TIGER using the Finn gamma spectrum for t. Both of these doses neglect the shielding that the body provides to the site of interest. Due to the limited range of beta particles, the body effectively shields the tissue at any site from about half of the beta radiation field (Kocher and Eckerman 1981). Similarly, the gamma dose recorded on a film badge worn at chest level in a large radiation field is reduced from the free-in-air gamma dose by a factor of 0.5 for low energy photons and 0.9 for high energy photons due to body shielding; the reduction is approximately 0.7 for a typical fallout gamma spectrum (Egbert et al. 1985). Therefore, the beta-to-gamma dose ratio $R_{\beta/\gamma}(x,t)$, defined as the beta dose to the skin at distance x from the source plane for an exposure at time t divided by the corresponding film badge (gamma) dose, can be expressed as:

$$R_{\beta/\gamma}(x,t) = [0.5D_\beta(x,t)/0.7D_\gamma(t)] \times N_\beta(t)/N_\gamma(t), \tag{1}$$

where $N_\beta(t)/N_\gamma(t)$ is the ratio of the beta and gamma emission rates at time t. The latter ratio, also obtained from the Finn compilation, is required because the doses D_β and D_γ are normalized per source particle in the transport code output.

The quantities $R_{\beta/\gamma}(x,t)$ have been calculated for discrete values of x ranging from 1 cm to 2 m and values of t from 0.5 h to 2 y. The results are presented in Table 1 for exposures at the Pacific test sites and in Table 2 for exposures at the Nevada Test Site. Fig. 5 displays the time dependence of $R_{\beta/\gamma}$ for Pacific test site exposures at two heights above the source plane: 100 cm, which is a representative distance for skin sites on the hands and forearms or in the area of the waist; and 160 cm, which is appropriate for facial sites. The ratios reach minima about 1 wk to 10 d after the burst, a result of the significant softening of the beta energy spectrum over this interval (Fig. 2). The dose ratios increase to large values at late times because of the dominance of beta emission over gamma emission for aged fallout. While the N_β/N_γ emission ratio is approximately unity the first few weeks after a detonation, it becomes progressively larger at later times, reaching a value greater than 3 at 1 y and nearly 8 at 2 y. However, the gamma doses accrued at these late times were typically small, so the corresponding late-time beta doses were also relatively small.

Few measurements of beta-to-gamma dose ratios for exposures to representative fallout or activation fields exist. One relevant set of data (AFSWP 1957) was obtained using a phantom masonite man placed in a fallout field. A comparison of dose ratios derived from the present methodology with those data reported in AFSWP (1957) for a height of 1 m above the surface is displayed in Fig. 6. The average deviation is about 30% during the first week after the detonation. The larger deviations thereafter are possibly due to the effects of weathering.

Beta-to-gamma dose ratios for eye exposure to mixed fission products

An approach similar to that for assessing beta dose to the skin was used to assess beta exposures to the lens of the eye, with the beta dose calculated by CEPXS/ONEDANT for a representative eye-level height of 160 cm above the source plane. The resulting beta-to-gamma dose ratios are presented in Table 3 for both the Pacific and Nevada test locations. It is seen that these ratios are substantially smaller than those for skin, a consequence

Table 1. Beta-to-gamma dose ratios for bare skin exposures to mixed fission products at Pacific test sites.

Time after detonation	Distance from source plane (cm)							
	1	20	40	80	100	120	160	200
0.5 h	36.4	24.2	17.7	11.9	10.4	9.1	7.0	5.4
1 h	32.5	21.4	15.5	10.3	8.9	7.8	5.9	4.5
2 h	32.0	20.8	15.0	9.9	8.5	7.4	5.5	4.2
4 h	40.3	25.9	18.5	12.0	10.3	8.9	6.7	5.0
6 h	51.1	32.6	23.1	14.9	12.7	11.0	8.2	6.2
12 h	65.6	41.0	28.6	17.8	15.0	12.8	9.3	6.8
1 d	65.1	38.7	25.8	14.9	12.2	10.0	6.8	4.7
2 d	64.4	35.2	22.1	11.8	9.3	7.4	4.7	2.9
3 d	62.8	32.2	19.3	9.8	7.6	6.0	3.6	2.1
1 wk	62.3	29.0	16.3	7.7	5.8	4.5	2.5	1.4
2 wk	65.5	30.5	17.1	8.1	6.2	4.7	2.7	1.6
1 mo	72.4	34.7	19.9	9.8	7.6	6.0	3.7	2.2
2 mo	85.7	39.8	22.8	11.8	9.5	7.8	5.1	3.3
4 mo	90.7	40.4	23.0	12.5	10.5	9.0	6.4	4.4
6 mo	94.6	42.5	24.5	13.9	11.9	10.4	7.7	5.5
9 mo	116.7	54.5	32.5	19.6	17.2	15.4	11.8	8.8
1 y	166.1	81.2	50.3	31.7	28.2	25.6	20.1	15.2
2 y	494.2	251.9	160.5	104.2	93.6	85.3	68.0	52.3

