾側の損傷は40歳と，頚損の年齢が高かった。平地転倒による受傷者の平均年齢は61.7歳で，高年齢者ほど高所転落と平地転倒による受傷が多かった[3)]。その10年後には労災病院脊髄損傷統計センターが全国労災病院での登録患者をまとめたデータを発

* Satoko MATSUMOTO HARMON et al, 北海道せき損センター

Demographic profile of spinal cord injury in Japan as a super-aging society

Key words：Epidemiology, Spinal cord Injury, Aging society

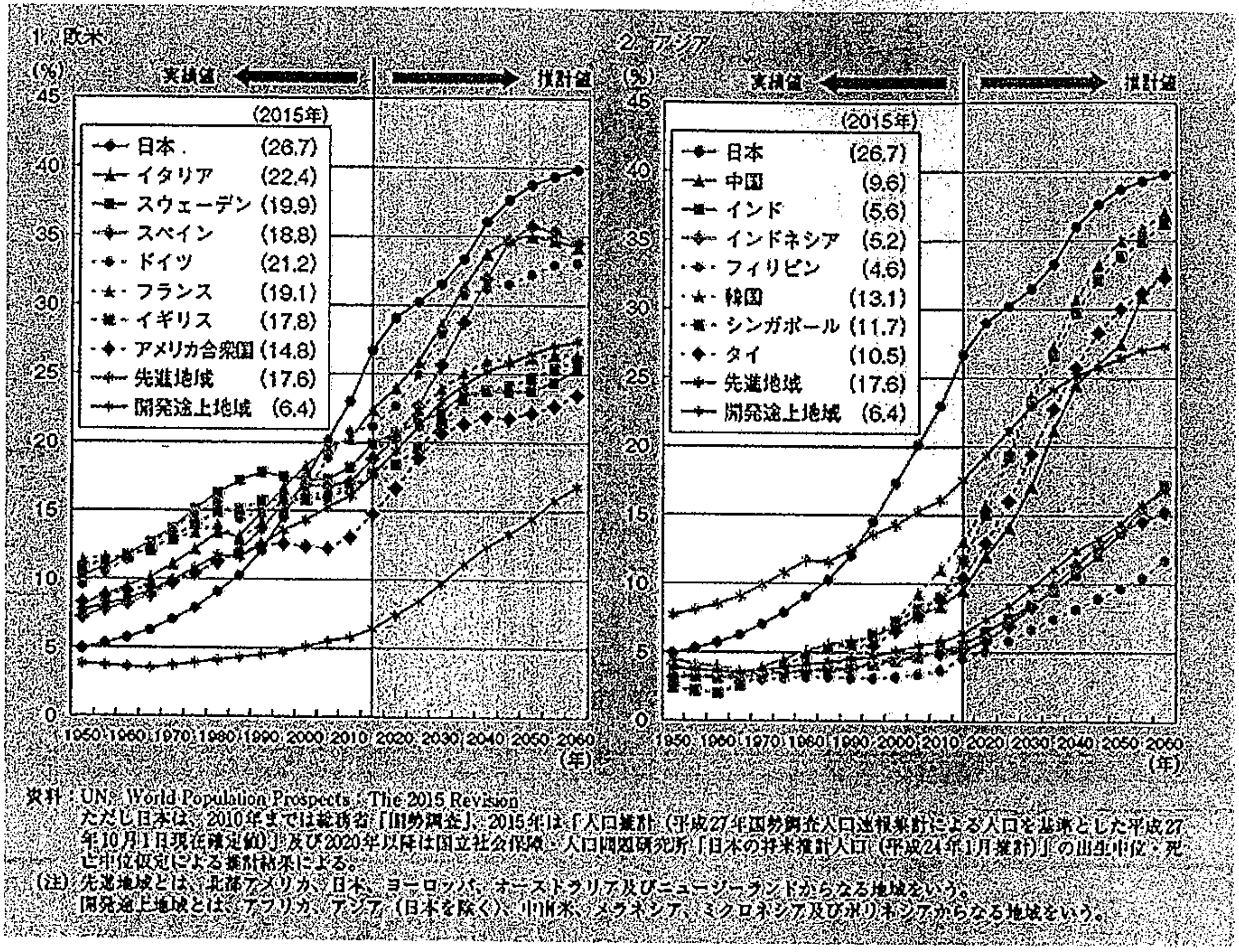

図 1　世界の高齢化率。平成 28 年度版高齢社会白書より抜粋（内閣府）
http://www8.cao.go.jp/kourei/whitepaper/w-2016/html/zenbun/s1_1_5.html

表した[6]。421 名の分析で 61 歳以上（117 名）を高齢者群とした場合，高齢者群は高所転落が原因の 1 位で 42.7%，次いで交通事故 29.1%，転倒 11.1% だった。若年者群での 1 位が交通事故 32.6%，転倒はわずか 5.9% と，年齢により受傷原因が異なっていた。

全国での新規脊損発生の詳細を把握する目的で，脊髄損傷登録管理事務局が福岡県で2006年に設立したのを皮切りに，日本脊髄障害医学会による定点調査が開始された。北海道，宮城県，千葉県，和歌山県，高知県で現在も調査が継続されている。福岡県では，県全体の発生率 30.8 人/100 万人/年（高齢化率 19.9%）が，高知県 112.1 人/100 万人/年（高齢化率 25.9%）[7]と大きく異なり，県内の高齢化率の異なる行政区分別に発生予測値を分析した。結果は地域の高齢化率や年代別にかかわらず高知県のような高値はなかった（63.8～84.7 人）[5)8)]。一方で徳島県からの報告では，2011 年と 2012 年の発生率は 121.4 人，117.1 人（100 万人/年）で同じ四国の高知県の報告に類似している[9]。われわれが行った北海道の発生調査では[10]，2009 年から 2015 年にかけて発生率は 39.1 人/100 万人/年（高齢化率 24.3%）から 63.5 人/100 万人/年（高齢化率 28.0%）へと増加した（図 2）。この間，高齢化率は数% 増加したが，発生率は 1.6 倍になっている。2015 年のデータでは，発生数の 23.7% が 75 歳以上で，北海道人口における 75 歳以上の割合 13.7% を大きく上回る。75 歳以上の発

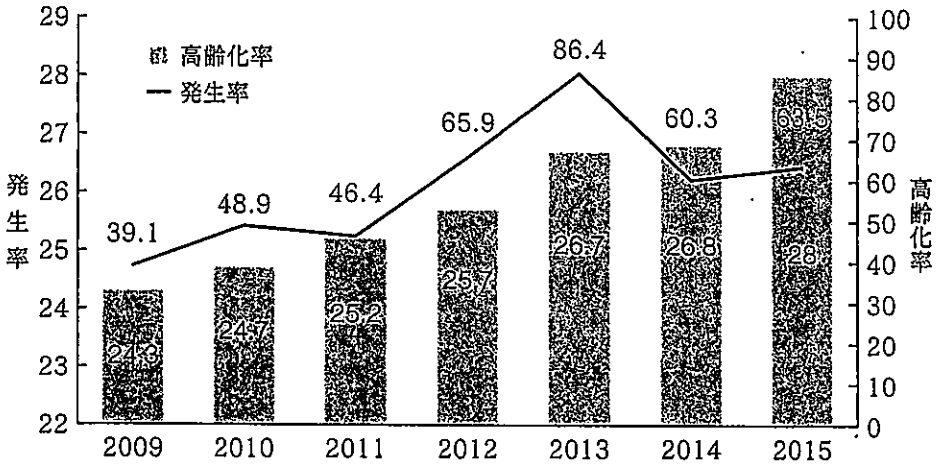

図 2　北海道の新規脊損発生率と高齢化率

生率は117.1人で，特に75歳以上男性では239.1人と全体発生率の約4倍であった。高齢者が潜在的にもつ脊損発生の危険度を示しているといえる。また北海道という降雪地域特有の特徴もデータから見えてきた。2012年から2015年に当センターに搬送された全脊損患者372名のうち，降雪期の受傷が62％で，そのうち75歳以上が53％であった。滑って転倒しやすい屋外での歩行時転倒と，除雪など屋外での活発な活動中の受傷がほぼ同率であった。30年前の全国調査を行ったときよりも明らかに高齢者の脊損は増えてきている。年齢によらず活動性が高い高齢者の増加と，脊椎には高齢者特有の変性変化が存在していることが相まって，高齢者脊損発生数を押し上げていると考えられる。

内閣府発表の高齢社会対策大綱[11]によると，高齢者の社会参加活動の促進は重要な項目として位置づけられている。高齢者，特に後期高齢者が安全な生活を送るためには，高齢者は脊損発生の潜在的リスクにさらされていることを啓発する必要がある。

Ⅱ．海外の状況[12]

国別に脊損の疫学を比較する際には，年齢・性別などと同様にその国の経済的状況を考慮して検討するのが一般的である。世界銀行により定義された年間国民総所得（Gross National Income；GNI）別の4分類（Low, Low middle, Upper middle, High income）ごとに，それぞれ異なる傾向がみられている。世界全体で外傷性脊損の発症年齢は二峰性で，18～32歳と65歳以上で，高齢のピークは女性患者の増加が寄与している[13]。日本を含むHigh incomeの国々（西ヨーロッパ，北米，High incomeのアジア諸国，オーストラリア）では高齢化が顕著で，これらの国々では65歳以上のピークが大きく広がっており，四肢麻痺がLow energyの転倒で発症するのが特徴的である（日本75％ vs 北米・オーストラリア47％，西ヨーロッパ51％）。北米で1935年から2008年に行われたコホート研究[14]では（n＝45,442），1970年代に比べ，受傷時平均年齢は8.8歳上昇し，60歳以上が4.6％から13.2％に増加した。交通事故が引き続き受傷原因1位だが，特に高齢者では転倒・転落が多く，全体の受傷原因2位になっている。高位頚損例が12.3％から27.2％に増え，不全麻痺も43.9％から52.7％に増加し人工呼吸器管理例が1.5％から4.6％に増えている。年間死亡率は，麻痺が高度，より高位，年齢が高いほど，非脊損者に比べて数倍の開きがあった（70～74歳；非脊損者2.6％，全脊損者8.4％，AIS A 10.8％，cervical AIS A 17.0％）。

WHO ISPCI（International Perspectives on Spinal Cord Injury）によると，外傷性と非外傷性脊損を合わせた新規発生率は40～80人/100万人/

年とされる。しかしながら非外傷性脊損に関する報告は少なく，オーストラリアでは非外傷性が26人/100万人/年と外傷性15人より多く，一方でカナダでは非外傷性53人に対して外傷性68人と，High incomeの国でも一定の傾向を見つけることは難しい。ISCoS（International Spinal Cord Injury Society）の分類によると[15]，非外傷性脊損には変性変化に伴う脊柱管狭窄由来の脊損も含まれることから，日本における広義の脊損発生率は潜在的にもっと高いことが推測され，今後さらに増加していくことが示唆される。

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頭頸部・体幹のスポーツ外傷

■編集
永廣信治　徳島大学病院長
西良浩一　徳島大学大学院医歯薬学研究部運動機能外科学教授

MEDICAL VIEW

頚椎・頚髄損傷

前田 健　独立行政法人労働者健康安全機構総合せき損センター整形外科

スポーツ外傷の発生と診断

発生する競技と診断

2006～2015年までの10年間で，総合せき損センターに入院加療となった脊椎・脊髄外傷症例801例のうち，スポーツ関連の症例（モータースポーツや海などへの飛込も含めて）は73例（9.1%）であったが，そのうち頚椎・頚髄損傷が54例を占めていた。体操（平行棒）中の転落と登山中の転落の2名のみが女性であったが，そのほか52例は全例男性であり，年齢は13～79歳，平均30歳であった。脊髄振盪が2例，上位頚椎外傷で麻痺なし例が2例あったが，残り50例はいずれもさまざまな程度の脊髄損傷を伴っていた。スポーツ種類別の頻度を表1に示す。原因として最も頻度の高いのは水中飛込に伴う頚椎損傷であり，続いてスキー，スノーボード，柔道と続く。以下原因スポーツ別にそれぞれの特徴を述べる。

水中飛込（19例）

比較的水深の浅い水中に頭から飛び込むことにより，プール床や海底で頭部を強打し頚椎・頚髄損傷を生ずる。日本脊髄障害医学会・脊損予防委員会の啓蒙活動により，学校や公共のプールでの飛込事故の頻度は大きく減少しているが，レジャーに関連した海や川への飛込を含めると現在でも最も頻度の高い受傷原因である。年齢は若く平均22歳（14～44歳），プール飛込が7例，プール以外が12例であった。特筆すべきは，プール飛込7例中，水泳部の部活中の飛込

表1 受傷原因別頻度
水中飛込はレジャー関連も含めた。

原因	症例数	平均年齢
水中飛込	19	22
スキー，スノーボード	5	38
柔道	4	20
トランポリン	3	26
登山	3	70
ラグビー	3	32
アメリカンフットボール	2	20
ゴルフ	2	69
サーフィン	2	31
体操	2	17
自転車	2	52
そのほか	24	

事故が3例あったことである。レジャーや遊びでのプール飛込のみならず，水泳選手でもリスクがあることに注意が必要である。

骨傷は特徴的である。19例中17例は頚椎屈曲外力＋軸圧により生じたcompressive flexionタイプの骨傷であり，いわゆる涙滴骨片を認めていた。受傷機転からすればもっともな結果である。ほかの2例は屈曲外力により頚椎前方脱臼を生じていた。骨傷レベルはC5が最も多く7例が完全麻痺であったが，そのほか全例でなんらかの四肢麻痺を生じていた。

●スキー，スノーボード(5例)

当センターは九州にあるため相対的な症例数は少なく，全例遠隔地よりヘリコプターなどの航空手段で搬送されている。スキーが2例，スノーボードが3例であった。比較的高齢の2例は滑走中の転倒に伴う頚椎過伸展により非骨傷性頚髄損傷を生じていた。ほかの3例は段差でのジャンプ，フリースタイルスキーでのエアなど危険を伴う手技により受傷しており，涙滴骨片や前方脱臼などの骨傷を生じていた。

●柔道(4例)

全例なんらかの投げ技に絡んで受傷している。投げられて受傷した症例もあるが，逆に相手を投げようとして前のめりに転倒する症例もある。いずれにせよ頭部から畳に落ち，頚椎を過屈曲することにより受傷していた。そのため骨傷は特徴的で，全例が頚椎前方脱臼であった。

●ラグビー，アメリカンフットボール(5例)

似たようなスポーツであるが，受傷機転はやや異なっているようである。ラグビーの場合，若年者の2例はいずれもスクラムが崩れ頭部が地面に接触し頚椎過屈曲を強制され前方脱臼を生じている。一方，アメリカンフットボールでは2例ともタックルの瞬間に生じており1例は頚椎過屈曲による前方脱臼，1例は涙滴骨片を生ずるcompressive flexion損傷である。すなわちアメリカンフットボールではヘルメットを装着しているため頭頂部から相手にぶつかりやすく，頚椎に軸圧がかかった状態で屈曲を強制され損傷したものと思われる。いずれにせよヘッドダウンした状態で頭からぶつかってしまうことが原因と考えられた。タックル時のヘッドアップの重要性があらためて認識される。ただし67歳でラグビー中に受傷した1例は頚椎過伸展損傷であり，高齢者においては脊柱管狭窄状態が内在している可能性があり，注意が必要である。

●トランポリン，体操(5例)

トランポリン，体操いずれも空中での回転に失敗し頭部より転落して損傷している。回転がついているためか，軸圧よりも頚椎屈曲外力が大きいと考えられ，全例頚椎前方脱臼を生じている。

●登山，ゴルフ(5例)

いずれも比較的高齢者に生じている。登山の3例は転落事故にて受傷しており，そのうち2例が非骨傷性頚髄損傷であった。ゴルフの2例はいずれもプレー中の転倒にて非骨傷性頚髄損傷を生じていた。

●そのほか

自転車レースでの転倒，組み体操中の転落，サーフィン中の転落，走り高跳びでの着地失敗などでの頚髄損傷も散見された。

スポーツ外傷の治療

先に記述した症例はすべて当センターに入院加療が必要となった比較的重症例である。以下では，軽症例を含め代表的な障害別に治療方針を記す。

神経根・腕神経叢障害

いわゆるburner症候群，stinger症候群（stingers）とよばれるものである。接触スポーツで衝撃を受けた際，頚椎過伸展により神経根が圧迫されたり，側屈に伴い腕神経叢に過伸長外力が加わることにより生ずる。まれに鎖骨上のErb's pointに直接外力が加わることにより腕神経叢障害を生ずる。一側の頚部痛，上腕痛，しびれ，脱力を生ずるが，症状は通常一時的なので，フィールド外で経過観察のみ行う。15分以内に症状が消失すればそのまま競技に復帰させてよいが，症状が1日以上持続するようであれば，症状の強さに応じてカラー装着，非ステロイド性抗炎症薬（non-steroidal anti-inflammatory drugs；NSAIDs）やリリカ®などの投薬を行うと同時に，ヘルニア，脊柱管狭窄，骨傷などの画像検索を行う。

脊髄振盪

Cervical cord neurapraxia（CCN）ともよばれ，頚髄の一過性障害である。片側上肢症状を呈するburner症候群と異なり，両上肢，両下肢，片側上下肢，あるいは四肢症状を呈する。通常は頚椎過伸展により脊髄が一過性に圧迫され生ずる。両上肢のアロデニア様症状を伴うことも多い。麻痺は数分～数日でほぼ消失するが，受傷当初は不可逆的な脊髄障害や骨傷を伴う頚椎外傷との区別がつきにくいため，頚部の安静を保ちただちに専門病院に送るべきである。受傷直後四肢がまったく動かない状態でも，搬送途中で徐々に動きの改善がみられる。フィラデルフィアカラーを装着すると同時に，頚部痛や四肢のしびれ，痛みが強ければNSAIDsやリリカ®，オピオイドなど対症療法を短期間行う。画像上脊柱管狭窄や軟部組織の損傷などがなければ，四肢症状の完全回復後カラーを除去する。脊柱管狭窄を合併している場合，予防的に頚椎手術（前方除圧固定，椎弓形成術など）を行うか否かは議論があるが，筆者らは基本的に手術適応とは考えていない。

非骨傷性頚髄損傷（図1）

ほとんどが頚椎過伸展損傷であり，高齢者に多い。スポーツ外傷以外も含めたすべての外傷性頚髄損傷のなかでは最も頻度の高い頚髄損傷型であり，近年高齢者のスポーツ参加が増すなか，スポーツに伴う非骨傷性頚髄損傷の頻度も増加している。典型的には中心性頚髄損傷（上肢に強い不全麻痺）を生ずるが，完全麻痺となることもある。非骨傷性といえども前縦靱帯や椎間板などの断裂，椎体や椎弓のマイナーな骨折などを合併していることが多い[1]。それゆえ受傷直後には椎体後方すべりなどの椎間不安定性が認められることもあるが，3週間程のフィラデルフィアカラー固定で椎間安定性が得られる。また，変性や靱帯骨化などで脊柱管狭窄が内在している症例も少なくない。除圧術の適応には議論があるが，受傷前に脊髄症状のまったくみられなかった症例に対する除圧術の効果はいまだ不明瞭であり，当センターでは基本的に除圧術は行わずカラー固定のみ施行し，早期離床，早期リハビリテーションを目指している。3週間程の単純なフィラデルフィアカラー固定で，除圧術を施行した場合と遜色のない程度の

麻痺回復が得られている[2)]。高齢者に多く，C3/4高位での損傷頻度が高いため，経過中の呼吸器合併症には特に注意が必要である。

頚椎前方脱臼(図2)

骨傷のなかでは最も頻度が高い。可及的早期の整復と内固定術が必要となる。整復に伴い脱出したヘルニアや断裂した黄色靱帯のたぐれ込みなどにより麻痺の増悪をきたすリスクがある。そのためtongやハローリングを用いた意識下の牽引による整復をまず試みる施設も多い。筆者らは即日観血的に後方整復固定術を施行しているが，事前のMRIにて椎間板の脱出や強い脊柱管狭窄状態があれば，観血整復固定術を後方から施行した後に体位を変換し，一期的に前方除圧固定術を併用している。後方固定術はlateral mass screwか棘突起wiring＋腸骨のサンドイッチグラフトを施行している。前方固定術は通常1椎間の国分法による腸骨移植術を施行している。術後はフィラデルフィアカラーを約6週間使用する。

図1 非骨傷性頚髄損傷

79歳，男性。ゴルフ場で転倒し受傷，カラーのみの保存療法にてASIA Impairment Scale(AIS)CからDへ改善。
a：受傷直後のMRI T2強調像。椎体前面の軟部にT2高信号病変を認める。髄内は淡くT2高信号となっている。
b：受傷後半年のMRI T2強調像。C3/4の責任病変に髄内T2高信号領域が残存。

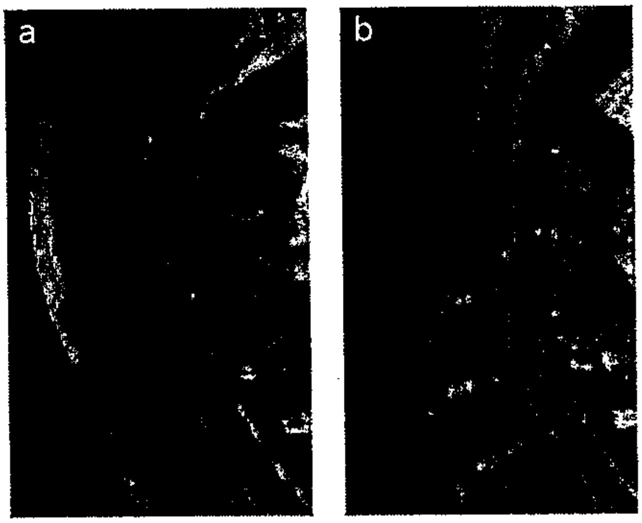

図2 C4前方脱臼

17歳，男子。柔道試合中に技をかけようとして前方に転倒し受傷。当日，一期的前方後方固定術を施行。受傷直後AIS C，退院時AIS D。
a：C4前方脱臼を認める。
b：C4/5間で右片側ロッキングと上関節突起先端の小骨折を認める。
c：MRIにて椎間板の脱出を認める。
d：術後X線像。

涙滴骨片を伴う椎体骨折（compressive flexion損傷）（図3）

頚椎をやや屈曲した状態で頭頂部から軸圧がかかり生ずる。当センターでは17例中14例が水中飛込によるものであった。涙滴骨片を伴う典型例では，椎体の縦骨折と椎弓骨折を合併している。手術が必要か否かは椎体破壊と後方靱帯損傷の程度による。Allenらはcompressive flexion損傷をその程度により5段階に分類している（表2）。Stage1，2であればフィラデルフィアカラー固定でよい。Stage3，4であれば内固定術の適応となるが，症例によりハローベストによる保存療法も可能である。内固定術はプレートを併用した前方からの椎体切除，腸骨移植術を行うか，後方よりlateral mass screwを用いて後方固定術を施行する。転位の強いStage5となれば，後方前方合併手術の適応となることが多い。

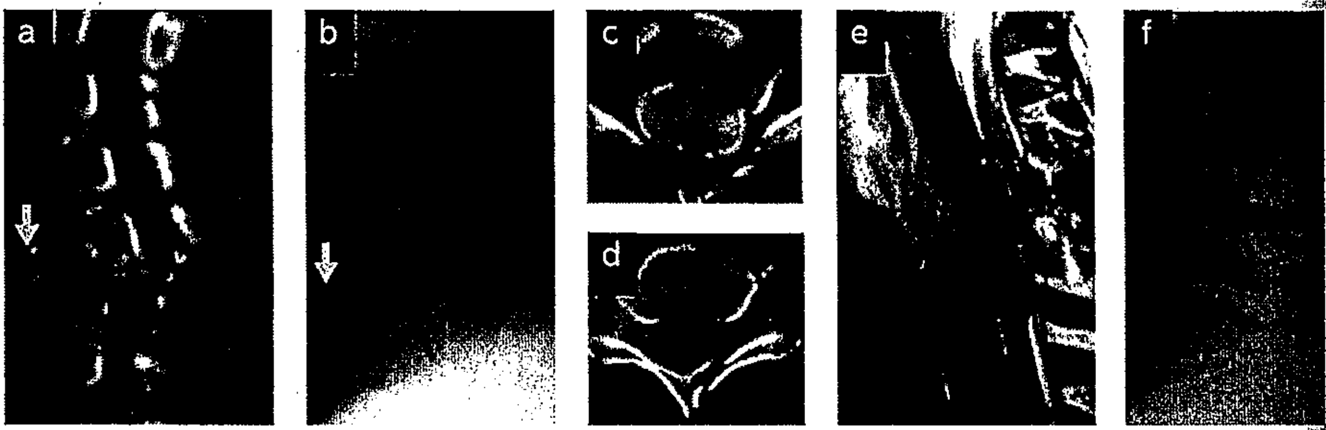

図3 Compressive flexion損傷（Stage5）

34歳，男性。飲酒後，海の浅瀬に飛び込み受傷。AIS A。
a，b：C5椎体の後方脱臼と同椎体前方に涙滴骨片（⇨）を認める。
c：C5椎体の縦骨折とその前方の涙滴骨片。
d：C6椎体にも縦骨折を認める。
e：MRI T2強調像。
f：一期的後方前方固定術を施行。

表2 Compressive flexion損傷のAllen分類

Compressive flexion stage	特徴
Stage1	椎体上前方の鈍化
Stage2	椎体前方の椎体高減少（くちばし状変形）
Stage3	涙滴骨片あり，椎体後方転位なし
Stage4	涙滴骨片あり，椎体後方転位 < 3 mm
Stage5	涙滴骨片あり，椎体後方転位 > 3 mm

競技復帰と予防

予後と競技復帰

不幸にして脊髄障害を合併した場合，ほとんどの例で多かれ少なかれ脊髄症状が遺残するため元の競技への復帰は不可能となる。ただし経過中になんらかの麻痺改善がみられることが多く，リハビリテーション次第でADLは大きく改善する。どの程度麻痺改善が得られるかは受傷時の脊髄損傷程度によるところが大きく，受傷直後完全麻痺であれば残念ながら完全麻痺のままである確率が相当に高い。当センターの調査では，最終的になんらかの手段で歩行可能(Frankel D)となる確率は，受傷初期に完全麻痺(Frankel A)であれば4%，運動完全麻痺，知覚不全麻痺(Frankel B)であれば約40%，運動知覚不全麻痺だが歩行不能(Frankel C)であれば約80%であった。歩行も含めたADL獲得に関しては年齢に依存する部分もきわめて大きく，若い患者であればリハビリテーション効果が大きく期待できる。

一方，脊髄障害を遺残していない症例に関して，元の競技への復帰が可能か否かはそれぞれの症例に応じて決められるが，いまだ一定の基準はなくさまざまなreturn to play criteriaが提唱されている[4-6]。特に，一度CCNを経験した選手に対する扱いには議論が多い。スポーツに伴うCCN経験者の約半数は複数回経験していたという報告がある一方[7]，永続的な脊髄障害を起こしたスポーツ選手に過去のCCN経験者はいなかったという報告もある[4]。すなわち，CCNを一度でも起こすと，スポーツ復帰後再びCCNを起こすリスクは比較的高いが，永続的な脊髄障害を起こすリスクはかなり低いと考えられる。CCNが一度でもあれば相対的なリスクがあるともいわれるが，一般的には表3に挙げられるような条件がすべて揃っていれば競技復帰には問題がないことはある程度コンセンサスがあるようである。その一方で，複数回のCCN，MRI上の髄内輝度変化，脊柱管の狭窄，3.5mm以上のすべりなどがあれば，競技復帰すべきではないとする報告が多い。また，脊髄症状の既往がなくても，burner症候群を繰り返している場合や神経根痛が長期間遺残している選手は，競技復帰へのrelative contraindicationといわれている[4-6]。

脊椎手術を受けた場合，中下位頚椎の1椎間固定に関しては，癒合が得られ臨床的に問題なければ競技復帰に支障はないといわれており，隣接椎間障害の発生率も一般症例より多いという報告はない。一方，3椎間以上の固定，C1-2固定，椎弓切除術後などでは競技復帰すべきではない(absolute contraindication)とされている[4-6]。

表3 CCN既往選手における競技復帰の十分条件

少なくともこれらの条件をすべて満たせば競技復帰に問題はない。
いずれか条件が満たない場合は，スポーツの種類や症例に応じて検討する。

CCN既往選手における競技復帰の条件
・CCNが1回のみ
・麻痺が完全回復
・頚部痛がない
・ROM制限がない
・脊柱管狭窄や脊椎アライメント異常がない

予防

回避することが難しい突発的な事故が多いが，事前の啓蒙と注意により避けることができる頚椎・頚髄損傷もある。まず第一に，安易な水中への飛込がいかに危険を伴うかを広く周知させることが重要である。学校の授業やプールでの飛込の禁止はもちろんのこと，水泳選手であっても水深が浅ければ頚椎損傷が起こりうることを認識する必要がある。レジャーの場では，飲酒後の飛込は特に危険であり避けるべきである。次にアメリカンフットボールやラグビーなどの接触スポーツにおいて，タックル時，あるいはラックの際のヘッドダウンの危険性について十分な指導が必要である。また，柔道で畳に頭から落ちそうなとき，防御姿勢を取ろうとして反射的に頚椎を屈曲することの危険性についても指導が必要であろう。

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専門医の整形外科外来診療

Clinical Practice for Advanced Orthopaedic Surgeons

——最新の診断・治療

冨士武史
田辺秀樹
大川　淳
編

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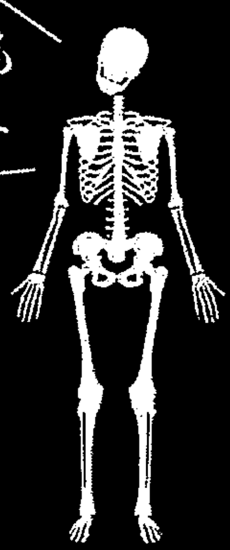

症候診断から始まる治療選択，
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18 脊椎損傷

ここ10年でわかったこと

【頻度】

- 新規脊髄損傷患者の発生頻度は約30〜40人/100万人であり，これは1990年の全国調査時と比較し著変はない．ただし，平均年齢は48.6歳から60歳に上昇し，高齢者の非骨傷性頚髄損傷を中心とした不全麻痺例が増加している．

【中下位頚椎】

- 非骨傷性頚髄損傷は最も頻度の高い頚髄損傷であり，基本的には頚椎過伸展損傷である．画像上明らかな脱臼・骨折はないが，多くの症例で前縦靱帯や椎間板などの軟部支持組織の損傷を伴っている（図1）[1]．しかし，3週間程度のフィラデルフィアカラーによる保存的治療で損傷椎間の安定性が得られやすい．脊柱管狭窄を伴う症例に対しては，近年早期の除圧術を勧める論文が散見されるが，早期手術的治療が真に有用だというレベルの高いエビデンスは存在しない．ランダム化試験では，手術的治療と保存的治療で差がなかった[2]．ただし，受傷後1〜3日以内の早期手術が有用である可能性があり，現在前向き試験が進行中である．

【胸腰椎】

- 麻痺発生の因子として，後方靱帯要素（棘上棘間靱帯，黄色靱帯，関節包）損傷の有無が重要である．破裂骨折であっても，後方靱帯損傷がなければ外固定による保存的治療を選択しうる．

❶ 本疾患の概念——骨折型，分類

i 上位頚椎

- 頻度の高い骨折として，環椎破裂骨折（Jefferson骨折），歯突起骨折，ハングマン骨折（軸椎関節突起間部骨折）があげられる．

ii 中下位頚椎

- 外傷メカニズムをもとに分類したAllen-Ferguson分類では，骨折型を8つに分類している[3]．最も頻度の高い骨傷はdistractive-flexion injury（前方脱臼，図2）であり，次にcompressive-flexion injury（涙滴骨折型，図3）の頻度が高い．subaxial cervical spine injury classification（SLIC）では，①骨折形態，②椎間板靱帯損傷，③麻痺による3項目で点数化することにより，手術適応の指針を示せるとしている[4]．

iii 胸腰椎

- Denis分類[5]では脊椎の運動単位をanterior, middle, posteriorに3分割し，骨折型を①圧迫骨折，②破裂骨折，③シートベルト型骨折，④脱臼骨折に分け（表1），middle columnの重要性を強調している．また，不安定性をきた

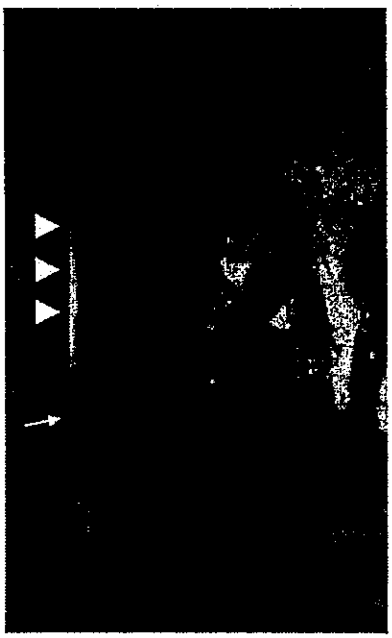

図1 非骨傷性頚髄損傷例のMRI T2強調画像
髄内のT2高信号変化がみられる．椎間板や前縦靱帯の損傷（矢印），椎体前方のT2高信号領域（矢頭）も認められる．

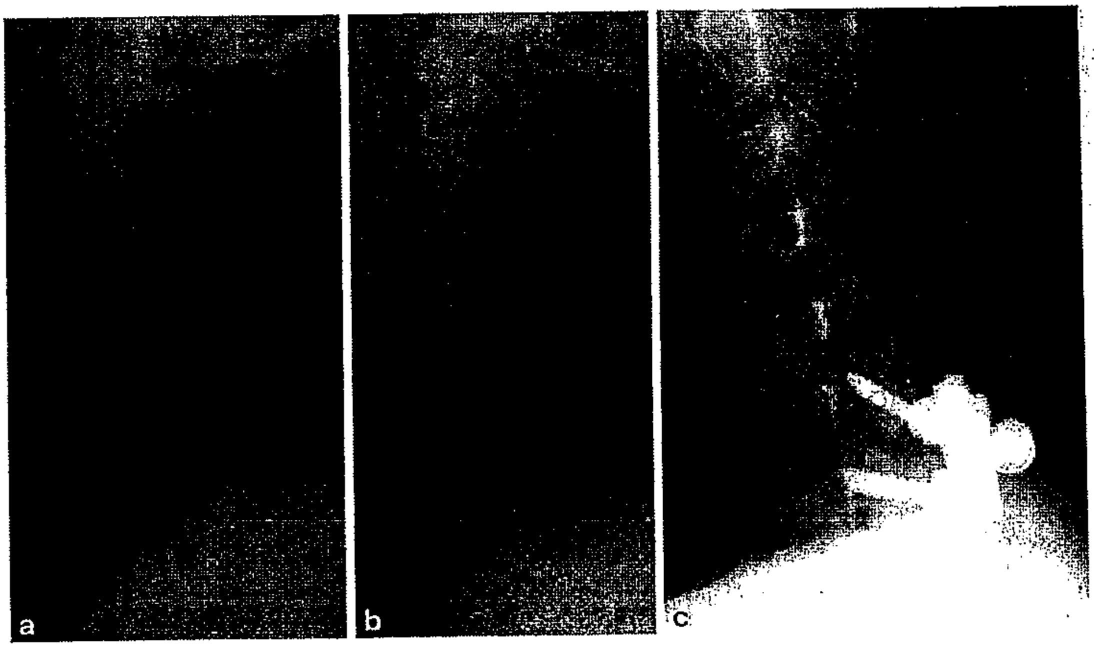

図2 頚椎前方脱臼
a：C4 前方脱臼（distractive-flexion injury）.
b：後方ワイヤリングによる固定.
c：lateral mass screw による固定.

