chapter 22

Internal Radiation Dosimetry

Absorption of energy from ionizing radiation can cause damage to living tissues. This is used to advantage in radionuclide therapy, but it is a limitation for diagnostic applications because it is a potential hazard for the patient. In either case, it is necessary to analyze the energy distribution in body tissues quantitatively to ensure an accurate therapeutic prescription or to assess potential risks. The study of radiation effects on living organisms is the subject of *radiation biology* (or *radiobiology*) and is discussed in several excellent texts, some of which are listed at the end of this chapter.

One of the most important factors to be evaluated in the assessment of radiation effects on an organ is the amount of radiation energy deposited in that organ. Calculation of radiation energy deposited by internal radionuclides is the subject of *internal radiation dosimetry*. There are two general methods by which these calculations may be performed: the *classic method* and the *absorbed fraction method*. Although the classic method is somewhat simpler, and the results by the two methods are not greatly different, the absorbed fraction method (also known generally as the *MIRD method*, after the Medical Internal Radiation Dose Committee of the Society of Nuclear Medicine) is more versatile and gives more accurate results. Therefore it has gained wide acceptance as the standard method for performing internal dosimetry calculations. The procedures to be followed in using the absorbed fraction method are summarized in this chapter. Dosimetry calculations for external radiation sources as well as health physics aspects of radiation dosimetry are discussed in Chapter 23. Some radiation dose estimates for nuclear medicine procedures are summarized in Appendix E.

A. RADIATION DOSE AND EQUIVALENT DOSE: QUANTITIES AND UNITS

Radiation dose, D, refers to the quantity of radiation energy deposited in an absorber per gram of absorber material. This quantity applies to any kind of absorber material, including body tissues. The basic unit of radiation dose is the *gray*, abbreviated Gy*:

$$1 \text{ Gy} = 1 \text{ joule energy deposited per kg absorber} \tag{22-1}$$

The traditional unit for absorbed dose is the *rad,* an acronym for radiation absorbed dose:

$$1 \text{ rad} = 100 \text{ ergs energy deposited per g absorber} \tag{22-2}$$

Since 1 joule = 10^7 ergs, 1 Gy is equivalent to 100 rads or, alternatively, 1 rad = 10^{-2} Gy = 1 cGy. As is the case for units of activity, progress in the transition from traditional to SI units varies with geographic location, with SI units dominating practice in Europe, whereas traditional units still are commonplace in the United States. In this chapter, radiation doses are presented in grays, with values in rads also indicated in selected examples.

Equivalent dose, symbolically indicated by H_T, is a quantity that takes into account the relative biologic damage caused by radiation interacting with a particular tissue or organ. Tissue damage per gray of absorbed dose

*This unit is named after Harold Gray, a British medical physicist best known for his discovery of the "oxygen effect" in radiation therapy.

depends on the type and energy of the radiation, and how exactly the radiation deposits its energy in the tissue. For example, an α particle has a short range in tissue and deposits all of its energy in a very localized region. In contrast, γ rays and electrons deposit their energy over a wider area. Table 22-1 shows the radiation weighting factors, w_R, used to calculate equivalent dose for different types and energies of radiation. The SI unit of equivalent dose is the *sievert*[*] (Sv). It is related to the average absorbed dose D in an organ or tissue, T, by

$$H_T = D_T \times w_R \tag{22-3}$$

Equivalent dose replaces an older quantity known as the *dose equivalent*. The dose equivalent is based on the absorbed dose at a point in an organ (rather than an average across the whole organ) and is weighted by quality factors, Q, that are similar to w_R. The unit for dose equivalent also is the Sv.

The traditional unit for dose equivalent is the roentgen-equivalent man (rem). The conversion factor between traditional and SI units is

$$1 \text{ rem} = 10^{-2} \text{ Sv} = 1 \text{ cSv} = 10 \text{ mSv} \tag{22-4}$$

*This unit is named after Rolf M. Sievert, best known for his development of elaborate mathematical models, including the Sievert integral, which for many years provided the basis for calculating radiation doses from implanted radium needles. He also constructed and performed many basic measurements with ionization chambers.

TABLE 22-1
WEIGHTING FACTORS FOR DIFFERENT TYPES OF RADIATION IN THE CALCULATION OF EQUIVALENT DOSE[†]

Type of Radiation	Radiation Weighting Factor, w_R
x rays	1
γ rays	1
Electrons, positrons	1
Neutrons	Continuous function of neutron energy
Protons >2 MeV	2
α particles, fission fragments, heavy ions	20

†Data from reference 1.

For radiations of interest in nuclear medicine (γ rays, x rays, electrons, and positrons) the radiation weighting factor is equal to 1. Therefore the equivalent dose or dose equivalent in Sv (or rem) is numerically equal to the absorbed dose in Gy (or rads).

