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A MODEL FOR EXPOSURE TO A SEMI-INFINITE CLOUD OF A PHOTON EMITTER*

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Abstract

The dose from a semi-infinite cloud of a photon-emitting radio-nuclide is an idealization of an exposure situation, but it is a useful one, particularly for noble gases of long radioactive decay half-times, e.g., ^{85}Kr . This paper presents an analysis of absorbed dose to body organs for monoenergetic photons emitted in an infinite cloud. Twelve photon energies in the range 0.01 to 4 MeV were used in these calculations, and the concentration in the cloud was considered uniform. The energy spectrum of scattered photons is first calculated by the method of Dillman, and the resulting fluence is used as the source on an anthropomorphic phantom, essentially as considered in MIRD Pamphlet No. 5. The dose to the various organs is obtained by the Monte Carlo technique. Also a method is described which provides estimates of absorbed dose to organs by use of calculated depth dose profiles in the phantom. This method is used for those organs for which the coefficient of variation of the Monte Carlo estimate exceeded 30%. It is expected that dose from photons emitted in the decay of a real radionuclide could be obtained by interpolation from these results.

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INTRODUCTION

Radionuclides present in the air may irradiate the body significantly as an external source in addition to the radiation received following inhalation or ingestion. In particular, the noble gases are of special importance due to the rapidity of their elimination from the body and the resulting low dose delivered from the internal source. In many cases the external source can be assumed to be infinite, particularly for radionuclides of long radioactive decay half-times, e.g., ^{85}Kr . Even when a finite cloud is assumed, one may be willing to accept the conservatism inherent in the assumption of an infinite cloud at a concentration approaching the maximum observed or assumed concentration rather than resort to more accurate, but much more complicated, calculations for the finite cloud. This paper presents estimates of dose to body organs for monoenergetic photons emitted in the infinite cloud. These sources are for the same twelve energies used in the calculations reported in MIRD Pamphlet No. 5 (Snyder et al., 1969) and use the same type of phantom and the Monte Carlo techniques developed there. It is expected that dose from photons emitted in the decay of a real radionuclide could be obtained by interpolation from these results. Previous results have usually been given only for a surface dose at the boundary of a half-space containing no emitter. However, these results give no indication of the depth dose within the body or of dose to individual body organs, and it is not always conservative in that there may be a considerable contribution to dose from photons transmitted through the body.

METHODS

If a hypothetical photon emitter, emitting 1 photon of energy E_0 per disintegration, is considered to be distributed uniformly in an infinite cloud with intensity of 1 $\mu\text{Ci/g air}$ $\&$ (3.2×10^9 disintegrations/day)/g air, the dose rate in the air is $51 E_0$ rad/day. If one considers an infinitesimal tissue element in the field, it will be irradiated by photons of a spectrum of energies not exceeding E_0 . The first objective of the approach taken here is to calculate this energy spectrum. Because the initial photon may be assumed to be emitted isotropically, all succeeding generations of photons will also be distributed isotropically. Thus one need only calculate the spectrum of energies in energy space. The procedure for calculating this energy spectrum has been developed by Dillman, (Dillman, 1973) and the reader is referred to his paper for further details concerning the method used.

Photons chosen randomly from this spectrum of energies were programmed to impinge randomly on the surface of the phantom, the distribution of angles being chosen to represent an isotropic emission of photons in the cloud, that is, the direction was chosen from the cumulative distribution

$$\text{Expectation } (\theta < \theta_0) = \frac{1}{4} \sin^2 \theta_0$$

θ being the acute angle the photon direction makes with the inward pointing normal to the surface. The phantom used was essentially that described in MIRD Pamphlet No. 5 (Snyder et al., 1969) with the modifications mentioned in the SEE report (Snyder et al., 1973) The photon