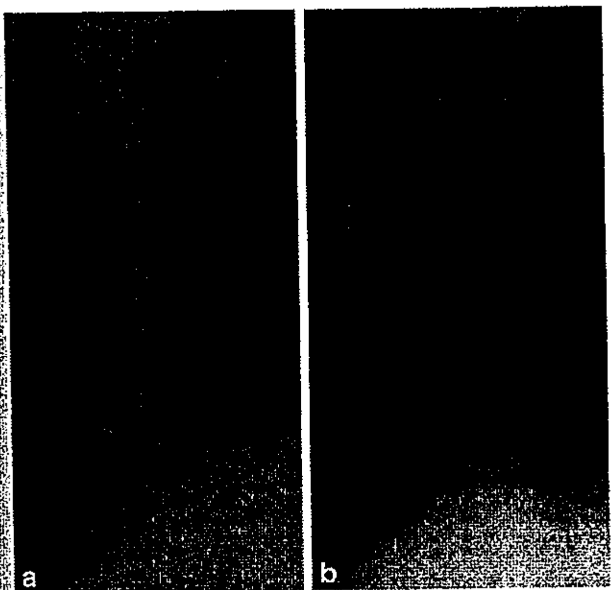

図3 涙滴骨折
a：涙滴骨折を伴う compressive-flexion injury.
b：前方椎体固定術後.

さない minor injury として，横突起骨折，関節突起骨折，外傷性分離，棘突起骨折をあげている．thoracolumbar spine injury classification (TLIC)[6] では，頚椎における SLIC 同様，①骨折形態，②後方靭帯要素の損傷，③麻痺による3項目で点数化し，手術適応の指針とした．TLIC では棘間棘上靱帯や黄色靱帯，関節包などの後方靱帯要素を重視している．最近，煩雑な AO 分類（Magerl 分類）を大幅に簡略化した新 AO 分類が発表された（表 2）[7]．

❷ 診察と検査のポイント

i 診察

- 脊椎局所の圧痛や運動痛とともに，四肢，骨盤，頭部，胸腹部などの合併損傷にも注意する．
- 皮膚外傷の部位により，受傷機転が類推できることがある．たとえば，非骨傷性頚髄損傷であれば前額部などに挫創があることが多く，頚椎過伸展損傷が推定される．
- 神経学的診察は次項「脊髄損傷」に譲る．

ii 画像検査

- 比較的軽傷の頚部外傷患者では，頚椎3方向（正面，側面，開口位），あるいは CT によるスクリーニングが勧められる．
- X 線側面像での retropharyngeal space の拡大は，重大な椎間支持組織の損傷を疑う．目安は「6 at 2, 2 at 6」（C2 レベルで 6 mm，C6 レベルで 2 mm）である．

表1 Denis 分類

type of fracture	column		
	anterior	middle	posterior
compression	compression	none	none or distraction
burst	compression	compression	none
seat-belt type	none or compression	distraction	distraction
fracture dislocation	compression, rotation, shear	distraction, rotation, shear	distraction, rotation, shear

［文献5より］

表2 新AO分類

大項目		細目	
A	compression	後壁損傷なし	A0：マイナーな骨折（横突起，棘突起など）
			A1：上位または下位終板骨折
			A2：上位 ＋ 下位終板骨折
		後壁損傷あり	A3：不全破裂骨折（上位または下位終板損傷）
			A4：完全破裂骨折（上位 ＋ 下位終板損傷）
B	tension band injury	B1：後方 tension band injury（骨性）	
		B2：後方 tension band injury（靱帯性 ± 骨性）	
		B3：前方 tension band injury	
C	displacement/translation	なし	

［文献7より］

- 不顕性骨折の鑑別に最も有用な検査はMRIであり，T1強調画像での低信号，あるいは脂肪抑制T2強調画像での高信号が特徴である．
- MRIにて潜在的な椎間支持組織損傷や軟部組織損傷を診断することができる（図1）[1]．損傷脊髄はT2高信号を呈する．
- 頚椎前方脱臼の自然整復例は見逃しやすく，注意が必要である．医師による慎重な動態撮影により，はじめて前方亜脱臼が判明することもある．初診時の動態撮影で異常がなく，後日坐位での撮影で判明することもある．

❸ 患者・家族への説明のコツ

i 手術の必要性

- 手術の目的は，①脊柱の安定性を確保すること，②脊髄の圧迫因子を除去すること，の2点である．手術を行うことで，脊髄の二次損傷を抑え，早期の離床，リハビリテーションを可能にする．ただ，患者・家族は麻痺に対する過度な期待をもっていることがあるので，障害を受けた脊髄そのものを手術により治療するわけではないことをあらかじめ説明しておくことが重要である．

ii 予後，合併症

- 麻痺患者の予後，合併症は「脊髄損傷」の項に譲る．

❹ 外来における治療

i 上位頚椎

- ハローベストなどによる保存的治療を選択することが多い．不安定性が強い症例は手術を選択する．偽関節となっても問題とならない場合もあり，特に高齢者であればフィラデルフィアカラーでの簡便な保存的治療を選択することもある．

ii 中下位頚椎

- フィラデルフィアカラーを装着し，必要に応じて専門医へ搬送する．場合によりハローベストによる固定を行う．

iii 胸腰椎

- 横突起骨折などのminor fractureであれば，軟性コルセットを作成し痛みに応じた自宅安静を

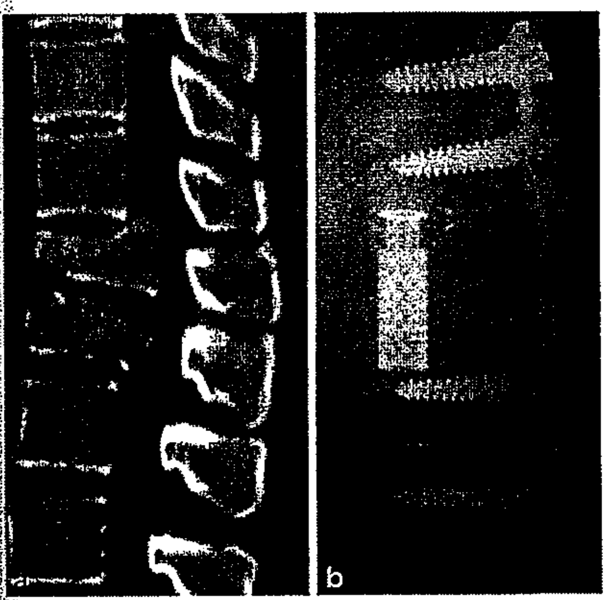

図4 破裂骨折
a：椎体粉砕の強い胸腰椎破裂骨折．
b：後方前方合併手術．

指示する．圧迫骨折や後方靱帯損傷のない軽度の破裂骨折であれば硬性コルセットや体幹ギプスなどで保存的治療を行う．

- 頚髄損傷や胸部合併症を有する胸腰椎損傷では，常に呼吸器合併症に注意を払う．初診時バイタルサインが安定していても，しばしば急変することがある．

⑤ 専門医への紹介のタイミング

- 原則的に，麻痺例や手術を要する骨傷例はできるだけ早く専門医への搬送をめざす．

⑥ 最近の手術方法

- 頚椎前方脱臼では，整復後後方からの棘突起ワイヤリングが主流であったが，近年では外側塊スクリューが使われることが多い（図2）．頚椎椎弓根スクリューも場合により有用であるが，多くの場合必ずしも必要としない．
- 胸腰椎部破裂骨折に対する後方固定に対しては，透視下に経皮的にスクリューやロッドを挿入する最小侵襲脊椎安定術（MISt）を選択する施設が増えている．ただ，通常の切開手術との優劣は明瞭ではない．椎体の粉砕が強ければ前方椎体置換術を併用する（図4）．

⑦ リハビリテーション

- 局所の痛みに応じて日常生活動作（ADL）拡大をめざす．ハローベスト装着例は，呼吸器合併症やピン刺入部の感染，ゆるみなどに注意する．ピンは刺入後24〜48時間で再度トルクを確認し，締め直す．ロッド-リングの接続部は週1回定期的に締め直すようにして，ゆるんでいないことを確認する．
- 麻痺患者のリハビリテーションに関しては，「脊髄損傷」の項に譲る．

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特集　高齢者の脊髄損傷

高齢者脊髄損傷の臨床像
― overview ―

前　田　　健*

要旨：高齢化社会の到来に伴い，本邦では今や外傷性脊髄損傷患者の中心は60歳以上の高齢者となっている。なかでも転倒など軽微な外傷機転による非骨傷性頚髄損傷と，骨粗鬆症に伴う胸腰椎偽関節後の遅発性脊髄麻痺例の増加が目立っている。頚髄損傷の場合，筋力で評価する神経学的回復は必ずしも高齢者で劣っているわけでないが，たとえ筋力がある程度得られても，歩行やその他のADL機能は高齢者で著しく劣っており，また痛みの程度も高齢者で強い傾向にあった。このような高齢者におけるADL獲得の障害は退院後の自宅復帰を困難とし，結局は寝たきりに近い状態となるリスクを伴っている。様々な合併症に対処しながら長期のリハビリテーションを実行できる施設の充実が望まれる。

はじめに

本邦における外傷性脊髄損傷の新規発生率は，100万人あたり年間30～50例とほぼ一定の頻度で推移していると考えられ，国際的にみても他の先進諸国内での頻度と同様である。ただ，本邦ではその極端な高齢化に伴い受傷患者の高齢化が急速に進んでおり，一昔前の脊髄損傷のイメージとは異なりつつある。メディアに取り上げられる脊髄損傷患者は，「事故による脊髄損傷後に，リハビリや社会でがんばる若者」像が多い。しかし実際の臨床現場では，60歳以上の高齢で受傷する患者が中心であり，80歳以上の新患患者もまれではない。さらに生命予後の改善から既受傷者の高齢化問題もある。本企画は「高齢者の脊髄損傷」がテーマであるが，これは決して脊髄損傷の特殊分野ではなく，今や脊髄損傷の中核をなすテーマといえるだろう。本稿では，総合せき損センターのデータを中心に，高齢者脊髄損傷，特に頚髄損傷の臨床像，転帰を概説する。

* Takeshi MAEDA，総合せき損センター，整形外科

Traumatic spinal cord injury in elderly patients；overview

Key words：Traumatic spinal cord injury, Elderly patients, Prognosis

Ⅰ．疫学/受傷機転

高齢化や自動車運転に関わる意識や環境の変化に伴い，脊椎・脊髄損傷の受傷原因にも変化がみられる。Shinguら[1]による1990～1992の全国的サーベイによると，新規脊損患者の平均年齢は48.6歳で20歳代と50歳代に2つのピークがみられる（表1）。また完全麻痺患者が33.7％を占めていた。総合せき損センターで行われている福岡県データベースによると[2]，2013年時点で新規脊損患者平均年齢63.7歳となっており，ピークは70歳代に一峰化している。完全麻痺の頻度は12.1％に減少し不全麻痺が増加していた。これらのデータからみてとれることは，若年者の高エネルギー外傷による骨傷を伴う脊髄損傷の頻度が減少し，

表 1　新規脊髄損傷患者の推移

	全国 (1990～1992)	福岡 (2013)
平均年齢	48.6	63.7
新規患者予測値 (人/100 万人)	40.2	36.2
Frankel A/B/C/D	33/16/27/24	15/10/32/43
年齢分布	20 歳代と 50 歳代にピークを持つ二峰性	70 歳代にピークを持つ一峰性

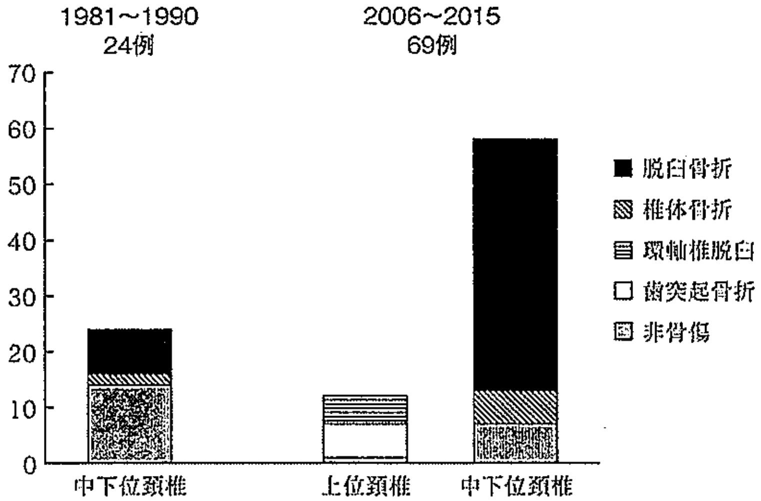

図 1　高齢者脊椎外傷手術症例の推移：頚椎

高齢者の転倒など低エネルギー外傷による非骨傷性頚髄損傷の頻度が増加傾向にあるということである。最近の非骨傷性頚髄損傷患者の調査[3]では，受傷機転として転倒や転落によるものがそのほとんどを占めている。特に目立つのは，① 高齢者の高所作業中（剪定，はしご作業など）の転落と，② 飲酒後の転倒であった。若年者の高所作業中転落に伴う頚髄損傷は少なく，高齢者の「まだまだ自分はできる」という感覚と，実際の身体能力低下とのギャップがあることを痛感する。

Ⅱ．脊椎外傷症例の実態

1．高齢者手術症例の推移

実際脊椎外傷の患者層はどのように変化したのであろうか。総合せき損センターにおける開設初期の 10 年（1981～1990）と最近の 10 年（2006～2015）の，高齢者（≧70 歳）脊椎外傷手術症例を比較したものを図 1（頚椎），図 2（胸腰椎）に示す。頚椎外傷に関しては初期の 10 年は 24 例と少なく非骨傷性脊髄損傷に対する手術症例が最も多かった。上位頚椎手術例はなかった。最近の 10 年は手術症例数が 69 例と増加しており，なかでも脱臼骨折（多くは前方脱臼）の増加が目立つ。これは社会の高齢化に伴う高齢者脱臼骨折例の絶対数増加によるものと考えられる。一方上位頚椎手術例の増加は，患者の絶対数増加に加え手術適応の拡大が関与していると思われる。逆に，非骨傷例頚髄損傷の手術症例は減少しているが，保存的治療への治療方針変換が大きく関与している。胸腰椎外傷に関しては高齢手術例の増加がより顕著であり，初期の 10 年はわずか 14 例であったのに対して，近年は 156 例と増加していた。Ankylosing spineなどの骨折/脱臼例も増加しているが，特に目立つのは遅発性脊髄障害などを伴う胸腰椎偽関節手術例の増加である。

2．急患入院例：最近の実態

非手術例も含めた急患入院例を調査した。2013～2015年の3年間で総合せき損センターに受傷後3日以内に入院した外傷症例を表2に示す(胸腰椎偽関節例は含まない)。頚髄・頚椎損傷の中では非骨傷性頚髄損傷が最も多く64％を占めており，他の頚椎骨傷例と比べ平均年齢が高く4割以上が70歳以上である。非骨傷性頚損は，欧米では中心性頚髄損傷と同義語的に扱われることが多いが，初診時完全麻痺（ASIA A）例も36％認められた。代表的な骨傷である前方脱臼例は半数以上が完全麻痺例であり，ほとんどが男性であった。

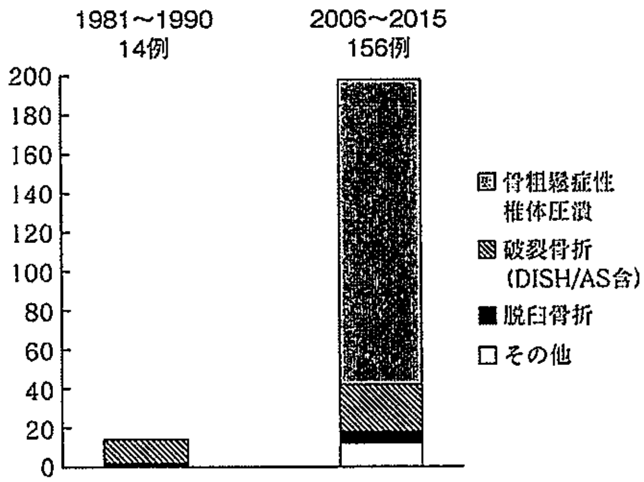

図2　高齢者脊椎外傷手術症例の推移：胸腰椎

頚髄損傷急性期の合併症としては呼吸器合併症が最も重要であるが，高齢者は当然そのリスクも高くなる。気管切開のリスクファクターを検討すると，受傷脊髄レベル（C5より近位）のほかに，完全麻痺であることと，高齢（>70歳）であることが有意に関連していた[4]。

3．経過（頚髄損傷）

2006～2015年の10年間において，受傷後3日以内に総合せき損センターに入院した頚髄損傷症例で受傷後6カ月以上入院加療を行った140症例の麻痺経過を表3に示す。受傷後6カ月時点でASIA impairment scale（AIS）Dとなった症例の割合は，初診時AIS Bで48％，AIS Cで84％であった。これを65歳以上の高齢者57例で比較すると（表4），B→Dが33％，C→Dが74％であり，高齢者で劣っていた。ただし，ASIA motor score（AMS）の平均値は，65歳未満の若年者が20.3→47.4（改善率39.0％）であったのに対して高齢者は21.9→51.3（改善率40.3％）であり，差はなかった。

AISはmanual muscle testing（MMT）3以上となったkey muscleで評価しているが，6カ月時点でAIS Dとなった症例の95％はFrankel D1以上であり，何らかの歩行機能を有していた。ただし実用歩行と考えられるFrankel D2以上となっ

表2　2013～2015年における脊椎脊髄外傷急患例（手術例/非手術例含む）内訳

			例数	平均年齢	%ASIA A
上位頚椎			14	59	15
中下位頚椎	非骨傷		103	67	36
	骨傷	DF	37	54	55
		CF	9	39	29
		その他	13	61	38
胸腰椎			60	49	24

非骨傷性脊髄損傷が最も多く，平均年齢も高い。
DF：distractive flexion injury
CF：compressive flexion injury

表 3　AISでみた転帰

		受傷後6カ月			
		A	B	C	D
入院時	A	49	6	4	
	B		2	11	12
	C			8	42
	D				6

表 4　AISでみた転帰（65歳以上）

		受傷後6カ月			
		A	B	C	D
入院時	A	16	2	2	
	B		2	6	4
	C			6	17
	D				3

表 5　受傷後6カ月時点でのAIS D患者の歩行能力

	D1以下	D2以上
≧65歳	18	6
<65歳	14	22

高齢者（≧65歳）で有意に実用歩行（Frankel D2以上）が少ない。

表 6　痛みと年齢

	60歳未満	60歳以上	
Pain score（total）	4.8	6.7	$p<0.05$
持続時間	2.1	2.4	NS
不眠の有無	0.6	0.8	NS
気分の落ち込み	0.9	1.4	$p=0.06$
ADL/リハへの影響	0.8	1.6	$p<0.05$

た症例は（表5），若年者が56％であったのに対して高齢者は21％であり，筋力が回復しても高齢者では歩行機能が追いついていない実態がわかる。また，全般的なADLの指標であるSpinal Cord Independence Measure（SCIM）scoreを比べても，若年AIS D症例の平均が69.2であるのに対し，高齢者は53.4と著しく劣っていた。われわれは，頚損患者の退院時のSCIM scoreの予測が受傷後1カ月時点でAMSと年齢によってかなり正確に算出可能であることを見いだしているが，その予測式は退院時SCIM score＝41.3＋0.8×上肢AMS（受傷後1カ月）＋1.0×下肢AMS（受傷後1カ月）－0.5×年齢であった[5]。ADLの指標であるSCIM scoreが筋力の指標であるAMSに依存することは当然であるが，加齢に伴うマイナス因子がいかに大きな比重を占めるかを同時に示している。同じ筋力（AMS）であっても，年齢が50歳違えばそれだけでSCIM scoreは25点，すなわち1/4低下する計算である。高齢者において歩行やADL改善の障害となるのは，バランス感覚や中枢性の運動能力の低下に加え，関節拘縮，関節や内臓の既往症/合併症，意欲の欠如など多因子が絡んでいると考えられる。また，高齢の脊損患者は痛みの訴えが若年者より多く，苦痛を伴うしびれや締めつけ感，関節運動痛などがリハビリテーションの障害となる（表6）[6]。痙性に関しては，Ashworth scaleでは年齢で差がなく明らかな関連はなかった。

Ⅲ．転　帰

総合せき損センターでは，重度の頚髄損傷であれば入院期間は約1年ほどである。年齢によりこの入院期間に大差はないが，退院後の転帰は大きく異なっている（図3）。概して60歳代から高齢になるに従って自宅復帰率が低下し転院率が増加する。この自宅復帰率の低下は高齢者のADL機能獲得の障害によるところが大きいが，合併する内科疾患や社会の核家族化なども強く影響していると考えられる。また，転院先についても，若年者であればさらに高次のリハビリテーションを継続できる施設が多いが，高齢者は社会的入院となりリハビリテーション効果は期待できない施設が

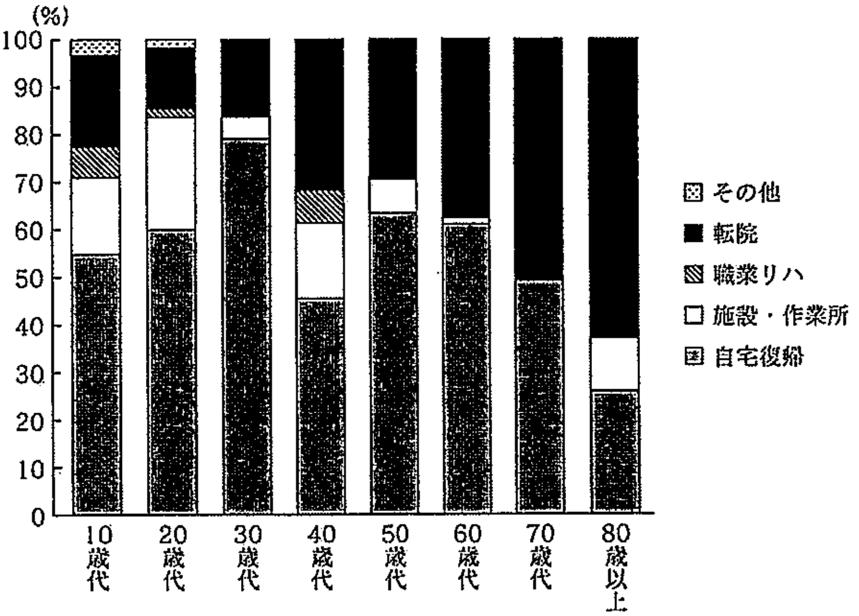

図 3　退院後の転帰

多い。この転院先の相違は Frankel D の歩行可能例では少ないが，Frankel C 以下の重度麻痺例では特に強い傾向にある。実際，リハビリテーション効果が入院当初より期待できず，あるいは内科合併症などにより早期に転院となりほぼ寝たきりとなる症例が少なくないことも事実である。しかし，辛抱強い集中的なリハビリテーションと住宅改造などの援助や家族指導などにより，60 歳以上の高齢者でも 5 割程度の自宅復帰率を達成できていた。このことは，今後増加するであろう高齢脊髄損傷患者を長期に受け入れることができる専門施設を拡充することがいかに重要であるかを示唆している。

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第3章：特殊病態に対する治療

骨粗鬆症性椎体骨折後後弯に対する治療*

椎体形成術を併用した後方 short fusion を中心に

前田　健**

はじめに

骨粗鬆症をベースにした椎体偽関節は胸腰移行部に生じることが多いが，後弯化に伴う矢状面バランスの破綻は必ず生じるといってよい．ただし，多くの場合，患者の主訴は偽関節局所より生じる腰痛，あるいは遅発性脊髄麻痺であり，後弯に伴うADL，コスメーシスの悪化や体幹前傾による歩行障害に関してはそれほど不満を感じていないこともしばしばである．もちろん，矢状面バランスの破綻自体が腰背部痛の原因となることはよく知られているが，偽関節に伴う腰背部痛は程度がより強く，座位でも頑固な痛みが生じることが多いなど，質的に異なるものである．このような偽関節による骨粗鬆症椎体骨折後後弯症に対して治療を行う際は，患者の愁訴を見極め，年齢や骨密度，全身状態を考慮したうえで，侵襲/手術効果のバランスを慎重に評価し治療計画を立てるべきであろう．ここでは，主に胸腰移行部での骨粗鬆症性椎体偽関節に対する治療について，患者の状態や希望に応じた治療選択について論じたい．

Key words
骨粗鬆症性椎体骨折
(osteoporotic vertebral fracture)
後弯（kyphosis）
後方固定（posterior short fusion）

保存的治療―初期治療の重要性と偽関節後の骨癒合について

骨粗鬆症を基盤とした新鮮椎体骨折において，初期治療の重要性はしばしば軽視されがちである．軟性コルセットを処方してそのまま可及的安静のみの指示を出しているケースも多いのではないだろうか．偽関節の発生率は概ね10～30%台と報告されている[3,8,9]．確かに日本整形外科学会の前向き研究によれば，外固定や臥床期間の違いで骨癒合率には明らかな差がなく[7]，Kimらによる前向き研究[4]もそれを支持している．一方，後藤ら[1]は初期の徹底した臥床（非荷重）とギプスによる外固定の重要性を報告している．すなわち，寝返りで腰痛がある間はベッド上の徹底した臥床を指示し（1～2週間），その後ギプスを巻き込んで荷重と歩行訓練を始めるというものである．岸川ら[5]も初期の徹底非荷重を支持しており，いずれもほぼ100%の骨癒合率を達成している．骨折による腰痛は大事な危険信号であり，安易に痛み止めを使用して無理に離床を促すような治療は控えるべきである．さらに後藤らは，偽関節となった後でも一定期間の非荷重とギプス治療にて骨癒

* Treatment Strategy for Thoracolumbar Kyphosis Caused by Osteoporotic Vertebral Fracture

** 総合せき損センター整形外科〔飯塚市伊岐須550-4〕／Ken MAEDA：Department of Orthopaedic Surgery, Spinal Injuries Center

0914-4412/17/¥400/論文/JCOPY

図 1　78 歳，女性
3 カ月前からの強い腰痛．10 日間ベッド上安静→4 週間体幹ギプス→4 週間軟性コルセット治療施行．
a：治療前立位，b：治療前臥位，c：治療前 MRI T2 強調像，d：治療開始後 5 カ月の立位（装具なし），腰痛著明軽減．

合は可能と報告している．われわれも，偽関節にて強い腰痛，あるいは下肢不全麻痺を認めるものの手術を拒否した症例に対しては，徹底した安静臥床とそれに続くギプス治療を行う（テリパラチド併用）ことにより，骨癒合とともに症状の著明改善を得ている（図 1）．骨粗鬆症性椎体骨折に対する保存治療の重要性は，今一度見直されるべきであろう．

BKP

いうまでもなく，balloon kyphoplasty（BKP）は重要な治療選択肢の 1 つである．適応には，①原発性の骨粗鬆症，②十分な保存治療を行っても改善がない，③後壁損傷がない，などの条件がつくが，実際の臨床現場では適応はより広く捉えられている．偽関節であれば多くの症例で後壁の高さは減じており何らかの後壁損傷はあることになるが，後壁連続性の明らかな途絶がなければ損傷なしとしている施設が多いだろう．われわれは，椎体内 cleft がある偽関節例で，麻痺がなく偽関節そのものが腰痛の原因となっている症例に対しては，まずは BKP を検討している．そのうえで，後壁の健全性，あるいは long fusion を併用した後弯矯正の意義などを症例ごとに検討し，最終的に適応を決めている．

椎体形成術を併用した short fusion

椎体偽関節に伴う遅発性麻痺例に対しては，リン酸カルシウム骨セメント（CPC）による椎体形成術を併用した short fusion を適応としてきた[6]．多くの症例は損傷した椎体後壁が突出して脊髄を圧迫しているが，椎体後壁の損傷がない一部の症例では上位椎間の黄色靭帯の肥厚や骨化が後方から脊髄を圧迫し麻痺を生じる．椎体後壁損傷による脊髄の圧迫には動的因子が大きく絡んでいるが，座位や立位に伴う局所後弯化よりも，荷重に伴う後壁の短縮と突出が重要である[2]．これは術前半座位での CT myelography（CTM）にて確認できる（図 2）．後方 short fusion の主な目的は後弯矯正ではなく，この動的因子の制御である．通常は椎弓切除を併用し，後方からの脊髄除圧を担保しているが，半座位 CTM にて脊髄後方に余裕があれば椎弓切除は行わないこともある（図 3）．この後方 short fusion では，術直後に得られた後弯矯正位は維持できず早期に矯正損失を生じることが多いため，術中は極力後弯矯正をしないこと

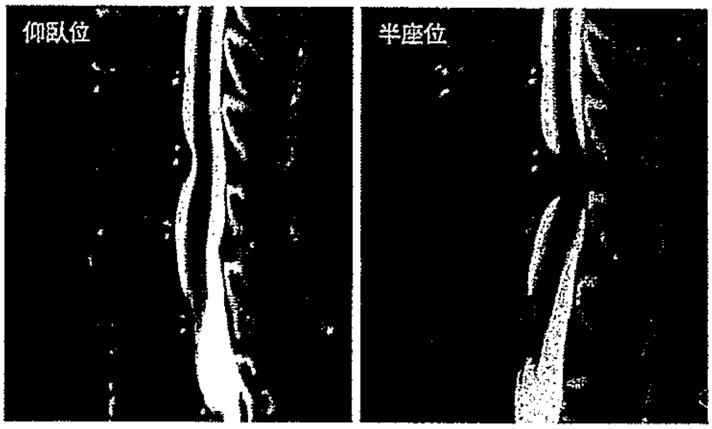

図 2　荷重下（半座位）での CTM にて後壁の短縮と後方突出が明らかとなる
局所後弯化以上にこの後壁短縮が麻痺発生に関与している．

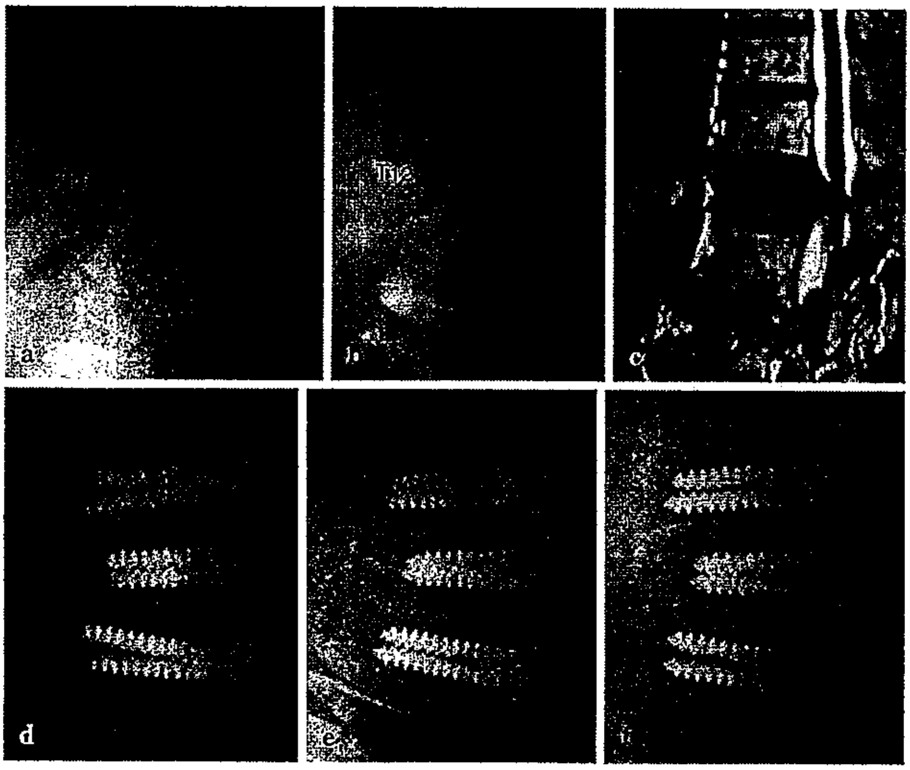

図 3　82 歳，女性
両下肢不全麻痺（Frankel D）＋腰下肢痛．後方固定のみ施行（除圧なし）．
a：術前臥位，b：術前座位，c：MRI T2 強調像，d：術直後，e：術後 1 年座位，
f：術後 1 年仰臥位．若干の椎体動揺性が残存し矯正損失も生じているが，腰下肢痛は著明改善している（Frankel E）．

がポイントである．CPC にて椎体形成術を施行した症例のほうが若干矯正損失は軽減できているが（図 4），それでも CPC の分節化による矯正損失を生じることが多い（図 5）．重要なことは，術後矯正損失と遅延する骨癒合にもかかわらず，術直後から麻痺と腰痛の軽減を得ることができる点である．わずかな制動（＋後方からの除圧）が大きく臨床効果に寄与することを痛感する．

方法

1）4 点支持器のパッドを後弯方向に調整し，なるべく腹臥位での後弯矯正がなされないように工夫している．

2）骨折椎上下の椎弓展開後，椎弓根スクリューは通常 1 above 1 below 挿入．この際，なる

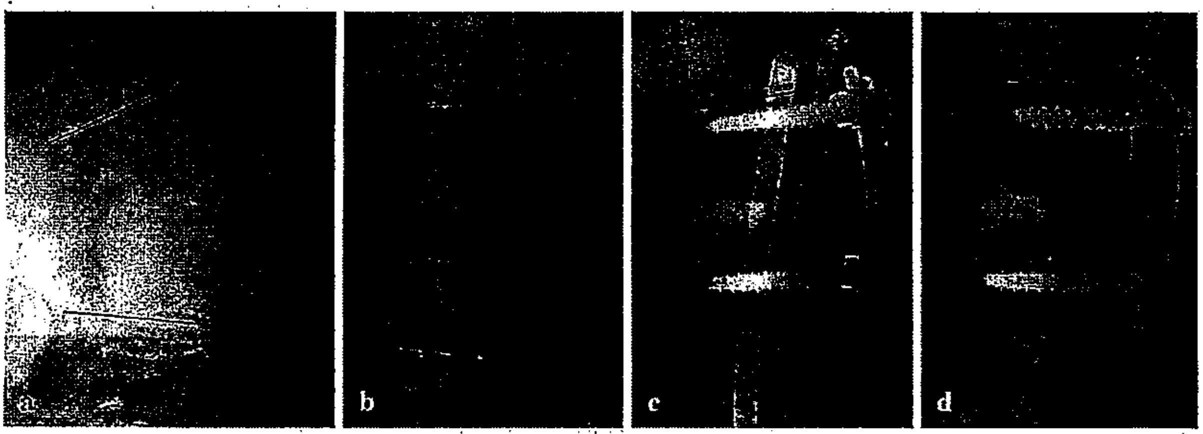

図 4　74 歳，女性
両下肢不全麻痺（Frankel C）＋腰下肢痛．椎弓切除＋後方固定＋CPC 椎体形成施行．術後痛み消失，Frankel D.
a：術前座位，b：術前仰臥位，c：術後 4 カ月座位，d：術後 4 カ月仰臥位．

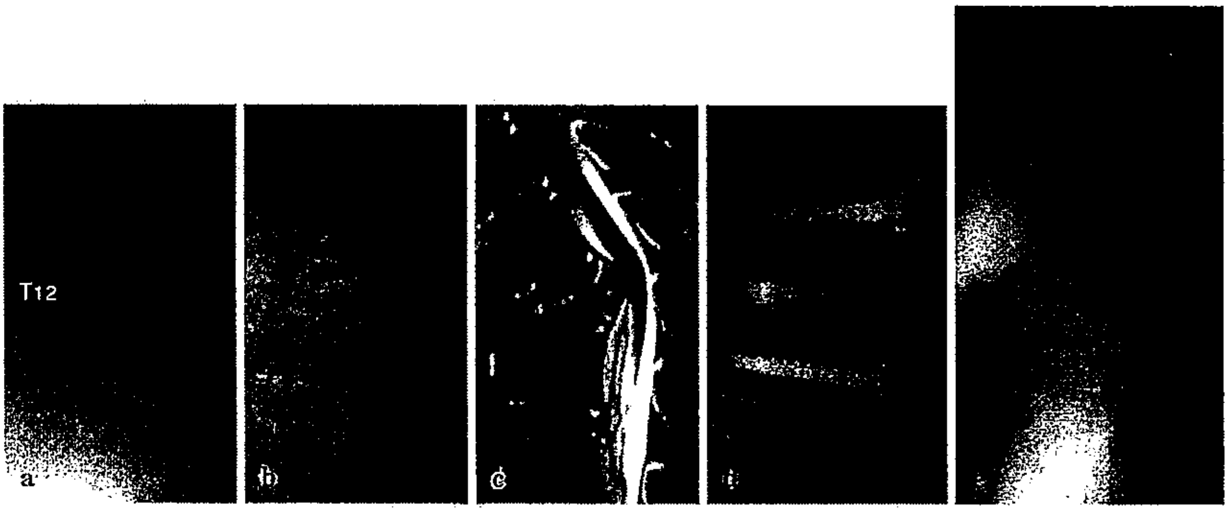

図 5　73 歳，女性
両下肢不全麻痺（Frankel C）＋腰下肢痛．椎弓切除＋後方固定＋CPC による椎体形成施行．
a：術前座位，b：術前仰臥位，c：半座位 CTM，d：術直後，e：術後 3 年立位．術後矯正損失を生じているが，腰下肢痛は著明軽減し杖なし独歩良好．