B. CALCULATION OF RADIATION DOSE (MIRD METHOD)

1. Basic Procedure and Some Practical Problems

The absorbed fraction dosimetry method allows one to calculate the radiation dose delivered to a *target organ* from radioactivity contained in one or more *source organs* in the body (Fig. 22-1). The source and target may be the same organ, and, in fact, frequently the most important contributor to radiation dose is radioactivity contained within the target organ itself. Generally, organs other than the target organ are considered to be source organs if they contain concentrations of radioactivity that exceed the average concentration in the body.

The general procedure for calculating the radiation dose to a target organ from radioactivity in a source organ is a three-step process, as follows:

1. The amount of activity and time spent by the radioactivity in the source organ are determined. Obviously, the greater the activity and the longer the time that it is present, the greater is the radiation dose delivered by it.
2. The total amount of radiation energy emitted by the radioactivity in the source organ is calculated. This depends primarily on the energy of the radionuclide emissions and their frequency of emission (number per disintegration).
3. The fraction of energy emitted by the source organ that is absorbed by the target organ is determined. This depends on the type and energy of the emissions (absorption characteristics in body tissues) and on the anatomic relationships between source and target organs (size, shape, and distance between them).

Each of these steps involves certain difficulties. Step 2 involves physical characteristics of the radionuclide, which generally are known accurately. Step 3 involves patient anatomy, which can be quite different from one patient to the next. Step 1 is perhaps the most troublesome. Such data on radiopharmaceutical

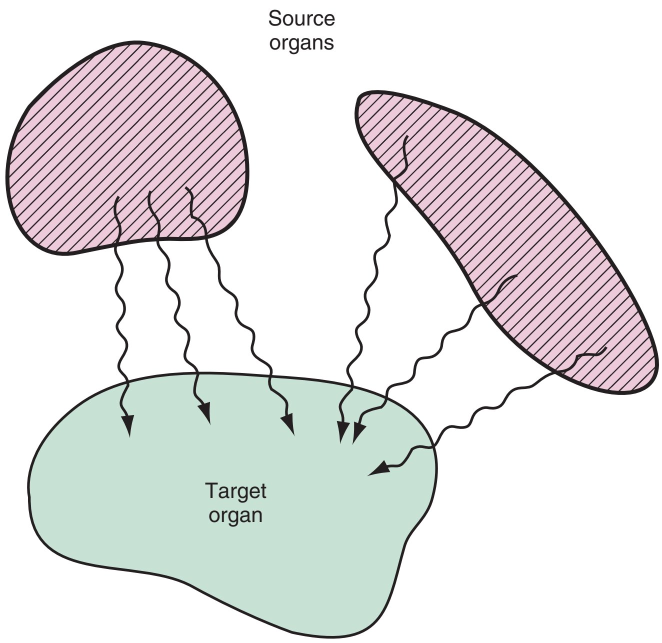

FIGURE 22-1 Absorbed dose delivered to a target organ from one or more source organs containing radioactivity is calculated by the absorbed fraction dosimetry method.

distribution as are available usually are obtained from studies on a relatively small number of human subjects or animals. There are variations in metabolism and distribution of radionuclides among human subjects, especially in different disease states. Also, the distribution of radioactivity within an organ may be inhomogeneous, leading to further uncertainties in the dose specification for that organ.

Because of these complications and variables, radiation dose calculations are made for anatomic models that incorporate "average" anatomic sizes and shapes. The radiation doses that are calculated are average values of D for the organs in this anatomic model. An exception is made when one is specifically interested in a *surface dose* to an organ from activity contained within that organ, for example, the dose to the bladder wall resulting from bladder contents. This is considered to have a value one-half the average dose to the organ or, in this case, the bladder contents.

In spite of the refined mathematical models used in the absorbed fraction model, the results obtained are only estimates of average values. Thus they should be used for guideline purposes only in evaluating the potential radiation effects on a patient.

2. Cumulated Activity, $\tilde{A}$

The radiation dose delivered to a target organ depends on the amount of activity present in the source organ and on the length of time for which the activity is present. The product of these two factors is the *cumulated activity* $\tilde{A}$ in the source organ. The SI unit for cumulated activity is the becquerel • sec (Bq • sec). The corresponding traditional unit is the μCi • hr (1 μCi = 3.7×10^4 Bq; 1 hr = 3600 sec; therefore, 1 μCi • hr = $3.7 \times 10^4 \times 3600 = 1.332 \times 10^8$ Bq • sec = 1.332×10^2 MBq • sec). Cumulated activity is essentially a measure of the total number of radioactive disintegrations occurring during the time that radioactivity is present in the source organ. The radiation dose delivered by activity in a source organ is proportional to its cumulated activity.

Each radiotracer has its own unique spatial and temporal distribution in the body, as determined by radiotracer delivery, uptake, metabolism, clearance and excretion, and the physical decay of the radionuclide. The amount of activity contained in a source organ therefore generally changes with time. If the time-activity curve is known, the cumulated activity for a source organ is obtained by measuring the area under this curve (Fig. 22-2). Mathematically, if the time-activity curve is described by a function $A(t)$, then

$$\tilde{A} \approx \int_0^\infty A(t)dt \qquad (22\text{-}5)$$

where it is assumed that activity is administered to the patient at time $t = 0$ and is measured to complete disappearance from the organ ($t = \infty$).