energy was determined by independent selection from the spectrum of Dillman (Dillman, 1973). A sample of 60,000 photons was used for each monoenergetic source, and the values of dose per photon incident on the phantom are tabulated in Table 1. The values not underscored had a coefficient of variation of less than 30% and were accepted on the basis of this calculation. In Table 2 the results have been normalized to provide estimates of dose rate (rad/day) corresponding to a concentration in the cloud of $1 \mu\text{Ci}/\text{m}^3$ of a hypothetical emitter with a yield of 1 photon per disintegration at the indicated energy. To do this, the absorbed dose per incident photon as determined by the Monte Carlo calculation has been multiplied by the surface area of the phantom ($14,576 \text{ cm}^2$) and by one-half the photon fluence in the infinite cloud. This factor varies with the energy of the initial photon; the fraction one-half represents the effect of the air-ground interface (Dillman, 1973). A second factor of one-half has been included in the calculation of photon fluence incident on the surface of the phantom to account for the fact that the presence of the phantom acts as a shield so that the phantom surface is irradiated only from the exterior. In addition, dose estimates were multiplied by the factor $10^{-6}/0.001293$ to convert the results from those for a source intensity of $1 \mu\text{Ci}/\text{g}$ of air to $1 \mu\text{Ci}/\text{m}^3$ (STP). The conversion factors are tabulated as a function of energy in Table 3.

To obtain more accurate estimates for calculated values with coefficient of variation greater than 30%, we plotted the average dose found in the Monte Carlo calculations for various regions of the phantom which are defined by a regular geometrical grid of surfaces.

Table 1. Absorbed Dose (rad /photon) for Selected Organs from Cloud Source
Initial Energy of Photons (MeV)

Organ	0.01	0.015	0.02	0.03	0.05	0.1	0.2	0.5	1.0	1.5	2.0	4.0
Bladder	3.2-23	3.6-18	1.4-16	1.8-15	2.9-15	5.0-15	6.4-15	1.4-14	2.8-14	4.1-14	4.2-14	2.1-13
Stomach	4.5-16	1.8-16	5.2-16	2.1-15	3.9-15	4.7-15	6.5-15	1.8-14	2.6-14	4.1-14	5.5-14	7.7-14
Sm. Int.	3.5-19	1.1-17	1.0-16	9.2-16	2.7-15	4.7-15	7.0-15	1.3-14	2.4-14	3.4-14	4.7-14	1.1-13
U.L.I.	6.1-19	2.7-18	1.8-16	1.3-15	3.0-15	4.6-15	7.2-15	1.4-14	2.8-14	4.5-14	7.2-14	1.3-13
L.L.I.	7.3-17	8.8-16	4.6-16	6.4-16	2.5-15	3.8-15	5.5-15	1.3-14	2.0-14	3.8-14	5.0-14	1.0-13
Kidneys	2.6-19	3.3-17	1.2-15	3.0-15	3.9-15	5.3-15	7.2-15	1.6-14	2.9-14	3.1-14	4.6-14	9.5-14
Liver	1.9-18	3.5-17	4.0-16	2.0-15	3.7-15	5.4-15	7.6-15	1.5-14	2.6-14	3.7-14	5.3-14	1.1-13
Lungs	1.8-16	3.8-16	6.3-16	2.7-15	4.5-15	6.1-15	8.8-15	1.7-14	2.9-14	4.2-14	5.7-14	1.1-13
Marrow	3.5-16	2.0-15	4.3-15	8.7-15	1.3-14	1.3-14	1.5-14	2.2-14	3.4-14	4.5-14	5.9-14	1.1-13
Yelllow	4.3-16	2.4-15	5.1-15	1.0-14	1.4-14	1.4-14	1.6-14	2.3-14	3.6-14	4.7-14	6.3-14	1.2-13
Red	7.4-16	1.6-15	3.5-15	7.3-15	1.1-14	1.2-14	1.4-14	2.1-14	3.1-14	4.3-14	5.5-14	1.0-13
Muscle	9.5-17	1.7-16	6.2-16	1.9-15	3.8-15	6.3-15	9.1-15	1.8-14	3.1-14	4.4-14	5.9-14	1.2-13
Ovaries	1.3-16	2.8-16	8.5-16	6.6-16	2.7-15	3.1-15	5.4-15	6.6-15	1.9-14	4.1-14	6.3-14	1.2-13
Pancreas	3.3-16	1.9-15	4.0-16	8.1-15	1.2-14	1.3-14	1.5-14	1.1-14	3.1-14	3.8-14	6.2-14	2.1-13
Skeleton	4.1-14	3.0-14	2.0-14	1.2-14	8.5-15	8.4-15	1.2-14	2.2-14	3.4-14	4.6-14	6.1-14	1.2-13
Spleen	4.5-17	1.8-16	3.5-16	1.8-15	3.6-15	4.4-15	8.1-15	1.9-14	3.1-14	4.8-14	7.2-14	1.3-13
Testes	1.6-15	2.2-15	5.8-15	7.3-15	5.4-15	6.8-15	1.3-14	2.0-14	2.8-14	5.0-14	3.7-14	1.1-13
Thymus	2.7-20	1.7-17	3.0-16	2.8-15	4.0-15	3.8-15	8.1-15	1.1-14	2.1-14	3.3-14	6.2-14	7.2-14
Thyroid	9.1-17	1.4-17	1.5-15	5.6-15	6.1-15	8.9-15	9.5-15	1.5-14	2.3-14	4.4-14	5.5-14	2.1-13
Uterus	1.8-20	2.5-19	3.8-17	6.8-16	1.0-15	3.0-15	6.0-15	1.2-14	2.2-14	3.0-14	4.7-14	9.2-14
Total Body	2.2-15	3.2-15	4.1-15	5.3-15	6.2-15	7.3-15	9.9-15	1.8-14	3.1-14	4.4-14	5.9-14	1.2-13