べく径が大きく長いスクリューを用いるようにしている．ただし，椎体前壁は貫通しないよう注意する．大動脈に対するリスクのみならず，椎体前壁損傷に伴う新規骨折を防止するためである．

3）骨折椎の椎弓切除を施行．必要に応じて，上下の黄色靭帯も十分に郭清する．

4）胸腰移行部での偽関節では，術後矯正損失に伴い下位椎のスクリューが尾側に変位しやすい．下位椎間（T12 骨折であれば L1-2 間）の棘上棘間靭帯は温存しながら椎間を剝離して，デシャンを用いてテクミロンテープ（5 mm）を下位椎弓に通しておく．テープの代わりに lamina hook を用いてもよい．上位椎には通常補強の必要はないが，症例によりテクミロンテープの併用，または 2 above まで椎弓根スクリューを挿入しておく．

5）偽関節椎の椎弓根を 7.5 mm で tapping しておく．透視下に鋭匙などで内部を可及的に郭清．椎体内洗浄時に左右が連続していることを確認．さらにオムニパークを椎弓根から注入して，透視下に椎体外に漏れがないことを確認しておく．バイオペックスを 9 g 準備しておき，透視下に左右椎弓根からなるべく多い量を注入する（通常 5〜9

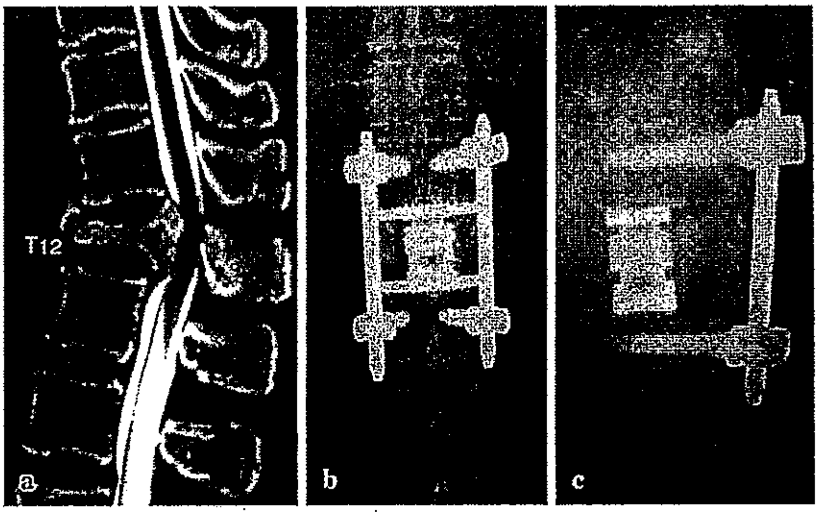

図 6　68 歳，女性
a：半座位 CTM．b，c：PPS＋XCORE cage．

g 程度）．

6）術後の矯正損失を見越してロッドの弯曲をやや強めにつけ締結する．残存椎弓上に骨移植を施行．椎体の不安定性を考えれば crosslink を設置したいが，後弯の強い症例や皮下脂肪の薄い症例では crosslink 直上の皮膚で縫合不全を生じるリスクがあるため用いていない．

以上の手術をなるべく 2 時間以内に終了するようにする．3 時間を超えては short fusion で低侵襲を目指す意味がないであろう．

軟性コルセットを装着し，CPC の硬化時間を考慮してギャッジアップは術後 24 時間経て開始する．

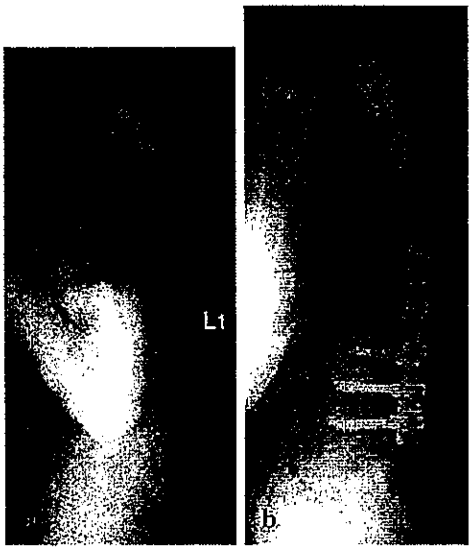

図 7　78 歳，女性
L1 椎体はほとんど消失している．
a：術前立位．b：PVCR 術後立位．

PPS と椎体置換

後方 short fusion の再手術率は約 1 割強であり，そのうち半数は矯正損失によるものであった[6]．特に，術前仰臥位/座位での椎体動揺性が大きな症例は当然術後の矯正損失も大きく，術後成績不良となる可能性がある．そのため，このような症例では，特に比較的若年であれば前方支柱の再建が望ましい．われわれは，後方から percutaneous pedicle screw（PPS）にて 1 above 1 below あるいは 2 above 2 below で固定した後，最近は XCORE cage を用いて前方支柱再建を行っている．術後は硬性あるいは半硬性コルセットを使用している（図 6）．

PVCR

極端な後弯化症例や，後弯変形に伴う矢状面バランスの破綻が主訴となっている症例は，しばしば変形が強く rigid である．このような症例に対

しては，全身状態が良好であれば posterior vertebral column resection（PVCR）の適応となる．椎体後壁や黄色靭帯と硬膜が強く癒着していることがあるので注意する．頻度の高い胸腰移行部の骨折であれば，VCR 椎の 3 above 3 below で固定し，術後は硬性コルセットを半年以上装着している（図 7）．

おわりに

骨粗鬆症性椎体骨折後後弯に対する治療は決して画一的なものではない．愁訴が偽関節椎そのものから生じる痛みなのか，矢状面バランス破綻に伴う腰痛や ADL 障害なのか，遅発性麻痺なのか，など見極める必要がある．加えて，患者の全身状態やコスメーシスに対するこだわり，long fusion に伴う諸問題などを考慮して治療方針を探る．患者の年齢や全身状態，骨密度などを考えながら，侵襲と sustainability のバランスを考えた手術を心がけたい．その意味では，椎体形成術を併用した後方 short fusion はかなり幅広い適応範囲をもつのではないかと考える．

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I．脊椎脊髄疾患

脊椎・脊髄損傷の診断

坂井宏旭[*1] 弓削 至[*2] 河野 修[*3] 前田 健[*4] 植田尊善[*5] 芝 啓一郎[*6]

Abstract 脊椎・脊髄損傷は，重篤な外傷の一つである．その患者背景は，本邦の高齢化により大きく変化している．また，近年，損傷した脊髄に対する新規治療法の可能性が大きな話題となっている．本稿では，まず，患者背景の変化((1)疫学調査結果，(2)頚椎手術に関する調査結果，(3)神経学的予後予測)について述べ，続いて，当院における脊椎・脊髄損傷の診察の流れを紹介する．さらに，デモンストレーション症例を使用し，各症例の麻痺の評価を行い，麻痺の評価法についての考え方を整理したい．さらには，今後行われるであろう脊髄損傷治療の神経学的評価の標準化の一助になれば，幸いである．

Key words 脊椎・脊髄損傷(spinal cord injury)，診断(diagnosis)

はじめに

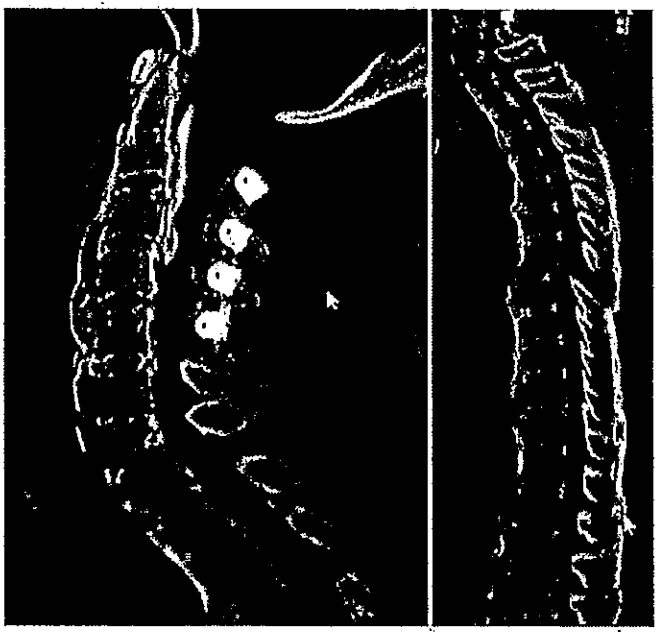
脊椎・脊髄損傷は，(1)中枢神経である脊髄の損傷，(2)その脊髄を保護し，体幹を支持する脊椎の損傷という2つの側面を持つ外傷であり，特に頚髄損傷は四肢をはじめとする全身の麻痺を呈する最も重篤な外傷の一つである．また，脊椎・脊髄損傷は社会の高齢化に伴い，その数は増加傾向にあると推測されている．一方で，他の疾患と同様，脊椎・脊髄損傷の治療方針は丹念な全身状態の評価管理に基づき，立てられるべきである(植田，伊藤，小松らによる頚髄損傷治療の総説は非常に秀逸なものであり，是非ご一読願いたい)[1)~4)]．我々は1979年，脊髄損傷治療の専門病院として開院以来，約2,600例の脊髄損傷患者の治療に携わり，様々な報告を行ってきた[5)]．近年，損傷脊髄に対する新規治療法(サイトカイン療法，細胞治療など)により神経機能回復の可能性も示唆され，神経学的評価の重要性が増している．

本稿では，特に外傷性脊椎・脊髄損傷にフォーカスをあて，「外傷性脊椎・脊髄損傷を取り巻く背景の変化」(1.福岡県における脊髄損傷疫学調査結果および当院脊髄損傷データベース解析結果，2.米国での脊椎手術における合併症調査結果，3.神経学的回復予後予測研究結果)，「診察について」(1.当センターにおける脊椎・脊髄損傷診察の流れおよび2.International Standards for Neurological Classification of Spinal Cord Injury(ISNCSCI)としてのAmerican Spinal Injury Association(ASIA)Impairment Scale(AIS))の考え方を述べることで，脊髄損傷における診断(特に神経学的評価)について整理したい(画像診断，バイオマーカーなどその他の補助診断に関しては，近年様々な総説が出ており，参考文献をご一読頂きたい)[6)~9)]．

*1 Hiroaki SAKAI，〒820-0053 飯塚市伊岐須550-4 総合せき損センター整形外科，部長
*2 Itaru YUGE，同，部長
*3 Osamu KAWANO，同，部長
*4 Takeshi MAEDA，同，部長
*5 Takayoshi UETA，同，副院長
*6 Keiichiro SHIBA，同，院長

表 1. 脊髄損傷の疫学調査

	全国 1990〜1992	福岡 2005	福岡 2013	徳島 2012
新規脊損患者平均年齢(歳)	48.6	57.8	63.1	63.7
高齢化率(%, 西暦)	12.1 (1990)	19.2 (2004)	22.5 (2011)	27.1 (2011)
新規脊損患者数予測値(人/100万人/年)	40.2	33.7	36.2	117.1



a|b 図 1. Ankylosing spinal disorders を伴う骨折
78 歳, 男性. 交通事故受傷. OPLL に対して椎弓形成術後
外傷性くも膜下出血, 血胸の合併あり
a：C6/7 椎間板レベルでの骨折
b：T7/8 椎間板レベルでの骨折

外傷性脊椎・脊髄損傷を取り巻く背景の変化

1. 福岡県における脊髄損傷疫学調査結果および当院脊髄損傷データベース解析結果

我々は, 2006 年当センター内に福岡県脊髄損傷登録管理事務局を設置し, 福岡県下の新規脊髄損傷に関する疫学調査を開始した[10)~13)]. 表 1 は, 全国疫学調査(1990〜1992 年), 福岡県調査結果(2005 年, 2013 年), 徳島県調査結果(2012 年)を比較したものである[14)15)]. 人口の高齢化率上昇に伴い, 新規脊髄損傷患者の受傷時平均年齢も上昇する傾向にあった(全国調査時平均年齢 48.6 歳：2013 年福岡県調査時平均年齢 63.1 歳). 新規脊髄損傷患者中の骨傷を伴わない頚髄損傷(いわゆる非骨傷性頚髄損傷)の割合は 56.7%で, その年代別発生数は 70 歳代をピークとした一峰性パターンを示し, Frankel C(41.0%), D(51.3%)の不全麻痺が大半を占めていた. さらに新規非骨傷性頚髄損傷患者中の 75 歳以上の割合は, 18.5%(2005 年)から 30.6%(2013 年)へと驚くべき勢いで増加していた.

新規非骨傷性頚髄損傷患者の特徴をとらえるため, 当院に入院した非骨傷性頚髄損傷患者の解析を行った. 当院に搬送された新規非骨傷性頚髄損傷患者の平均年齢は 68 歳で, その損傷高位は, C3/4 椎間板レベル＝63.8%, C4/5 椎間板レベル＝21.3%, C5/6 椎間板レベル＝12.8%, C6/7 椎間板レベル＝2.1%であった. これらのことより, 新規非骨傷性頚髄損傷患者のうち, 高齢者の C3/4 椎間板レベルでの非骨傷性頚髄損傷の割合が最も多いことが予想された.

続いて, 当院における 70 歳以上の脊椎外傷手術症例について解析を行った. 70 歳以上の脊椎外傷手術症例数は, 38 例(1981〜1990 年)から 224 例(2006〜2015 年)へと増加していた. その特徴として, 上位頚椎骨折, 胸腰椎レベルでの骨粗鬆症を伴う椎体骨折および強直性脊椎炎(AS), びまん性特発性骨増殖症(DISH), 後縦靱帯骨化症(OPLL)などの ankylosing spinal disorders を伴う脊椎骨折の症例が増加していた(図 1). また, これらの症例は周術期合併症が多く, その管理の困難な症例が存在した.

2．米国での頚椎手術における合併症調査結果

2007年，米国における全国入院患者データベースを用いた変性疾患に対する頚椎手術の合併症発生率，入院中死亡率の調査結果が報告された[16]．この報告によると，頚椎後方固定術は，合併症発生率10.5%，入院中死亡率0.44%ともに最も高い術式であった．さらに，頚椎手術における最も頻度が高い全身合併症は，呼吸器合併症であった(発生率0.67%)．また，年齢による解析結果では，20～34歳の患者群の合併症発生率2.21%，入院中死亡率0.03%に対し，75歳以上の患者群の合併症発生率12.1%，入院中死亡率1.33%であった(合併症発生率の調整オッズ比：4.1，入院中死亡率の調整オッズ比：18.6)．

3．神経学的回復予後予測研究結果

2011年，欧州の多施設研究による，脊髄損傷患者における受傷後1年の歩行能力に関する予後予測研究の結果が報告された[17]．この報告によると，受傷後1年の歩行能力獲得の予後予測因子は，受傷時年齢，受傷後15日以内のL3領域のmotor score，light touch sensory，S1領域のmotor score，light touch sensoryの5つであった．年齢に関する結果では，65歳以上の脊髄損傷患者群における歩行能力獲得率は，64歳以下の患者群と比較し，統計学的有意に低かった．しかし，この研究において，受傷後72時間以内に神経学的初期評価が行われた割合は19%に過ぎず，受傷後早期の予後予測に関しては結論に至っていない．

一方，我々も神経学的回復を評価するため，2005年，当センターにおいて脊髄損傷データベースを立ち上げた．我々のデータベース解析の結果では，受傷後72時間における予後予測は，約80%の確率で可能であったが，受傷後14日における予後予測の確率約90%と比較すると，低い傾向にあった．これらのことは，受傷後早期の神経学的評価の困難さを示していると考えられる．

診察について

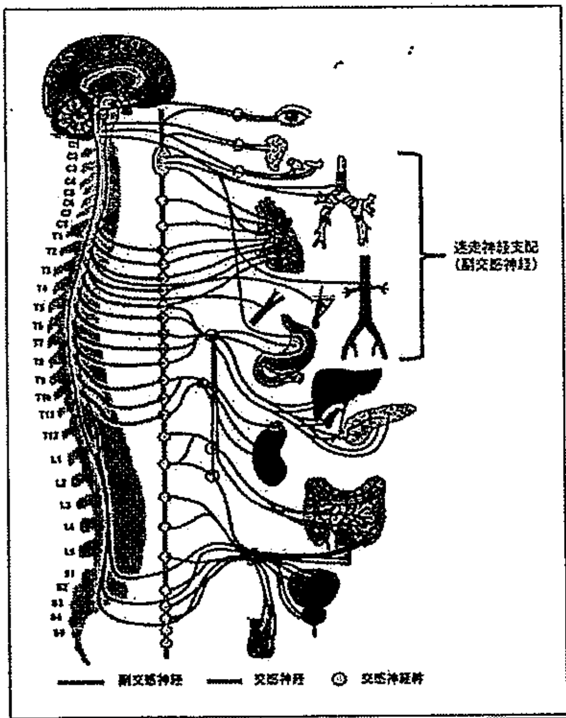
前述のごとく，他の疾患と同様，脊椎・脊髄損傷の治療方針は丹念な全身状態の評価管理に基づき，立てられるべきである．特に初期の診療にあたっては，Japan Advanced Trauma Evaluation and Care(JATEC)の推奨する外傷初期診療ガイドラインに沿って行うことが望ましい[18](詳細は，非常に良くまとめられているガイドラインをご参照頂きたい)．ガイドラインではfirst surveyとして，A：気道評価・確保と脊椎保護，B：呼吸評価，C：循環評価の処置を行い，全身状態が安定化した後に，D：神経学的評価を行うこととされている．

一方で，脊髄損傷(特に頚髄損傷)に伴う特有の全身状態の変化(A：気道評価；気管支収縮，気道分泌物増加，B：呼吸評価；呼吸筋麻痺，C：循環評価；神経原性ショック(neurogenic shock：後述))について念頭に置き，診療を行うべきである．

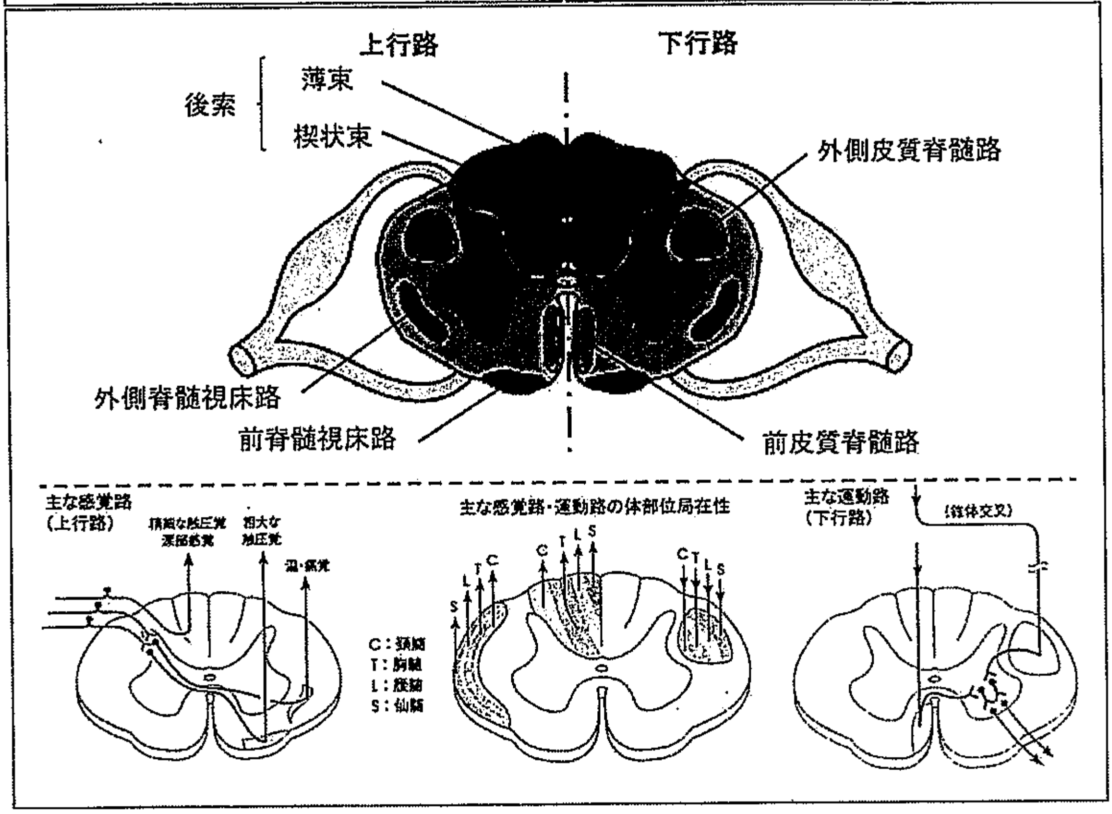
神経系は，自律神経系(交感神経，副交感神経)，体性神経系(感覚神経，運動神経)からなる．交感神経の節前ニューロンは胸髄および上位腰髄の側角に存在し，副交感神経の節前ニューロンは中脳・延髄の副交感神経核および仙髄に存在する(図2-a)．一方，体性神経系は，主な感覚路(上行路)として，後索(同側の精細な触圧覚，深部感覚)，外側脊髄視床路(対側の温・痛覚)，前脊髄視床路(対側の粗大な触圧覚)，主な運動路(下行路)として，外側皮質脊髄路(主に四肢遠位筋の制御)，前皮質脊髄路(主に体幹筋や四肢近位筋の制御)がある(図2-b)．これらを走行する神経は，内側から頚髄，胸髄，腰髄，仙髄の順で分布している(仙髄領域の神経が最も外側を走行する)．

1．当センターにおける脊椎・脊髄損傷診察の流れ

当院の診察の特徴は，医師，看護師，リハビリスタッフのチームで診察を行うことである．これにより，患者の初療時の神経学的所見を含める全身状態をチームで共有し，患者の将来的なゴール



		交感神経	副交感神経
心臓	心拍数	増加	低下
	収縮力	増加	低下
血管平滑筋		一般的には収縮	弛緩
気管支	平滑筋	弛緩	収縮
	分泌	一般的には抑制	亢進



a/b

図 2.
a ：自律神経系(ASIA e-learning サイトより改変)
b ：体性神経系(ASIA e-learning サイトより改変)

までも大まかにイメージ,共有することができる.

神経学的所見をとるにあたり,(1)脊髄の損傷高位,(2)脊髄の横断面での損傷範囲(完全麻痺か不全麻痺か)が,自律神経系および体性神経系それぞれの神経系にどのような影響を及ぼすかを考慮しなければならない.では,最も診察する頻度が高いと考えられる頚髄損傷を例として,当院での脊髄・脊椎損傷診療の流れを紹介する(図3は当院で使用している神経チャートである).

四肢の動きが低下し頚髄損傷を疑う場合,損傷

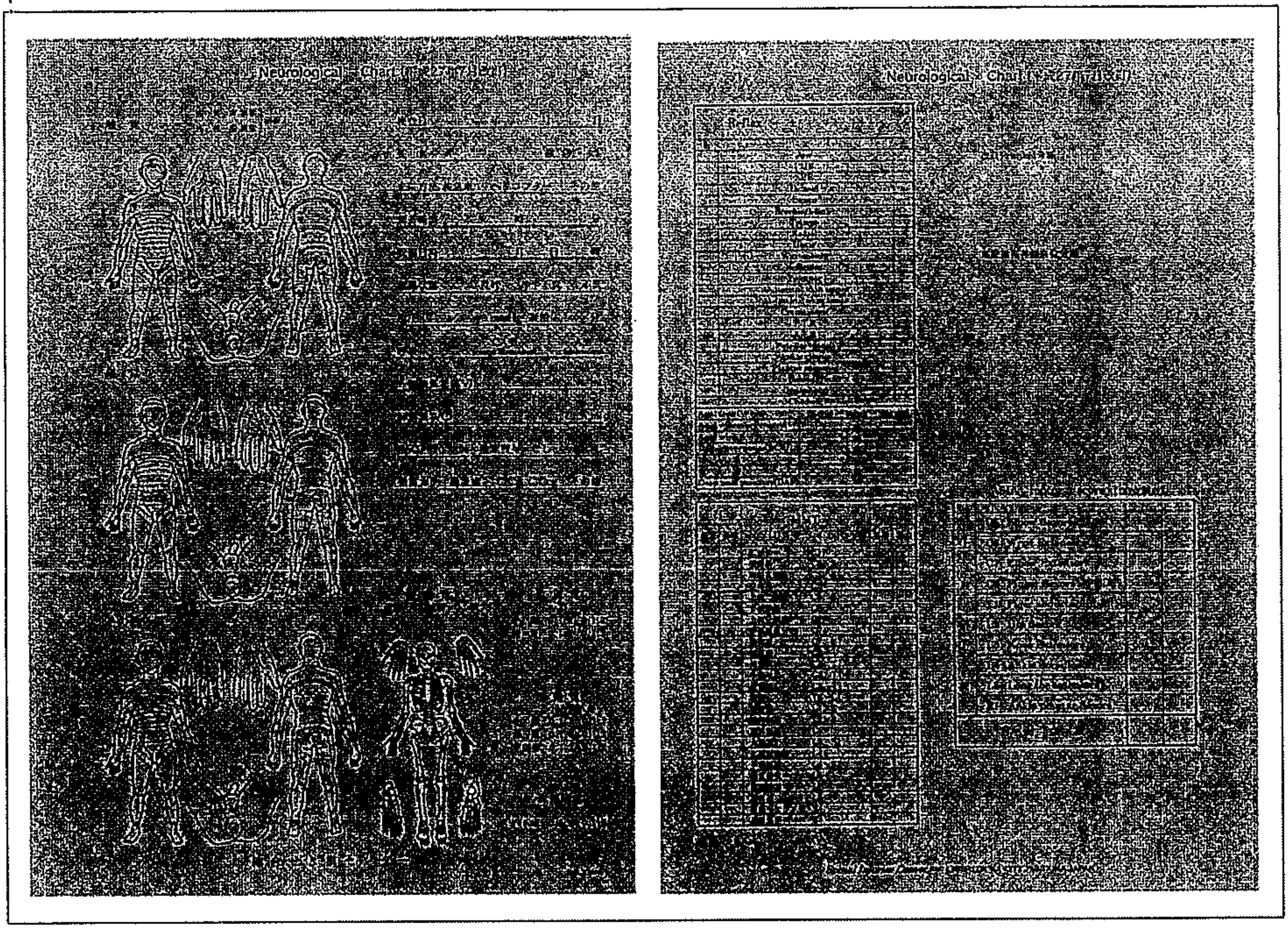


図 3. せき損センターで用いている神経学的チャート

高位以下の交感神経系の遮断による副交感神経優位の状態である可能性を念頭に置いておく．頚髄損傷の場合，気管支平滑筋：収縮，気管支分泌：亢進，心拍数：低下，心収縮力：低下，血圧：低下などの神経原性ショックを呈することがしばしば存在する(図 2-a)．気管支分泌が亢進しているため，痰の吸引などを行ったとき迷走神経反射を誘発し，高度徐脈になることもあるため，注意を要する．

全身状態が安定，意識清明化したことを確認後に，まず評価すべきはやはり呼吸状態である．C4 以上の頚髄損傷では，横隔神経(C3-5 の髄節に存在する)，肋間筋，腹筋が障害される(腹式呼吸の消失)．C5 以下の頚髄損傷でも，肋間筋，腹筋が障害される．前述のごとく，頚髄損傷では副交感神経優位で気管支分泌の亢進があり，呼吸筋の障害が合併することで痰の排出が困難となり，無気肺や肺炎を起こしやすくなる．当院は，呼吸状態の評価のため，血液ガス検査に加え，簡易型レスピトメーターを用い，努力肺活量を測定している(図 4-a)．努力肺活量 500 m*l* 以下の症例は，今後，呼吸状態が悪化，2 型呼吸不全($PaO2 \leq 60$ Torr，$PaCO2 \geq 45$ Torr)を呈し，気管切開を行う可能性が高くなる．さらに，AIS＝A の症例では，気管切開率は 84% まで上昇する(図 4-b)．このことは，頚椎の手術が必要な症例において，後方からのアプローチを選択する大きな指標となる(前方アプローチを用いた頚椎手術後，呼吸状態が悪化した症例で気管切開を行った場合，頚椎前方に感染，縦隔膿瘍へと進展する可能性がある)．

呼吸の評価に続いて，脳神経，四肢，体幹の神経学的診察を行う．診察開始時は意識清明であっても，診察中に意識障害などを呈する症例も存在する．そのような症例では，頭蓋内の血管病変な

a
b

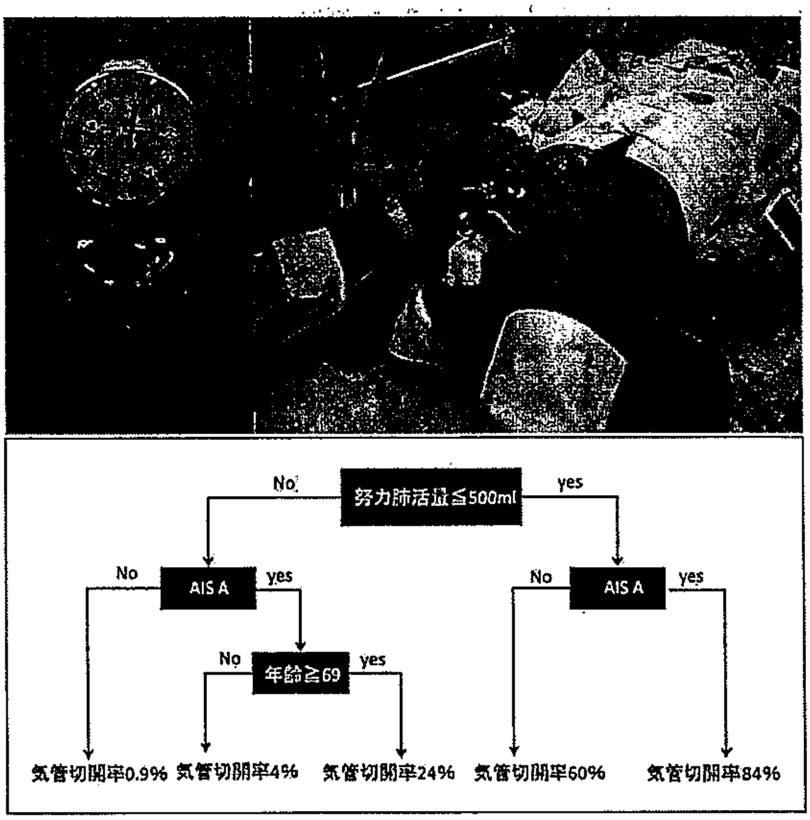


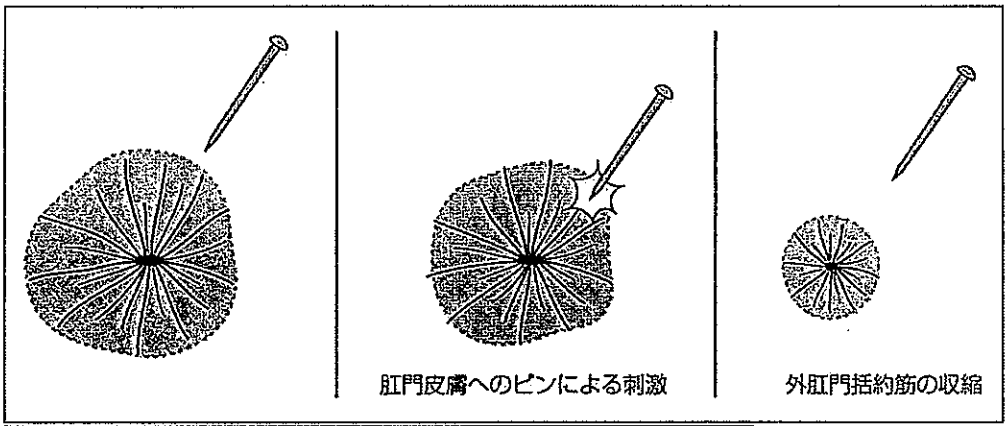
図 4.
a：肺活量の評価(左：簡易型レスピロメーター，右：簡易型レスピロメーター使用の実際)
b：気管切開のリスク因子

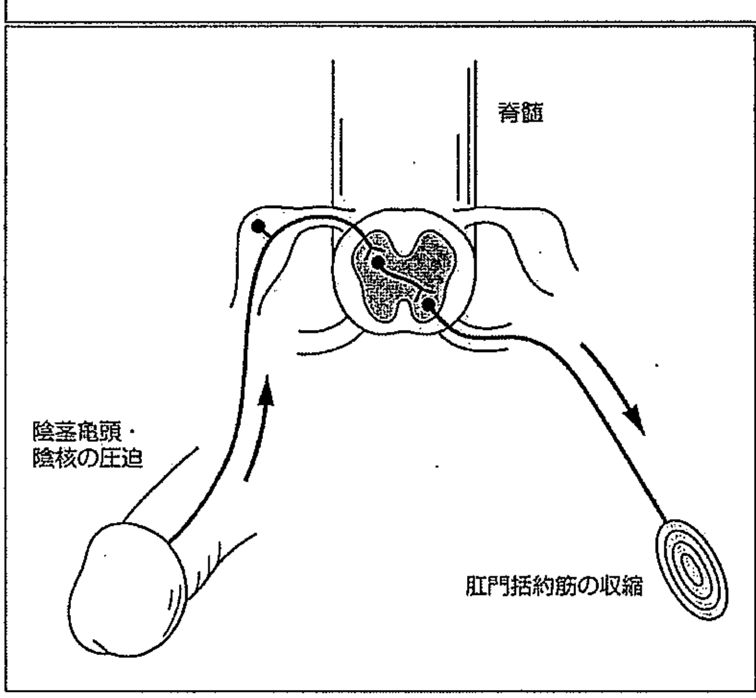
a|b

図 5. 椎骨動脈描出不良症例
77歳，男性．50 cm の高さより転落受傷．四肢麻痺出現，C4/5椎間板レベルでの頸髄損傷．徐々に意識状態悪化
a：MR angiography にて椎骨動脈描出不良
b：MRI diffusion 画像にて広範囲の小脳梗塞あり

どを念頭に置き，画像検査を行う(最近は，頭部MRI，頭頸部MRA を追加することが多い：図5)．当院では，四肢，体幹の診察は，感覚→運動→反射→肛門周囲の順で，各検査を頭側→尾側の順に行っている(いずれの診察順にしても系統立てて見落としがないよう，しかし手早く診察を行うべきである．感覚検査においては尾側から頭側へ検査を行うと大まかな感覚障害のレベルを把握しやすい)．また，spinal shock(後述)の存在を念頭に置き，診察を行っている．