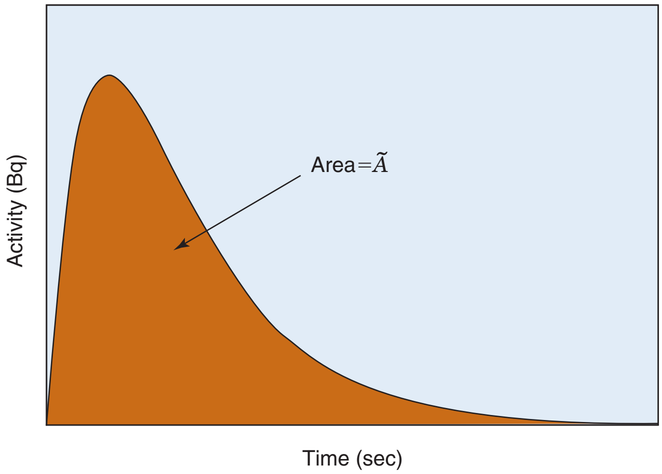

FIGURE 22-2 Hypothetical time-activity curve for radioactivity in a source organ. Cumulated activity $\tilde{A}$ in Bq • sec is the area under the curve (equivalent to the integral in Equation 22-5).

To estimate the radiation dose received from a particular radiotracer, time-activity curves for all the major organs are required. These can be obtained from animal studies (which are then extrapolated with some uncertainty to the human), imaging studies in normal human subjects, prior knowledge of the tracer kinetics, or some combination of these approaches. Time-activity curves can be quite complex, and thus Equation 22-5 may be difficult to analyze. Frequently, however, certain assumptions can be made to simplify this calculation.

Situation 1: Uptake by the organ is "instantaneous" (i.e., very rapid with respect to the half-life of the radionuclide), and there is no biologic excretion. The time-activity curve then is described by ordinary radioactive decay (Equations 4-7 and 4-10):

$$A(t) = A_0 e^{-0.693t/T_p} \tag{22-6}$$

where T_p is the physical half-life of the radionuclide and A_0 is the activity initially present in the organ. Thus

$$\begin{aligned} \tilde{A} &\approx A_0 \int_0^\infty e^{-0.693t/T_p}\, dt \\ &= \frac{T_p A_0}{0.693} = 1.44 T_p A_0 \end{aligned} \tag{22-7}$$

The quantity $1.44T_p$ is the average lifetime of the radionuclide (see Chapter 4, Section B.3). Thus the cumulated activity in a source organ, when eliminated by physical decay only, is the same as if activity were present at a constant level A_0 for a time equal to the average lifetime of the radionuclide (Fig. 22-3).

EXAMPLE 22-1

What is the cumulated activity in the liver for an injection of 100 MBq of a ^{99m}Tc-labeled sulfur colloid, assuming that 60% of the injected colloid is trapped by the liver and retained there indefinitely?

Answer

$$\begin{aligned} \tilde{A} &= 1.44 \times 100 \text{ MBq} \times 0.60 \times 6.0 \text{ hr} \\ &= 518.4 \text{ MBq} \cdot \text{hr} \\ &= 1.87 \times 10^6 \text{ MBq} \cdot \text{sec} \end{aligned}$$

Situation 2: Uptake is instantaneous, and clearance is by biologic excretion only (*no physical decay, or physical half-life very long in comparison with biologic excretion*). In this situation, biologic excretion must be carefully analyzed. Frequently, it can be described by a set of exponential excretion components, with a fraction f_1 of the initial activity A_0 being excreted with a (biologic) half-life T_{b1}, a fraction f_2 with half-life T_{b2}, and so on (Fig. 22-4). The cumulated activity then is given by

$$\begin{aligned} \tilde{A} &\approx A_0 \int_0^\infty f_1 e^{-0.693t/T_{b1}}\, dt \\ &\quad + A_0 \int_0^\infty f_2 e^{-0.693t/T_{b2}}\, dt + \ldots \\ &= 1.44 T_{b1} f_1 A_0 + 1.44 T_{b2} f_2 A_0 + \ldots \end{aligned} \tag{22-8}$$

EXAMPLE 22-2

Suppose that 100 MBq of ^{99m}Tc-labeled microspheres are injected into a patient, with essentially instantaneous uptake of activity

