

# ABSORBED FRACTIONS FOR SMALL VOLUMES CONTAINING PHOTON-EMITTING RADIOACTIVITY

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## 1. INTRODUCTION

The absorbed fraction  $\phi$  is the ratio of the energy absorbed in a given target volume to the energy emitted by a radioactive source. The use of absorbed fractions to calculate the dose from radionuclides within the body has been described in previous MIRD publications (1-4). The average dose  $\bar{D}$  delivered to a target of mass  $m$  is given by

$$\bar{D} = \frac{\bar{A}}{m} \sum_i \phi_i \Delta_i \quad (1)$$

where  $\bar{A}$  is the cumulated activity;  $\phi_i$  is the absorbed fraction for a given energy  $E_i$ , target configuration, and source geometry; and  $\Delta_i$  is the equilibrium dose constant. Values of  $\Delta_i$  for a number of photon and charged particle emitters have recently been compiled by Dillman (5,6).

This pamphlet reports values of absorbed fractions for photon emitters in relatively small, unit-density absorbing volumes (1-500 g) containing either a central point or a uniformly distributed photon source. The purpose of these data is to supplement the tables of absorbed fractions published in *MIRD Pamphlet 3* for absorbing volumes of 300 g and larger. The present data, however, differ in one important respect from absorbed fractions published earlier. In the results given below it is assumed that the volume containing the activity is imbedded within a large scattering medium of the same composition. Backscattered radiation from these surroundings is included in the absorbed fractions tabulated below.

The composition of the unit-density absorbing medium used as an analog for soft tissue in this study is listed in Table 1. The mean free path, and the total attenuation and energy-transfer coefficients of the material are listed in Table 2 for the source energies considered here. A comparison of absorbed fractions in this material and in other tissue analogs is given in Section 7.

## 2. SPECIFIC ABSORBED FRACTIONS

The photon absorbed fractions listed in *MIRD Pamphlet 3* and in *MIRD Pamphlet 4* were obtained by summing the energy losses from a sequence of photon interactions generated by means of Monte Carlo techniques. A different approach for calculating absorbed fractions, which is not subject to large uncertainties for small volumes, was used in this study. First, specific absorbed fractions, the fractions of the emitted energy absorbed per gram of material, were calculated by a combination of Monte Carlo simulation and analytical calculations, and then the absorbed fractions, presented here, were determined by appropriate integrations.

**TABLE 1. COMPOSITION OF SOFT-TISSUE ANALOG USED IN THIS STUDY**

Element	% mass
Oxygen	71.39
Carbon	14.89
Hydrogen	10.00
Nitrogen	3.47
Chlorine	0.10
Sodium	0.15

**TABLE 2. TOTAL ATTENUATION COEFFICIENTS,  $\mu$ , ENERGY TRANSFER COEFFICIENTS,  $\mu_K$ , AND MEAN FREE PATHS,  $\lambda$ , FOR UNIT-DENSITY TISSUE DESCRIBED IN TABLE 1**

$E_i$ (MeV)	$\mu$ (cm <sup>-1</sup> )	$\mu_K$ (cm <sup>-1</sup> )	$\lambda$ (cm)
0.030	0.320	0.134	3.12
0.040	0.236	0.0576	4.24
0.060	0.192	0.0285	5.21
0.080	0.176	0.0247	5.68
0.100	0.165	0.0247	6.06
0.140	0.150	0.0267	6.67
0.364	0.110	0.0322	9.09
0.662	0.0853	0.0323	11.7
1.460	0.0577	0.0283	17.3
2.750	0.0413	0.0233	24.2

Preparation of the specific absorbed-fraction values used in this study has been described previously (7-9). Briefly, photon trajectories were analyzed to determine the spectral distribution of the energy fluence passing through concentric spherical shells of differential thicknesses at various distances from a point source. Then an expectation value of the energy transfer from this fluence was calculated using mass energy-transfer coefficients. Only scattered photons were considered in these calculations. The kerma from unscattered photons was calculated analytically so as not to contribute to the sampling error in the determination of the specific absorbed fractions. For small targets, the method outlined above has two additional advantages over the energy tabulation method of obtaining absorbed fractions. The number of photon trajectories intersecting a thin shell is much greater than the number of energy losses within it, so that the sampling error is correspondingly reduced. Equally important is that the energy losses considered are expected values, proportional to the energy-transfer coefficient, rather than variable energy losses with values ranging between zero and the source energy. The specific absorbed fractions used in this study have sampling errors of less than 2% over the range of dimensions considered here (7).