感覚検査は，触覚(筆を使用，light touch)および痛覚(爪楊枝を使用，pin prick dull discrimina-





a/b

図 6.
a：Anal wink. Spinal shock を離脱したことを示す脊髄反射
b：球海綿体反射(bulbocavernous reflex：BCR)．Spinal shock を離脱した後，はじめに現れる脊髄反射

tion：爪楊枝の鋭端と鈍端の区別がつくか)の脱失，鈍麻，過敏などを評価．位置覚(母趾の背屈，底屈)の評価を主に行っており，必要時は，振動覚を追加している．運動検査は，上肢筋力(広頚筋，僧帽筋，胸鎖乳突筋，三角筋，上腕二頭筋，手根伸筋，上腕三頭筋，手根屈筋，指伸筋，指屈筋，母指球筋，小指球筋，骨間筋)，下肢筋力(腸腰筋，股関節内転筋，股関節外転筋，大腿四頭筋，下腿屈筋，前脛骨筋，足趾伸筋，腓腹筋・ヒラメ筋，足趾屈筋)を MMT0〜5 の 6 段階で評価している．反射は，上腕二頭筋腱反射，腕橈骨筋腱反射，上腕三頭筋腱反射，膝蓋腱反射，アキレス腱反射を検査し，病的反射の有無を評価している．肛門周囲の評価は，完全麻痺か不全麻痺かの判断に非常に重要である(仙髄回避：sacral sparing，後述)．まずは，肛門周囲の触覚，痛覚を評価する．痛覚の評価時に，anal wink(図 6-a)の有無を確認する．続いて，検者の示指を患者の肛門に挿入し，肛門への挿入感，anal tone，肛門括約筋の随意収縮(voluntary anal contracture：VAC)，deep anal pressure：DAP(後述)，球海綿体反射(bulbocavernous reflex：BCR；図 6-b)，抜去時に肛門からの抜去感を評価する．

1）神経原性ショック(neurogenic shock)

上位胸髄より高位の脊髄損傷によるショック．その本態は自律神経系失調(交感神経系の遮断に伴う副交感神経系優位の状態)によって引き起こされた末梢血管弛緩による血液分布異常性ショック(distributive shock)に大別される．その症状は，低血圧にもかかわらず徐脈を呈し，四肢末梢の皮膚温は温かく，乾燥している．外傷に伴うショックであるので，その診断はまず，出血性

ショック(低血圧，頻脈，四肢末梢の冷感)を否定することが重要である．

2）脊髄ショック(spinal shock)

Spinal shock に関する明確な定義はされておらず，病態および臨床的意義は未だ議論の余地がある．一般的に，脊髄ショックは脊髄が損傷を受けたときに，損傷高位以下のすべての脊髄反射(深部腱反射，表在反射など)が消失した状態と考えられている．また，患者は弛緩性麻痺，感覚脱失を呈し，消失した脊髄反射は，徐々に回復し，痙性麻痺に移行する．当センターでは受傷 72 時間後において，BCR：64%，anal wink：27%，PTR：10%の割合で認めた．我々は，spinal shock を離脱する際にはじめに出現する反射は BCR のことが多く，その反射出現の時期が早いほど，麻痺の改善が良い傾向にあると考えている．一方，plantar response がはじめに出現する反射であるとの報告も存在する．いずれの場合にせよ，脊髄反射を認めない spinal shock 期の神経学的評価は非常に困難であることを理解したうえで，診療を行うべきである．

3）仙髄回避(sacral sparing)

図のごとく，仙髄からの上行路，仙髄への下行路は脊髄の最外側を走行しており，最も損傷を受けにくく，また，最初に回復する部位であることが知られている．一見完全麻痺のようにみえても，仙髄神経機能が残存している場合は，完全麻痺ではなく不全麻痺であり，麻痺の回復が期待できる．Hoppenfeld はこの徴候として，母趾底屈筋反射，肛門括約筋反射，肛門周囲の感覚残存を挙げている．しかし，反射自体は索路機能残存を示すものではなく，除外されるべきであろう．これらのことより，ISNCSCI においても，肛門周囲感覚，DAP，VAC などが確認できれば，仙髄回避が起こっている(不全麻痺)と考えられている．

4）Deep anal pressure(DAP)

検者が示指を肛門に挿入し優しく肛門直腸壁(S4/5 由来の陰部神経の体性感覚で支配されている)を押すことで感じる圧覚が DAP 感覚．この持続的に感じる圧覚の存在の有無を記録，再現性のある圧覚は感覚不全を示す．

これらの評価をもとに，当センターでは，麻痺の程度について改良 Frankel 分類(表 2-a)と AIS(表 2-b)を用いて，麻痺の高位について Zancolli 分類を参考にした脊髄損傷高位評価法(表 2-c)にて評価を行っている．改良 Frankel 分類と AIS はともに Frankel 分類をもとに発展させた分類である．改良 Frankel 分類は，Frankel 分類の B，C，D を細分化し，A-C2 は麻痺の状態を，D1〜D3 は歩行状態を表し，患者の ADL がイメージしやすい．一方で，麻痺状態のスコア化について，ISNCSCI のようなルールが存在せず，スコアの標準化が課題である．

2．ISNCSCI としての AIS の考え方

ISNCSCI は，motor score(上肢は C5-T1 の 5 髄節，下肢は L2-S1 の 5 髄節について，両側 key muscle を決め，MMT0〜5 点で評価し，合計点数を算出)，sensory score(C2-S5 の 28 髄節について，両側 sensory point を決め，light touch，pin prick のそれぞれを 0〜2 点で評価し，合計点数を算出)を評価し，麻痺状態のスコア化を行う．さらに，VAC，DAP などについて評価を行う(ASIA の e-Learning サイト：https://lms3.learnshare.com/home.aspx に詳細が記載されている)．各髄節の評価を行った後，以下の順で，麻痺の高位評価，麻痺の横断面での評価を行う．

1）左右の sensory level の決定

左右の light touch，pin prick それぞれについて，いずれも正常な皮膚髄節のなかで最尾側皮膚髄節を記載．

2）左右の motor level の決定

左右の key muscle それぞれについて，MMT3 以上の筋力があり，その key muscle の上位 key muscle が MMT5 であれば，MMT3 の key muscle を正常筋髄節として記載．筋髄節が存在しない領域では，皮膚髄節を同様に取り扱う．

3）Neurological level of injury(NLI)の決定

ステップ 1，2 で決定された正常皮膚髄節，筋髄

表 2.

a：改良 Frankel 分類

Frankel A	仙髄の知覚(肛門周辺)脱失と運動(肛門括約筋)完全麻痺
Frankel B	運動完全(下肢自動運動なし)，知覚不全
B1	仙髄領域のみ触覚の残存
B2	仙髄領域を含めた広範囲の触覚の残存
B3	仙髄領域を含めた痛覚の残存
Frankel C	運動不全で有用でない(歩行できない)
C1	下肢筋力 1～2(仰臥位で自立膝立て不能)
C2	下肢筋力 3 程度(仰臥位で自立膝立て可能)
Frankel D	運動不全で有用である(歩行できる)
D0	下肢筋力 4～5 あり，歩行可能と考えられるが急性期のため正確な判定不能
D1	車いす併用例：補助具を用いて屋内のみ 10 m 以上歩行可
D2	杖歩行または中心性損傷 杖歩行例：下肢装具など必要であるが屋外歩行も安定し車いす不要 中心性損傷例：下肢装具類不要で安定しているが，上肢機能が悪いため，入浴や衣服脱衣などに部分介助を必要とする
D3	独歩自立例：筋力低下，知覚低下はあるも独歩で上肢機能も含めて日常生活に介助不要
Frankel E	神経学的脱落所見なし(自覚的しびれ感，反射亢進はあってよい)

b：International Standards for Neurological Classification of Spinal Cord Injury(ISNCSCI)/ASIA impairment Scale(AIS)

A＝Complete
S4-5 の仙髄領域の知覚運動完全麻痺
B＝Sensory incomplete
運動機能ではなく知覚が損傷高位以下仙髄までの遺残している
C＝Motor Incomplete
損傷高位以下に運動機能の残存があり，損傷高位以下の key muscle の半数以上が筋力 0～2
D＝Motor incomplete
損傷高位以下に運動機能の残存があり，損傷高位以下の key muscle の半数以上が筋力 3 以上
E＝Normal

c：脊髄損傷高位評価法(総合せき損センター)

脊髄高位	脊椎高位		評価筋と MMT
C1，2	C1		僧帽筋，胸鎖乳突筋などの頚部筋：0～3
C3	C2		頚部筋：4～5 横隔膜：完全またはほぼ完全麻痺
C4	C3		横隔膜：機能あり(自発呼吸ほぼ十分) 上肢筋力：0
C5	C3/4	A	上腕二頭筋：1～3
		B	上腕二頭筋：4～5
C6	C4/5	A	手根伸筋：1～3
		B	手根伸筋：4～5
C7	C5/6	A	上腕三頭筋：1～3
		B	上腕三頭筋：4～5
C8	C6/7	A	指屈筋：1～3
		B	指屈筋：4～5
T1	C7		骨間筋：4～5

節のうち最も頭側のレベルをNLIとして決定する.

4）完全麻痺か不全麻痺かを決定

Sacral sparingの有無により決定. VACを認めず, S4-5レベルすべてのsensory score＝0, DAPも認めない場合にのみ, 完全麻痺と判断する. それ以外の場合は, 不全麻痺と判断する.

5）AIS gradeの決定

ステップ4で完全麻痺と判断されれば, AIS＝Aと評価し, ZPP：zone of partial preservationを記載する.

ZPPはmotor score, sensory scoreのそれぞれで残存している最尾側髄節を記載する.

ステップ4で不全麻痺と判断し, かつ, 運動完全麻痺と判断されれば, AIS＝Bと評価する.

運動完全麻痺とは, VACを認めないか, もしくはステップ2で決定したmotor levelより3髄節尾側を超えた4髄節以下でmotor scoreを認めない場合.

ステップ4で不全麻痺と判断し, かつ, 運動不全麻痺と判断されれば, AIS＝CかDかを評価する.

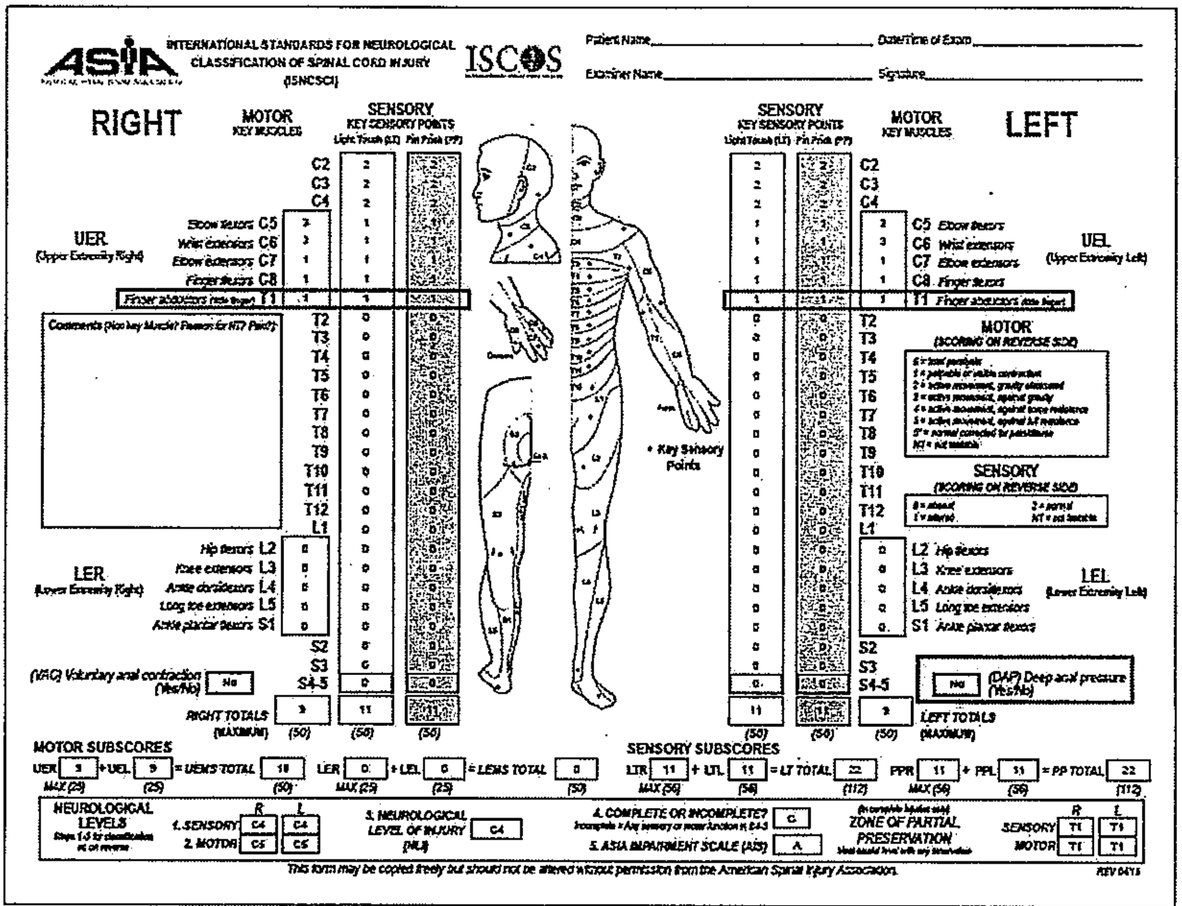
NLIより下の髄節において, key muscleの半数以上がMMT2以下の筋力を有する場合は, AIS＝Cと評価する. また, key muscleの半数以上がMMT3以上の筋力を有する場合は, AIS＝Dと評価する.

初診時の神経学的所見で異常がなければ, intactと記載する. 初診時, 麻痺があり, その経過中, すべての髄節において, 感覚, 運動ともに正常な場合は, AIS＝Eと評価する.

このようなルールに加えて, AIS＝BとCの判断のため, non-key muscleについての記載など, さらなる詳細のルールが存在する. これらにより, トレーニングを受けずにAISを正確に評価することは困難な印象を受ける恐れがある. これらを解決するため, 近年, web上でAIS評価のためのアルゴリズムが公開されている(http://isncscialgorithm.azurewebsites.net/). 今回は, このアルゴリズムを用いて, AIS＝A, B, Cの評価のため, 極端なデモンストレーション症例について検討した.

図7-aは, 両小指外転筋の収縮をわずかに認め, 両上肢尺側の感覚鈍麻, 両下肢の麻痺を呈した症例である. まず, 正常な皮膚髄節のなかで最尾側皮膚髄節は右C4/左C4であるから, sensory levelは, 右C4/左C4と記載する. MMT3以上の筋力は, 両側肘屈曲筋(C5)・手関節伸展筋(C6)であるが, それぞれその上位key muscleでMMT5である筋髄節を認めない(C4は筋髄節が存在しない). 筋髄節が存在しない領域では, 皮膚髄節を同様に取り扱うというルールに従いC4髄節がMMT5と考え, motor levelは右C5/左C5と記載する. これらより, NLIは正常皮膚髄節, 筋髄節のうち最頭側のC4と記載できる. 続いて, sacral sparingの有無を確認し, VAC(No), S4-5 sensory score＝0, DAP(No)であることより, 完全麻痺(C)と評価, 記載する. 完全麻痺であることより, ZPPの評価が必要となり, 残存筋髄節, 皮膚髄節の最尾側であるT1を右T1/左T1とsensory, motorともに記載する. 以上のことより, AIS＝Aと評価, 記載する. 改良Frankel分類でも, Frankel＝Aとなる.

図7-bは, 両小指外転筋の収縮は認めず, 両指屈筋の収縮をわずかに認め, 両上肢尺側の感覚鈍麻, 両下肢の麻痺を呈した症例である. 図7-aを参考に考えていくと, sensory levelは右C4/左C4, motor levelは右C5/左C5, NLIはC4と記載できる. Sacral sparingに関しては, VAC(No), S4-5 sensory score＝0, DAP(Yes)であることより, 不全麻痺(I)と評価, 記載する. さらに, AIS＝BかCかの判断のため, 損傷高位以下のnon-key muscleに関してもMMTの評価を行う. 図7-bでは, motor level右C5/左C5の3髄節尾側であるC8髄節を超えたT1髄節(4髄節尾側)以下で, 運動完全麻痺であるので, AIS＝Bと評価, 記載する. 改良Frankel分類ではB1である.



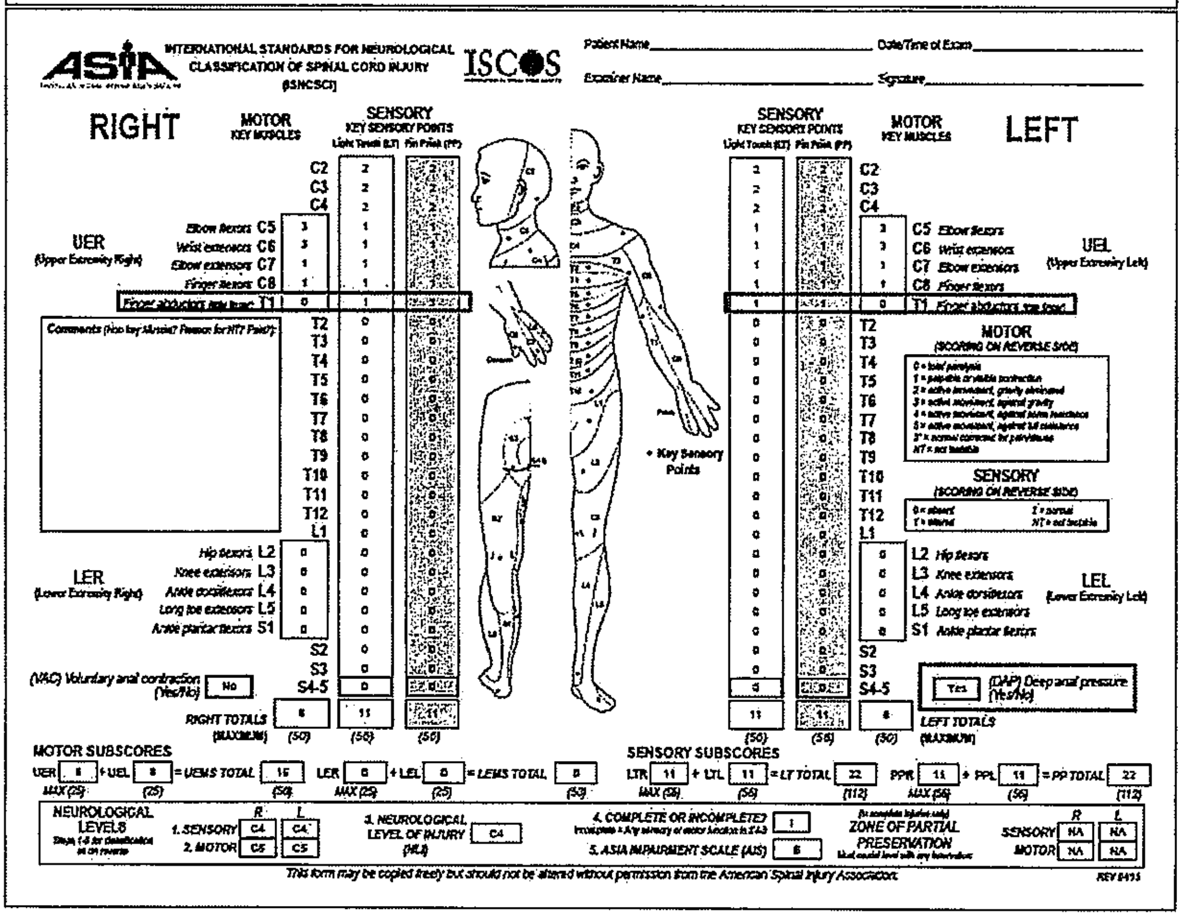


図 7.

a：AIS A のデモ症例
b：AIS B のデモ症例

a/b

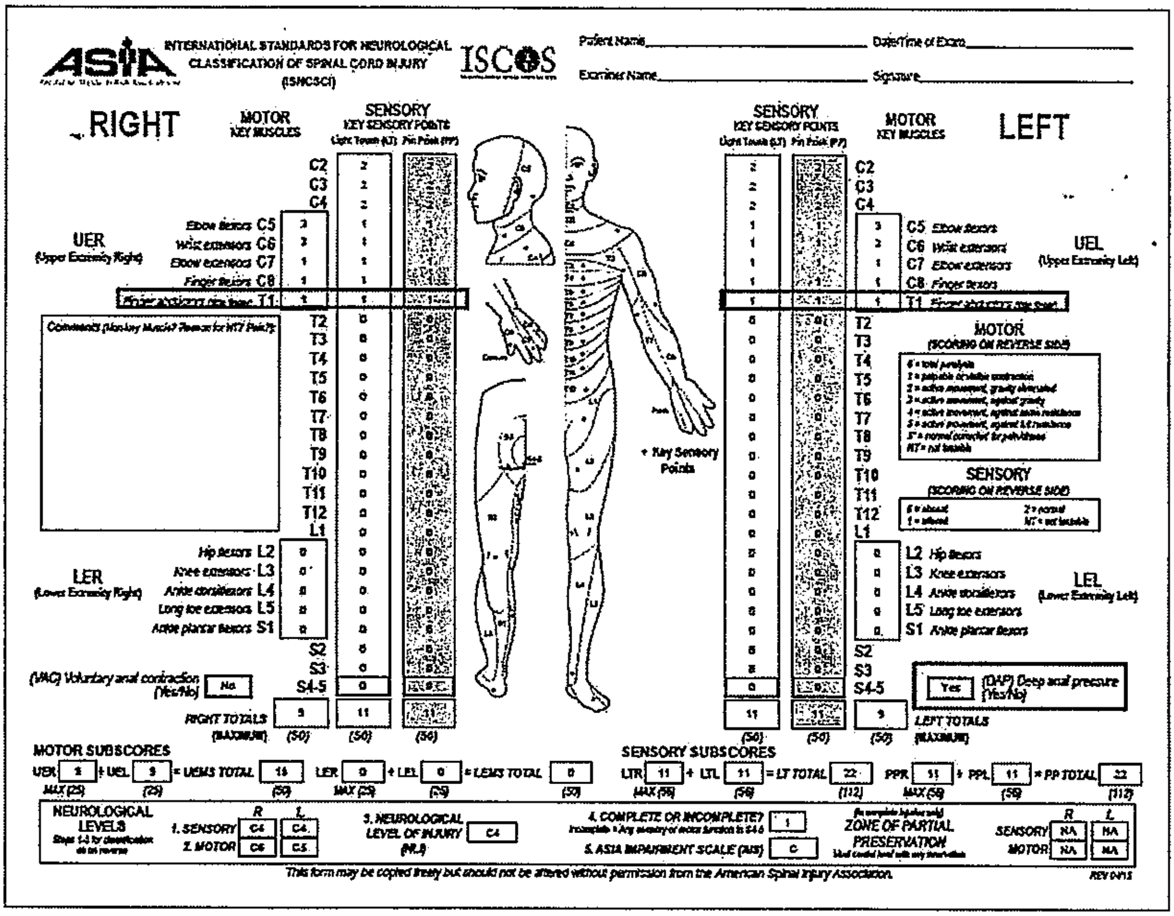


図 7. つづき
c：AIS C のデモ症例

図 7-c は，図 7-a と同様に両小指外転筋の収縮をわずかに認め，両上肢尺側の感覚鈍麻，両下肢の麻痺を呈した症例である．図 7-a を参考に考えていくと，sensory level は右 C4/左 C4，motor level は右 C5/左 C5，NLI は C4 と記載できる．Sacral sparing に関しては，VAC (No)，S4-5 sensory score＝0，DAP (Yes) であることより，不全麻痺 (I) と評価，記載する．さらに，AIS＝B か C かの判断のため，損傷高位以下の運動機能の評価を行う．図 7-c では，motor level 右 C5/左 C5 の 3 髄節尾側である C8 髄節を超えた T1 髄節 (4 髄節尾側) で，両側小指外転筋の収縮を認めるので，AIS＝C と評価，記載する．しかし，改良 Frankel 分類では B1 である．

このように AIS の評価と改良 Frankel 分類の評価で乖離を認める症例が存在する可能性がある．また，spinal shock という未だに病態が解明されていない問題が存在し，受傷直後の神経学的診断の難しさを理解する必要性がある (受傷直後の AIS＝A，改良 Frankel 分類＝A は，本当に正しい評価なのだろうか？)．これらの問題を理解したうえで，再現性のある神経学的所見，麻痺の評価を行わなければならない．そのためには，ASIA の e-Learning やアルゴリズムを活用しつつ，一症例一症例を大切に診察していく必要がある．

終わりに

脊椎・脊髄損傷は，高齢化に伴い，今後増加することが予想される．しかし，脊髄損傷に関しては，系統的な教育を受ける機会が少ないことが現状である．脊髄損傷の神経学的診断は困難なものではあるが，一方，その他の疾患の診断に対して，非常に役に立つものである．本稿が，読者の日常診療の一助となれば幸いである．

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1 基礎知識

1 脊髄損傷者のリハビリテーション

わが国の脊髄損傷の特徴

① 疫学（高齢化と重度化）

脊髄損傷者の医療に携わる際には、脊髄損傷の特徴を把握しておく必要があります。わが国では過去2回の全国調査が行われています[1、2]。

第1回の全国調査（1990～1992年）[1]では、発生頻度は人口100万人あたり年間40.2人と推計され、全体の75%が頸髄損傷者で、受傷時の年齢は20歳と59歳にピークをもつ二峰性の分布を示しました（図1）。原因は、交通事故がもっとも多く（43.7%）、転落（28.9%）、転倒（12.9%）が続きます。この調査が、全国的な発生頻度を出した唯一のものです。第2回の全国調査（2002年）[2]では、前回よりも高齢化していることが明らかとなりました。

現在、労災病院関連施設がリハビリテーション（以下、リハビリ）治療を施した外傷性

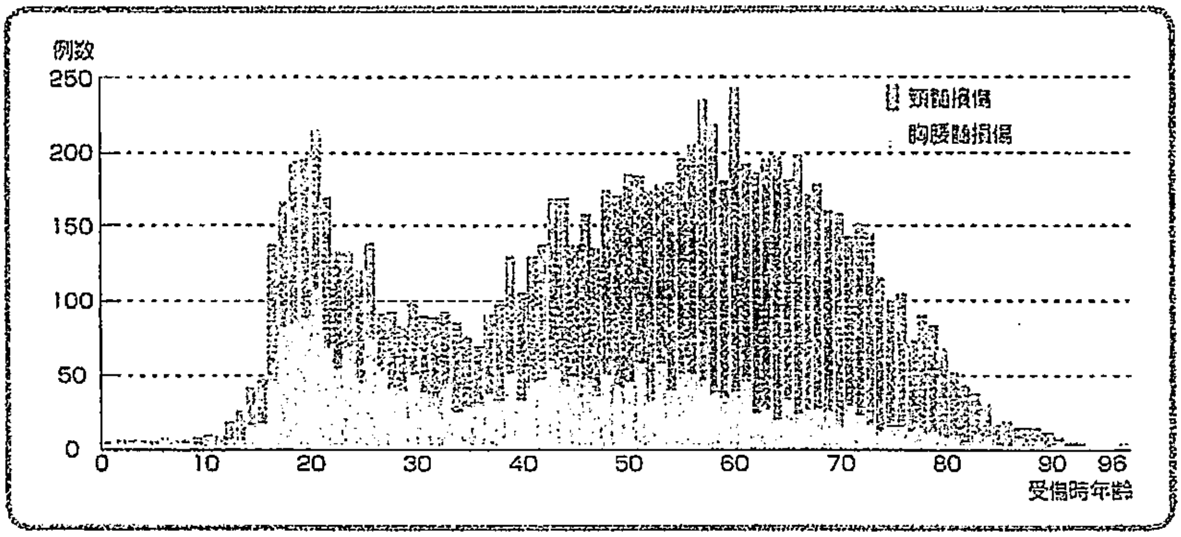

図1 脊髄損傷者の年齢分布

Shingu, H. et al. A nationwide epidemiological survey of spinal cord injuries in Japan from January 1990 to December 1992. Paraplegia. 33 (4). 1995. 183-8. より改変

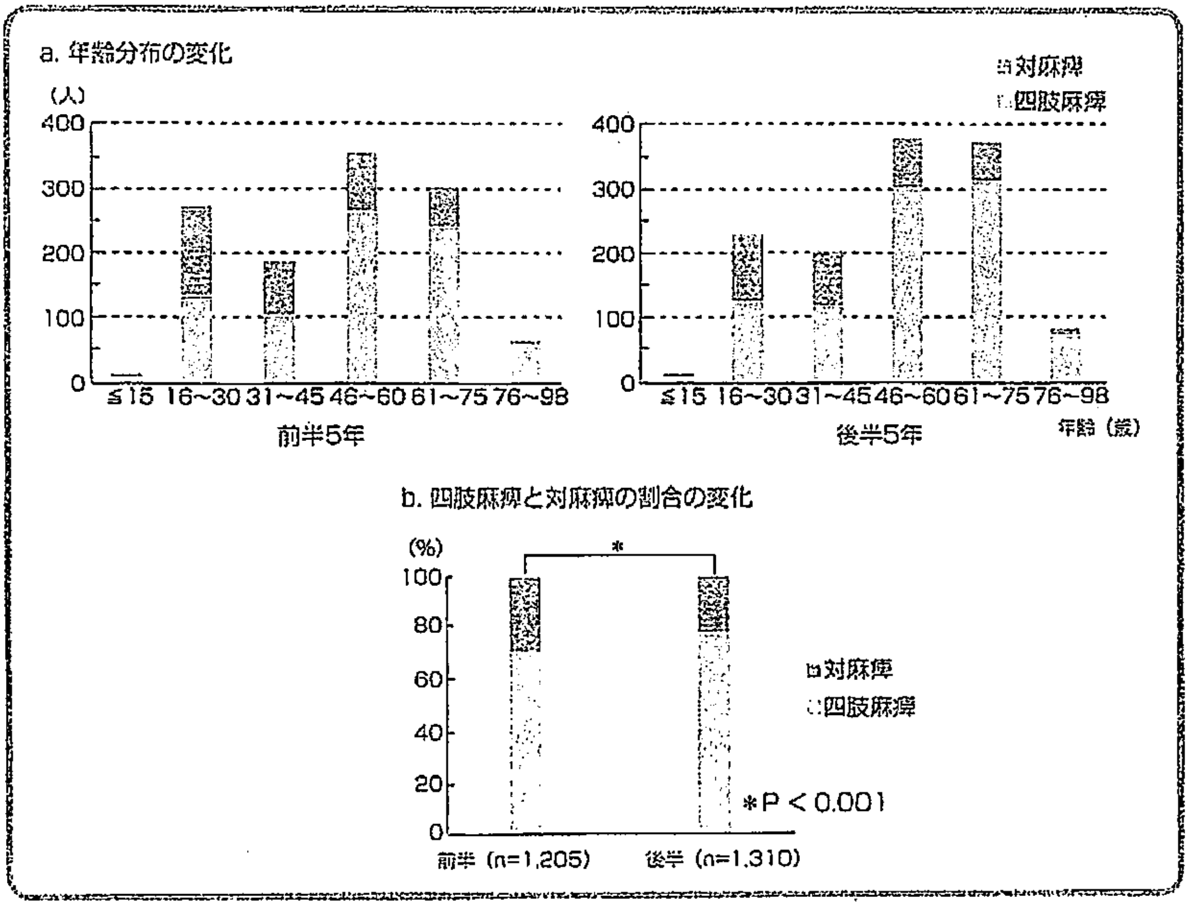

図2 1997～2006年度における前後半の比較

時岡孝光ほか."治療対象者の現状". 脊髄損傷の治療から社会復帰まで：全国脊髄損傷データベースの分析から. 全国脊髄損傷データベース研究会編. 東京, 保健文化社, 2010, 9-22.