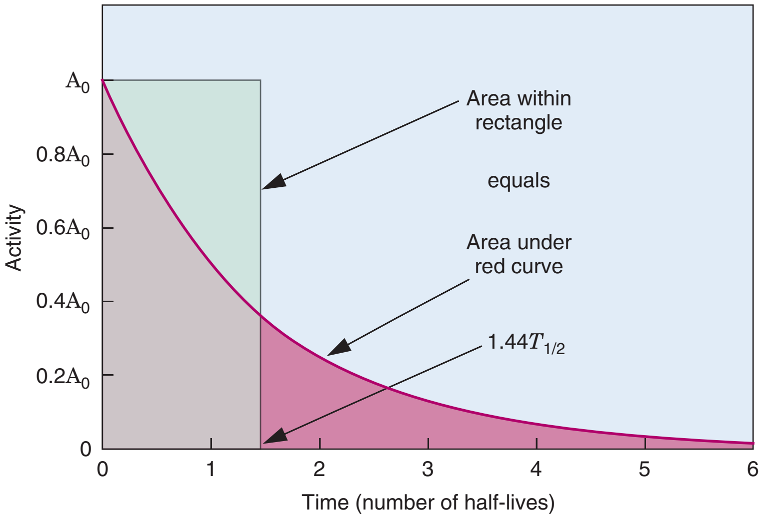

FIGURE 22-3 Illustration of relationship between $\tilde{A}$ and average lifetime (1.44 T_p) of a radionuclide for simple exponential decay.

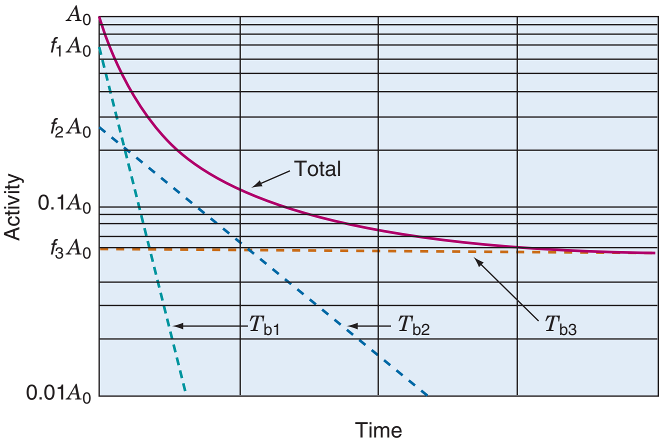

FIGURE 22-4 Illustration of a multicomponent exponential excretion curve. Fraction f_1 is excreted with biologic half-life T_{b1}, f_2 with half-life T_{b2}, f_3 with half-life T_{b3}, and so on.

by the lungs. What is the cumulated activity in the lungs if 60% of the activity is excreted from the lungs with a biologic half-life of 15 minutes and 40% with a biologic half-life of 30 minutes?

Answer

Because ^{99m}Tc physical decay is much slower than the biologic excretion process, we may assume that no physical decay occurs during the time that activity is present in the lungs. Thus (Equation 22-8)

$$\begin{aligned}\tilde{A} &= (1.44 \times 1/4 \text{ hr} \times 0.60 \times 100 \text{ MBq}) \\ &\quad + (1.44 \times 1/2 \text{ hr} \times 0.40 \times 100 \text{ MBq}) \\ &= (21.6 + 28.8) \text{ MBq} \cdot \text{hr} \\ &= 50.4 \text{ MBq} \cdot \text{hr} \\ &= 1.81 \times 10^5 \text{ MBq} \cdot \text{sec}\end{aligned}$$

Situation 3: Uptake is instantaneous but clearance by both physical decay and biologic excretion are significant. In this case, if biologic excretion is described by a single-component exponential curve with biologic half-life T_b, and the physical half-life is T_p, then the total clearance is described by a single-component exponential curve with an *effective half-life* T_e given by*

$$\frac{1}{T_e} = \frac{1}{T_p} + \frac{1}{T_b} \tag{22-9}$$

*Equation 22-9 can be derived from Equations 4-2 and 4-9 by treating biologic excretion as the equivalent of a second pathway in a "branching" radioactive decay scheme.

or

$$T_e = \frac{T_p T_b}{(T_p + T_b)} \qquad (22\text{-}10)$$

Cumulated activity is given by

$$\tilde{A} \approx 1.44 T_e A_0 \qquad (22\text{-}11)$$

If there is more than one component to the biologic excretion curve, then each component has an effective half-life given by Equation 22-9 for that component, and the cumulated activity is computed with effective half-lives replacing biologic half-lives in Equation 22-8.

EXAMPLE 22-3

Suppose in Example 22-2 that because of a metabolic defect 60% of the activity is excreted from the lungs with a half-life of 2 hours and 40% with a half-life of 3 hours. What is the cumulated activity in the lungs for a 100 MBq injection for this patient?