Table 2. Absorbed Dose Rate (Rad /Day) for Selected Organs from Cloud Source
Assumes 1 $\mu\text{Ci}/\text{m}^3$ in Air

Organ	Initial Energy (MeV)											
	0.01	0.015	0.02	0.03	0.05	0.1	0.2	0.5	1.0	1.5	2.0	4.0
Bladder	2.95 -14	1.25 -8	1.20 -6	5.02 -5	2.65 -4	1.09 -3	1.98 -3	5.97 -3	1.34 -2	2.29 -2	2.30 -2	1.25 -1
Stomach	4.25 -7	6.00 -7	4.65 -6	6.03 -5	3.61 -4	1.00 -3	2.06 -3	7.47 -3	1.26 -2	2.32 -2	2.97 -2	4.50 -2
Sm. Int.	3.30 -10	3.80 -8	8.00 -7	2.65 -5	2.52 -4	1.00 -3	2.19 -3	5.48 -3	1.15 -2	1.91 -2	2.61 -2	6.50 -2
U.L.I.	6.02 -10	9.51 -9	1.55 -6	3.75 -5	2.79 -4	9.52 -4	2.30 -3	6.11 -3	1.34 -2	2.55 -2	3.95 -2	7.50 -2
L.L.I.	6.99 -8	3.05 -6	3.85 -6	1.85 -5	2.29 -4	8.13 -3	1.75 -3	5.51 -3	9.49 -3	2.15 -2	2.75 -2	6.03 -2
Kidneys	2.45 -10	1.10 -7	1.01 -5	8.49 -5	3.61 -4	1.12 -3	2.29 -3	6.51 -3	1.41 -2	1.75 -2	2.50 -2	5.49 -2
Liver	1.80 -9	1.20 -7	3.45 -6	6.01 -5	3.40 -4	1.17 -3	2.42 -3	6.48 -3	1.26 -2	2.09 -2	2.93 -2	6.50 -2
Lungs	1.69 -7	1.29 -6	5.05 -6	7.49 -5	4.25 -4	1.32 -3	2.81 -3	7.02 -3	1.40 -2	2.36 -2	3.14 -2	6.83 -2
Marrow	3.30 -7	7.03 -6	3.69 -5	2.51 -4	1.32 -3	2.79 -3	4.70 -3	8.97 -3	1.67 -2	2.55 -2	3.27 -2	6.52 -2
Yellow	3.85 -7	8.01 -6	4.25 -5	2.90 -4	1.32 -3	3.00 -3	5.11 -3	9.52 -3	1.74 -2	2.66 -2	3.44 -2	7.00 -2
Red	2.50 -7	5.49 -6	2.98 -5	2.09 -4	1.00 -3	2.55 -3	4.41 -3	9.03 -3	1.50 -2	2.45 -2	3.00 -2	5.97 -2
Muscle	6.99 -7	8.50 -6	3.30 -5	1.45 -4	4.98 -4	1.35 -3	2.85 -3	7.51 -3	1.49 -2	2.49 -2	3.25 -2	6.96 -2
Ovaries	9.02 -8	5.98 -7	5.05 -6	5.53 -5	3.48 -4	6.48 -4	1.72 -3	2.75 -3	9.01 -3	2.31 -2	3.47 -2	7.03 -2
Pancreas	1.21 -7	9.49 -7	7.50 -6	1.90 -5	2.52 -4	7.97 -4	1.86 -3	4.11 -3	1.51 -2	2.14 -2	3.40 -2	1.25 -1
Skeleton	3.09 -7	6.48 -6	3.45 -5	2.30 -4	1.11 -3	2.80 -3	4.68 -3	9.11 -3	1.65 -2	2.58 -2	3.35 -2	7.01 -2
Skin	3.85 -5	1.04 -4	1.75 -4	3.45 -4	7.51 -4	1.79 -3	3.78 -3	8.99 -3	1.94 -2	2.71 -2	3.95 -2	7.50 -2
Spleen	4.25 -8	6.00 -7	3.00 -6	5.02 -5	3.30 -4	9.52 -4	2.55 -3	8.00 -3	1.48 -2	2.82 -2	2.05 -2	6.47 -2
Testes	1.50 -6	7.51 -6	5.01 -5	2.09 -4	5.01 -4	1.45 -3	4.08 -3	8.49 -3	1.35 -2	1.85 -2	1.65 -2	4.20 -2
Thymus	2.50 -11	5.97 -8	2.60 -6	8.00 -5	3.70 -4	8.00 -4	2.56 -3	4.58 -3	1.01 -2	2.29 -2	3.41 -2	1.15 -1
Thyroid	8.49 -8	5.00 -8	1.29 -5	1.59 -4	5.97 -4	1.92 -3	3.02 -3	6.25 -3	1.09 -2	2.51 -2	3.03 -2	1.25 -1
Uterus	1.68 -11	8.50 -10	3.30 -7	1.95 -5	9.49 -5	6.49 -4	1.88 -3	5.03 -3	1.04 -2	1.68 -2	3.59 -2	5.51 -2
Total Body	2.05 -6	1.10 -5	3.50 -5	1.49 -4	6.02 -4	1.55 -3	3.15 -3	7.52 -3	1.48 -2	2.49 -2	3.25 -2	7.00 -2