脊髄損傷者のデータベース（全国脊髄損傷データベース）を構築しています。2010年には、1997～2006年度の10年間に登録された3,006例のデータを分析した結果が公表されました。全国脊髄損傷データベースでも原因としてもっとも多いのは交通事故ですが、年齢階層でみると高齢者は交通事故の割合が低くなり、転落・起立歩行時の転倒の割合が高くなっています[3)]。また、10年間を前半の5年と後半の5年で比較検討し、ここでも高齢化（図2-a）と重度化（対麻痺に比べて四肢麻痺が増加していること）（図2-b）が進行していることを指摘しています[3)]。

② 生活習慣病の増加

わが国を含めた先進国においては、急性期の初期治療と慢性期における健康管理法の向上により、脊髄損傷者の平均余命は飛躍的に改善しました[4)]。しかし、それにともなって生活習慣病の増加が大きな問題となっており、依然として健常者に比べて死亡率は高いとされています[5)]。

脊髄損傷者においては、健常者よりも心血管疾患の有病率が高く、主要な死因の一つとして報告されています[6〜8]。心血管疾患の有病率が高い大きな理由は、健常者に比べて脂質異常症や糖尿病、内臓脂肪の蓄積のような心血管疾患のリスクを有する率が高いからです[9〜12]。それらには、麻痺による不活動のほか、交感神経活動の低下や筋肉量の減少による基礎代謝の低下などもかかわっています[13,14]。さらに"筋肉量の減少"については、近年、「運動中に活動している骨格筋の筋細胞からはインターロイキン6などのサイトカインが産生、分泌され、それらは脂肪の分解やインスリン抵抗性をブロックする」ことが証明され[15,16]、こちらのメカニズムも関与している可能性があります[15,17]。Kouda ら[14]は、「頸髄損傷者と健常者において、ハンドエルゴメータを用いた運動（最大酸素摂取量の60%の運動強度で20分間）をすると、健常者は運動後に血中のインターロイキン6が増加したのに対して、筋肉量の少ない頸髄損傷者では運動後も増加しなかった」という非常に興味深い報告をしています。脊髄損傷者における生活習慣病については、社会復帰後の食生活や運動習慣が大いに関与するので、入院中に予防の大切さを話しておく必要があります。

脊髄損傷のリハビリ医療の課題と魅力

現在の医療制度では、リハビリ医療に長期間を要する疾病や障害をもつ人は、複数の医療機関が連携して社会復帰を目指すことになります。脊髄損傷者も例外ではありません。とくに中高齢の脊髄損傷者は、身体の予備能の低下や併存する内科疾患により長期間のリハビリ医療を要するケースも多く[18]、連携の必要性は高まる傾向にあります。そして、そこにかかわる医療機関には、「いかなる時期を担当しようとも、目の前にいる脊髄損傷者がもつ可能性を見失うことなく責任をもって役割を果たし、次のステップにバトンタッチすること」が求められています。

一人の脊髄損傷者が社会復帰するまでに複数の医療機関が携わるということは、より多くの方にその魅力を感じ取っていただくチャンスであり、それは、すなわち「脊髄損傷のリハビリ医療の普及・発展」を意味します。すでにその魅力にお気付きの方も多いと思いますが、ここにその一部を挙げておきます。

①脊髄損傷者も高齢化の傾向があるとはいえ、リハビリの対象となるほかの疾病に比べ若

年者が多く、社会復帰の形態が多岐にわたります。そこには多大なエネルギーを要しますが、成果とともに大きな喜びや達成感が得られ、皆で共有することができます。

②脊髄損傷者が障害者スポーツなどへ社会参加することは、皆に夢を与えます。また、そこでの成長や活躍から、医療従事者は自己の存在価値を強く感じることができます。

③感覚障害により痛みなどの典型的な症状がない状況での診療は、視診・触診の重要性を再認識することができ、基本に立ち返る医療ともいえます。

リハビリ医療のための診断と評価

① 全身理学的所見と神経学的所見（機能障害の評価）

1）全身理学的所見

脊髄損傷では知覚障害などによって自覚症状に乏しいので、いずれの時期も全身理学的所見を正確にとることがきわめて重要です。そのことで合併症（皮膚や膀胱、直腸、呼吸器、循環器など）の存在も把握できます。

2）神経学的所見

神経学的所見は、まずは知能など脳の機能を評価しておきます。わが国に多い頸髄損傷では、中高齢での受傷と頭部外傷の合併の頻度が高いためです。また同様の理由で嚥下障害の評価も欠かせません。脊髄損傷者の死因の第１位は呼吸器にかかわるものであり[19]、嚥下障害と呼吸機能障害の存在下で生じる誤嚥性肺炎はとくに注意が必要です。

損傷レベル（脊髄の損傷の高さ）と麻痺の程度（完全麻痺、不全麻痺など）の診断は、脊髄損傷の神経学的および機能的国際評価法（American spinal injury association：ASIA）に基づいて、運動障害と知覚障害を診察して行います。ただし、頸髄損傷についてはASIAによる評価だけでは詳細な予後予測は困難なため、Zancolli上肢機能分類も用います。詳細は１章-2「麻痺の分類と評価」に譲りますが、これらは脊髄損傷の医療における共通の言語として理解しておきましょう。

② ADL（活動の制限の評価）

機能障害によって生じるADLの評価には、Functional independence measure（以下、FIM）やBarthel Indexを用いるのが一般的です。前述のごとく、わが国では中高齢で受傷する頸髄損傷者が多いので、認知に関する項目を含むFIMでの評価は欠かせません。

FIMでは「しているADL」を評価するので、そこでの看護師の役割は非常に重要です。

③ 社会生活への参加の制限の評価

脊髄損傷者が社会復帰するための生活場所の確保は、「脊髄損傷のリハビリ」において非常に大きなウエイトを占めます。現在、入院している医療機関から直接、家庭復帰ができなくても、住宅の建築物や介護のマンパワー、経済的な状況、利用可能な社会資源などの情報を早期に収集します。また、生産年齢にある脊髄損傷者では、職業復帰の可能性を必ず評価しておきましょう。それだけでも、本人にとっては職業復帰への動機付けになることがあります。

リハビリ医療のプログラム

評価に基づいたゴールの設定、設定されたゴールに向けてのリハビリ訓練、合併症の管理（予防と治療）、日常生活や職業にかかわる環境の整備がおもな内容です。

① ゴールの設定

1）ゴールの設定と共有

神経学的所見から予想される獲得可能なADLに、年齢や体型、体力、合併症の存在、社会的背景、本人や家族の考えを加味して、短期ゴール（ADLのゴール）と長期ゴール（社会生活に関するゴール）を設定します。当然、途中で修正されることもありますが、急性期であろうと慢性期であろうと、個々の脊髄損傷者にふさわしい長期ゴールは1つで、そのゴールは皆で共有しておかなければなりません。回復期リハビリテーション病棟では、急性期で示すことが困難だったゴールを設定し、今後の方向性をより明確にする必要があります。

2）障害の告知と受容

ゴールの設定は医療従事者だけでなく本人や家族とともに行い、その情報を共有します。その際に避けて通ることができないのが、医療従事者からの障害の告知と、脊髄損傷者やその家族の障害の受容です。障害の告知については、麻痺の回復の見込みがないことを告げるのが目的ではなく、リハビリ医療を受けることでなにができるようになるのか、そのために具体的になにをすべきかを提示し、脊髄損傷者や家族の混乱した状況を整理するのが目的であることを認識しておきましょう。

② リハビリ訓練

リハビリ訓練は、通常、理学療法と作業療法を行い、嚥下障害などを合併する症例には言語聴覚療法も行います。急性期医療では、損傷された脊椎の安定性に応じて、呼吸器感染や深部静脈血栓症、廃用の予防のための訓練を行います。

車椅子上の座位が可能になりはじめたころからは、体力が許す限りベッドで横になることは避けるよう、医療従事者も心掛けておきましょう。こうした日々の積み重ねによって、廃用の予防や耐久性の向上、起立性低血圧や排便障害の改善が期待できます。訓練室で過ごす時間は非常に限られているので、病棟などでの生活場面などのすべてをリハビリの一環としてとらえておきたいものです。

③ 合併症の管理

1）合併症管理の重要性

脊髄損傷の合併症は、多くの場合、複数生じますが、急性期から存在して経過とともに症状が和らぐものや、亜急性期や慢性期になってはじめて出現するものなど多彩です。したがって亜急性期以降も、たんに「病状が安定した脊髄損傷者を急性期から受け入れるだけの医療」では成り立ちません。

合併症管理の良否が、その後の脊髄損傷者の運命を決めていたということもしばしば経験します。とくに重度の褥瘡は治癒するまでの期間はいうまでもなく、いったん治癒した後も、瘢痕化した部分は容易に再発を繰り返し、長きにわたってリハビリ医療の進行を妨げます。

図３に内田の調査による頸髄損傷者（図 3-a）と胸腰髄損傷者（図 3-b）の死因の推移[19]を、図４に米国のデータベースから脊髄損傷者の再入院の原因を示しました[20]。これらから、尿路や呼吸器、皮膚などの合併症の管理がいかに大切かが理解できます。

2）退院後の自己管理のための教育

社会復帰後は本人や家族による管理、いわゆる「自己管理」が主体となるので、入院中にはそのための教育が必要です。合併症の「自己管理」では、その予防と治療に関する知識や技術を習得するだけでなく、生活のなかでその管理に費やす時間や労力が占める割合をバランスよく設定できることが大切です。したがって、生活場面で最もかかわりの深い看護師の役割が非常に重要となります。

④ 生活環境の整備、職業的アプローチ

ADL の将来像が、ある程度みえてきた時点で、本格的に生活環境を整備します。職業復

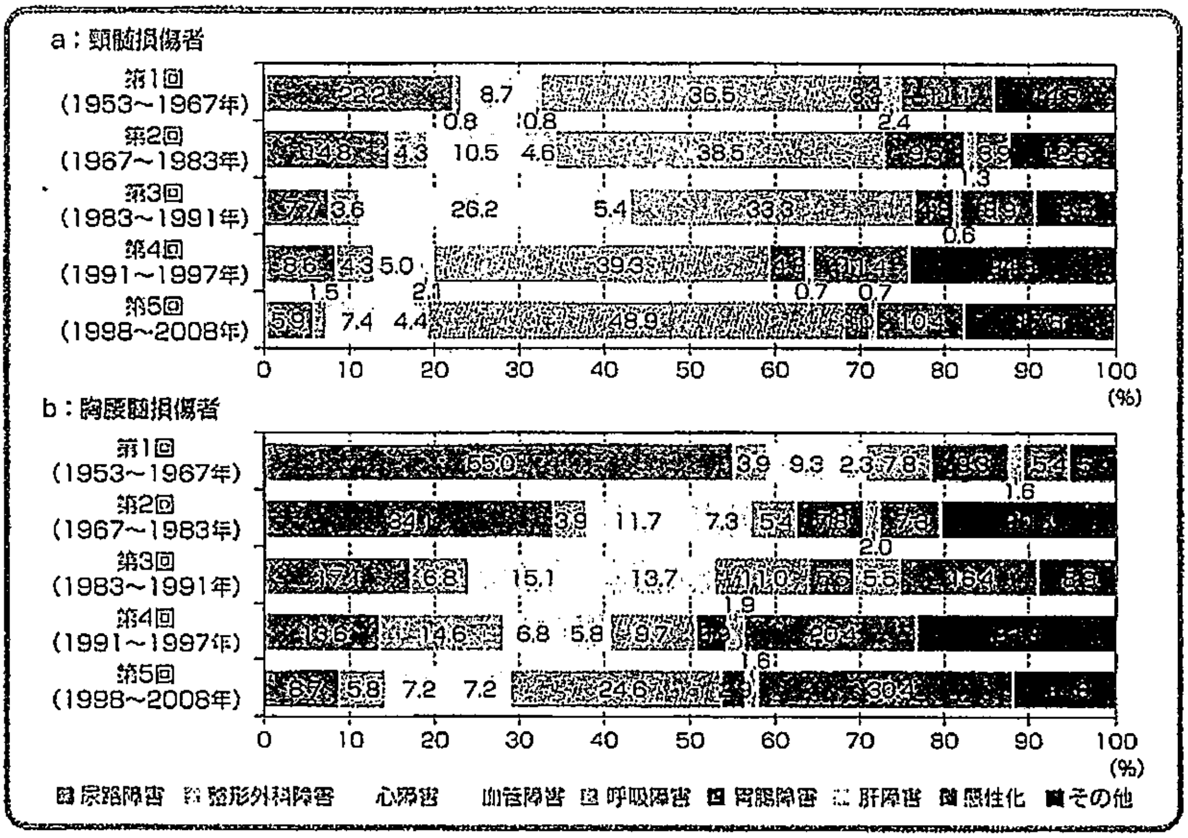

図3 脊髄損傷者の死因の推移

清潔間欠導尿などが普及し排尿管理の方法が確立するとともに、尿路系の割合が減少する。
内田竜生．"脊髄損傷者の死因と標準化死亡比"．脊髄損傷の治療から社会復帰まで：全国脊髄損傷データベースの分析から．全国脊髄損傷データベース研究会編．東京，保健文化社．2010．158-68．より改変

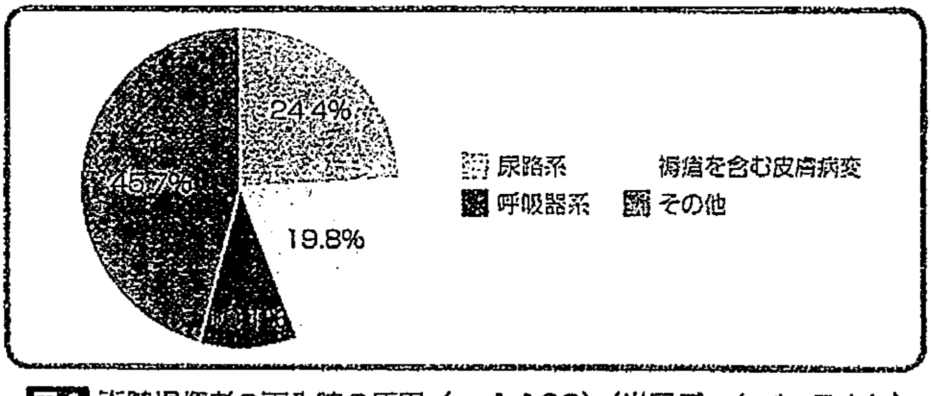

図4 脊髄損傷者の再入院の原因（n=1,162）（米国データベースより）

Cardenas, DD. et al. Etiology and incidence of rehospitalization after traumatic spinal cord injury : a multicenter analysis. Arch Phys Med Rehabil. 85 (11). 2004. 1757-63. より改変

帰については、受傷前に仕事に就いていた者では、まずは配置転換も含めた現職場復帰を目指し、それが不可能ならば他職種への変更や職業リハビリへの移行などを検討するのが原則です。職業復帰に関してはおもに医療ソーシャルワーカー（MSW）が介入します。

（古澤一成）

ここがPoint

①脊髄損傷のリハビリ医療に携わるにあたって、わが国の脊髄損傷の特徴（高齢化と重度化、社会復帰後の生活習慣病の増加）を把握しておく必要があります。

②脊髄損傷のように長期のリハビリ医療を要する疾病では、「個々にふさわしい長期ゴール」を病院間で共有することが大切です。

③社会復帰する際には障害や合併症の「自己管理」が不可欠です。その習得において、入院中の生活場面でもっともかかわりの深い看護師の役割は非常に重要です。

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MB Med Reha No.209：21-29, 2017

特集／脊髄損傷のリハビリテーション最前線

脊髄損傷慢性期リハビリテーションのマネージメント —回復期から維持期のリハ医療で知っておきたいこと—

古澤一成*

Abstract　脊髄損傷の回復期から維持期では，以下のような点を理解したうえで，社会的アウトカムにこだわったリハビリテーション(以下，リハ)医療を施したい．

1．医療制度について

現在の医療制度においては，複数の医療機関が連携して脊髄損傷者の長期ゴールを目指すことになる．そこにかかわるすべての医療機関が「目の前にいる脊髄損傷者がもつ可能性を見失うことなく責任をもって役割を果たし，次のステップにバトンタッチしていくこと」で，この医療は成り立つ．また，いくつもの医療機関がかかわるということは，より多くの者が脊髄損傷のリハ医療の魅力を感じるチャンスでもある．

2．我が国の脊髄損傷者の特徴

我が国では，高齢受傷者の増加と重度化，社会復帰後の生活習慣病の増加が社会問題となっており，早急な対応が必要である．

3．合併症の管理について

脊髄損傷者が社会復帰するためには，合併症の管理が非常に重要である．本稿では，生命予後に影響を及ぼすもの，社会参加やQOLに影響を及ぼすものについて解説した．回復期から維持期のリハ医療においての1つの目標は，脊髄損傷者や家族の「合併症の自己管理の習得」である．

Key words：頚髄損傷(cervical spinal cord injury)，生活習慣病(life style related disease)，骨格筋(skeletal muscle)，マイオカイン(myokines)，自己管理(self-management)

現在の医療制度における脊髄損傷のリハビリテーション医療

現在の医療制度においては，社会復帰に長期間要する疾病や障害では，複数の医療機関が連携して1つのゴールを目指すことになる．脊髄損傷その代表的な疾病である．昨今，増加する中高齢の脊髄損傷者では，身体の予備能の低下や併存する内科疾患により長期間のリハビリテーション(以下，リハ)医療を要するケースも多く[1]，連携必要性は高まる傾向にある．

脊髄損傷のリハ医療において，回復期から維持に携わる医療機関に求められるのは，① ただ単に紹介されるのを待つのではなく，急性期の医療機関と積極的に連携をとって社会復帰までのスムースな流れをつくること，② 急性期医療で示すことが困難だった詳細なゴールを設定し，今後の方向性をより明確にすること，③ 良好な社会的アウトカムにこだわり，急性期にかかわった医療機関とその成果を共有すること，④ それを果たすための知識や技術，そして高いレベルの意識をもつことである．社会的アウトカムにこだわるというのは，必ずしも，その医療機関から直接，職業復帰などの転帰を得ることだけを示すものではない．たとえ，その転帰が得られなくても，最終的にそのゴールに到達するための最良のステップを選択していることが重要である．

ゴールの設定については，急性期から慢性期のリハ医療を通じて，個々の脊髄損傷者にふさわし

* Kazunari FURUSAWA，〒716-1241 岡山県加賀郡吉備中央町吉川7511　吉備高原医療リハビリテーションセンター，副院長

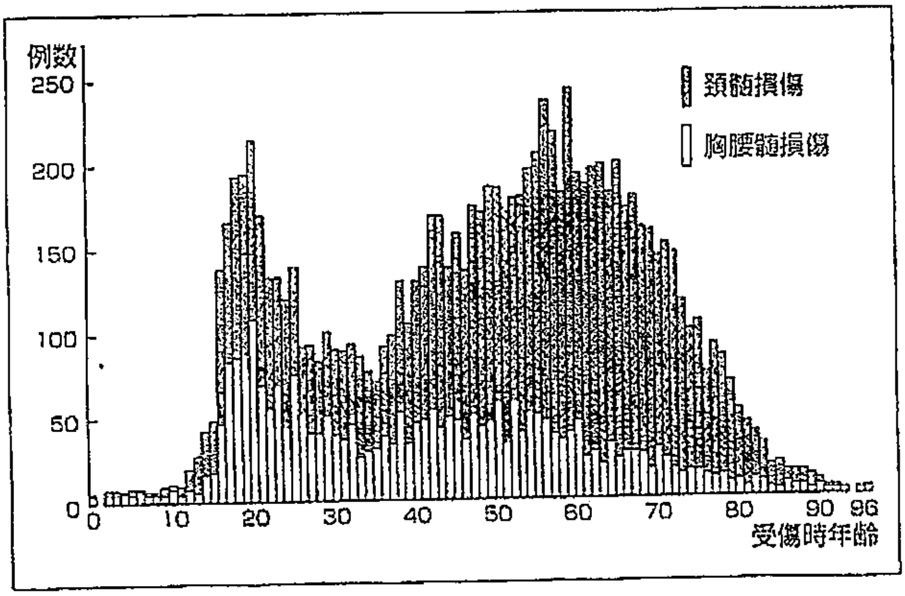


図 1.
脊髄損傷者の年齢分布
(1990～92年)
(文献2より改変)

い長期ゴールは1つであることを認識し，各医療機関がそのゴールを共有しておくことが大切である．医療制度を優先したゴールだけを脊髄損傷者や家族に提示するようなことはあってはならない．いかなる時期を担当しようとも，目の前にいる脊髄損傷者がもつ可能性を見失うことなく責任をもって役割を果たし，次のステップにバトンタッチしていく必要がある．

良好な社会的アウトカムを得るために欠かせないのが，生活環境の整備や職業的なアプローチである．脊髄損傷者が社会復帰するための生活場所の確保は，「脊髄損傷のリハ」において非常に大きなウェイトを占める．現在，入院している医療機関から直接，家庭復帰ができなくても，住宅などの建築物やマンパワー，経済的な状況，利用可能な社会資源などの情報は収集する．また，生産年齢にある脊髄損傷者では職業復帰の可能性を評価しておく．それだけでも，本人にとっては職業復帰への動機づけになることがある．職業復帰については，受傷前に仕事に就いていた者では，まずは配置転換も含めた原職場復帰を目指し，それが不可能ならば他職種への変更や職業リハへの移行などを検討するのが原則であることを知っておきたい．

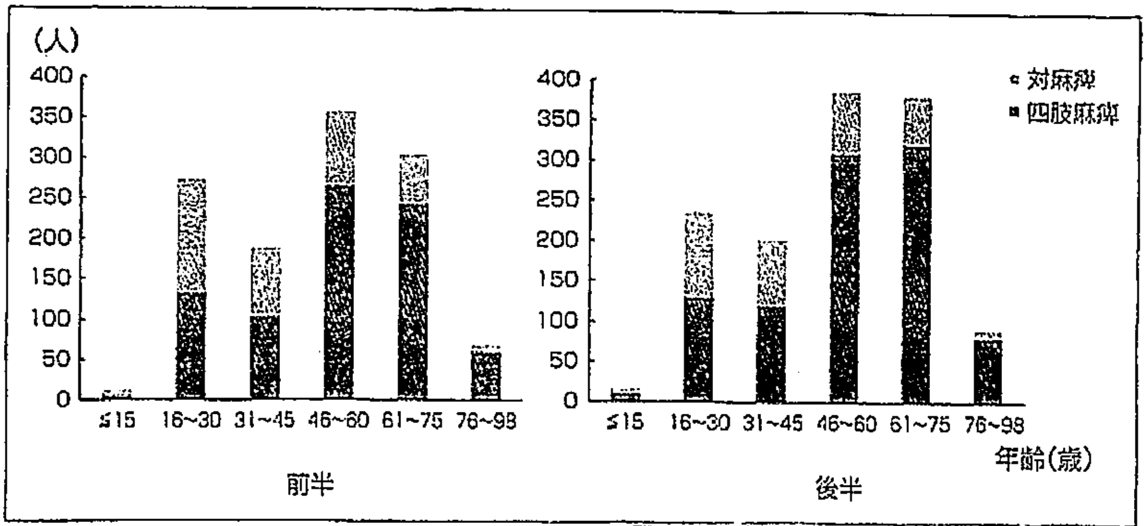
後述する「合併症管理のための患者教育」とともに，「生活環境の整備」や「職業的なアプローチ」などの非採算な部分へエネルギーを注ぐことが，社会的アウトカムの質を向上させる．

脊髄損傷のリハ医療の魅力

1人の脊髄損傷者が社会復帰するまでに複数の医療機関が携わるということは，より多くの者がその魅力を感じとるチャンスであり，そのことが「脊髄損傷のリハ医療の普及・発展」につながる．多少，情緒的な表現になるが，臨床現場で感じる脊髄損傷のリハ医療の魅力を挙げておく．① 脊髄損傷者も高齢化の傾向があるとはいえ，リハの対象となる他の疾病に比べ若年者が多く，社会復帰の形態が多岐にわたる．良好な社会的アウトカムを得るためには多大なエネルギーを要するが，成果とともに大きな喜びや達成感が得られ，皆で共有することができる．② 脊髄損傷者が障害者スポーツなどで社会参加することは，皆に夢を与える．また，そこでの成長や活躍から，医療者は自己の存在価値を強く感じることができる．③ 感覚障害により痛みなどの典型的な症状がない状況での診療は，視診・触診の重要性を再認識することができ，まさに基本に立ち返る医療といえる．

我が国の脊髄損傷者の特徴

脊髄損傷の医療に携わる際には，我が国の脊髄損傷者の特徴を把握しておく必要がある．本稿では，脊髄損傷の疫学における課題と社会復帰後の慢性期に生じる生活習慣病について，それぞれの対応も含めて述べる．



a
b

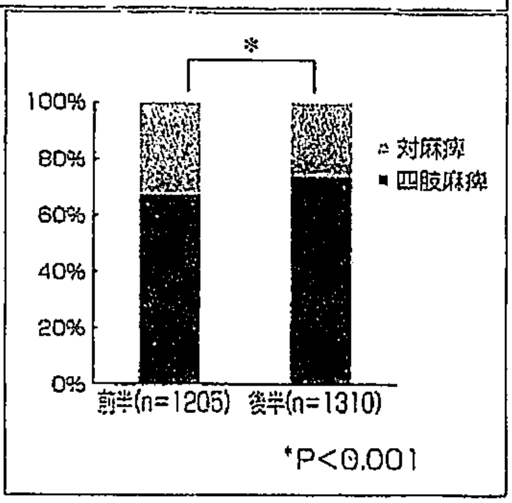


図 2.
1997～2006 年における前後半の比較
a：年齢分布の変化
b：四肢麻痺と対麻痺の割合の変化
(文献 4 より)

1．疫学(高齢化と重度化)

1）現 状

我が国においては過去 2 回の全国調査が行われている[2][3]．第 1 回の調査(1990～1992 年)[2]では，発生頻度は人口 100 万人当たり年間 40.2 人と推計され，全体の 75％が頚髄損傷者で，受傷時の年齢は 20 歳と 59 歳にピークをもつ二峰性の分布を示した(図 1)．この調査が，全国的な発生頻度を出した唯一のものである．第 2 回の全国調査(2002 年)[3]では，前回よりも高齢化していることが明らかとされている．

現在，労災病院関連施設がリハ治療を施した外傷性脊髄損傷者のデータベース(全国脊髄損傷データベース)を構築しており，2010 年には，1997～2006 年度の 10 年間に登録された 3,006 例のデータを分析した結果を公表した．この 10 年間を前半の 5 年と後半の 5 年に分けて比較検討し，ここでも高齢化(図 2-a)と重度化(対麻痺に比べて四肢麻痺が増加していること)(図 2-b)が進行していることを指摘している[4]．我が国は世界一の長寿国となり超高齢化社会に突入しており，脊髄損傷もそれを反映して高齢者の受傷が増加している．また，全国脊髄損傷データベースにおいて，原因として最も多いのは交通事故であるが，年齢階層でみると高齢者は交通事故の割合が低くなり，転落・起立歩行時の転倒の割合が高くなっており[4]，このことは四肢麻痺が増加している 1 つの要因となっている．

2．慢性期のリハ医療での対応

脊髄損傷では，損傷高位に関係なく，運動麻痺以外に，いわゆる「脊髄損傷の合併症」が存在する．それらは，膀胱直腸障害や神経障害性疼痛，褥瘡，性機能障害など多岐にわたるため，いずれの時期においても社会復帰を目指すうえで複数の診療科のかかわりが欠かせない．リハ医療の対象のなかでは，最も「包括的医療」の必要性が高い疾病の 1 つといっても過言ではない．その「包括的医療」も，増加傾向にある中高齢の頚髄損傷と，若年の脊髄

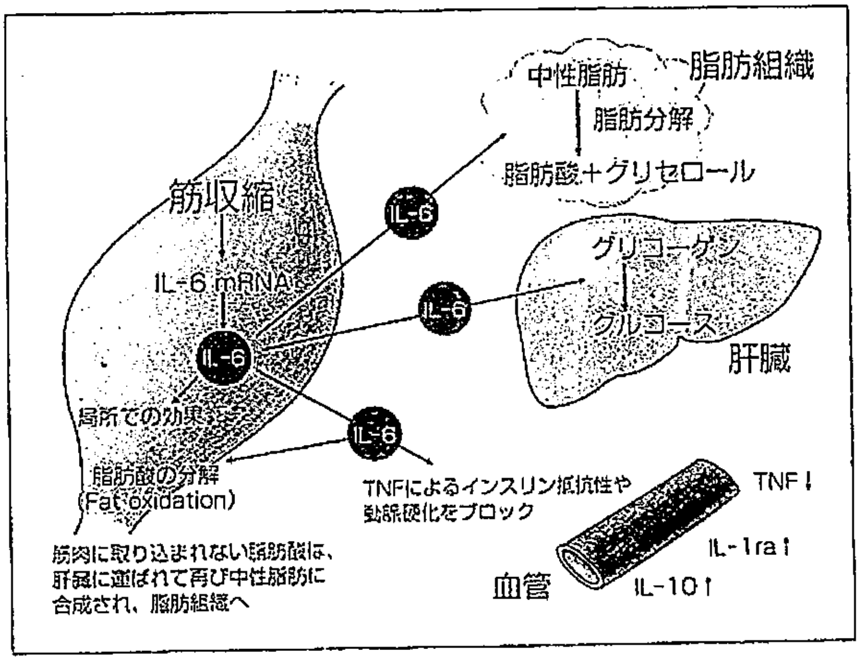


図 3.
マイオカインによる生理学的効果
(文献 18 より改変)

損傷対麻痺者では，目指すゴールが異なるため，当然，両者は分けて考える必要がある．中高齢の頚髄損傷者の多くは，介助を要し社会復帰後は外出の頻度も少なく生活のエリアも狭い．日常生活は，合併症や併存する内科疾患の管理が大きなウェイトを占め，公的なサービスを利用して身体の機能や ADL の維持に努めているのが現状である．したがって，回復期から維持期の入院でのリハ医療は，将来の生活の場所を考慮した「地域密着型の包括的医療」となる．一方，若年の対麻痺者は，障害は残存するものの社会復帰後も体力などの身体的な面や，「参加の制限」のレベルでの発展が大いに期待できる．特に職業復帰や職業リハへの移行が見込まれる者において，急性期から回復期・維持期へ移行する際には，それらを視野に入れたリハ医療機関の選択が理想的で，こちらは「広域型の包括的医療」といえる．

生産年齢にある頚髄損傷者については，「職業復帰」も大きな課題である．昨今，情報技術(information technology：IT)の発展普及により，就労形態も変化しつつある．なかでも SOHO(small office home office)は，重度の障害をもつ頚髄損傷者にとっては非常に有利な環境である．脊髄損傷，特に頚髄損傷の麻痺や合併症に対する理解を示し，ほぼ完全な在宅就労の形態をとる企業も現れ，今や頚髄損傷者の就労も現実的なものとなってきている．

3．生活習慣病の増加

我が国を含めた先進国においては，急性期の初期治療と慢性期における健康管理法の向上により，脊髄損傷者の平均余命は飛躍的に改善している[5]．しかし，それに伴って，社会復帰後の脊髄損傷者における生活習慣病の増加が大きな問題となっており，依然として健常者に比べて死亡率は高いとされている[6]．

心血管疾患は，障害の有無にかかわらず主要な死因の1つであるが，脊髄損傷者は健常者よりもその有病率が高い[7)~10)]．また，健常者よりも若年で発症する傾向があることもいわれている[10]．Myers ら[10]は，脊髄損傷における心血管疾患についての総説のなかで，「症候性心血管疾患の有病率は健常者では 5～10％であるのに対して，脊髄損傷者では 30～50％であった」としている．脊髄損傷者で心血管疾患の有病率が高い大きな理由は，健常者に比べて脂質異常症や糖尿病，内臓脂肪の蓄積のような心血管疾患のリスクを有する率が高いことにある[10)~13)]．それらには，麻痺による不活動の他，交感神経活動の低下や筋肉量の減少による基礎代謝の低下などもかかわっており[10)14)15)]，早急に解決すべき問題である[10]．

本稿では，「筋肉量の減少」について触れておく．2004 年，Pedersen らの研究グループが，運動中に活動している骨格筋の筋細胞でインターロイキン 6(IL-6)が産生，分泌されることを，初めてヒ

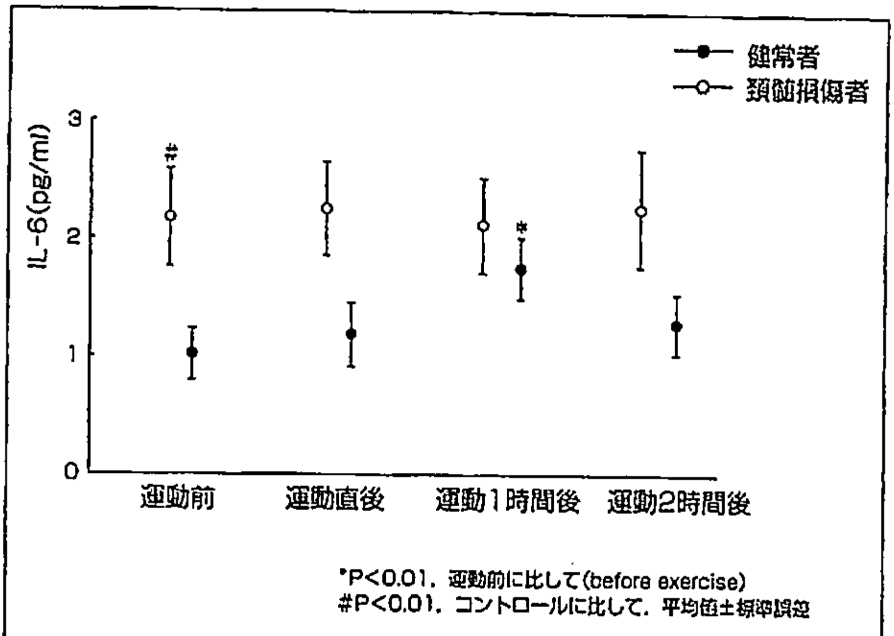


図 4.
頚髄損傷者の20分間の運動における IL-6の変化
(文献15より改変)

トで証明した[16]．現在，IL-6以外のサイトカインも産生されることがわかっており，それらはマイオカインと呼ばれている．インスリン抵抗性の抑制や脂肪の分解，炎症性サイトカインである腫瘍壊死因子産生の抑制などの作用を有し[17]，運動による生理学的効果の一部はマイオカインを介して発揮される(図3)[18]．今や骨格筋は内分泌器官として認識されている[17]．

運動による血中IL-6の上昇は，その時間や強度，運動に動員される筋肉の量などと関連し，筋損傷とは関係がない．脊髄損傷者においては，神経支配を失ったことや活動量の低下により全身の筋肉量は減少しており，IL-6の産生に支障をきたしている可能性がある．Koudaら[15]は，「頚髄損傷者と健常者において，ハンドエルゴメータを用いた運動(最大酸素摂取量の60%の運動強度で20分間)をすると，健常者は運動後に血中のIL-6が増加したのに対して，筋肉量の少ない頚髄損傷者では運動後も増加しなかった」という非常に興味深い報告をしている(図4)．慢性期の脊髄損傷者で生活習慣病が多いことについては，これらの事実が関与している可能性がある．

脊髄損傷者において，心肺機能を維持し，心血管疾患のリスクファクターとなる疾病の発症を防ぐためには，通常の生活で行う活動だけでは不十分であり，効果的な運動の介入や食生活の改善など，健康的なライフスタイルの確立が欠かせない[1)19]．脊髄損傷者における生活習慣病については，社会復帰後の大きな問題として認識されているが，上記のような理由から，脊髄損傷者本人や家族には入院中からその事実と改善策を示しておく必要がある．

合併症の管理

脊髄損傷の合併症は多くの場合，複数生じるが，急性期から存在し経過とともに症状が和らぐものや，亜急性期や慢性期になって初めて出現するものなど多種多様である．したがって，亜急性期以降も，単に「病状が安定した脊髄損傷者を急性期医療から受け入れるだけの医療」では成りたたない．

合併症の管理の良否が，その後の脊髄損傷者の運命を決めていたということをしばしば経験する．特に重度の褥瘡は治癒するまでの期間はいうまでもなく，一旦，治癒した後も瘢痕化した部分は容易に再発を繰り返し，長きにわたってリハ医療の進行を妨げる．本稿では，「生命予後への影響」と「社会参加やQOLへの影響」という観点から，合併症の管理の重要性を述べる．

1．生命予後に影響を及ぼす合併症

呼吸機能障害による感染は，生命予後に大きく影響するため，その管理が非常に重要である．Hartkoppらによると[20]，40年間にわたるフォローのなかで死亡した236例の脊髄損傷者の分析

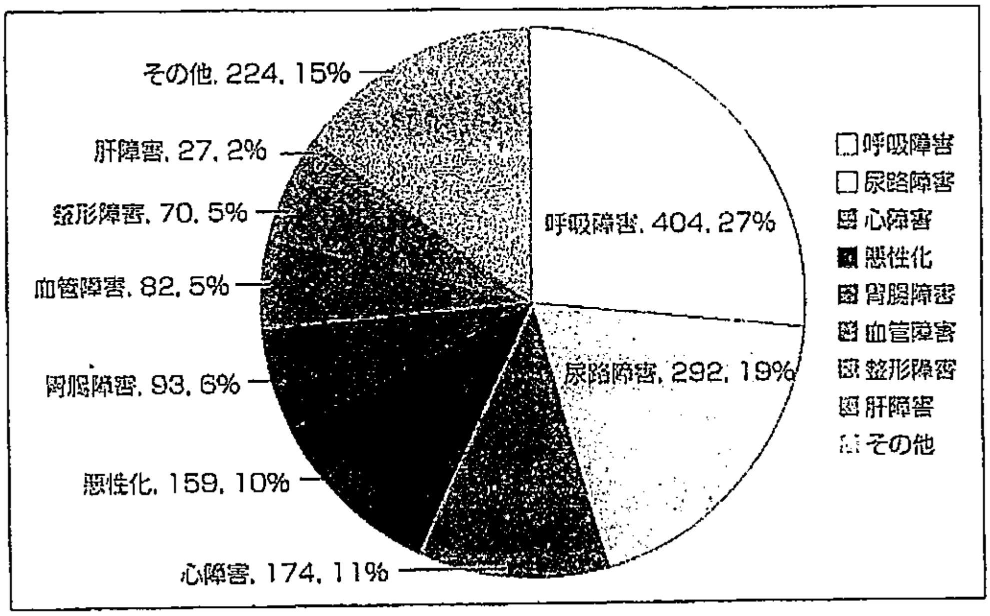


図 5.
脊髄損傷者の死因の集計
(文献22より)

から，最も多い死因は肺疾患，特に肺炎，自殺，虚血性心疾患であったとしている．854 例の死亡者を調査した DeVivo ら[21]の報告においても，脊髄損傷の合併症のなかでは呼吸機能障害による肺炎は主要な死因の 1 つであり，肺炎での死亡は年齢や性別，人種などをマッチさせた一般人口の 37.1 倍であった．

内田[22]は，労災病院および労災リハ作業所を受療し死亡の確認ができた 1,525 例の死因について調査をしている．図 5 は全体の死因の集計，図 6 はそれぞれ頚髄損傷者，胸腰髄損傷者の死因の推移である．まず，全体をみると呼吸機能障害によるものが 27%を占め最も多い(図 5)．頚髄損傷者における推移は，尿路系に由来するものの割合が年々減少し，一方，呼吸機能障害による割合は増加し，最近では半数近くを占めるに至っている(図 6-a)．胸腰髄損傷者では，間欠導尿による排尿管理が確立し，昭和 20～40 年代に半数以上を占めていた尿路系に由来する死亡は減少し，最近では呼吸機能障害や悪性腫瘍による死亡が増加して両者で半数以上を占めるに至っている(図 6-b)．

増加している中高齢の頚髄損傷者においては，「四肢麻痺」そのものに加えて「加齢」「頚椎の手術」「頭部外傷の合併の可能性」など，嚥下障害を引き起こすリスクを抱えており，その評価は欠かせない．呼吸機能障害と嚥下障害の存在下で生じる誤嚥性肺炎は特に注意が必要である．