Answer

The effective half-lives for the two components of biologic excretion are (Equation 22-10)

$$T_{e1} = 6 \times 2/(6+2) = 1.5 \text{ hr}$$

$$T_{e2} = 6 \times 3/(6+3) = 2 \text{ hr}$$

Thus applying Equation 22-8, with T_e replacing T_b,

$$\begin{aligned}\tilde{A} &= (1.44 \times 1.5 \text{ hr} \times 0.60 \times 100 \text{ MBq}) \\ &\quad + (1.44 \times 2 \text{ hr} \times 0.40 \times 100 \text{ MBq}) \\ &= (129.6 + 115.2) \text{ MBq} \bullet \text{hr} \\ &= 244.8 \text{ MBq} \bullet \text{hr} \\ &= 8.81 \times 10^5 \text{ MBq} \bullet \text{sec}\end{aligned}$$

Situation 4: Uptake is not instantaneous. The equations developed thus far will overestimate radiation doses when uptake by the source organ is not rapid in comparison with physical decay, that is, if a significant amount of physical decay occurs during the uptake process, before the activity reaches the source organ of interest. This situation arises with radionuclides that have a slow pattern of uptake in comparison with their physical half-life. Frequently, uptake can be described by an exponential equation of the form

$$A(t) = A_0(1 - e^{-0.693t/T_u}) \qquad (22\text{-}12)$$

where T_u is the biologic uptake half-time. In this case, cumulated activity is given by

$$\tilde{A} \approx 1.44 A_0 T_e (T_{ue} / T_u) \qquad (22\text{-}13)$$

where T_e is the effective excretion half-life (Equation 22-10) and T_{ue} is the effective uptake half-time

$$T_{ue} = \frac{T_u T_p}{T_u + T_p} \qquad (22\text{-}14)$$

EXAMPLE 22-4

A radioactive gas having a half-life of 20 seconds is injected in an intravenous solution. It appears in the lungs with an uptake half-time of 30 seconds and is excreted (by exhalation) with a biologic half-life of 10 seconds. What is the cumulated activity in the lungs for a 250-MBq injection?

Answer

The effective uptake half-time is (Equation 22-14)

$$T_{ue} = 20 \times 30/(20+30) = 12 \text{ sec}$$

and the effective excretion half-life is

$$T_e = 20 \times 10/(20+10) = 6.7 \text{ sec}$$

Thus, from Equation 22-13,

$$\begin{aligned}\tilde{A} &= 1.44 \times 250 \text{ MBq} \times 6.7 \text{ sec} \\ &\quad \times (12 \text{ sec}/30 \text{ sec}) \\ &= 964.8 \text{ MBq} \bullet \text{sec}\end{aligned}$$

3. Equilibrium Absorbed Dose Constant, Δ

Given $\tilde{A}$ for the source organ, the next step is to calculate the radiation energy emitted by this amount of cumulated activity. Energy emitted per unit of cumulated activity is given by the *equilibrium absorbed dose constant* Δ. The factor Δ must be calculated for each type of emission for the radionuclide. It is given by*

$$\Delta_i = 1.6 \times 10^{-13} N_i E_i \text{ (Gy} \cdot \text{kg/Bq} \cdot \text{sec)} \quad (22\text{-}15)$$

where E_i is the average energy (in MeV) of the i^{th} emission and N_i is the relative frequency of that emission (number emitted per disintegration) by the radionuclide. In traditional units, the equilibrium absorbed dose constant is

$$\Delta_i = 2.13 N_i E_i \text{ (rad} \cdot \text{g/}\mu\text{Ci} \cdot \text{hr)} \quad (22\text{-}16)$$

EXAMPLE 22-5

A certain radionuclide decays by emitting β particles in 100% of its disintegrations with $\bar{E}_\beta = 0.3$ MeV. This is followed immediately in 80% of its disintegrations by emission of a 0.2-MeV γ ray and in 20% by emission of a 0.195-MeV conversion electron and a 0.005-MeV characteristic x ray. What are the equilibrium absorbed dose constants for the emissions of this radionuclide?

Answer

$$\begin{aligned}
\Delta_\beta &= (1.6 \times 10^{-13}) \times 1.0 \times 0.30 \\
&= 4.80 \times 10^{-14} \text{ Gy} \cdot \text{kg/Bq} \cdot \text{sec} \\
\Delta_\gamma &= (1.6 \times 10^{-13}) \times 0.80 \times 0.20 \\
&= 2.56 \times 10^{-14} \text{ Gy} \cdot \text{kg/Bq} \cdot \text{sec} \\
\Delta_e &= (1.6 \times 10^{-13}) \times 0.20 \times 0.195 \\
&= 6.24 \times 10^{-15} \text{ Gy} \cdot \text{kg/Bq} \cdot \text{sec} \\
\Delta_x &= (1.6 \times 10^{-13}) \times 0.2 \times 0.005 \\
&= 1.60 \times 10^{-16} \text{ Gy} \cdot \text{kg/Bq} \cdot \text{sec}
\end{aligned}$$

The product of cumulated activity $\tilde{A}$ and equilibrium absorbed dose constant Δ_i is the radiation energy emitted by the i^{th} emission, in Gy • kg, during the time that radioactivity is present in a source organ.

EXAMPLE 22-6

Assume that the radionuclide in Example 22-5 is used for the problem described in Example 22-4. What is the total amount of energy emitted from radioactivity contained in the lungs in Example 22-4?