### 3. CALCULATION OF ABSORBED FRACTIONS BY INTEGRATION

To obtain absorbed fractions from these specific absorbed fractions, it is necessary to integrate the specific absorbed fraction values over the geometry of interest. For example, the absorbed fraction  $\phi$  for a point source irradiating a volume  $v$  with density  $\rho$  is

$$\phi = \rho \int \Phi(r) dv, \quad (2)$$

in which  $\Phi(r)$  is the point specific absorbed fraction as a function of distance  $r$ . Equation 2 is general in that the source need not be within  $v$ . Neither is Eq. 2 necessarily limited to unbounded absorbers since correction factors for boundary effects can be used to allow for an air interface (7,9).

Absorbed fractions for extended sources can be considered by appropriate integration of Eq. 2. If the activity is uniformly distributed within a volume  $v_2$ , which may or may not be part of the target volume  $v_1$ ,

$$\phi(v_1 \leftarrow v_2) = \frac{\rho}{v_2} \int \int \Phi(r) dv_1 dv_2. \quad (3)$$

For all except the simplest geometries, Eqs. 2 and 3 must be integrated by computer calculations. Therefore a program using a Simpson's rule integration scheme was prepared to perform the operations indicated above. This program is for ellipsoidal targets and source volumes, either or both of which may contain an excluded ellipsoidal volume located within it. The program input consists of inner boundary and outer boundaries of the ellipsoidal target volume, the same parameters for the source, specific absorbed fractions for the initial photon energy, and the coordinates of the center of the source relative to the center of the target.

The programming of the integration is somewhat simplified by using the same number of mesh points and mesh spacing for all traverses of a given coordinate ( $x$ ,  $y$ , or  $z$ ) and simply forcing the values of  $\Phi(r)$  used outside the volume to zero. This introduces a small amount of round-off error, but additional studies have

TABLE 3. ABSORBED FRACTIONS FOR CENTRAL POINT SOURCES IN UNIT-DENSITY SPHERES SURROUNDED BY SCATTERING MEDIUM

Mass (g)	Photon energy (MeV)										Radius (cm)
	0.030	0.040	0.060	0.080	0.100	0.140	0.364	0.662	1.460	2.750	
1	0.079	0.035	0.017	0.015	0.015	0.015	0.018	0.018	0.016	0.013	0.62
2	0.102	0.046	0.023	0.019	0.020	0.020	0.023	0.023	0.020	0.016	0.78
4	0.133	0.061	0.030	0.025	0.025	0.026	0.030	0.029	0.026	0.021	0.98
6	0.153	0.071	0.035	0.029	0.029	0.030	0.034	0.034	0.029	0.024	1.13
8	0.171	0.080	0.039	0.033	0.033	0.033	0.038	0.038	0.033	0.027	1.24
10	0.185	0.088	0.043	0.036	0.036	0.036	0.041	0.041	0.036	0.029	1.34
20	0.236	0.115	0.057	0.047	0.046	0.047	0.053	0.052	0.046	0.036	1.68
40	0.299	0.150	0.075	0.061	0.060	0.060	0.067	0.066	0.057	0.046	2.12
60	0.342	0.175	0.088	0.072	0.070	0.069	0.077	0.076	0.066	0.053	2.43
80	0.376	0.195	0.100	0.082	0.078	0.078	0.085	0.084	0.073	0.059	2.67
100	0.402	0.211	0.109	0.089	0.085	0.085	0.092	0.090	0.078	0.063	2.88
200	0.492	0.272	0.146	0.119	0.111	0.110	0.117	0.114	0.099	0.080	3.63
300	0.551	0.318	0.171	0.138	0.131	0.126	0.132	0.129	0.111	0.090	4.15
400	0.591	0.352	0.191	0.155	0.147	0.140	0.145	0.141	0.122	0.099	4.57
500	0.627	0.378	0.213	0.172	0.160	0.155	0.159	0.154	0.133	0.108	4.92