2．社会参加，QOL に特に影響を及ぼす合併症

脊髄損傷者は，運動機能の回復以外には，排尿・排便，性機能に関する問題と疼痛に関心をもっており，これらは QOL に大きな影響を及ぼしている[23)~25)]．脊髄損傷における排泄に関して，排尿管理は確立された感があるが，排便の問題は生命予後に直接影響を及ぼさないため，多くの場合，医療従事者における関心は薄い．さらに，脊髄損傷者本人も他人に相談しにくいことから，コントロールが不十分なままで社会復帰していることも少なくない．Han ら[26]は，受傷後 6 か月以上経過した脊髄損傷者 72 例における排便管理に関する調査を行っている．それによると，日常生活への影響として，「食事の制限をしている」とした者が全体の 80.0%，「外出が制限される」が 64.6%，「排便管理の難しさと不幸せを感じる」が 48.8%であった．また，Kim ら[27]は，地域で生活する 388 例の脊髄損傷者における排便管理と QOL との関連を調査している．QOL を著しく低下させる要因として，「肛門周囲の皮膚のトラブル」「ガスの漏れ」「便失禁」「長時間の排便」「痔疾患」を挙げ，医療従事者には，これらの予防や治療，特に排便時間の改善を求めている．排便管理で重要なのは，生活のなかでその管理に費やす時間と労力が占める割合をバランスよく設定することである．「便失禁」を過度に意識すると，当然，排便は「長時間」になり，脊髄損傷者の生活や，人生までもが「排便」に支配される．当センターでも，脊髄損傷者は排

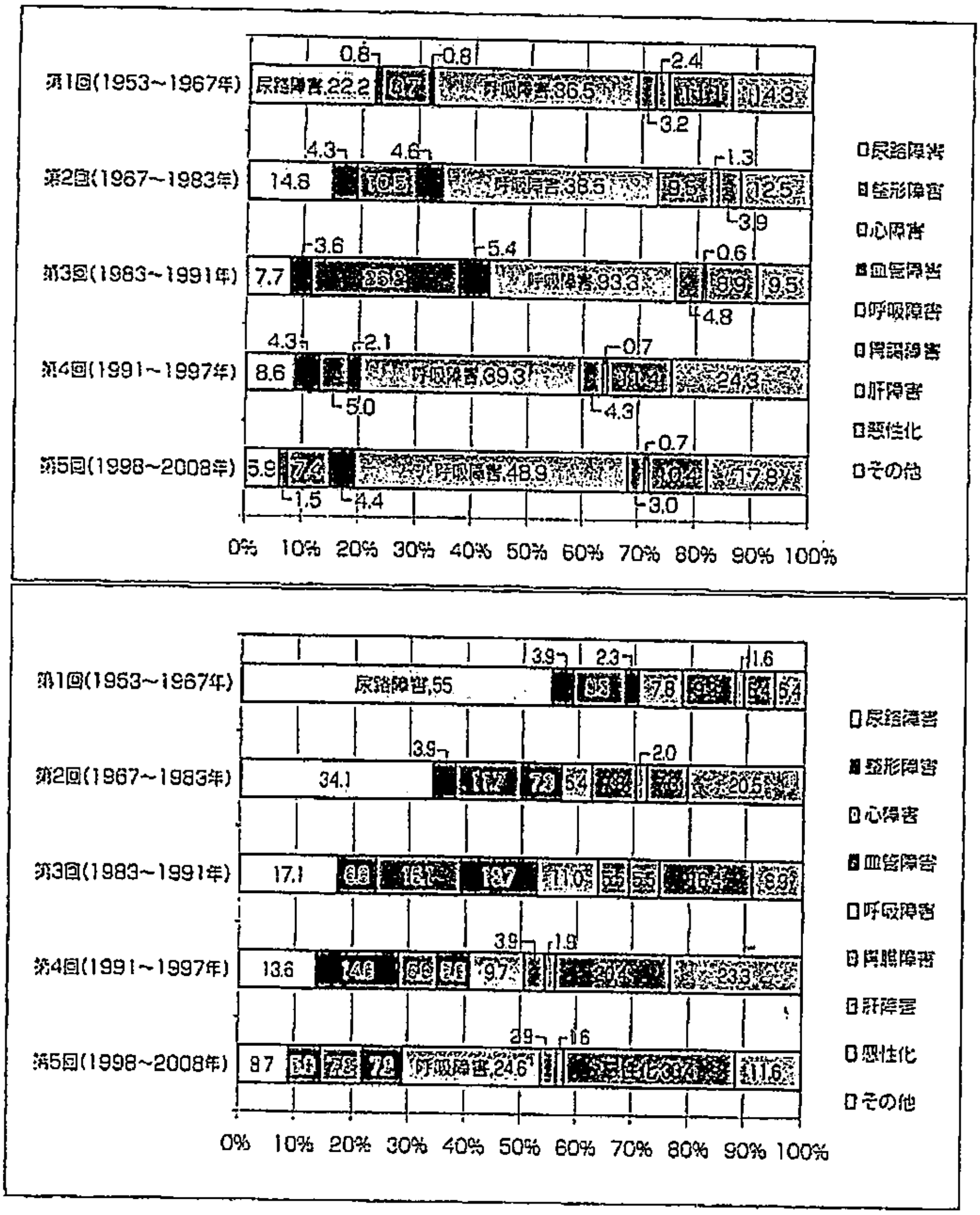


図 6.
脊髄損傷者の死因の推移
a：頚髄損傷者
b：胸腰髄損傷者
（文献 22 より改変）

便にある程度の時間を要し，便失禁も必ず経験する．しかし，排便管理においても，医療従事者が脊髄損傷者と向き合い，ともに「便失禁」や「長時間の排便」を軽減するように努め，脊髄損傷者にその「標準」を示すことができれば，「排便障害」単独で社会参加までも妨げるようなことはほとんどない．

排便障害については，そのコントロールが「良好でない」と感じると社会参加までも妨げること，その点において，回復期から維持期のリハ医療での脊髄損傷者へのかかわりが，人生を大きく左右する可能性があることを知っておく必要がある．回復期から維持期のリハ医療に携わる者は，まずは，脊髄損傷者の「排便障害」に関心をもって欲しい．

3．自己管理の重要性

社会復帰後は本人や家族による管理，いわゆる「自己管理」が主体となる．したがって，「合併症の管理」のゴールの 1 つは「自己管理の習得」である．「排便管理」でも述べたように，合併症の管理に費やす時間と労力は，その他の日常生活とのバランスを考慮して設定される．したがって，「自己管理」は，その予防と治療に関する知識や技術を習得するだけでなく，生活のなかで実践するための応用力も身につけておく必要がある．社会的アウトカムにこだわるリハ医療に，合併症の自己管理の習得のための「指導と教育」は欠かせない．

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PI-LL≦10°, PT＜20°はすべての年齢層に当てはまるのか

目指すべき PI-LL および Pelvic Tilt はすべての年齢層にあてはまるのか？

術後 2 年経過症例からの検討

稲見 聡* 種市 洋*

Are The Optimum PI-LL And PT Values Constant Irrespective of Age Groups?

Satoshi INAMI Hiroshi TANEICHI

Key words：成人脊柱変形(adult spinal deformity), 矢状面アライメント(sagittal alignment), 年齢(age)

成人脊柱変形術後患者 73 例を対象にして，年齢が矢状面パラメータへ及ぼす影響を調査した．術後成績が良好な症例を若年群(65 歳未満)と高齢群(65 歳以上)に分け比較すると，PI-LL(pelvic incidence-lumbar lordosis)(若年群：10°，高齢群：11°)と PT(pelvic tilt)(若年群：25°，高齢群：28°)の値に有意な差がなく，TK(thoracic kyphosis)(若年群：28°，高齢群：38°)は高齢群が有意に大きかった．成人脊柱変形の手術治療は主に矯正固定術であり，手術で固定した角度で長い期間を過ごすことになる．よって，手術における矯正目標値は，年齢層を超越し経年的な変化を加味した値が理想的と考える．

はじめに

成人脊柱変形(adult spinal deformity：ASD)に関する多くの研究により，各種矢状面パラメータの標準値や矯正の目標値が示されている[1-4]．手術における腰椎前弯(lumbar lordosis：LL)獲得の指標としては，pelvic incidence(PI)にマッチした LL の重要性が広く認識され，各種の予測式が示されている[5-7]．一方，臨床においては，PI と LL のミスマッチを呈する症例も多く存在し，それらにおいては，矢状面アライメントの代償作用がさまざまな程度で関与している．このミスマッチとそれに対する代償作用が複雑に関連して患者の QOL に大きな影響を与えるが，この様態はさまざまであり，いまだに不明な点も存在する[8,9]．

Scoliosis Research Society(SRS)-Schwab 分類における sagittal modifier では，PI-LL＜10°，pelvic tilt(PT)＜20° を目標値としているが[10]，実際にはこの基準から外れても QOL のよい症例は多数経験する．また，健常者の矢状面パラメータに関する研究では，年齢層によりパラメータの標準値が異なることが報告され，高齢になるほど PI-LL や PT の値は大きいことが示されている[11]．

本稿では，PI-LL＜10° の妥当性をわれわれが

* 獨協医科大学整形外科学〔〒321-0293 栃木県下都賀郡壬生町北小林 880〕Department of Orthopaedic Surgery, Dokkyo Medical University, School of Medicine

表1　年齢層別の矢状面パラメータの比較

	若年群	高齢群	P値
TK：thoracic kyphosis(°)	28	38	0.045
LL：lumbar lordosis(°)	40	44	0.452
PT：pelvic tilt(°)	25	28	0.363
PI-LL：pelvic incidence-lumbar lordosis(°)	10	11	0.761
DLL-LL：Dokkyo formula LL(°)	3	0	0.289

Wilcoxon 検定

作成したLLとPIの関係式を用いて考察し，さらにASD術後患者を対象にして，年齢が矢状面パラメータへ及ぼす影響を調査する．

▶対象と方法

対象は当院で手術加療を行った，ASDの手術症例73例である．神経筋疾患や慢性関節リウマチの合併症を有する症例，また脊柱変形の主病態が骨粗鬆症性椎体骨折によるものは除外した．平均年齢64.8±8.1歳で，男性17例，女性56例であった．SRS-Schwab分類はL：33例，D：7例，N：33例であった．

術後2年時の以下のパラメータを計測し解析した．計測項目は胸椎後弯(thoracic kyphosis：TK)，LL，PT，PI，PI-LL，われわれが報告したLL矯正目標値算出式[6]：Dokkyo formula(LL=0.6PI+11)から算出したLL(DLL)，DLL-LL，sagittal vertical axis(SVA)，およびOswestry Disability Index(ODI)である．本シリーズの年齢分布を解析すると，中央値：65歳(最大値：80歳，最小値：44歳)であった．年齢層別に各パラメータの比較を行うために，中央値の65歳を基準とし65歳以上を高齢群，65歳未満を若年群として各パラメータの比較を行った(Wilcoxon検定，$P<0.05$)．

▶結果

1. 術後2年時の各パラメータ値

TK：33.1°，LL：38.8°，PT：27°，PI：50.2°，PI-LL：11.4°，DLL：41.2°，DLL-LL：2.4°，SVA：42.8mm，ODI：15.6%(最大値66.7，最小値0，75%分位点25)であった．

2. 年齢層別の矢状面パラメータの比較(表1)

手術後の成績良好例を解析対象とするために，ODIが75%分位点である25以下の症例を抽出し，57例で解析を行った．

高齢群と若年群の比較で有意差を認めたパラメータはTKのみで，PI-LLやPTは年齢層別で有意な差は認めなかった．

▶考察

1. PI-LLについて

ASD手術において適切なLLを獲得するためには，個人固有の骨盤形態であるPIにマッチした指標が必要であり，SRS-Schwab分類においてはPI-LL<10°が提唱されている[10]．これは主に術前のASD患者を対象にして，導き出された指標である．一方，われわれはASD術後患者の成績良好例を対象にして，LL=0.6PI+11の関係式が成り立つことを報告してきた[6]．この2つの式を詳しくみると，近似点と相違点があることがわかる(図1)．

PIが50°の場合では，LLの値は両式ともに約40°と近似する．しかし相違点は，われわれの式では目標とするPI-LLは一定の値ではなく，PIの大きさにより変化することである．つまりPIが小さな値の場合は，LLはPIに近い値が必要になりPI-LL<10°が必須となる．一方，PIが大きな場合はSchwabらよりも小さなLLとなり，PI-LL>10°が許容されることである．PI-LLを矯正の指標として用いる場合，PIが約50°の症例ではPI-LL<10°でよいが，それ以外の場合は

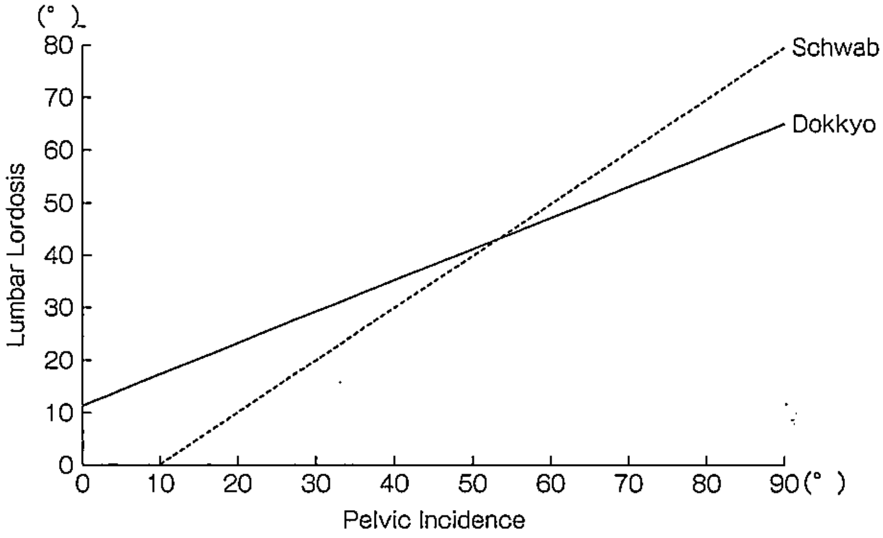

図1　目標とする腰椎前弯の比較
Schwab の式（点線：LL＝PI－10）と Dokkyo formula（実線：LL＝0.6 PI＋11）は，PI が 50° 近傍では LL＝約 40° で一致する．Dokkyo formula では，PI が小さい場合は Schwab の式よりも大きな LL が必要であり（PI-LL は小さい），PI が大きい場合は Schwab の式よりも少ない LL が許容される（PI-LL は大きい）．

前記事項を加味するべきと考えている．DLL は PI の大小も加味した LL の指標であり，われわれは矯正の目標値を考える際に PI-LL のみならず DLL も併せて考えている．

2. 年齢層によるパラメータの比較

PI-LL は高齢群：11°，若年群：10° で，年齢層による差はなく，いずれの群においてもおおむね PI-LL＝10° であった．また DLL-LL は高齢群：0°，若年群：3° で年齢層による差は認めなかった．年齢によらず，DLL は QOL 良好な症例の LL を表しているといえる．一方，TK は高齢群：38° で若年群：28° と，高齢者では有意に大きな値であった（参考データとして挙げると，術前の TK 値は高齢群：17°，若年群：12° と高齢者が大きく，また術直後から術後 2 年での TK 増加量は高齢群：8°，若年群：5° と，有意差はないが高齢者が大きな値であった）．高齢者では加齢性変化により術前から TK が大きく，術後の増加量も多いと考える．

年齢層別に矢状面パラメータを調査した研究によると，経年的に LL は減少し，PT と SVA は増大することが示され，75 歳以上の年齢層では，PT＝28.5° を標準値とする報告がある[11]．本シリーズにおいて年齢層による PT 値に有意差はなく，高齢群：28°，若年群：25° であった（表 1）．これは QOL 良好な症例群の値であるが，SRS-Schwab 分類での PT 値に比較すると大きな値である[10]．本シリーズの術後患者の 2 年経過時においては，PT＞20° でも許容されるといえる．

まとめ

手術における至適な LL を考えるうえで，本研究においては PI-LL と DLL-LL のいずれにおいても，年齢層による違いは認めなかった．ASD に対する手術治療は主に矯正固定術であり，その後の人生を手術で固定した角度で長年過ごすことになる．よって，手術における矯正目標値は，年齢層を超越し経年的な変化を加味した値が理想的であろう．DLL は LL 関連のフォーミュラのなかでは求める LL が小さい部類に入るが[5-7]，若年者と高齢者の両年齢層においてよい指標となっていた．

筋量の減少や下肢関節の可動域の減少は，避けることができない加齢性変化であり，経年的に矢状面グローバルアライメントに大きな影響を及ぼすと考える．本研究でも高齢群で TK は大きな値であり，加齢により胸椎後弯が増加することが予想され，固定上位端の選択に際しては TK と年齢の因子を考える必要がある．また，多くの症例が

PT＞20° でも QOL は良好であったが，長期的には股関節への影響も考える必要があるかもしれない．骨盤後傾は股関節には非生理的環境であり，変形性股関節症との関与も危惧される．さらに長期的な視野で考えると，筋量減少が進行した場合でも代償作用の維持が可能なのか，現在明確な研究はない．これらは今後の長期観察で調べる必要がある．

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原 著　特集　成人脊柱変形　Original Article

Pelvic Incidenceにマッチした適切な腰椎前弯は椎体形状により決定される

Intrinsic Regulator of Physiological Lumbar Lordosis Is a Shape of the Vertebral Body

飯村拓哉　稲見　聡　森平　泰　竹内大作　上田明希
司馬　洋　大江真人　浅野太志　野原　裕　種市　洋

Takuya Iimura, Satoshi Inami, Hiroshi Moridaira, Daisaku Takeuchi, Haruki Ueda, You Shiba, Makoto Ooe, Hutoshi Asano, Yutaka Nohara, Hiroshi Taneichi

要　旨

本研究ではPI-LLミスマッチのない腰椎生理的矢状面アライメントは，椎体形状，椎間板形状のいずれか，または，双方から形成されるかを明らかにする．椎間板変性や椎体骨折のない若年者111例の全脊柱立位側面X線像を用い，腰椎椎体角，椎間板角ほか，各種矢状面，骨盤パラメータを検討した結果，PIにマッチした適切な腰椎前弯は椎体形状により決定されることが明らかになった．

Abstract

Introduction : We hypothesized that physiological lumbar lordosis (LL) matched with pelvic incidence (PI) is inherently regulated by a shape of the vertebral body and the intervertebral disc. The aim of this study was to clarify intrinsic regulator of PI-LL matching.

Methods : Total of 111 young individuals who underwent whole spine standing lateral X-ray with clavicle position were enrolled. Exclusion criteria were : Lenke 3-6 type curve AIS ; spondylolisthesis ; transitional vertebrae ; and disc degeneration. There were 20 male and 91 female patients with a mean age of 15 years (range : 10-25 years). Relationships between PI and vertebral body angle (BA : L1-5) and those between disc angle (DA : T12/L1-L5/S1) was analyzed by using a simple regression model. Post hoc power analysis confirmed the statistical significance when Power was 0.8 or more.

Results : A mean BA in each level was-1.5° in L1, 0.3° in L2, 2.2° in L3, 4.4° in L4, and 9.1° in L5. An average DA in each disc was 2.0° in T12/L1, 3.6° in L1/2, 6.1° in L2/3, 8.0° in L3/4, 9.4° in L4/5, and 8.9° in L5/S1. There were statistically significant relationship between PI and BAs : BAL1 ($p=0.0095$, Power 0.84), BAL2 ($p<0.0001$, Power 1.0), BAL3 ($p<0.0001$, Power 1.0), BAL4 ($p<0.0001$, Power 0.99), and BAL5 ($p=0.0301$, Power 0.71). Whereas, there were no statistically significant relationship between PI and DAs.

Conclusion : Intrinsic regulator of physiological lumbar lordosis matched with PI was a shape of the vertebral body.

Key words : 成人脊柱変形 (adult spinal deformity)，矢状面アライメント (sagittal alignment)，腰椎前弯 (lumbar lordosis)

獨協医科大学医学部医学科整形外科学〔〒321-0293 栃木県下都賀郡壬生町北小林880〕Department of Orthopaedic Surgery, Dokkyo Medical University
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はじめに

生理的矢状面アライメントにはpelvic incidence (PI)にマッチした腰椎前弯(LL)が必要とされ，この脊柱骨盤適合が人間工学的グローバルバランスを維持する基本となる[1)2)]．一方，LLの形状はsacral slope(SS)の影響を強く受けて決定されることも示されている[3)]．LLは各レベルの腰椎椎体角と椎間板角の総和である．腰椎椎体角，椎間板角に関する研究はあるものの[4)]，これらと矢状面，骨盤パラメータの関連を検討した研究はほとんどない[5)]．

本研究の目的は，PIにマッチした生理的LLがどのように形成されているか，すなわち，椎体形状，椎間板形状，あるいは，その双方により形成されるかを解明することである．

対象と方法

本研究は獨協医科大学病院生命倫理委員会の承認(承認番号：27089)のもと実施された．2006年4月から2015年3月に椎間板変性や椎体骨折のない若年者でclavicle position[6)]による全脊柱立位側面X線像が得られた111例を対象とした．胸腰椎・腰椎に主カーブを有するLenke 3～6型思春期特発性側弯症，腰椎分離症，明らかな椎間板変性，移行椎例は除外した．男20例，女91例で平均年齢15歳(10～25歳)であった．脊柱変形パラメータとして胸椎および腰椎側弯Cobb角，矢状面パラメータとしてsagittal vertical axis(SVA)，胸椎後弯(TK)，LL，PI，pelvic tilt(PT)，SS，椎体角(BA：L1～5)，椎間板角(DA：T12/L1～L5/S1)(+：前方開角)を計測した(図1)．BA，DAのLLに占める割合(%)はBA/LL，DA/LLとした．BA，DA，BA/LL，DA/LLとPIの相関を解析した．統計検定は対応のあるt検定，単純回帰分析を行った．すべて事後の検出力分析を行い統計学的有意差はp値でなくPower(1－β)＞0.08を有意とした．統計検定にはJMP 10.0.2とG*Power 3.1を用いた．

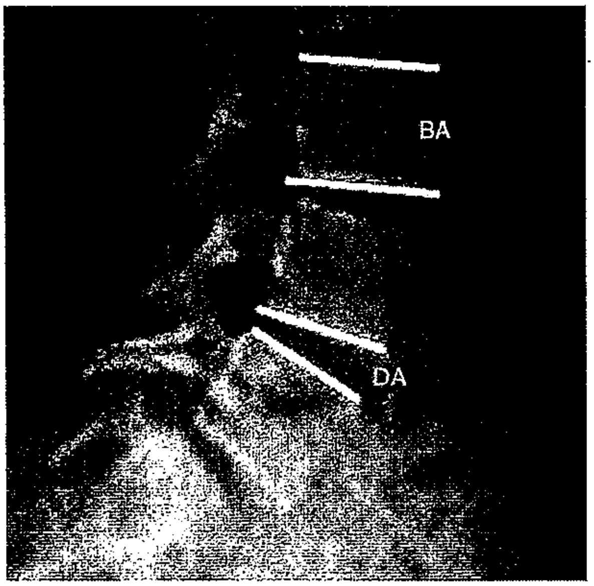


図1　椎体角(BA)と椎間板角(DA)の計測

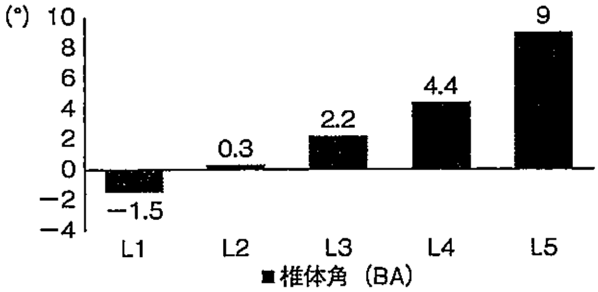
結　果

各パラメータの平均値を示す(表1)．PI-LLミスマッチはなかったが，TKは小さい傾向があった．BA，DA(図2a，b)，BA/LL，DA/LLの平均値を示す(図3a，b)．BAはL1がわずかな後方開角，それ以外は下位になるほど有意に前方開角が大きくなった．DAはすべて前方開角であった．T12/L1からL3/4までは有意に大きくなったがL3/4より下位は8～9°でほぼ一定だった．PIとLLは高い正の相関を示し，LL＝0.39PI＋35.7が示された(図4)．PIとBAの相関を示す(図5)．L1からL4で有意な相関を示し，PIが大きくなるにつれ椎体前方開角が有意に大きくなった．一方，DAは全てでPIと相関を示さなかった．PIとBA/LLはL1から3で正の相関を示した(図6)．

表1　脊柱変形パラメータ

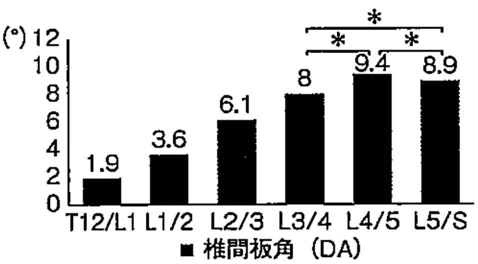
胸椎側弯Cobb角	34±24°
腰椎側弯(L1～S1)Cobb角	15±12°
SVA	－2±2 cm
TK	16±10°
LL	54±10°
PI	47±12°
PI-LL	－7.1°

PI-LLミスマッチはなく，TKは小さい傾向があった．



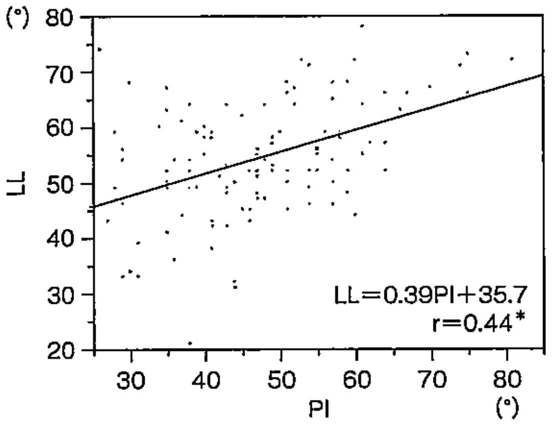
(all combinations p<0.001, Paired t-test)

図2a
BAは下位になるほど有意に前方開角が大きくなった.



(*N. S., all other combinations p<0.001, Paired t-test)

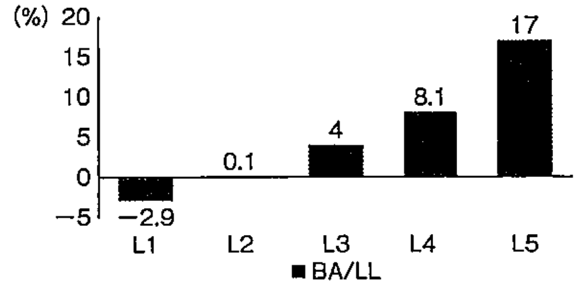
図2b
DAはT12/L1からL3/4までは有意に大きくなったがL3/4より下位は一定であった.



(*1−β>0.08)

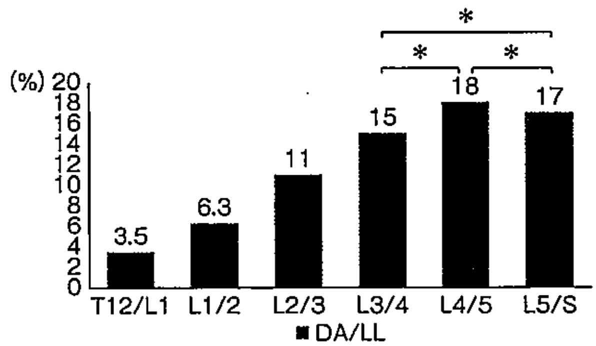
図4　PIとLLの相関
PIとLLは高い正の相関を示した.

PIが大きくなると上位腰椎の椎体前方開角がLLに占める割合が相対的に大きくなった．PIとDA/LLは有意な相関を示さなかった.



(all combinations p<0.001, Paired t-test)

図3a
BA/LLは下位になるほど有意に前方開角が大きくなった.

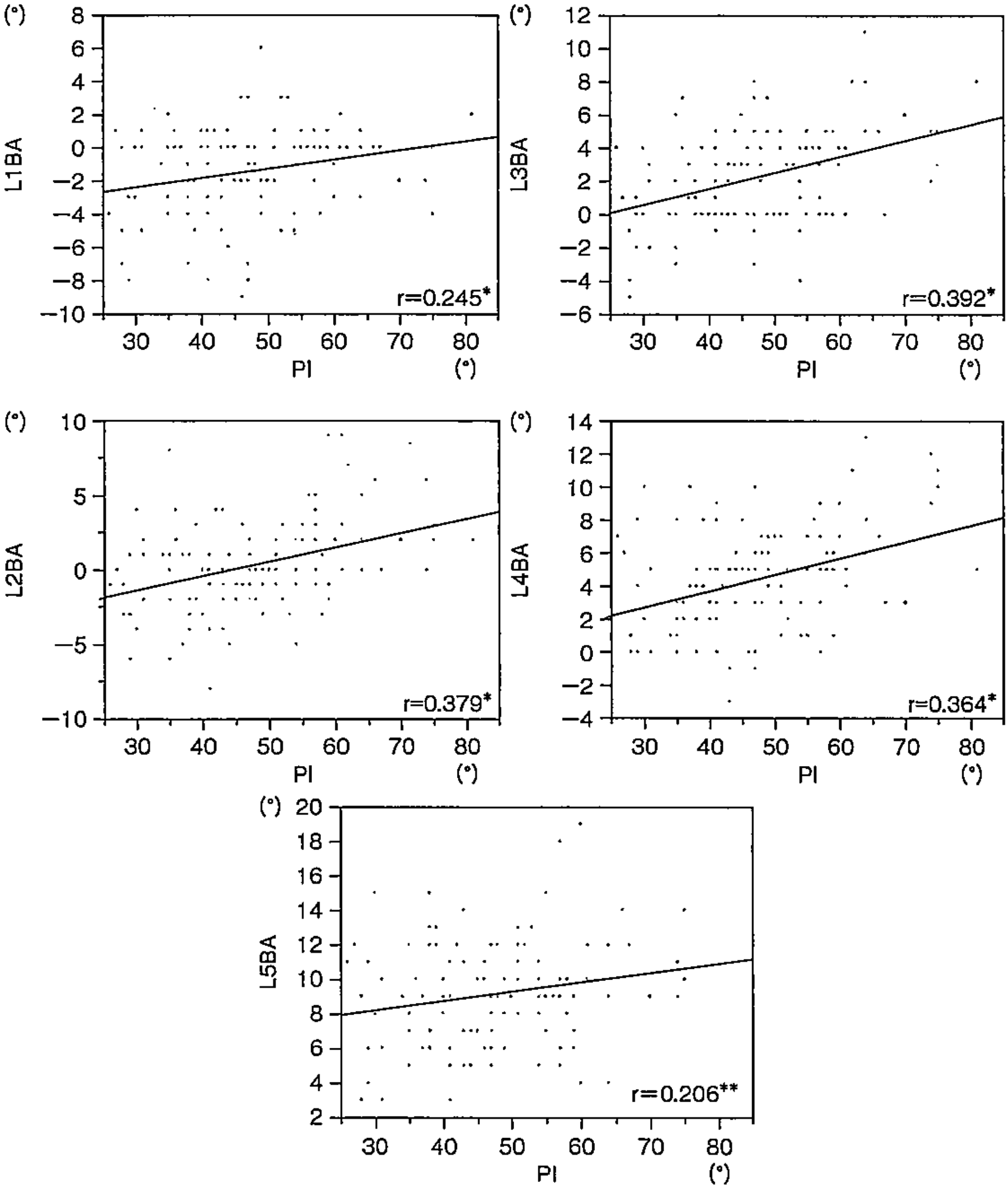


(*N. S., all other combinations p<0.001, Paired t-test)

図3b
DA/LLはT12/L1からL3/4までは有意に大きくなったがL3/4より下位は一定であった.

考　察

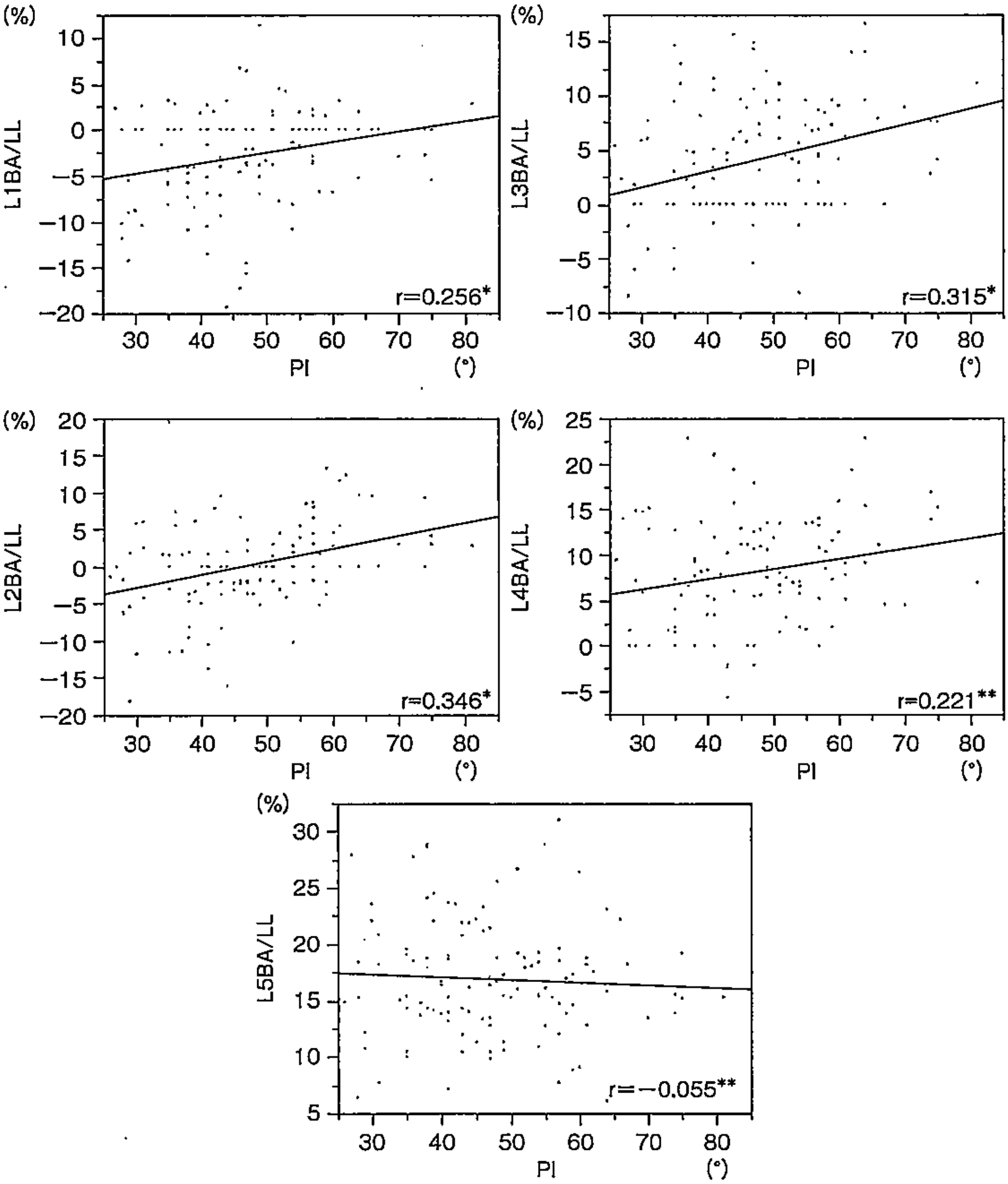
Roussoulyらの述べるように正常な成人ではPIはLL, SS, PTと正の相関関係にある[3]．Mac-Thiongらによると正常若年者ではPI：49.1±11.0°，LL：48.0±11.7°，SS：41.4±8.2°，PT：7.7±8.0°と各パラメータの平均値は成人と異なるも，PIと各パラメータの相関はLL($p<10^{-15}$)，SS($p<10^{-15}$)，PT($p<10^{-15}$)と成人同様に高いとした[7)8)]．PI-LLミスマッチのない本シリーズでもPIとLLは高い正の相関を示した．本シリーズで得られた若年者のPI-LLフォーミュラ(LL=0.39PI+35.7)は以前に示されたLegayeら(LL=0.6PI+35.4)[9)]や大和ら(LL=0.45PI+31.8)[10)]のものと近似している．このことから生理的脊柱骨盤適合例では，腰椎前弯をPIの一次方程式で表すとPIの係数は0.5前後であると推察される．ま



(*1−β>0.08, **N. S.)