Table 2. Beta-to-gamma dose ratios for bare skin exposures to mixed fission products at the Nevada Test Site.

Time after detonation	Distance from source plane (cm)							
	1	20	40	80	100	120	160	200
0.5 h	36.0	24.6	18.3	12.4	10.8	9.6	7.6	5.9
1 h	32.2	21.8	16.1	10.8	9.4	8.2	6.4	4.9
2 h	31.6	21.2	15.5	10.3	8.9	7.8	6.1	4.6
4 h	40.1	26.6	19.3	12.7	10.9	9.5	7.3	5.6
6 h	50.5	33.3	24.0	15.7	13.4	11.7	9.0	6.9
12 h	64.7	41.8	29.7	18.7	15.9	13.7	10.2	7.6
1 d	64.2	39.6	26.9	15.9	13.0	10.9	7.7	5.4
2 d	63.4	36.3	23.3	12.7	10.1	8.2	5.4	3.5
3 d	62.0	33.4	20.5	10.7	8.4	6.7	4.2	2.6
1 wk	61.6	30.3	17.5	8.4	6.4	5.0	3.1	1.8
2 wk	64.7	31.9	18.4	8.9	6.8	5.3	3.3	2.0
1 mo	71.6	36.2	21.3	10.7	8.3	6.7	4.3	2.7
2 mo	84.6	41.5	24.3	12.6	10.2	8.5	5.9	3.9
4 mo	89.4	42.2	24.4	13.3	11.1	9.6	7.1	5.0
6 mo	93.4	44.3	26.0	14.6	12.5	11.0	8.5	6.2
9 mo	114.7	56.5	34.3	20.3	17.8	16.0	12.8	9.7
1 y	164.0	84.3	52.9	32.8	29.1	26.5	21.7	16.8
2 y	487.7	260.5	168.1	107.5	96.1	88.1	72.9	57.3

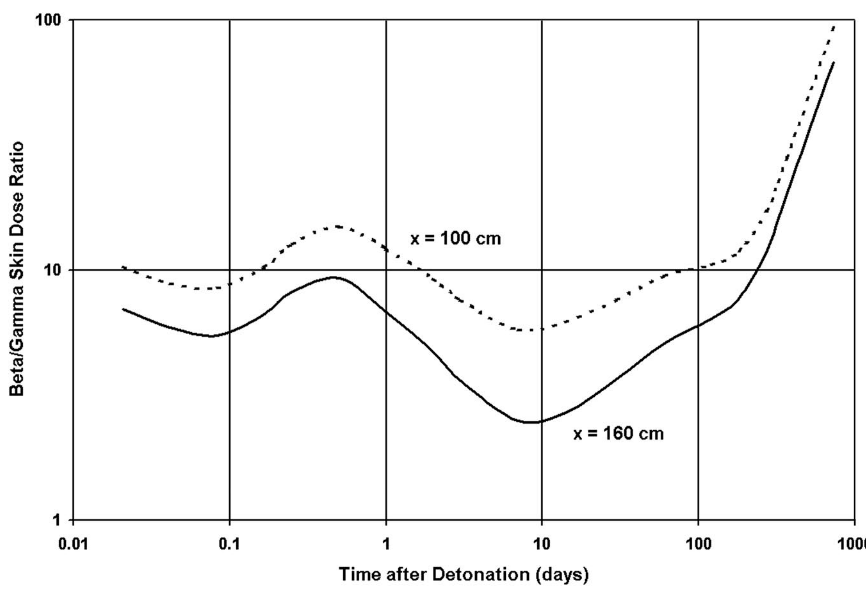

Fig. 5. Time dependence of beta-to-gamma skin dose ratios for Pacific test site exposures.

of the greater thickness of material (300 mg cm^{-2}) overlying the sensitive layer as compared to the skin exposure (approximately 7 mg cm^{-2}). Fig. 7 illustrates the change of the eye dose ratio with time after detonation. The temporal change is qualitatively similar to that depicted in Fig. 5 for the skin dose ratios.