evaluated this source of error (see below). Interpolation of specific absorbed fractions between the points entered as input is accomplished either by using an Aitken interpolation scheme (10) or, for values within 1 cm of the source, an analytical expression of the form:

$$4\pi r^2 \Phi(r) = (a_0 + a_1 r + a_2 r^2 + a_3 r^3 + a_4 r^4) e^{-\mu r} \quad (4)$$

Coefficients  $a_0, a_1, \dots$ , for each photon source energy were found by fitting the specific absorbed fraction data to Eq. 4 by the method of Fletcher and Powell (11). This procedure fitted the data between 0 and 12 cm with an accuracy of about 1%. The coefficient  $a_0$  is identical with the mass energy-transfer coefficient.

4. ABSORBED FRACTIONS FOR CENTRAL POINT SOURCES

Absorbed fractions from central point sources in small spherical targets ranging in mass from 1 to 500 g are given in Table 3. It should be noted that unlike the absorbed fractions listed in Tables 10 and 11 of *MIRD Pamphlet 3*, all the results presented in this pamphlet include a contribution from backscattered radiation.

Table 4 lists absorbed fractions for ellipsoids containing a central point source. The axes of these ellipsoids are in the ratio of 1:2:4. Table 5 lists the absorbed fraction for thinner and more elongated ellipsoids (axes 1:3:8) containing a central point source.

**TABLE 4 ABSORBED FRACTIONS FOR CENTRAL POINT SOURCES IN UNIT-DENSITY ELLIPSOIDS SURROUNDED BY SCATTERING MEDIUM (AXES 1:2:4)**

Mass (g)	Photon energy (MeV)									
	0.030	0.040	0.060	0.080	0.100	0.140	0.364	0.662	1.460	2.750
1	0.068	0.031	0.015	0.013	0.012	0.013	0.016	0.015	0.013	0.011
2	0.088	0.040	0.020	0.016	0.016	0.017	0.020	0.020	0.017	0.014
4	0.115	0.053	0.026	0.022	0.021	0.022	0.026	0.026	0.022	0.018
6	0.132	0.062	0.030	0.025	0.025	0.026	0.030	0.029	0.026	0.021
8	0.147	0.069	0.034	0.028	0.027	0.029	0.033	0.032	0.028	0.023
10	0.159	0.075	0.037	0.031	0.030	0.031	0.036	0.035	0.031	0.025
20	0.203	0.099	0.049	0.040	0.039	0.040	0.045	0.045	0.039	0.032
40	0.256	0.128	0.065	0.053	0.051	0.052	0.058	0.057	0.049	0.040
60	0.293	0.150	0.077	0.062	0.060	0.060	0.066	0.065	0.057	0.046
80	0.322	0.166	0.088	0.071	0.068	0.068	0.073	0.072	0.063	0.051
100	0.345	0.181	0.096	0.077	0.074	0.074	0.079	0.078	0.068	0.055
200	0.426	0.236	0.128	0.103	0.097	0.096	0.101	0.098	0.086	0.069
300	0.478	0.273	0.151	0.122	0.114	0.112	0.117	0.113	0.099	0.080
400	0.515	0.301	0.169	0.137	0.124	0.124	0.129	0.124	0.108	0.088
500	0.547	0.326	0.185	0.150	0.139	0.136	0.139	0.134	0.117	0.095

**TABLE 5. ABSORBED FRACTIONS FOR CENTRAL POINT SOURCES IN SMALL UNIT-DENSITY ELLIPSOIDS SURROUNDED BY SCATTERING MEDIUM (AXES 1:3:8)**