Answer

The total energy emitted per Bq • sec is the sum of the equilibrium absorbed dose constants for the β, γ, conversion electron and x-ray emissions:

$$\begin{aligned}
\Delta &= \Delta_\beta + \Delta_\gamma + \Delta_e + \Delta_x \\
&= 8.0 \times 10^{-14} \text{ Gy} \cdot \text{kg/Bq} \cdot \text{sec} \\
&= 8.0 \times 10^{-8} \text{ Gy} \cdot \text{kg/MBq} \cdot \text{sec}
\end{aligned}$$

The cumulated activity is 9.65×10^2 MBq • sec. Using these values and Equation 22-1, the total energy emitted is

$$\begin{aligned}
\tilde{A} \times \Delta &= 9.65 \times 10^2 \text{ MBq} \cdot \text{sec} \times 8.0 \\
&\quad \times 10^{-8} \text{ Gy} \cdot \text{kg/MBq} \cdot \text{sec} \\
&= 7.72 \times 10^{-5} \text{ Gy} \cdot \text{kg} \\
&= 7.72 \times 10^{-5} \text{ joules}
\end{aligned}$$

Values of Δ are presented in Appendix C for some of the radionuclides of interest in nuclear medicine. A full listing can be found in reference 2.

4. Absorbed Fraction, ϕ

The final step is to determine the fraction of the energy emitted by the source organ that is absorbed by the target organ. This is given by the *absorbed fraction* ϕ. The absorbed fraction depends on the amount of radiation energy reaching the target organ (tissue and distance attenuation between source and target organs) and on the volume and composition (e.g., lung, bone) of the target organ. Thus it depends on the type and energy of the emission and on the anatomic relationship of the source-target pair. In a dosimetry calculation, a value of ϕ must be determined for each type of emission from the radionuclide and for each source-target pair in the calculation. The notation $\phi_i(r_k \leftarrow r_h)$ is used to indicate absorbed fraction for energy delivered from a source organ (or region), r_h, to a target organ, r_k, for the i^{th} emission of the radionuclide.

The total energy absorbed by a specific target organ thus is given by

$$\text{Total energy absorbed (Gy} \cdot \text{kg)} = \tilde{A} \sum_i \phi_i(r_k \leftarrow r_h)\Delta_i \quad (22\text{-}17)$$

The summation Σ_i includes values of ϕ_i and Δ_i for all the emissions of the radionuclide and

*Essentially the energy emitted per nuclear disintegration: 1 MeV/dis = 1.6×10^{-13} Gy • kg/Bq • sec.

values of $\phi_i(r_k \leftarrow r_h)$ for the source-target pair. $\tilde{A}$ is the cumulated activity in the source organ h. The energy absorbed by the target organ divided by the target organ mass m_t gives the *average absorbed dose* in grays to the target organ from activity in the source organ:

$$\bar{D}(r_k \leftarrow r_h) = \frac{\tilde{A}}{m_t} \sum_i \phi_i (r_k \leftarrow r_h)\Delta_i \tag{22-18}$$

The total dose to the target organ then is obtained by summing the doses from all of the source organs, h, in the body.

Values of ϕ have been calculated for mathematical humanoid models incorporating organs and anatomic structures of "average" size and shape (Fig. 22-5). The model used for many years was that published by the MIRD committee of the Society of Nuclear Medicine.[3] Cristy and Eckerman[4] subsequently developed a series of models representing newborn, 1-year-old, 5-year-old, 10-year-old, 15-year-old, and adult individuals. Stabin and associates extended the model to women and pregnant women.[5] Organ masses for the adult male phantom developed by Cristy and Eckerman are given in Table 22-2. Most of the values for their adult male model are similar to the model originally developed by the MIRD committee; however, there are some significant differences as well, such as in the mass and values of ϕ for bone marrow. Consequently, the Cristy and Eckerman models now have replaced the older MIRD model.

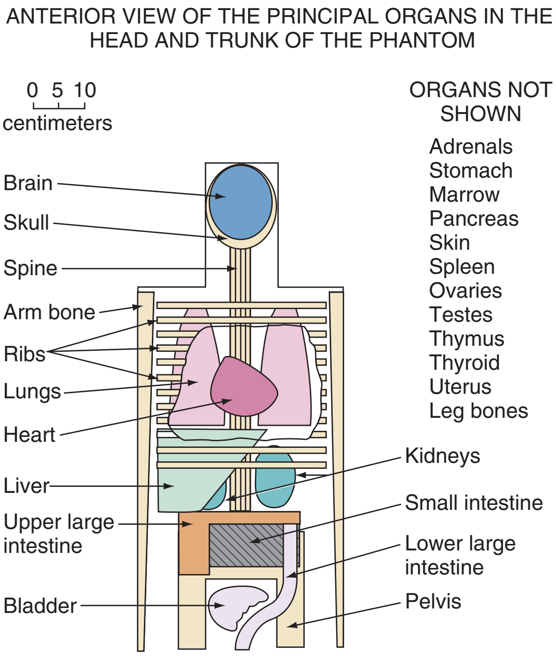

FIGURE 22-5 Representation of an "average man" used for MIRD dose calculations and tables. (*Adapted with permission from Snyder WS, Fisher HL Jr, Ford MR, Warner GG: Estimates of absorbed fractions for monoenergetic photon sources uniformly distributed in various organs of a heterogenous phantom.* J Nucl Med Suppl *3:9, 1969.*)