Shielding effects of clothing

If the skin site of interest was covered by clothing during the exposure, the beta-to-gamma dose ratio is reduced because even relatively thin layers of material can effectively attenuate beta radiation. Note that the film badge dose, in the denominator of the beta-to-gamma dose ratio, is unaffected because the badge is assumed to have been worn external to any clothing. To account for the presence of clothing, calculations with CEPXS/ONEDANT were repeated with a clothing layer, representative of "coverall" material (from U.S. NRC 1992), inserted in the geometric construct as indicated in Fig. 3. The resulting reductions in beta skin dose, and hence in the beta-to-gamma dose ratios, are quantified in Table 4 as factors that are applied as multipliers of the values of $R_{\beta/\gamma}$ in Tables 1 and 2. It is seen that, except for locations close to the source plane, the presence of clothing

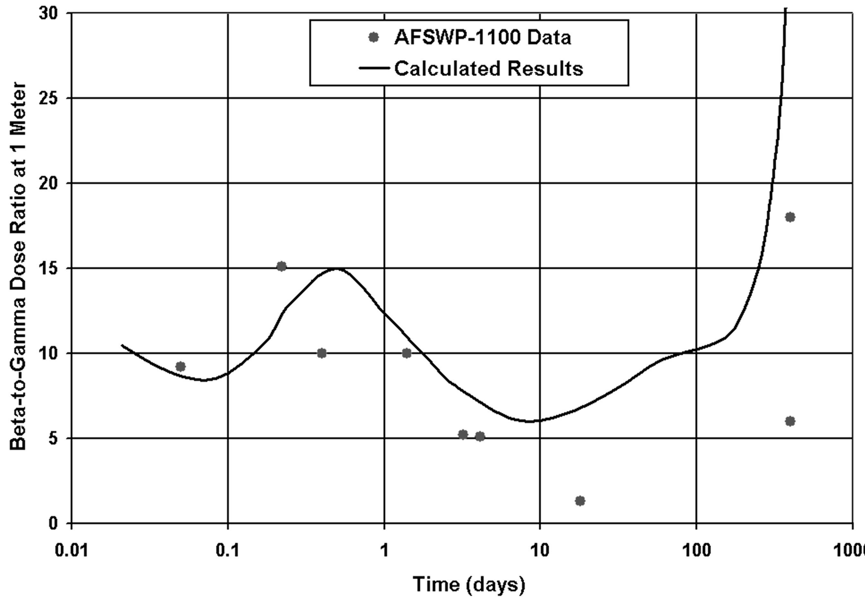

Fig. 6. Comparison of calculated and measured beta-to-gamma dose ratios.

Table 3. Beta-to-gamma dose ratios for eye exposures to mixed fission products.

Time after detonation	For Pacific exposures	For NTS exposures
0.5 h	1.67	1.76
1 h	1.24	1.32
2 h	1.10	1.17
4 h	1.38	1.47
6 h	1.74	1.84
12 h	1.79	1.89
1 d	0.91	0.98
2 d	0.36	0.39
3 d	0.19	0.21
1 wk	0.10	0.11
2 wk	0.12	0.14
1 mo	0.22	0.24
2 mo	0.45	0.48
4 mo	0.83	0.89
6 mo	1.27	1.35
9 mo	2.91	3.09
1 y	4.51	4.78
2 y	13.2	14.0

reduces the beta dose by 10 to 30%. Heavier clothing, such as field jackets, would attenuate the beta dose even more.