図5　PI と BA の相関
PI と BA は L1から L4で有意な相関を示し，PI が大きくなるにつれ椎体前方開角が有意に大きくなった．

た．「手術成績の最低保障ライン」の指標を示した獨協フォーミュラ(LL＝0.59PI＋11.1)[11]でも，PI の係数は同様であった．これらのデータは脊柱骨盤適合例の PI の係数を 1 としている Schwab らのフォーミュラ[12]は生理的でない可能性を示唆している．BA と PI は高い相関を示したが，DA は相関を示さなかった．このことから，PI に適合した LL は椎間板形状ではなく，主に椎体形状により決定されることが明らかとなった．さらに，BA/LL と PI の相関は上位腰椎(L1～L3)のみでみられたことは興味深い事実である．すなわち，PI が大きな例では，下位腰椎のみの前方開角では限



(*1−β>0.08, **N. S.)

図6　PI と BA/LL の相関

PI と BA/LL は L1から L3で正の相関を示した．PI が大きくなるにつれ上位腰椎の前方開角が LL に占める割合が有意に大きくなった．

界があるため，相対的に上位腰椎椎体の前方開角を大きくすることにより PI にマッチした LL 形成が行なわれているものと考えられる．この点に関して Anwar らは PI の大きな例は上位腰椎において椎体角と椎間板角の和である motion segment (MS) の割合が大きく，下位腰椎において MS の割合が小さかったという同様の報告がある[5]．

本研究の臨床応用を考察する．de novo 腰椎変性後側弯症の基本的病態は椎間板の非対称性変形であるが，椎体骨折や椎体変形を伴う例は少なくない．本症の変形矯正術では，椎体骨折などによる矢状面椎体楔状変形がないか軽度の例に対する

矯正は基本的に椎間板で行う．すなわち側方腰椎椎体間固定術(LIF)などが適応となり[13]，その際必要な前弯角は中下位腰椎では概ね10°，上位腰椎では5°程度となる．一方，椎体骨折などによる著しい椎体変形を伴う例では経椎弓根的椎体骨切り術(PSO)や脊柱骨切り(VCR)などの椎体骨切り(3カラム骨切り)術が適応される[13]．

本研究は，PIにマッチした生理的腰椎前弯がどのように形成されるかを調査するため，変性およびPI-LLミスマッチのない平均15歳の若年者を対象とした．しかしながら，正常若年者のみが対象ではなく，胸椎カーブを有する思春期特発性側弯症が多く含まれるため，TKがやや小さいなど，完全に生理的な矢状面アライメントを再現していない可能性がある．

まとめ

PIにマッチしたLLは椎体形状により決定されることが明らかとなった．

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LLIFの手術手技*

XLIF

森平　泰**　種市　洋

はじめに

椎間板の変性や破綻を主因とした腰椎疾患に対して，側方経路腰椎椎体間固定（lateral lumbar interbody fusion：LLIF）を応用した報告が増加している．LLIFは2001年にPimentaが内視鏡を用いた神経モニタリングなしの手技で初めて報告し，その後レトラクターの改良と神経モニタリングシステムの開発を経て，より安全で系統的な手技extreme lateral interbody fusion（XLIF）となって普及した．2006年のXLIFの初めての報告後[4]，従来の前方椎体間固定（anterior lumbar interbody fusion：ALIF）や後方からのposterior lumbar interbody fusion（PLIF）/transforaminal lumbar interbody fusion（TLIF）に代わる低侵襲手術として，良好な成績が数多く報告されている[1,6,10]．

XLIFは，ALIFの手技を小皮切かつ直視下に行えるように発展させたもので，後腹膜臓器や大血管を大きく展開することなく脊椎に到達することで，前方手術の侵襲と合併症リスクを軽減できるとされている[2,4]．また，後方からの椎体間固定術と異なり，椎弓や椎間関節などの脊椎後方要素を温存しながら，硬膜や神経根をよけることなく，面積の大きなケージを椎体間に設置することができる[5,6]．

XLIFの利点は，そのままALIFの利点ともいえるが，椎間板側面から広範囲な椎間解離が可能で，ケージを椎体外縁のring apophysisを支持する形で設置することで，椎間を介して強力に変形を矯正できること，前・後縦靱帯を温存しながら椎間高を獲得することでligamentotaxisによるすべりと回旋の矯正ができること，脊柱管や椎間孔の間接的神経除圧が可能であること，出血が少ないこと，骨癒合率がよいことが挙げられる[1,2]．

これらの利点を反映して，LLIFは2013年にわが国へ導入された後，3年間で6,000例を超える症例に行われたが，一方で2016年1月にXLIFにおいて腸管損傷からの死亡事故が報告された．XLIFは部品の自主回収を行い一時中断されたが，その後承認条件の下に再開されている．本稿では，XLIFという革新的新規術式を安全かつ有用に行うために，再度，手術手技についての重要点を確認していきたい．

Key words
XLIF（extreme lateral interbody fusion）
手術手技（surgical technique）
成人脊柱変形（adult spinal deformity）

* Surgical Technique of XLIF for Lumbar Disease

** 獨協医科大学整形外科学〔〒321-0293 下都賀郡壬生町北小林880〕／Hiroshi MORIDAIRA, Hiroshi TANEICHI：Department of Orthopaedic Surgery, Dokkyo Medical University

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表 1　XLIF の適応疾患

・腰椎変性すべり症・腰椎分離すべり症 (Grade II 以下)
・腰椎変性後側弯症を中心とした成人脊柱変形
・椎間板性腰痛
・固定隣接椎間障害
・PLF/PLIF/TLIF 後の偽関節や再手術症例
・後方除圧術後の再狭窄や椎間不安定症例
・化膿性椎間板炎
・透析脊椎症
・関節リウマチ
・その他

XLIF の適応

XLIF の適応は，椎間板の変性や破綻を主因としたすべての腰椎疾患である．感染症症例であれば，XLIF ケージの代わりに自家腸骨片の挿入に改変するなど，従来の ALIF の多くの手技に応用できる．後方手術の再手術においては，癒着した神経組織を展開する必要がない本手術は特に有用である[10]．表 1 に適応疾患を示す．

適応の限界は，L5/S1 椎間（仙骨の腰椎化した L5/6 椎間はときに可能），アプローチを阻害する血管走行異常症例や，high iliac crest 症例，後腹膜腔の癒着（腎臓手術後など），高度のすべり症である．すべりが大きくなると，上下の椎体の重なりがケージ前後幅 18 mm に不足してくる[6]．High iliac crest 症例に対する L4/5 椎間施行においては，レトラクターを椎間板に対して垂直に設置することを基本とする XLIF より，腸骨陵を避けて前側方にレトラクターを設置する oblique lateral interbody fusion（OLIF）に分がある．同様に，すべり症や後弯症の L4/5 椎間にてしばしば遭遇する，いわゆる rising psoas sign 症例においても，大腰筋を前方からよける OLIF に分があり，大腰筋を割いて進入する XLIF では大腰筋とともに腰神経叢が前方に位置するためレトラクターの設置が困難な症例がある．

一方，XLIF は左右を問わないが，OLIF は前側方から進入するため，大静脈を避けた左進入を基本とする．椎間の傾斜や椎体の回旋のために，左からの LLIF 施行が困難な変性側弯症症例において，XLIF の右進入を選択できる利点は大きい．XLIF の最も得意とする疾患は，低侵襲に椎間を介して強力な矯正が可能な成人脊柱変形であり[2,5,8,9]，本稿では XLIF に加えて，後方から open の Ponte 骨切り（全椎間関節切除：Schwab Grade 2 骨切り[7]）を加えた hybrid 法の手術成績についても言及したい[3]．

XLIF の手術手技

1 患者の体位と透視の確認

左右どちらからも進入できるが，術前の全脊柱 X 線でターゲットとする椎間の傾きや進入の妨げとなり得る肋骨および腸骨の位置を，MRI，CT で大血管と腰神経叢の位置を確認し，総合的に進入側を決定する．

X 線透視可能なベッド上に患者を正確な側臥位にしてテープで固定する．腸腰筋を弛緩させるため，股関節および膝関節は 30 度程度の屈曲位で固定する．腸骨稜と大腿骨大転子の間で通常 20〜30 度程度ジャックナイフ位とすることで，腰椎椎間への進入が容易となる．ただし，過度のジャックナイフ位は大腰筋や腰神経叢を緊張させ術中操作による侵襲を高めるため，注意を要する．肋骨や腸骨がレトラクター設置の妨げとなる場合は，必要十分な量の骨切除をためらわずに行い，移植骨とすればよい．

XLIF 手技中の正確な X 線透視は，合併症回避の要である．垂直透視で進入椎間の正 lateral 像が得られてはじめて，術者は安全で的確な位置にレトラクターを設置できる．同様に，水平透視で進入椎間の正 AP 像が得られることではじめて，術者は安心して反対側の線維輪や骨棘を切りにいける．変形症例では，各椎間で回旋の程度が異なり，また，矯正が加わることによって回旋の度合いも変化するため，別椎間に移る際，その都度，手術台を操作して正確な X 線透視を確認する必要がある．

2 後腹膜アプローチ

術者は患者の背側に立つ．原法の 2 皮切アプ

ローチでは，まず後外側の副皮切から後腹膜腔に入り，そこから入れた術者の指を頼りに，椎間板の直上にレトラクター設置用の主皮切をあけて，ダイレーション後にレトラクターを設置する．しかし，このアプローチは，主皮切からレトラクター設置までのダイレーション操作が術者の指を頼りとしたブラインド操作であり，剥離が不十分であると臓器損傷が生じる可能性がある．ダイレーション操作は主皮切を少し広げて，直視下に後腹膜腔の十分な剥離と大腰筋の位置を確認しながら行うことを勧めたい．

1皮切アプローチは，椎間高位で椎体側面を前後3等分し，後縁から1/3の部位を中心に切開を加える．皮膚切開後は，電気メスを使用せずに鈍的に皮下を展開し，外・内腹斜筋，腹横筋を同定して筋層ごとに展開し，腹横筋膜を鈍的に割くと後腹膜腔に達する．1皮切アプローチで直視下に後腹膜腔に到達していると，後外側の副皮切をあけるメリットはなく，最近はもっぱら1皮切アプローチを行っている．

後腹膜腔に到達したら，後腹膜脂肪内で示指を滑らせて，横突起の前面，第12肋骨，腸骨の内壁を触り腹膜の剥離を確認する．綿球を用いて後腹膜脂肪を腹膜および腹腔臓器とともに前方へ落とし込み，大腰筋の側面を展開する．

③ 経大腰筋間進入とMaXcessレトラクターの設置

XLIFでは必ず，腰神経叢を背側によけながらダイレーターを用いてMaXcessレトラクターを設置し，レトラクターの開大で腹側の大腰筋を前方に押し分けて椎間板を展開する．X線透視下に椎間高位を確認し，1stダイレーターでどの位置で大腰筋を分けるかを，神経モニタリングを用いて決定する．ダイレーター先端からの電気刺激にて，モニターの数値と色で，容易にダイレーターからの腰神経叢の方向と近さが認識できる．レトラクター設置位置は後縁から1/3の部位を狙うが，神経叢が腹側では感知されず，背側に感知される位置まで前方にずらしていく必要がある．神経叢を背側によけた位置で，ガイドワイヤーを1stダイレーター内に通して椎間板内に刺入して位置を固定し，続いて電気刺激で確認しながら2nd，3rdダイレーターを用いた後レトラクターを設置する．

レトラクター設置後にX線透視lateral像で椎間板における前後の位置を確認した後に，AP像で椎間板への設置角度が平行かを確認する．レトラクターが腹側に設置された場合は，レトラクターを背側の腰神経叢を包んだ大腰筋ごと背側に少しばかりスライドさせることができる．この場合は，背側の横突起との間で腰神経叢が挟まれることに十分留意して，手際のよい操作が求められる．光源を設置したらレトラクター内を直視下に覗き込み，軟部組織をブレードの背面によけ，必要に応じてバイポーラで血管を凝固する．電気刺激用ボールプローベで神経の位置を確認した後に椎間板shimでレトラクターを最終固定し，その後レトラクターを腹側に優しくゆっくりと開大して，椎間板側面を必要十分の範囲で展開する．最後に，前方レトラクターを椎間板側面から前縦靭帯に向かって沿わせて設置して，腹側の大血管や尿管をよける（図1）．

④ 椎間板掻爬

ケージと同じ前後径であるボックスカッターにて椎間板線維輪の切除範囲をマーキングした後，メスで線維輪を切開し鉗子で除去する．最初にコブエレベーターを用いて頭尾側の軟骨終板を骨性終板から剥離しておくことが，確実な椎間板内掻爬に効果的である．またこのとき，X線透視AP像で確認しながら反対側の線維輪まで解離しておくことは，椎間を平行に開大するために必要である．小さめのトライアルから徐々に椎間を拡げていくと，直視下に椎間板内の残存する髄核や軟骨終板が確認しやすい．過度の椎間開大で前縦靭帯が断裂するとケージが不安定となるので注意を要する．ラスプやリングキュレットは，残存組織の除去に有効だが，骨性終板を損傷しないように丁寧に用いる．

⑤ ケージ挿入

トライアルを徐々に大きくし，至適な緊張のサ

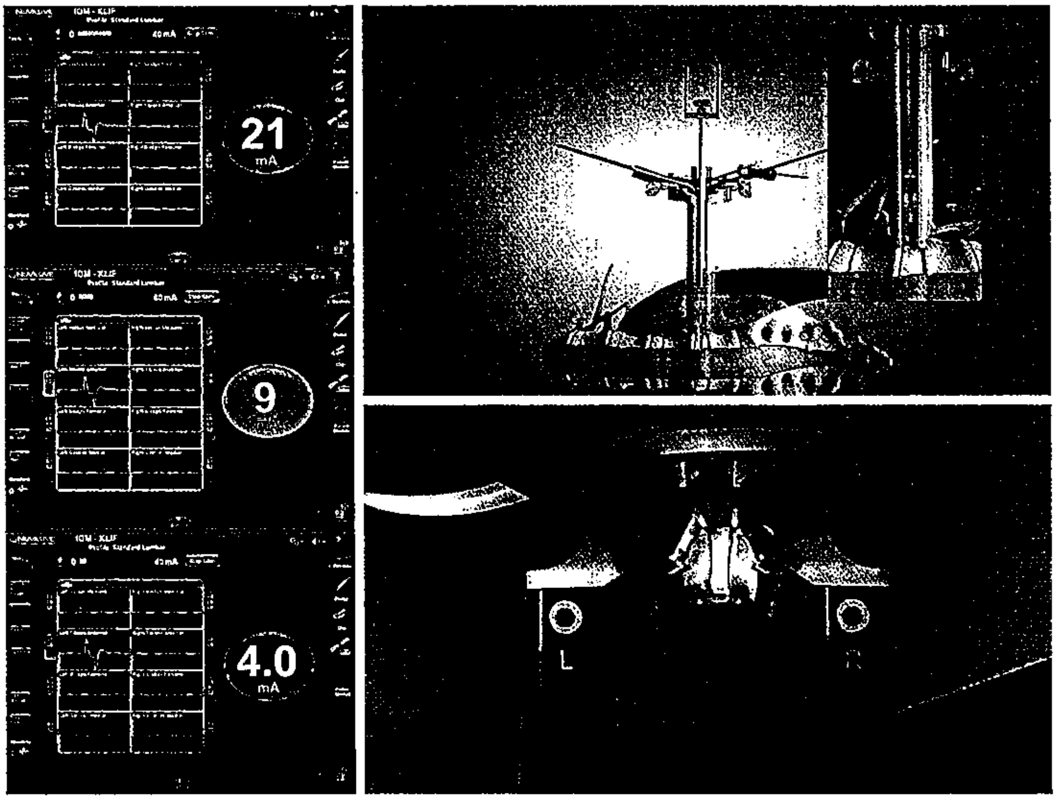

図 1 神経モニタリングと MaXcess レトラクターの設置

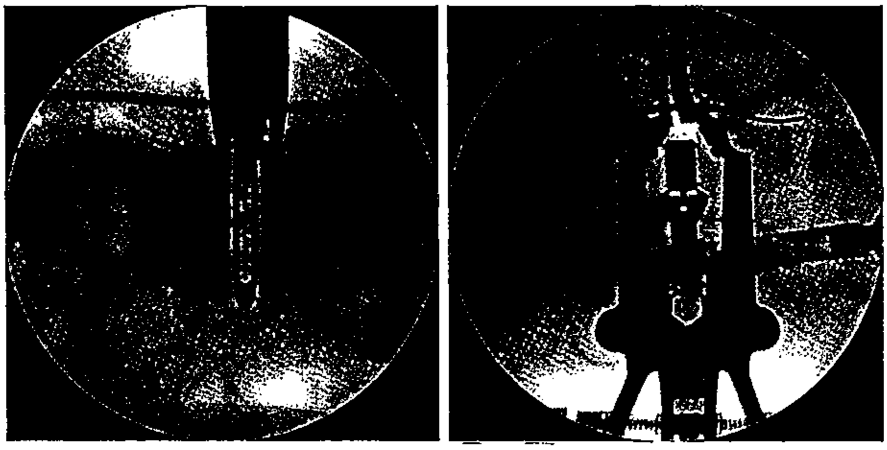

図 2 X 線透視によるケージ位置の確認

イズでケージの高さを最終決定する．トライアルの時点で，X 線透視 AP 像だけでなく，一度だけトライアル支持器をはずして lateral 像で前後の位置を確認しておくことを勧めたい（図 2）．狙った位置になければ，この時点であればケージの位置と高さの修正が可能である．最終決定したケージ内に移植骨を充填し，スライダーを用いてケージを挿入する．

成人脊柱変形への応用（図 3，4）

われわれは，成人脊柱変形の矯正に応用する LLIF として，基本的には XLIF を用いている．斜めに進入する OLIF は，椎間板進入口付近から深部は直視下に確認できず，透視下にシェーバーを用いて椎間板掻爬を行うが，椎間板の真横から進入する XLIF は，レトラクター越しに直視下に

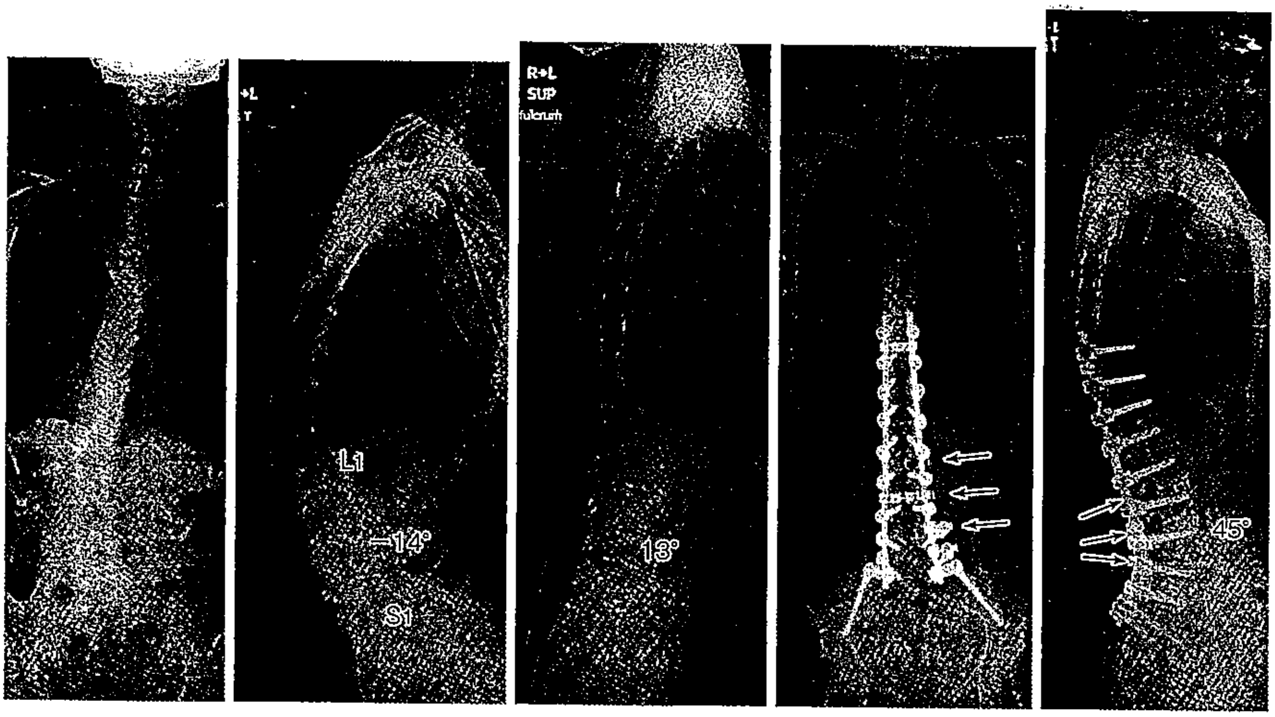

図 3　68歳，女性
右側からのL2/3/4/5のXLIFを施行した後に，後方からL2/3/4/5のPonte骨切りを併用した後方矯正固定術（T10-腸骨）を施行．出血量は1,076 mlであった．

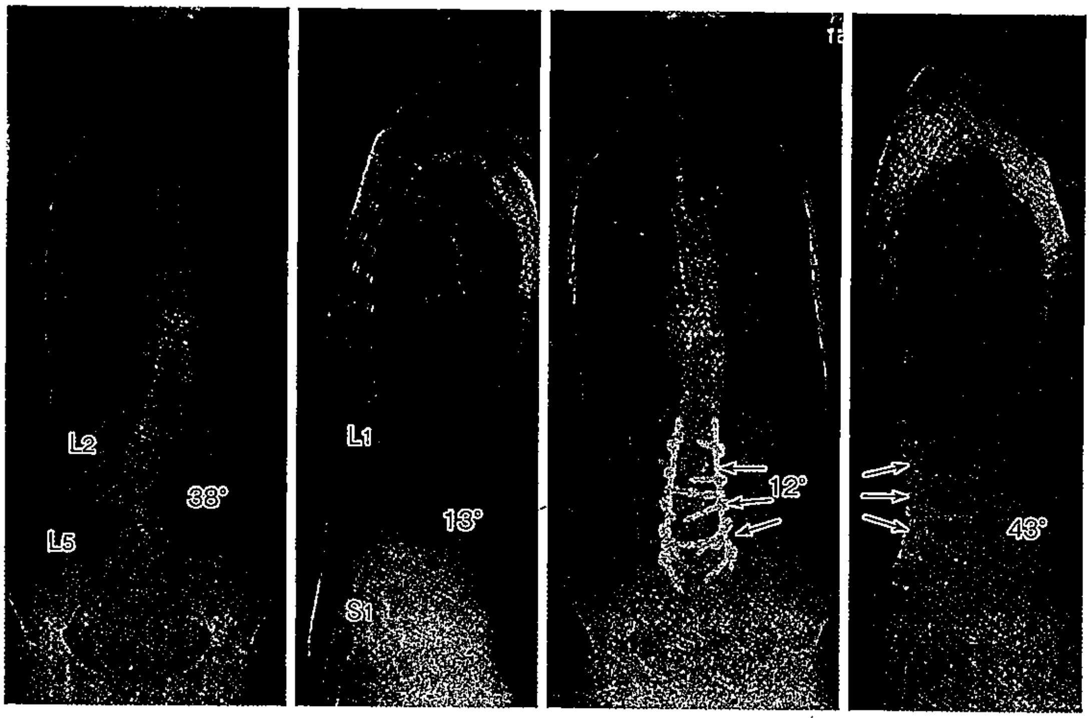

図 4　63歳，女性
右側からのL2/3/4/5のXLIFを施行した後に，後方からL2/3/4/5のPonte骨切りを併用した後方矯正固定術（L1-S1）を施行．出血量は720 mlであった．

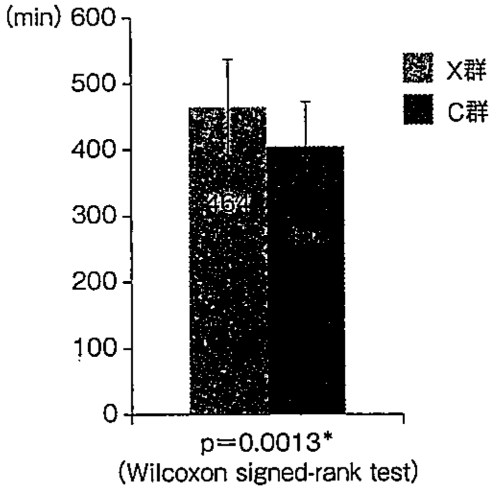

図 5　総手術時間

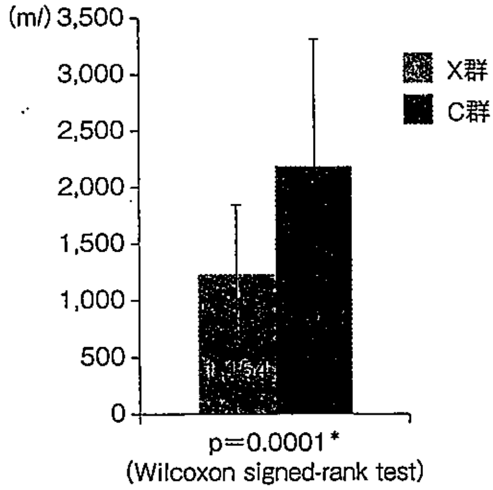

図 6　出血量

椎間板内を反対側まで確認しながら掻爬が行える．このことは，骨粗鬆症を合併することの多い高齢者において，骨性終板損傷の発生を防ぎつつ，広範な掻爬と前方解離ができる XLIF の利点である．変性すべり症など通常の変性疾患と，変形矯正への応用で大きく異なるのは，側弯と椎体回旋の存在である．高度変形症例では，進入椎間の回旋変形を補正するために，大きく傾いた手術台に患者をテープで括りつけながらの操作となる．時間経過とともに体位の維持が難しくなるため，手際のよい手術操作が求められる．

XLIF に続いて施行する後方手術では，われわれは基本的に open で施行している．確実な後方骨移植と，後方からの解離が可能である．後方要素の必要十分な解離を行うことは，骨脆弱性のある脊椎に挿入されたインプラントに無理な力が加わるのを防ぐ．解離が不十分な状態でインプラント任せの矯正を行えば，スクリューのゆるみや骨折を生じ，不十分な矯正で手術を終えることとなる．

腰椎前弯を獲得するために，4 点フレーム上で，股関節を十分に伸展させた体位をとる．変形脊柱の可動性の増大と同時に移植骨を得るために，固定範囲の棘突起と棘上棘間靭帯を切除し，下関節突起の切除をルーチンに行う．Pelvic incidence (PI) にマッチした腰椎前弯作成のために，術前の柔軟性評価にて，体位で得られる腰椎前弯に加えて，どれだけの前弯角度を獲得すべきなのか計算しておく．先行した XLIF によって前方開大した椎間に，Ponte 骨切りを加えて後方短縮させることで，効果的に前弯を獲得できる．XLIF が施行できない L5/S や，ときに L4/5 に，腰仙椎部の側弯の矯正と全周性固定を目的に，必要に応じて PLIF・TLIF を施行する．後方インプラントの設置の際には，至適な前弯をつけたロッドに，通常尾側アンカーから cantilever technique にて連結していき，ロッドの rotation と *in situ* bending にて冠状面のグローバルバランスを修正した後に，さらにスクリュー間に圧縮力をかけて前弯形成を加える．椎間孔狭窄による神経根症状が出現する危険があるため，XLIF による椎間板高の増大だけでなく，上関節突起を切除しておくことで，心置きなく腰椎前弯を形成することができる．また，適応外である L5/S に加えて，L4/5 においても XLIF 施行が困難な症例が少なからず存在するが，そうした症例では，上中位腰椎で XLIF によって強力に側弯矯正されることで，残った腰仙椎部側弯によるバランス悪化（oblique take-off）が生じることがある．XLIF による側弯矯正の偏りが最後まで残らないように，後方手術の際に十分注意を払う必要がある．

表 2　周術期合併症

	X 群	C 群
Major		
手術部位感染（深部）	1	1
血管損傷（要塞栓術）	0	1
脳梗塞	1	0
その他（深部静脈血栓症など）	2	3
Minor		
手術部位感染（表層）	1	1
ケージの脱転	1	—
術中大量出血（>3,000 m*l*）	0	8
一過性の知覚障害	12	—

成人脊柱変形に対する XLIF と open の後方矯正術による hybrid 法（従来法との比較）

1 対象および方法

XLIF と後方 open 手術による hybrid 法を施行した矢状面グローバルアライメント異常のある成人脊柱変形 40 例（X 群）を対象とした．年齢は平均 67.3 歳（49〜82 歳）で，性別は男性：9 例，女性：31 例であった．SRS-Schwab 分類では，L（TL/Lumbar only）：17 例，D（Double curve）：4 例，N（No major coronal deformity）：19 例であった．一方，従来法を施行した成人脊柱変形の中から，年齢（±5 歳），性別，SRS-Schwab 分類で 1：1 にマッチングさせた 40 例を C 群として，X 群と周術期の安全性と矯正効果について比較した．検討項目は，手術侵襲，周術期合併症と，術前・術後 4 週時の変形矯正のパラメータである．

2 結果

X 群では XLIF を平均 2.2 椎間に施行し，固定椎間数は平均 6.7 椎間であった．C 群では 13 例で 3 カラムの骨切りを施行し，19 例で後方から多椎間の PLIF を行い，固定椎間数は平均 7.6 椎間であった．総手術時間は，X 群が平均 464 分（334〜608 分），C 群が平均 405 分（285〜540 分）で，X 群にて有意に長かった（$p<0.01$）（図 3）．出血量は，X 群が平均 1,154 m*l*（335〜2,529 m*l*），C 群が平均 2,051 m*l*（623〜5,230 m*l*）で，X 群にて有意に少なかった（$p<0.01$）（図 4）．X 群の変形矯正（術前/術後-平均）は，腰椎側弯 Cobb 角（Schwab 分類 L および D）：49.0/17.3 度，腰椎前弯角（lumbar lordosis：LL）：4.8/39.8 度，PI−LL：47.1/12.1 度，骨盤後傾（pelvic tilt：PT）：36.0/23.3 度，冠状面バランス（C7 plumb line：C7 PL）：3.0/1.7 cm，sagittal vertical axis（SVA）：12.9/3.6 cm で，C 群の腰椎側弯 Cobb 角：49.6/17.0 度，LL：1.9/40.4 度，PI−LL：49.2/9.0 度，PT：35.5/22.6 度，C7 PL：4.2/1.9 cm，SVA：11.9/3.1 cm と比較して，いずれも有意差を認めなかった．

周術期合併症は，両群に手術部位感染を深部 1 例ずつ，表層 1 例ずつ認めたほか，C 群に塞栓術を要した血管損傷を認め，C 群の 8 例で出血量 3,000 m*l* 以上を認めた．X 群で XLIF ケージの脱転を 1 例認め術中にケージを抜去したが，腹部臓器損傷，大血管損傷はなかった．XLIF 進入側の一過性の知覚障害が 12 例にみられたが，保存治療で軽快した（表 2）．

まとめ

XLIF は椎間板側面から強力な椎間板解離が可能で，面積の大きなケージを設置することで，側弯変形を矯正しながら椎間板高を開大する．われわれの XLIF を併用した hybrid 法と従来法との症例対照研究から，XLIF の応用により，従来法と同等の矢状面の変形矯正が，出血量の大幅な軽減の下に可能であった．側方経路進入による術後の下肢症状を 3 割の症例に認めたが一過性であり，重篤な術中合併症はなかった．XLIF は，直視下に後腹膜腔の十分な剝離と大腰筋の位置を確認しながら行えば安全な手技であり，合併症の生じやすい高齢者に対する変形矯正術の低侵襲化が期待できる．

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次｜号｜予｜告

脊椎脊髄ジャーナル Vol. 30 No. 11

脊椎手術体位の工夫—周術期合併症を避けるため

特集にあたって……東京慈恵会医科大学脳神経外科 谷 諭
脊椎手術による合併症の現状
医師の立場から……藤枝平成記念病院脊髄脊椎疾患治療センター 南 学，他
看護師の立場から……新百合ヶ丘総合病院脳神経外科 水野順一，他
脊椎手術における体位による身体への影響の検討……東京慈恵会医科大学脳神経外科 川村大地，他
脊椎手術における周術期合併症予防の工夫
頭蓋頸椎移行部手術の工夫……愛知医科大学脳神経外科 高安正和
中下位頸椎前方手術での体位の工夫……札幌麻生脳神経外科病院 飛騨一利
中下位頸椎後方手術での体位の工夫……ツカザキ病院脳神経外科 下川宣幸
胸椎（側弯症）手術での工夫……浜松医科大学整形外科 大和 雄，他
側臥位手術での工夫……国立病院機構北海道医療センター 伊東 学
腰椎後方手術での体位の工夫……三楽病院三楽脊椎脊髄センター 佐野茂夫
髄外腫瘍手術での体位の工夫……大阪市立大学脳神経外科 高見俊宏

Nomade
……東北大学大学院医学系研究科多発性硬化症治療学寄附講座 三須建郎
イラストレイテッド・サージェリー
経皮的内視鏡下腰椎椎間孔拡大術（PELF）……市立御前崎病院脳神経外科 北浜義博

編集上の都合により内容が若干異なる場合がありますので，ご了承ください．

Ⅱ．脊柱アライメント異常

日本人に至適な脊柱骨盤アライメント：獨協フォーミュラ

稲見 聡[1]，種市 洋[1]
1：獨協医科大学整形外科

Summary

成人脊柱変形手術後2年以上経過し，生活の質(quality of life；QOL)が良好な症例を対象にして，腰椎前弯角(lumbar lordosis；LL)と骨盤形態角(pelvic incidence；PI)の関係を調査した結果，LL＝0.59PI＋11.12の式が得られた。本稿では，式におけるPIの係数とY切片の意味について考察し，解説する。

はじめに

高齢者人口の増加に伴い，いわゆる成人脊柱変形(adult spinal deformity；ASD)の患者はまれではなく，病態が複雑なため適切な理解が必要である。この疾患の特徴は，腰椎や胸腰椎部で脊柱アライメントに異常が生じ，体幹の立位バランスが崩れ，生活動作が強く障害されることである。特に矢状面アライメント異常は，腰痛や身体機能の障害によりQOLを著しく低下させることが知られている[1)~4)]。そして，矢状面での脊柱骨盤グローバルアライメントにおいては，PIの重要性が過去の研究で指摘されている[5)~7)]。

近年のASD患者に対する矯正手術の普及に伴い，PIにマッチしたLLが矯正の指標として示され，理想的なLLを求める計算式が複数報告されている。そのなかでも，Scoliosis Research Society (SRS)-Schwab分類が示した，PI-LL＜10°は，LLの評価として現在広く用いられている[8)]。

一方，PIの値は健常者においても大きな幅があり[9)~12)]，日常の臨床でも30～80°程度の症例を経験する。骨盤の形態が異なれば，立位や歩行にかかわる脊柱骨盤の力学的特性も異なることが予想される。過去の研究でもPIが大きい場合には，骨盤後傾による代償作用が有効に作用することが報告されている[13)]。また，実際の臨床においては，PI-LL＞10°でも手術成績がよい例は珍しくない。

上記の背景から，筆者らは「理想的なPI-LLの値は一定ではなくPIの大きさを反映し変化する」との仮説を立て，ASD術後患者を対象にして解析を行った[14)]。本稿では，解析の結果得られたPIとLLの関係を示すフォーミュラについて解説する。

成績良好例における，PIとPI-LLの関係

ASD手術後，2年以上経過した48例(年齢60.7±9.7歳)を対象とした。最終観察時の脊柱変形パラメータは，胸椎後弯角：30.0±13.9°，胸腰椎後弯角：9.2±7.5°，LL：38.6±11.0°，骨盤傾斜角：24.9±9.8°，PI：49.7±11.4°，PI-LL：11.0±12.6°，sagittal vertical axis：36.6±44.6mm，側弯Cobb角：13.3±10.2°であった。最終観察時のOswestry Disability Index(ODI)は14.4±9.9(0～35.6)％であった。