Calculations of ϕ are complex, and the tables are quite lengthy for "penetrating" radiations (photons with energy $\gtrsim$10 keV) because of the energy dependence of photon attenuation and absorption; however, the situation is simpler for nonpenetrating radiations (photons with energy $\lesssim$10 keV and electrons), for which it can be assumed that all of the emitted energy is "locally absorbed," that is, within the source organ itself. For these emissions, $\phi = 1$ when the target and the source are the same organ, $\phi = 0$ otherwise. In dosimetry calculations, it is useful to sum the equilibrium absorbed dose constants for the nonpenetrating radiations and treat them as a single parameter, Δ_{np}, because the absorbed fractions for all of these emissions are equal (unity when the source and target are the same organ, zero otherwise).

EXAMPLE 22-7

Compute the absorbed dose delivered to the lung by nonpenetrating radiations in the problem described by Examples 22-4 and 22-5.

Answer

The nonpenetrating radiations are the β particles ($\Delta_\beta = 4.80 \times 10^{-14}$ Gy • kg/Bq • sec), conversion electrons ($\Delta_e = 6.24 \times 10^{-15}$ Gy • kg/Bq • sec), and 5 keV characteristic x-rays ($\Delta_x = 1.60 \times 10^{-16}$ Gy • kg/Bq • sec). Thus $\Delta_{np} = 5.44 \times 10^{-14}$ Gy • kg/Bq • sec. Cumulated activity is $\tilde{A} = 9.65 \times 10^8$ Bq • sec. Lung mass is 1 kg (see Table 22-2). Thus the average radiation dose delivered by these emissions to the lungs is

$$\begin{aligned}\bar{D} &= (9.65 \times 10^8 \text{ Bq} \cdot \text{sec}) \\ &\quad \times (5.44 \times 10^{-14} \text{ Gy} \cdot \text{kg/Bq} \cdot \text{sec}) \\ &\quad \times (\phi = 1)/1 \text{ kg} \\ &= 5.25 \times 10^{-5} \text{ Gy (5.25 mrad)}\end{aligned}$$

5. Specific Absorbed Fraction, Φ, and the Dose Reciprocity Theorem

The specific absorbed fraction is given by

$$\Phi = \frac{\phi}{m_t} \tag{22-19}$$

TABLE 22-2
ORGAN MASSES FOR THE CRISTY AND ECKERMAN ADULT MALE PHANTOM

Organ	Mass (g)	Organ	Mass (g)
Adrenals	16.3	Lungs	1000
Brain	1420	Ovaries	8.71
Breasts (excluding skin)	351	Pancreas	94.3
Gallbladder contents	55.7	Skeleton	
Gallbladder wall	10.5	Active marrow	1120
Gastrointestinal Tract		Cortical bone	4000
Lower large intestine contents	143	Trabecular bone	1000
Lower large intestine wall	167	Skin	3010
Small intestine contents and wall	1100	Spleen	183
Stomach contents	260	Testes	39.1
Stomach wall	158	Thymus	20.9
Upper large intestine contents	232	Thyroid	20.7
Upper large intestine wall	220	Urinary bladder contents	211
Heart contents	454	Urinary bladder wall	47.6
Heart wall	316	Uterus	79.0
Kidneys	299	Remaining tissue	51,800
Liver	1910		

From Cristy M, Eckerman K: *Specific Absorbed Fractions of Energy at Various Ages From Internal Photon Sources (ORNL Report ORNL/TM-8381 V1–V7).* Oak Ridge, TN, 1987, Oak Ridge National Laboratory.

It is the fraction of radiation emitted by the source organ that is absorbed *per gram* of target organ mass. The absorbed dose equation can be written using specific absorbed fractions as

$$\bar{D}(r_k \leftarrow r_h) = \tilde{A}\sum_i \Phi_i(r_k \leftarrow r_h)\Delta_i \quad (22\text{-}20)$$

The *dose reciprocity theorem* says that for a given organ pair the specific absorbed fraction is the same, regardless of which organ is the source and which is the target:

$$\Phi_i(r_k \leftarrow r_h) = \Phi_i(r_h \leftarrow r_k) \quad (22\text{-}21)$$

This simply says that the energy absorbed per gram is the same for radiation traveling from r_h to r_k as it is for radiation traveling from r_k to r_h, a fact that seems intuitively obvious.*

*Strictly speaking, the dose reciprocity theorem is precisely correct only when both the source and target materials are homogeneous absorbing materials. However, this requirement is not stringent and the theorem is sufficiently accurate (<1% error) for most applications in the human body. One situation in which the required conditions are not met is when red marrow is a source or target organ. This is evident in Tables 22-3 to 22-5, which are discussed in the next section.