Effect of actinides

The impact on the beta-to-gamma dose ratio of the actinide content in weapon debris was evaluated by including in the Finn spectra the beta and gamma contributions from the actinide isotopes reported for a large Pacific detonation (Hicks 1984) and repeating the previously described CEPXS/ONEDANT and ITS TIGER calculations for skin exposure. The fractional changes in the beta-to-gamma dose ratios due to the actinides for this example are given in Table 5. Except for skin sites relatively close to the source plane, the presence of actinides generally causes a reduction in the dose ratio. This is especially pronounced from a few days to a few weeks after the detonation, when the enhancement in gamma dose from the actinides is significantly larger than the beta dose enhancement. The effect of actinides on the dose ratio at early and late times is small. Note that the beta dose will generally not be underestimated if the presence of actinides is neglected entirely for distances greater than 40 cm.

Beta-to-gamma dose ratios for exposure to neutron-activated soil

Table 6 presents beta-to-gamma dose ratios for the exposure of bare skin to neutron-activated soil at the NTS. This radiation source was modeled by considering the beta and gamma emissions following neutron activation of a representative NTS soil type (that of Area 7, from Egbert et al. 1985) consisting of the radiologically significant elements sodium (0.79% by weight), silicon (25.03%), potassium (1.92%), calcium (6.72%), and manganese (0.071%). The derived dose ratios are much smaller than those for fallout, a consequence of the fact that soil attenuates the beta emissions much more effectively than it does the gammas. At later times, the ratios are essentially zero at waist and head level because the remaining radioisotopes (^{46}Sc and ^{60}Co) emit relatively hard gammas and very soft betas. The beta-to-gamma dose ratio for the lens of the eye for a person standing on

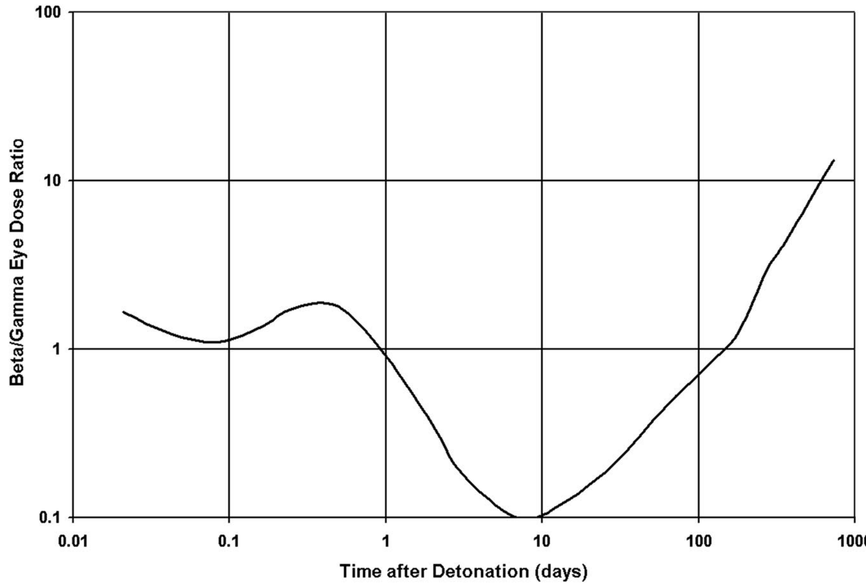

Fig. 7. Time dependence of beta-to-gamma eye dose ratios for Pacific test site exposures.

Table 4. Modifying factors for the shielding effects of clothing.

Time after detonation	Distance from source plane (cm)							
	1	20	40	80	100	120	160	200
1 h	0.59	0.74	0.80	0.83	0.84	0.86	0.87	0.87
2 h	0.59	0.73	0.79	0.84	0.84	0.85	0.87	0.87
6 h	0.57	0.72	0.78	0.83	0.84	0.85	0.86	0.87
1 d	0.52	0.67	0.73	0.78	0.80	0.81	0.82	0.83
1 wk	0.40	0.54	0.66	0.71	0.72	0.74	0.74	0.78
2 wk	0.40	0.55	0.66	0.71	0.72	0.73	0.77	0.74
1 mo	0.41	0.56	0.67	0.73	0.74	0.75	0.78	0.77
1 y	0.42	0.62	0.78	0.86	0.87	0.87	0.88	0.88

Table 5. Modifying factors for the presence of actinides.