Mass (g)	Photon energy (MeV)									
	0.030	0.040	0.060	0.080	0.100	0.140	0.364	0.662	1.460	2.750
1	0.057	0.026	0.013	0.011	0.010	0.011	0.013	0.013	0.011	0.009
2	0.074	0.034	0.016	0.014	0.014	0.014	0.017	0.017	0.014	0.012
4	0.097	0.045	0.022	0.018	0.018	0.019	0.022	0.022	0.019	0.015
6	0.111	0.052	0.026	0.021	0.021	0.022	0.025	0.025	0.022	0.018
8	0.124	0.059	0.029	0.024	0.023	0.024	0.028	0.028	0.024	0.020
10	0.134	0.064	0.032	0.026	0.026	0.026	0.030	0.030	0.026	0.021
20	0.172	0.084	0.042	0.035	0.033	0.034	0.039	0.038	0.033	0.027
40	0.217	0.109	0.055	0.045	0.043	0.044	0.049	0.048	0.042	0.035
60	0.248	0.127	0.065	0.053	0.051	0.052	0.057	0.056	0.048	0.040
80	0.273	0.143	0.074	0.060	0.057	0.058	0.063	0.062	0.054	0.044
100	0.294	0.155	0.081	0.066	0.063	0.063	0.069	0.067	0.058	0.048
200	0.362	0.200	0.107	0.087	0.082	0.081	0.087	0.085	0.073	0.060
300	0.405	0.230	0.126	0.103	0.096	0.095	0.100	0.097	0.084	0.069
400	0.439	0.255	0.142	0.116	0.108	0.106	0.111	0.107	0.092	0.076
500	0.466	0.275	0.155	0.127	0.113	0.115	0.119	0.115	0.099	0.082

It is seen by comparing Tables 3, 4, and 5 that elongation of a target organ of fixed mass reduces the absorbed fraction, and that this change becomes somewhat larger as the mass of the target organ is reduced. However, for the small target volumes considered in this pamphlet, the absorbed fractions are not a very sensitive function of target shape, and it should be possible to interpolate the tabulated data for most geometries of clinical interest.

5. ABSORBED FRACTIONS FOR UNIFORMLY DISTRIBUTED SOURCES

Tables 6, 7, and 8 list, respectively, the absorbed fraction from a photon source uniformly distributed within spheres and each of the two types of ellipsoids described above. The mass of these absorbing volumes ranges from 1 to 100 g. Because of round-off errors in the numerical evaluation of the double integration indicated in Eq. 3, the data for uniformly distributed sources are somewhat less accurate than those given

in Tables 3-5 where the round-off error is about  $\pm 0.001$ . In Tables 7-9 the round-off error increases from  $\pm 0.001$  for the smallest absorbers to about  $\pm 0.008$  for the 100-g absorbers.

The dose is a maximum at the geometric center of a uniform concentration of activity within a finite symmetric absorber. The dose reciprocity relation given in Ref. 1 allows the absorbed fractions,  $\phi$ , given in Tables 3-5 for point sources to be used to calculate specific absorbed fractions,  $\Phi_0$ , at the center of uniform sources of the same mass and shape. The relationship between these quantities is

$$\Phi_0 = \frac{\phi}{m} \tag{5}$$

6. LIMITATIONS IN APPLYING THESE ABSORBED FRACTIONS

Transport and deposition of energy by secondary electrons has not been considered in the present calculations. For the smaller absorbers listed in the tables

**TABLE 6. ABSORBED FRACTIONS FOR UNIFORMLY DISTRIBUTED SOURCES IN SMALL UNIT-DENSITY SPHERES SURROUNDED BY SCATTERING MEDIUM**