Table 3. Number of Photons/Day Impinging on Phantom*

Conversion Factors for Photon Cloud Source

Initial Energy	Photon Flux Density	Photons/ Day**	Photons/ Day***
(MeV)	(photons/cm ² /sec)		
0.01	1.92×10^3	2.42×10^{12}	1.87×10^9
0.015	7.09×10^3	8.93×10^{12}	6.90×10^9
0.02	1.77×10^4	2.23×10^{13}	1.72×10^{10}
0.03	5.91×10^4	7.45×10^{13}	5.76×10^{10}
0.05	1.90×10^5	2.39×10^{14}	1.85×10^{11}
0.1	4.40×10^5	5.54×10^{14}	4.28×10^{11}
0.2	6.50×10^5	8.16×10^{14}	6.31×10^{11}
0.5	8.60×10^5	1.08×10^{15}	8.35×10^{11}
1.0	9.99×10^5	1.26×10^{15}	9.74×10^{11}
1.5	1.16×10^6	1.46×10^{15}	1.13×10^{12}
2.0	1.13×10^6	1.42×10^{15}	1.10×10^{12}
4.0	1.20×10^6	1.52×10^{15}	1.17×10^{12}

* Surface area of phantom - 14576 cm²

** Assuming 1 $\mu\text{Ci/gm}$ of air at STP

*** Assuming 1 $\mu\text{Ci/m}^3$ of air at STP

The trunk of the phantom is cut by 4 horizontal planes into 5 slices or tiers, each 14 cm in height. The trunk, whose outer surface is an elliptic cylinder defined by

$$\frac{x^2}{20^2} + \frac{y^2}{10^2} = 1, 0 \leq z \leq 70, \quad (2)$$

is cut by 4 concentric elliptical surfaces

$$\frac{x^2}{(\rho \cdot 20)^2} + \frac{y^2}{(\rho \cdot 10)^2} = 1, \rho = 4/5, 3/5, 2/5, 1/5. \quad (3)$$

Finally, two planes

$$x + y = 1 \quad x - y = 1 \quad (4)$$

further subdivide the regions formed by the elliptical surfaces. The intersections of these surfaces and the regions they define are presented in Figure 1 which also shows subdivisions of the head and leg regions of the phantom as originally defined. However, only the subregions of the trunk were used in this paper. The average dose in each of these regions was used as an additional datum from the Monte Carlo calculations and had the advantage that, generally speaking, their coefficients of variation were smaller than those calculated for many of the particular organs. Moreover, their regular variations of size and of depth below the irradiated surfaces of the phantom undoubtedly produced considerable regularity in their joint statistical behavior. To obtain greater accuracy, the four central volume elements--that is, those lying inside the central ellipse defined by $\rho = 1/5$ --were averaged together.