次に，本研究の目的は理想的なPI-LLの値を求めることなので，術後患者のなかから成績良好例のみを抽出し，解析対象とした。最終観察時ODIの

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75パーセンタイル(ODI＝22%)以下をQOL良好と定義した。QOL良好群(n＝36)においてPIとPI-LLの関係を回帰分析で解析すると，PI-LL＝0.41PI－11.12(r＝0.45，p＝0.0059)の式が導かれた(図1)。

予測式から理想的なPI-LLは一定の値ではなく，個人のPIの大きさにより変化する値であることがわかる。実際の数値を予測式に当てはめると，ほぼ平均的な値であるPI＝50°の場合に理想的なPI-LLは9°となり，Schwab分類に一致する[8]。一方，PIが30°と小さい値ではPI-LLは1°と計算され，また，PIが80°と大きな場合にはPI-LLは22°となる。つまり，PIが小さい場合はPI-LLは0°に近く，PIが大きな場合は10°より大きなPI-LLが許容されることが，この式で示されている。

PI-LLの値がPIによって変化することが明らかになったが，さらにその理由を考察する。Duval-Beaupèreら[5]は，PIが小さいと股関節伸筋が作動するためのレバーアームが短くなるために，economical standing postureに不利になることを指摘している。またRoussoulyら[15]は骨盤後傾の許容量はPIにより規定され，PIが小さいと骨盤後傾による代償作用の許容量が小さいと述べている。これらのことから，PIが小さい場合はPIに厳密にマッチしたLLが必要であり，PI-LLは小さな値になると考える。

一方，PIが大きい場合は，股関節伸筋は長いレバーアームをもち，さらに仙骨と大腿骨頭中心間の距離も大きくなる[9,15]。Legayeら[6]は，骨頭中心と仙骨終板中点の距離をsagittal pelvic thickness(SPT)と定義し，この値がPIと相関があることを報告している(図2)。つまりPIが大きいと仙骨と骨頭中心の距離が大きく，C7 plumb lineが骨頭後方に保持されるので，大きなPI-LLが許容されると考える。

図1 術後成績良好例におけるPIとPI-LLの関係

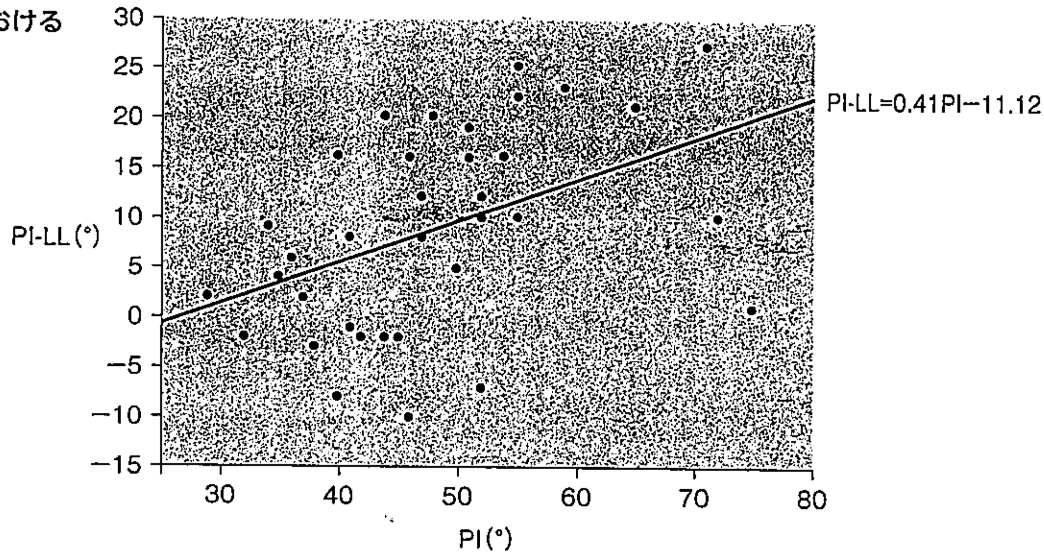
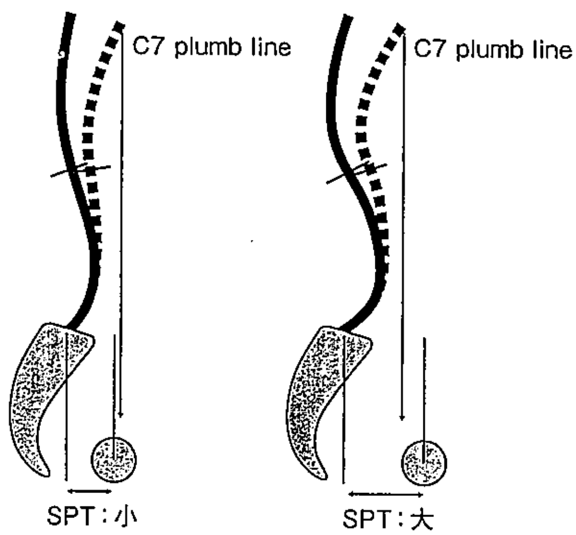


図2 Sagittal pelvic thickness(SPT)の違いによるグローバルアライメントの比較

良好なアライメント(実線)からLLが減少した場合(破線)，SPTが大きいとC7 plumb lineは骨頭中心の後方にとどまる。



PIとLLの関係

本解析で得られた式，PI-LL＝0.41PI－11.12を，LLを独立変数としてアレンジすると，LL＝0.59PI＋11.12となる。これまでにもPIを基に，LLを導く予測式が報告され[6),7),16)〜19)]，矯正手術の指標となってきた。

Legayeら[19)]は，平均年齢24歳の健常ボランティアを対象に，LL＝(PI×0.5481＋12.7)×(1.087＋21.61)＝0.596PI＋35.415という式を提唱している。そしてMac-Thiongら[20)]は，平均年齢12歳の健常者を対象に，LL＝0.6PI＋17.6という式を示した。

さらに，Le Huecら[21)]は平均年齢37歳の健常者を対象に，年齢を考慮した式，LL＝0.6PI＋32.9－0.23(age)を求めた。この式に70歳を代入すると，LL＝0.6PI＋16.8となる。また，本誌の他項(p.68〜75)で詳述されているYamatoら[22)]は，LL＝0.45PI＋31.8と報告している。

予測式の係数とY切片の意味を考える

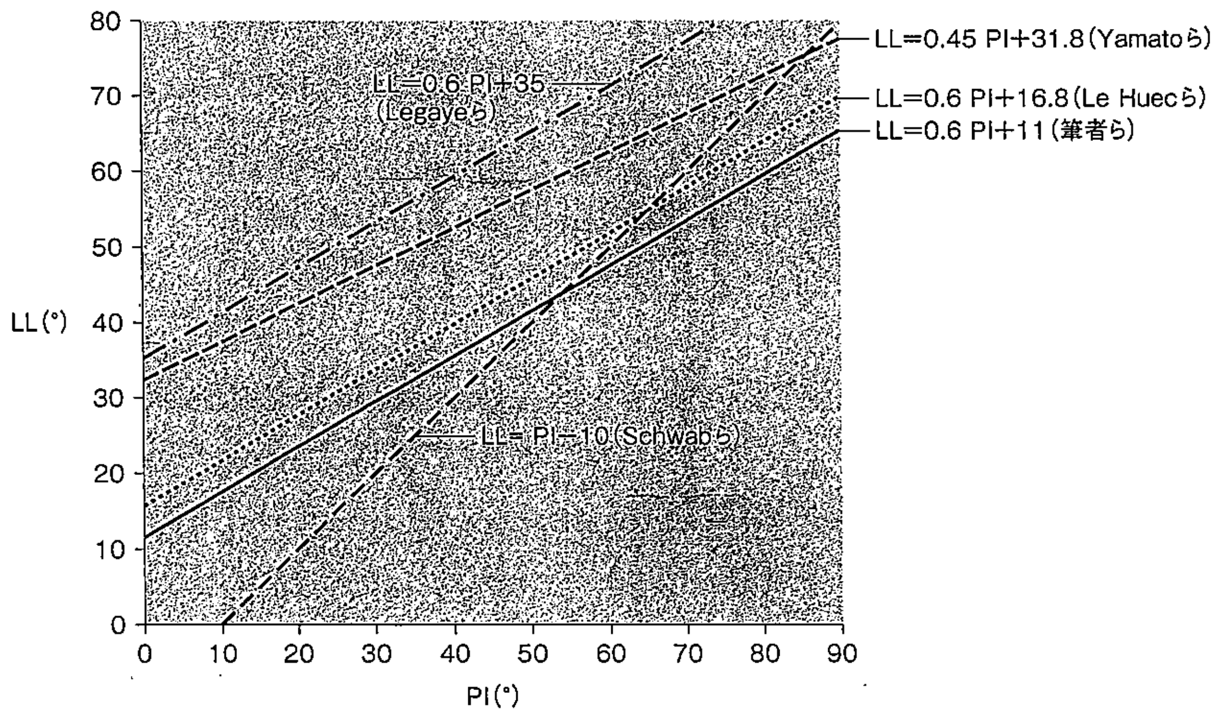
ここでPIの係数に注目すると，筆者らとLegayeら，Mac-Thiongら，Hasegawaらの式はおおむね0.6で，Yamatoらも0.45と近い値であり，これらから係数はおおむね0.5程度と考える。一方，SRS-Schwab分類(LL＞PI－10°)の係数は，1である。PIの係数が1なのか，0.5前後の値なのかは，きわめて重要なことである。つまり，SRS-Schwab分類以外のすべての式において，LLの増加割合はPIの増加の50%に過ぎず，PIが大きくなるほどPIとLLの差(PI-LL)が大きくなることを意味している。

これらの式では「PIが小さい場合はPI-LLは小さな値が必要で，PIが大きい場合はより大きなPI-LLが許容される」ことを物語っている。各式をグラフで示すと(**図3**)，SRS-Schwab分類の式のみ，他とまったく異なる性状であることが，視覚的に理解できる。

一方，Y切片はそれぞれの式で隔たりがある。この理由としては母集団の背景の違いが関与すると考える。術後患者を対象としているのは筆者らのみで，他の解析では健常ボランティアを対象にしている。また，対象者の年齢は若年者から高齢者まで大きな違いがある。Le Huecら[21)]の年齢を考慮した式で示されるように，加齢によりY切片は小さな値になる。Le Huecらの式に70歳を代入するとLL＝0.6PI＋16.8となり，筆者らの式と近似することは，偶然の一致ではなく，重要なポイントであろう。

図3 各予測式の比較

Schwabらの式は他と比較して，傾きとY切片がまったく異なる。



ASD手術において目指すアライメントとは健常者のアライメントなのか，その場合は若年者か高齢者か，それとも術後成績良好例から目指すアライメントを探るべきなのか，これらは現在明確な答えはなく，今後の研究に期待したい。また，患者は手術時に矯正固定された角度で歳を重ねていくことを念頭に置いて，長期的な評価に基づき，至適なアライメントを考える必要がある。

現在の課題と今後の展望

健常者の矢状面パラメータにおいてもばらつきは大きい。その要因としては，各人における個性，つまり，筋力や関節可動域，さらには生活様式の違い等が影響していると考える。このような個性を考慮した至適アライメントを明らかにする必要がある。

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第2章：治療

脊柱変形に対する矯正固定術のプランニング*

胸腰椎部・骨盤

森平　泰** 種市　洋

はじめに

胸腰椎から骨盤にかけての脊柱アライメント異常，いわゆる腰曲がりに対して，積極的に手術が行われるようになっている．特に矢状面アライメントの異常は，手術を受けていない患者のみならず術後の患者においても，痛みや日常生活障害に密接に関わる因子であることが過去の研究で明らかとなり[3]，矢状面，冠状面の弯曲に回旋が加わった複雑な変形である成人脊柱変形をどのように適切に矯正するかは，近年，脊椎外科医にとって最も重要な課題の１つである．

成人脊柱変形は，おおまかに，変性側弯症，二次性変性側弯症，後弯症に分類できる[7,15]．変性側弯症は，変性すべり症と同様に椎間板の加齢変性が主因であり，椎間板高の減少は腰椎の側弯のみならず後弯を引き起こす．変性側弯症は，60歳以上の発症で，進行が早く，比較的柔らかく，しばしば脊柱管狭窄を合併し，矢状面グローバルアライメント異常を認めるという特徴がある．一方で，二次性変性側弯症は，特発性側弯症が成人期まで遺残したものであり，特発性側弯症で認めるすべてのカーブの種類があり，一般的な変性側弯症とは性質が異なる．二次性変性側弯症は，進行が遅く，硬いカーブで，しばしば胸椎および腰椎カーブの移行部で後弯を合併するという特徴がある．また，変性側弯症より早期に，40歳台から外来に訪れる[4]．

後弯症も一次性と二次性に分類できる．最も一般的なものは多椎間の椎間板加齢変性による一次性の後弯症である．二次性の後弯症には，医原性である脊椎固定術後のものが含まれる．古典的には，特発性側弯症に対するHarrington法による矯正術後のflat back syndromeである[1]が，今日多く遭遇するのは，多椎間の腰椎固定術（posterior lumbar interbody fusion〔PLIF〕，transforaminal lumbar interbody fusion〔TLIF〕）後の矢状面アライメント異常である．二次性の後弯症には，ほかに外傷後後弯が含まれる．比較的若年にみられる椎体骨折や脱臼骨折などの外傷後に後弯位で癒合した硬い後弯症と，骨粗鬆症を合併した高齢者の椎体圧潰や偽関節などの柔らかい後弯症に分けられる[7,10]．

脊柱管狭窄が主体の軽度変形例に対する治療が神経除圧と不安定性椎間の安定化であるのに対して，高度変形例では不良アライメントとグローバルバランスの改善が治療の主目的となる．われわ

Key words
成人脊柱変形（adult spinal deformity）
治療戦略（surgical strategies）
分類（classification）

* Surgical Strategies for Subtypes of Adult Thoracolumbar Spinal Deformity

** 獨協医科大学整形外科学〔〒321-0293 下都賀郡壬生町大字北小林880〕／Hiroshi MORIDAIRA, Hiroshi TANEICHI：Department of Orthopaedic Surgery, Dokkyo Medical University

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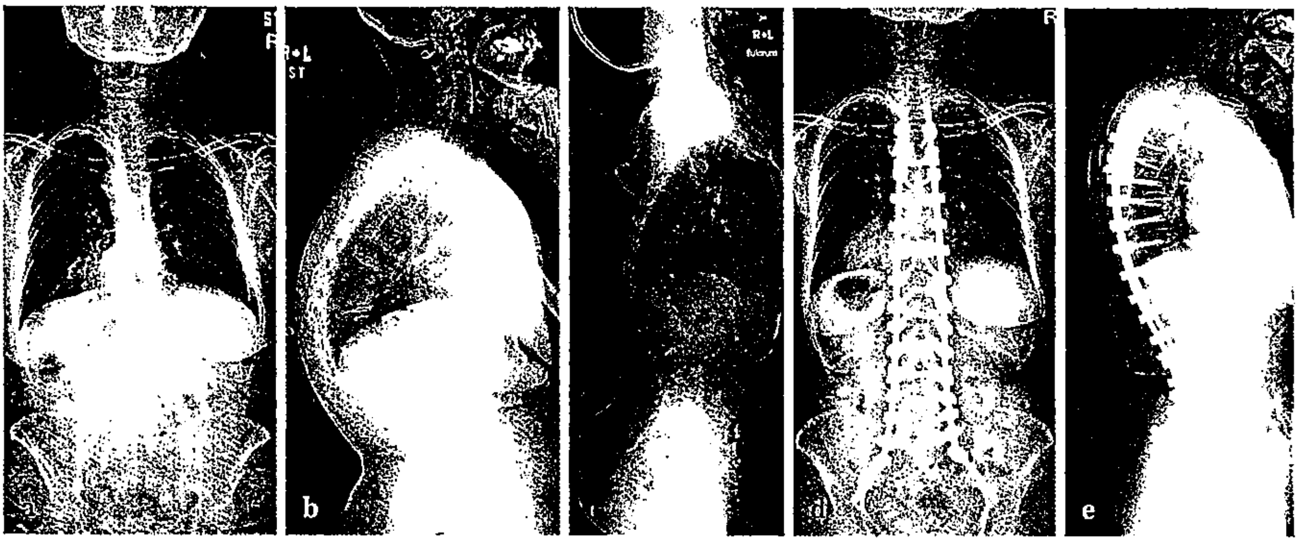

図 1　タイプ 1：柔軟な後弯変形を有する冠状面バランスのよい変形
冠状面バランスはよく (a); 胸椎および胸腰椎に椎体変形による後弯がある (b) も比較的柔らかく，FBB により概ね良好な矢状面アライメントが得られる (c)．Ponte 骨切りと後方インストゥルメンテーションによる矯正固定のみで良好なアライメントとグローバルバランスが得られる (d, e)．

れは胸腰椎から骨盤にかけての成人脊柱変形を，カーブの種類と柔軟性から 5 タイプに分けて治療を行ってきた[10,12]．本稿では，lateral interbody fusion (LIF) 併用による低侵襲化にも触れながら，タイプ別の治療戦略について述べる．

成人脊柱変形の柔軟性評価

脊柱変形に対する適切な術式選択には，正確な柔軟性評価が必須である．成人脊柱変形の術前評価では，side bending による側弯の柔軟性評価に加えて，fulcrum backward bending (FBB) 法による後弯の柔軟性評価を行う．

患者を X 線透視台上に仰臥位とし，後弯の頂椎付近にウレタンフォーム製の小枕を敷いて，腰椎の最大後屈位を強制し，全脊柱側面 X 線像を撮像する．この FBB 法の有用性を検証するための研究では，FBB で得られる腰椎前弯を仮想腰椎前弯 (virtual lumbar lordosis：VLL) とすると，VLL は骨切りを併用しないインストゥルメンテーション手術で得られる LL ときわめて高い精度で一致することが明らかになった[11]．そこでわれわれは，pelvic incidence (PI)－VLL をもとに術前計画を立ててきた．

タイプ 1：柔軟な後弯変形を有する冠状面バランスのよい変形

冠状面バランスがよく (C7 plumb-line distance〔PD〕<3 cm)[6]，後弯が柔軟な (PI－VLL<20 度)[9] タイプである (図 1)．このタイプの変形では，冠状面バランスが保たれているため側弯変形の解離が必要ない．また，4 点フレーム上の腹臥位で概ね良好な腰椎前弯が得られるため，後方インストゥルメンテーションのみによる後方矯正固定術が適応となる．タイプ 1 の変形は最も侵襲が少ない手術で治療できるため，80 歳以上の症例であっても治療可能である．骨粗鬆症が高度な症例においては，矯正時の椎弓根スクリュー (PS) のゆるみや椎体骨折を防ぐために，1～3 椎間の Ponte 骨切りなどの後方要素の骨切り (Schwab Grade 1 or 2 骨切り)[8] を加えてもよい．

固定上端椎 (upper instrumented vertebra：UIV) は胸椎部脊柱変形の状況により決定するが，概ね T10 前後とする．固定下端椎 (lower instrumented vertebra：LIV) は基本的に S1 である．本症のほとんどが腰仙椎間に変性があり，高率に骨粗鬆症を合併するため，L5 を LIV にすることは固定下端の破綻のリスクが高く推奨できない．

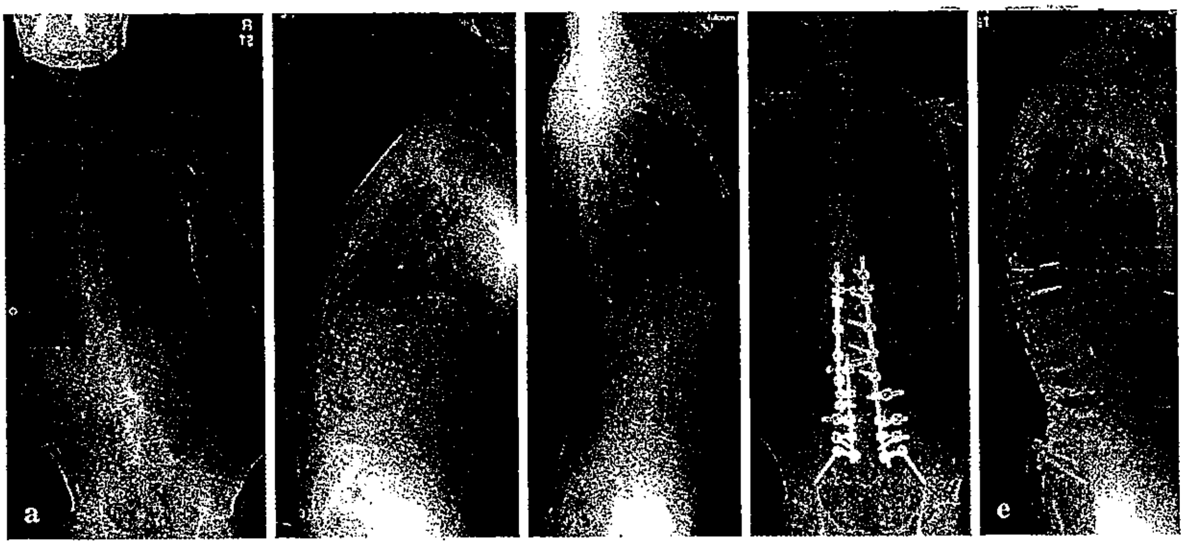

図 2 タイプ 2：柔軟な後弯変形を有する冠状面バランスの悪い側弯．
冠状面グローバルバランスが不良な硬い側弯症（a）で，腰椎後弯がある（b）も比較的柔軟で，FBB により腰椎前弯が得られる（c）．硬い側弯変形のある L2-4 に対して LIF と TLIF による IVR を行い，側弯は良好に矯正され，冠状面バランスが正常化している（d）．Rod de-rotation 法を加えた後方インストゥルメンテーションによる矯正で良好な腰椎前弯を獲得している（e）．

腰仙椎固定の下位アンカーは S1 PS と腸骨スクリューなどによる 4 点固定（4-point fixation）が必須と考える．

タイプ 2：柔軟な後弯変形を有する冠状面バランスの悪い側弯

硬い側弯による冠状面バランスが不良で（C7 PD＜3 cm），後弯が柔軟な（PI－VLL＜20 度）タイプである（図 2）．主として冠状面バランス改善を目的に側弯矯正を行うが，骨棘形成や骨性架橋を伴う硬い側弯症は，後方解離のみでは十分な側弯矯正はできない．硬い椎間をターゲットに Ponte 骨切りと，前方ないし後方からの徹底的な椎体間解離（intervertebral release：IVR）を組み合わせて矯正する[14]．近年，本邦でも多く施行されることになった LIF は IVR の強力な手段である．PLIF/TLIF の手技と異なり硬膜外腔の操作がないため出血量低減に有効で，低侵襲化の観点からも推奨できる[5]．変形矯正のアンカーには PS を用いて，凸側の rod de-rotation 法を加える．この矯正法は腰椎の回旋を矯正しながら椎体を前方に押し込むため，腰椎側弯を前弯に変化させる．

矢状面バランスの再建からみると，タイプ 2 の変形において PI に適合した LL を得ることは，タイプ 1 同様に困難ではなく，LIF を用いて短椎間で十分な LL を獲得することで，胸腰移行部の後弯が軽度な症例では UIV を L2 にできる症例も少なくない．

タイプ 3：側弯が軽度な硬い後弯

胸腰椎や腰椎の後弯が硬く FBB において十分に矯正されず（PI－VLL＞20 度），側弯が軽度（＜30 度）なタイプである（図 3）．腰椎変性疾患や外傷に対する不適切な後方固定術後の矢状面アライメント異常に多くみられる．強力な矢状面アライメント矯正が期待できる pedicle subtraction osteotomy（PSO）の適応で，1 椎体の骨切りにより約 30 度の後弯矯正が可能である[2]．われわれはいわゆる egg shell 手技でなく，ノミを用いた椎体内楔状骨切りを行うことにより正確な矯正角度を獲得するようにしている．PSO では骨切り椎の後方要素は大きく摘出されるため，上下椎間を十分量の移植骨にて橋渡しをする後側方固定（posterolateral fusion：PLF）が必要である．

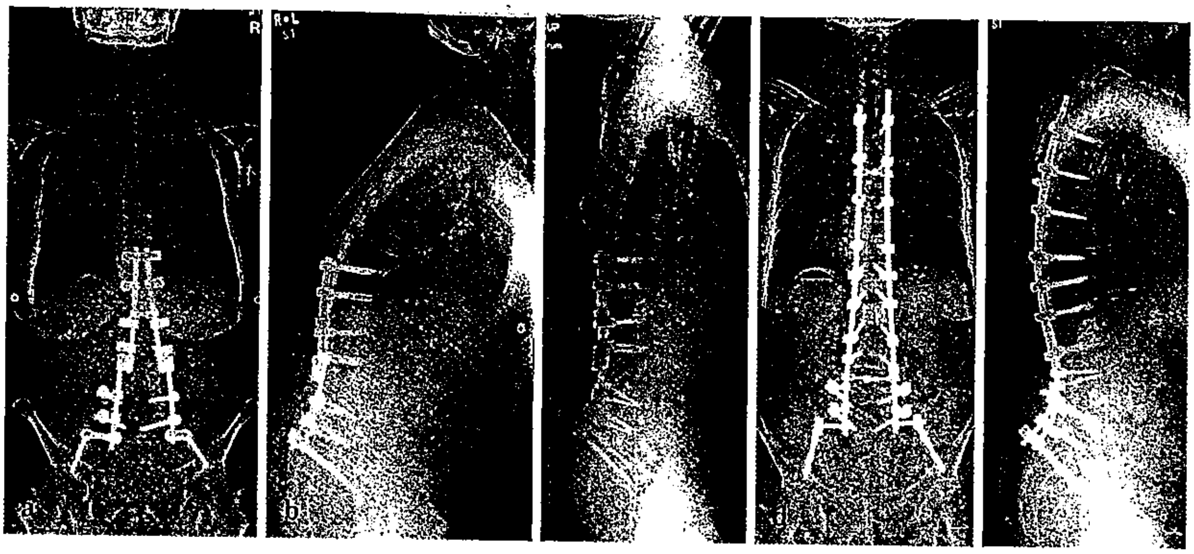

図 3　タイプ 3：側弯が軽度な硬い後弯
骨粗鬆症性椎体圧潰に対する固定術後の矢状面アライメント異常で冠状面変形はない (a). 腰椎は骨盤のアライメントと不適合のままで骨癒合が完成し，胸椎後弯も加わって矢状面バランスは著しく不良である (b, c). L4 の PSO により腰椎前弯を獲得し，上位胸椎まで後方固定術を延長することで，良好な矢状面アライメントが獲得できている (d, e).

タイプ 3 のうち，変形の主体が椎間板である一次性の後弯症には，PSO に代わって LIF を併用した矯正術が可能となる．変形が大きく硬い椎間で必要数の LIF を行って，側弯矯正と同時に前方を開大させさておき，続いて後方手術の際に，その椎間で Ponte 骨切り（全椎間関節切除：Schwab Grade 2 骨切り）[8]を行って後方短縮させ十分な LL を獲得することで，矢状面アライメントを改善させる．

タイプ 4：側弯が高度な硬い後弯

後弯が硬く（PI－VLL>20 度），側弯も高度（>30 度）なタイプである（図 4）．PSO は基本的に二次元的アライメント矯正のための手技で，三次元変形矯正には向かないため，vertebral column resection（VCR）が適応となる[2]．後方単独 VCR や前後合併アプローチによる VCR が行われるが，いずれも脊柱 3 カラムを切断し矯正するので，きわめて硬い三次元的変形も強力かつ短椎間で矯正できる．前方支柱（ケージ）設置が必須であるが，後方から設置する場合は，椎間板および椎体切除後のギャップに左右から 2 個設置するのがよい．前後合併 VCR は，前方から大きな面積のケージを安全に設置でき，また出血量低減のメリットもある．

タイプ 3 同様，タイプ 4 においても，椎体変形が少なく椎間癒合のない症例においては，LIF が強力な手段となっている．椎体切除を行わずに必要数の椎間で LIF を施行することで，広範囲の椎間板切除による強力な矯正と，大きな面積のケージによる矯正位保持が可能である．

タイプ 5：下位腰椎前弯にて矢状面バランスが代償された側弯

矢状面バランスが保たれているにもかかわらず，側弯が高度（>30 度）なタイプである（図 5）．特発性側弯症の遺残症例に多く，慢性腰痛，肋骨の骨盤への食い込みや，体幹の短縮による上腹部症状を呈する．前方矯正術（anterior spinal fusion：ASF）では全周性の椎間解離と前方インストゥルメンテーションによる強力な三次元的矯正が可能であり，先行して同レベルの後方解離術を施行することで短椎間での矯正固定が可能となる[13]．腰椎後側弯はあるが，下位腰椎の過前弯に

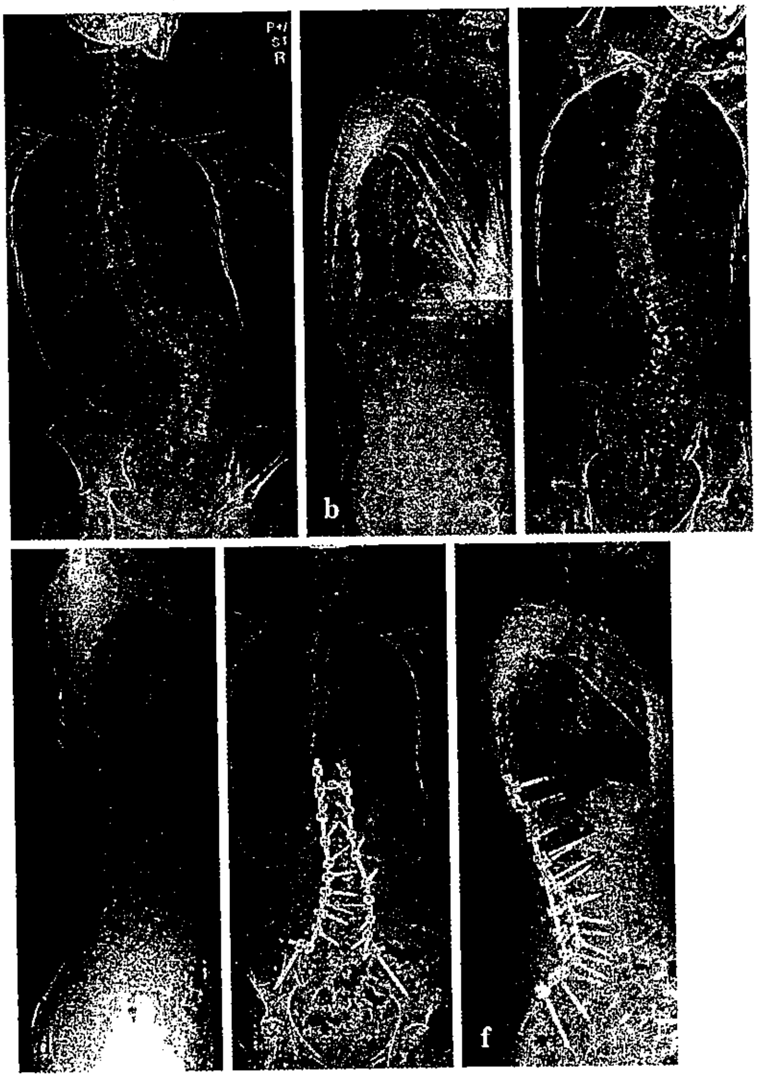

図 4　タイプ 4：側弯が高度な硬い後弯
冠状面グローバルバランスが不良な硬い側弯症（a, c）で，矢状面アライメント異常もある（b）．FBB により矢状面アライメントが矯正されない（d）．硬い側弯変形のある L1-4 に LIF を用いた IVR を行って冠状面バランスを矯正し（e），その椎間で Ponte 骨切りを加えて後方短縮させることで十分な腰椎前弯を獲得している（f）．

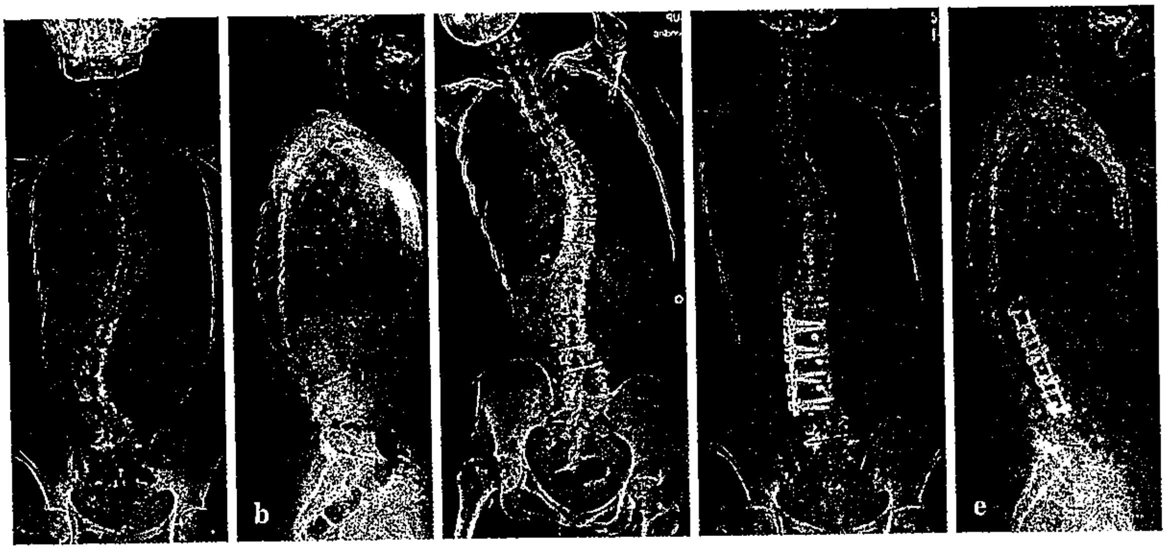

図 5　タイプ 5：下位腰椎前弯にて矢状面バランスが代償された側弯
矢状面グローバルバランスが下位腰椎前弯にて代償されている側弯症（a〜c）で骨粗鬆症は軽度である．前方矯正固定術により L4〜S1 の 2 椎間を温存したままで良好な腰椎アライメントが獲得できている（d, e）．術前に L4/5 椎間板は左側が bone on bone になっているが（a），術後は L4 が水平化されている（d）．

より矢状面グローバルバランスを代償している症例では，固定下端をL3ないしL4に設定したASFにより良好なアライメントとバランスの矯正が期待できる．ASFは変形矯正とその維持を椎体スクリューに依存するため，適応は骨粗鬆症が軽度な症例に限られるが，成人脊柱変形の矯正術において，腰仙椎移行部に2椎間以上の可動椎間を温存できるのはこのタイプのみである．

まとめ

胸腰椎から骨盤にかけての成人脊柱変形を，カーブの種類と柔軟性から5タイプに分けて，タイプ別の治療戦略について述べた．術前に検討すべき事項は，カーブの形，矢状面および冠状面のグローバルバランス，矢状面脊柱骨盤アライメント異常，変形の硬さ，脊柱管狭窄，骨質が挙げられる．それに加えて，患者の年齢や全身状態は必須となり，理想的なアライメント獲得のための妥協しない術式を計画する一方で，患者の全身状態がそれを許容できるかを常に考慮する必要がある．矯正手術は，広範囲な固定，3カラムの骨切りや多椎間の椎間板解離（IVR）の併用など，概して高侵襲になりやすい．しかし，多くの症例が比較的柔らかい変形であることを踏まえて，不必要な高侵襲手術は厳に慎むべきである．一方で，低侵襲手術にこだわるあまりに，解離が不十分な状態で，インプラント任せの矯正を行えば，スクリューのゆるみや骨折を生じ，不十分な矯正で手術を終えることとなる．変形のタイプと柔軟性を正確に評価し，柔軟な変形には過剰な解離操作や骨切りを行わない術式を選択し低侵襲性を追求すること，また硬い変形には3カラムの骨切りや前方法を駆使した効率的な矯正を行い，固定範囲の短縮を図ることが重要である．

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