Mass (g)	Photon energy (MeV)									
	0.030	0.040	0.050	0.080	0.100	0.140	0.364	0.662	1.460	2.750
1	0.050	0.023	0.011	0.009	0.009	0.010	0.011	0.011	0.010	0.008
2	0.064	0.030	0.014	0.012	0.012	0.012	0.014	0.014	0.012	0.010
4	0.081	0.038	0.019	0.016	0.015	0.016	0.018	0.018	0.016	0.013
6	0.092	0.043	0.022	0.018	0.017	0.018	0.020	0.020	0.018	0.014
8	0.103	0.049	0.024	0.020	0.020	0.020	0.023	0.023	0.020	0.016
10	0.111	0.054	0.027	0.022	0.021	0.022	0.025	0.024	0.021	0.017
20	0.139	0.070	0.035	0.029	0.027	0.028	0.031	0.031	0.027	0.022
40	0.174	0.090	0.046	0.037	0.036	0.036	0.039	0.038	0.033	0.027
60	0.230	0.121	0.064	0.050	0.048	0.048	0.053	0.052	0.045	0.035
80	0.286	0.152	0.079	0.064	0.061	0.061	0.066	0.065	0.056	0.046
100	0.306	0.165	0.087	0.070	0.067	0.066	0.072	0.070	0.061	0.050

**TABLE 7. ABSORBED FRACTIONS FOR UNIFORMLY DISTRIBUTED SOURCES IN SMALL UNIT-DENSITY ELLIPSOIDS SURROUNDED BY SCATTERING MEDIUM (AXES 1:2:4)**

Mass (g)	Photon energy (MeV)									
	0.030	0.040	0.060	0.080	0.100	0.140	0.364	0.662	1.460	2.750
1	0.045	0.021	0.010	0.008	0.008	0.009	0.010	0.010	0.009	0.007
2	0.058	0.027	0.013	0.011	0.011	0.011	0.013	0.013	0.011	0.009
4	0.073	0.035	0.017	0.014	0.014	0.014	0.016	0.016	0.014	0.012
6	0.082	0.040	0.020	0.016	0.016	0.016	0.018	0.018	0.016	0.014
8	0.092	0.045	0.022	0.018	0.018	0.018	0.021	0.020	0.018	0.015
10	0.100	0.049	0.024	0.020	0.019	0.020	0.022	0.022	0.019	0.016
20	0.125	0.063	0.032	0.026	0.025	0.025	0.028	0.028	0.024	0.020
40	0.155	0.081	0.042	0.034	0.032	0.032	0.035	0.035	0.030	0.025
60	0.192	0.101	0.052	0.043	0.040	0.041	0.044	0.044	0.037	0.031
80	0.229	0.121	0.063	0.051	0.049	0.049	0.053	0.052	0.045	0.037
100	0.244	0.131	0.069	0.056	0.053	0.053	0.057	0.056	0.049	0.040

**TABLE 8. ABSORBED FRACTIONS FOR UNIFORMLY DISTRIBUTED SOURCES IN SMALL ELLIPSOIDS SURROUNDED BY SCATTERING MEDIUM (AXES 1:3:8)**

Mass (g)	Photon energy (MeV)									
	0.030	0.040	0.060	0.080	0.100	0.140	0.364	0.662	1.460	2.750
1	0.041	0.019	0.009	0.008	0.007	0.008	0.009	0.009	0.008	0.007
2	0.049	0.023	0.011	0.009	0.009	0.010	0.011	0.011	0.010	0.008
4	0.063	0.030	0.015	0.012	0.012	0.012	0.014	0.014	0.012	0.010
6	0.071	0.034	0.017	0.014	0.013	0.014	0.016	0.016	0.013	0.012
8	0.079	0.038	0.019	0.016	0.015	0.016	0.018	0.018	0.015	0.013
10	0.085	0.042	0.021	0.017	0.017	0.017	0.019	0.019	0.016	0.014
20	0.117	0.059	0.031	0.024	0.024	0.024	0.027	0.027	0.022	0.019
40	0.158	0.080	0.041	0.034	0.032	0.033	0.036	0.036	0.031	0.025
60	0.179	0.093	0.048	0.039	0.037	0.038	0.041	0.041	0.035	0.029
80	0.197	0.104	0.054	0.045	0.042	0.043	0.046	0.045	0.039	0.032
100	0.212	0.113	0.060	0.049	0.046	0.046	0.050	0.049	0.043	0.035