Time after detonation	Distance from source plane (cm)							
	1	20	40	80	100	120	160	200
1 h	1.04	1.01	1.01	1.00	1.00	0.99	0.98	0.98
2 h	1.11	1.06	1.03	1.01	1.01	1.01	1.02	1.00
6 h	1.29	1.13	1.05	1.01	1.01	1.01	0.99	0.97
1 d	1.58	1.21	1.02	0.93	0.93	0.94	0.94	0.91
1 wk	1.69	1.15	0.88	0.68	0.66	0.62	0.64	0.64
2 wk	1.28	1.05	0.91	0.81	0.79	0.81	0.81	0.75
1 mo	1.07	1.01	0.98	0.96	0.96	0.95	0.95	0.95
1 y	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

neutron-activated soil at the NTS was determined to be less than 0.01 for all times after detonation.

Application

For an acute exposure to fallout field radiation, the beta dose to a specific skin location is estimated by extracting the value of $R_{\beta/\gamma}(x,t)$ from Table 1 (for Pacific sites) or Table 2 (for the NTS), interpolating as required for the appropriate distance (x) from the source plane and time (t) after detonation. To reduce application variability, anatomic location has been standardized with respect to distance from the contaminated plane surface, as indicated in Table 7 (based on a reference individual 180 cm tall). The value of $R_{\beta/\gamma}(x,t)$ may be modified by the factors of Table 4 if necessary to account for clothing that covered the anatomical location of interest during exposure. The resulting ratio,

Table 6. Beta-to-gamma dose ratios for bare skin exposures to neutron-activated soil at the Nevada Test Site.

Hours after detonation	Distance from source plane (cm)		
	1	100	160
0.5	0.257	0.121	0.084
1	0.250	0.118	0.081
2	0.239	0.111	0.076
3	0.228	0.105	0.071
4	0.219	0.100	0.067
5	0.211	0.095	0.064
6	0.204	0.091	0.061
7	0.198	0.088	0.059
8	0.194	0.085	0.057
9	0.190	0.083	0.055
10	0.186	0.081	0.053
12	0.181	0.078	0.051
15	0.176	0.075	0.049
20	0.171	0.071	0.046
24	0.168	0.070	0.045
36	0.164	0.066	0.042
48	0.162	0.063	0.039
72	0.164	0.058	0.035
120	0.275[a]	0.050	0.029
168	1.391[a]	0.045	0.025

[a] The increased ratio is due to the decay of ^{45}Ca, which has a comparatively long half-life and predominantly emits soft beta particles.

Table 7. Standard distances from ground source plane for various anatomical locations.

Anatomical location	Distance from source plane (cm)
foot	1
shin	20
knee	40
mid-thigh	70
waist	100
stomach	120
mid-chest	140
face and head	160
top of head	180

when multiplied by the individual's film badge gamma dose (or reconstructed equivalent) accrued during the acute exposure, provides an estimate of the beta dose.

For chronic exposures (e.g., for an individual residing in a fallout field for an extended period), the beta dose is obtained by summing (integrating) over the period of exposure. This will generally require that the time dependence of the gamma dose be modeled, taking care to include only those components of gamma dose accrued concurrently with the beta dose. If, for example, a person is exposed to a combined beta and gamma environment while outside and gamma only while inside, the component of gamma dose accrued while outside is the proper multiplier of the beta-to-gamma dose ratio.

In both acute and chronic exposure scenarios, the total skin dose is obtained by summing the beta and gamma doses. Eye dose and exposure to neutron-activated soil are treated in an analogous manner.

The skin and eye doses reconstructed with this methodology for exposures to large radiation fields are intrinsically conservative (i.e., high-sided) because, as discussed previously, a number of effects that preferentially diminish the beta dose are not included in the formulation. One can further ensure that the derived beta dose is not underestimated by using an upper bound of the gamma dose in the application of this methodology (a convention adopted in the NTPR Program).

CONCLUSION

A method is presented to reconstruct beta dose to the skin and/or lens of the eye on the basis of a concurrently accrued film badge gamma dose for personnel who were present in a large residual radiation field that resulted from a nuclear detonation. The formulation is applicable to personnel who were exposed up to 2 y after a detonation to fallout or to neutron-activated soil. This methodology, which provides conservative estimates made in the interest of not underestimating the true value, has been used extensively for dose reconstruction purposes in the NTPR Program.

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