Figure 1

Fig. 1

The technique employed to provide the above mentioned estimates was based on the use of these 85 geometrical subregions in the adult phantom. These regions allow one to plot depth dose profiles in the phantom, along the major and minor axes of the elliptical cross-section, for each of the five tiers in the trunk. These profiles were constructed for each photon energy. The data were fit, by use of a computer, with a smooth curve and the resulting sets of curves were used to provide estimates of the absorbed dose to the organs of interest. Typical depth dose profiles in tier one (the lowest tier in the trunk), plotted for photon energies of 0.03 and 1 MeV, are shown in Figure 2. A schematic drawing of each organ was prepared which gave the location of the organ in the tier and the subregions which comprised the tier. Figure 3 shows a view of tier one and the location of the bladder in the geometric volume elements. By combining these schematic drawings and the depth dose profiles, an estimate of the absorbed dose to each organ or region was derived. These estimates of absorbed dose were used in the tables for organs which had a coefficient of variation in excess of 30%.

Before extensive use of this method was made in this study, a number of checks were made with statistically reliable data. The technique, described above, was used to provide estimates of absorbed dose to the major organs of the phantom for cases where the coefficients of variations were much less than 30%. These tests demonstrated that the technique could provide reliable estimates of absorbed dose for the majority of organs. Table 4 presents a comparison of absorbed dose from the Monte Carlo calculation and the absorbed dose estimated

Fig 2. DOSE PER PHOTON, FROM INFINITE CLOUD. (ENERGIES 1 Mev AND 0.03 Mev)

Table 4 - Comparison of Estimated and Calculated Absorbed
Dose to Selected Organs

ABSORBED DOSE (RAD/PHOTON) FROM SOURCE IN CLOUD						
Organ	0.2 MeV			2 MeV		
	Monte Carlo Calculation	Estimate From Depth-Dose	Ratio MC/DD	Monte Carlo Calculation	Estimate From Depth-Dose	Ratio MC/DD
	($\times 10^{-15}$)	($\times 10^{-15}$)		($\times 10^{-14}$)	($\times 10^{-14}$)	
Bladder	6.35	7.52	0.844	4.18	5.20	0.804
Stomach	6.45	9.05	0.713	5.46	5.53	0.987
ULI	7.25	7.04	1.03	7.25	4.75	1.53
LLI	5.51	7.60	0.725	5.00	5.18	0.965
Kidneys	7.18	8.28	0.867	4.65	5.34	0.871
Lungs	8.82	8.30	1.06	5.69	5.38	1.06
Ovaries	5.44	7.82	0.696	6.29	5.24	1.20
Pancreas	5.94	8.05	0.737	6.17	5.31	1.16
Spleen	8.06	9.05	0.891	3.73	5.52	0.676
Testes	12.8	9.34	1.37	3.01	5.52	0.545
Thymus	8.15	8.08	1.01	6.20	5.27	1.18
Thyroid	9.49	10.4	0.913	5.55	5.50	1.01
Uterus	6.00	6.76	0.888	2.44	4.68	0.521

as described above. The photon energies of 0.2 and 2 MeV were chosen to illustrate this technique since the Monte Carlo calculations gave results with coefficients of variation of less than 30% and thus the calculated results were considered to be reliable. Organs for which estimates did not agree closely with calculated values were generally very complex (e.g., the upper large intestine) and extended into several tiers and many subregions of the phantom. However, by modifying the techniques, when applied to specific organs with very complex geometries, estimates of absorbed dose were derived which provided estimates of absorbed dose within 30% of the calculated values. After these checks were completed, the technique was applied to provide estimates of absorbed dose per incident photon (Table 1) and thus dose rate (Table 2) to complete the tabulations. As pointed out previously, these estimates have been underscored in Tables 1 and 2. It is readily apparent that, in general, these estimates were required for low energy photons and/or for organs which had small volumes.

The absorbed dose from photons emitted in the decay of a real radionuclide may be obtained by interpolation or by extrapolation from these results. Clearly, the results will depend to some extent on the interpolation formula used, but for the extrapolated values, it appears the linear extrapolation to 0 probably produces a conservative estimate of dose since the dose versus energy curves we have examined appear to be concave upward in the energy region up to 50 keV.

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