**TABLE 9. COMPARISON OF ABSORBED FRACTIONS CENTRAL POINT SOURCES IN SPHERICAL ABSORBING VOLUMES**

Mass (g)	0.030 MeV					0.100 MeV				
	Soft tissue*	Water	Muscle†	Ratio		Soft tissue*	Water	Muscle†	Ratio	
	$\phi_T$	$\phi_W$ ‡	$\phi_M$ ‡	$\phi_T/\phi_W$	$\phi_M/\phi_W$	$\phi_T$	$\phi_W$ ‡	$\phi_M$ ‡	$\phi_T/\phi_W$	$\phi_M/\phi_W$
1	0.079	0.097	0.100	0.81	1.03	0.015	0.017	0.017	0.88	1.00
2	0.102	0.123	0.127	0.83	1.03	0.020	0.021	0.021	0.95	1.00
4	0.133	0.155	0.160	0.86	1.03	0.025	0.027	0.027	0.93	1.00
10	0.185	0.211	0.218	0.88	1.03	0.036	0.038	0.038	0.95	1.00
20	0.236	0.265	0.273	0.89	1.03	0.046	0.049	0.049	0.94	1.00
40	0.299	0.331	0.340	0.90	1.03	0.060	0.063	0.064	0.95	1.00
100	0.402	0.436	0.446	0.92	1.02	0.085	0.090	0.090	0.94	1.00
200	0.492	0.527	0.539	0.93	1.02	0.111	0.117	0.118	0.95	1.01
400	0.591	0.625	0.637	0.95	1.02	0.146	0.154	0.155	0.95	1.01

\* With composition given in Table 1.

† ICRU muscle (72.9% O, 12.3% C, 10.2% H, 3.5% N, 0.5% S, 0.3% K, 0.2% P, 0.08% Na, 0.02% Mg) by weight.

‡ Calculated using buildup factors and Eq. 8 of Ref. 2.

(note that a 1-g sphere has a radius of only 6.2 mm) some of the energy initially transferred to electrons by high-energy photons may be deposited outside of the target volume. For example, 1-MeV photons will produce Compton electrons having energies up to approximately 800 keV. From Berger's results in *MIRD Pamphlet 9* (12) we note that such electrons will deposit almost half their energy more than 2 mm from their point of origin. In such cases, calculations based on Eq. 1 and the absorbed fractions presented here must be considered as upper limits to the absorbed dose.

The point source functions used in preparing the tables given above apply rigorously only to targets imbedded in an infinite medium. However, if the source and absorbing volume are at least one mean free path (see Table 2) from a nonreflecting boundary such as air, the use of an infinite medium approxima-

tion will introduce little error—in no case more than 10% (7,9). Although all of the values given in the tables are for the unit density tissue analog described in Table 1, absorbed fractions in materials of similar atomic composition but of different density  $\rho_2$  can be obtained by replacing the  $m$ , the mass value in the tables, by  $m/\rho_2^2$  (13).

#### 7. ABSORBED FRACTIONS IN OTHER TISSUE ANALOGS

Some of the results obtained in this study for "soft tissue" are compared in Table 9 with absorbed fractions for two other tissue analogs, water and a composition proposed by the ICRU to represent muscle (14). At low photon energies, absorbed fractions in soft tissue are smaller than in the other two materials, each of which has a somewhat larger photoelectric cross section. Differences in the absorbed fractions

(and specific absorbed fraction) between various soft-tissue analogs depend on both the source energy and the dimensions of the absorber since energy transfer is a function of the spectral distribution of the photon energy fluence as well as energy-transfer coefficients. Specific absorbed fractions in "soft tissue" and water have been compared in detail and the results shown to be independent of the method of calculation (7,9). At high photon energies where photoelectric interactions do not make an appreciable contribution to the energy transfer, specific absorbed fractions in "soft tissue" and water are very nearly the same, and absorbed fractions under these conditions will not differ appreciably. However, at photon source energies below 100 keV, energy absorption is increasingly sensitive to atomic composition, as shown in Table 9. Since the differences in the atomic composition of the tissue analogs listed in Table 9 are comparable with differences in the atomic composition between various types of soft tissue within the body, Table 9 gives some idea of the error introduced in using a single substance to describe low-energy photon absorption in a variety of target organs.

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