The dose reciprocity theorem is useful when tables for ϕ are not available for all source-target organ pairs. If $\phi\ (r_k \leftarrow r_h)$ is known, then $\phi\ (r_h \leftarrow r_k)$ can be obtained from the dose reciprocity theorem. Rewriting Equation 22-21 in terms of ϕ:

$$\frac{\phi(r_h \leftarrow r_k)}{m_h} = \frac{\phi(r_k \leftarrow r_h)}{m_k} \quad (22\text{-}22)$$

$$\phi(r_h \leftarrow r_k) = \frac{m_h}{m_k} \times \phi(r_k \leftarrow r_h) \quad (22\text{-}23)$$

The specific absorbed fractions for a range of different phantoms are available in references 4 and 6.

6. Mean Dose per Cumulated Activity, *S*

Radiation dose calculations for penetrating radiations can be quite tedious, especially when there are multiple emissions to consider. The problem has been simplified by the introduction of *S* (sometimes also known as the dose factor, *DF*), the mean dose per unit cumulated activity:

$$S(r_k \leftarrow r_h) = \frac{1}{m_k} \sum_i \phi_i(r_k \leftarrow r_h)\Delta_i$$
$$= \sum_i \Phi_i(r_k \leftarrow r_h)\Delta_i \quad (22\text{-}24)$$

The quantity S has units of Gy/Bq • sec. It has been calculated for different source-target organ pairs for a wide variety of radionuclides of interest in nuclear medicine.[7] Tables 22-3 to 22-5 present values of S for ^{99m}Tc, ^{131}I, and ^{18}F, respectively. Given the values of S and cumulated activity, $\tilde{A}$, the average dose to an organ is given by

$$\bar{D}(r_k \leftarrow r_h) = \tilde{A} \times S(r_k \leftarrow r_h) \quad (22\text{-}25)$$

EXAMPLE 22-8

Calculate the radiation dose to the liver (LI) to an average adult male for an injection of 100 MBq of ^{99m}Tc sulfur colloid. Assume that 60% of the activity is trapped by the liver, 30% by the spleen (SP), and 10% by red bone marrow (RM), with instantaneous uptake and no biologic excretion.

Answer

The cumulated activities for the three source organs are (Equation 22-5)

$$\tilde{A}_{\mathrm{LI}} = 1.44 \times 6.0 \text{ hr} \times 0.60 \times 100 \text{ MBq}$$
$$= 518.4 \text{ MBq} \bullet \text{hr}$$
$$= 1.87 \times 10^6 \text{ MBq} \bullet \text{sec}$$

$$\tilde{A}_{\mathrm{SP}} = 1.44 \times 6.0 \text{ hr} \times 0.30 \times 100 \text{ MBq}$$
$$= 259.2 \text{ MBq} \bullet \text{hr}$$
$$= 9.33 \times 10^5 \text{ MBq} \bullet \text{sec}$$

$$\tilde{A}_{\mathrm{RM}} = 1.44 \times 6.0 \text{ hr} \times 0.10 \times 100 \text{ MBq}$$
$$= 86.4 \text{ MBq} \bullet \text{hr}$$
$$= 3.11 \times 10^5 \text{ MBq} \bullet \text{sec}$$

The values of S for ^{99m}Tc are (see Table 22-3)

$$S(\mathrm{LI} \leftarrow \mathrm{LI}) = 3.16 \times 10^{-6} \text{ mGy/MBq} \bullet \text{sec}$$

$$S(\mathrm{LI} \leftarrow \mathrm{SP}) = 7.22 \times 10^{-8} \text{ mGy/MBq} \bullet \text{sec}$$

$$S(\mathrm{LI} \leftarrow \mathrm{RM}) = 8.96 \times 10^{-8} \text{ mGy/MBq} \bullet \text{sec}$$

Therefore, the absorbed doses are

$$\bar{D}(\mathrm{LI} \leftarrow \mathrm{LI}) = (1.87 \times 10^6 \text{ MBq} \bullet \text{sec})$$
$$\times (3.16 \times 10^{-6} \text{ mGy/MBq} \bullet \text{sec})$$
$$= 5.91 \text{ mGy}$$

$$\bar{D}(\mathrm{LI} \leftarrow \mathrm{SP}) = (9.33 \times 10^5 \text{ MBq} \bullet \text{sec})$$
$$\times (7.22 \times 10^{-8} \text{ mGy/MBq} \bullet \text{sec})$$
$$= 6.74 \times 10^{-2} \text{ mGy}$$

$$\bar{D}(\mathrm{LI} \leftarrow \mathrm{RM}) = (3.11 \times 10^5 \text{ MBq} \bullet \text{sec})$$
$$\times (8.96 \times 10^{-8} \text{ mGy/MBq} \bullet \text{sec})$$
$$= 2.79 \times 10^{-2} \text{ mGy}$$

The average total dose to the liver is therefore

$$\bar{D} = 5.91 + 6.74 \times 10^{-2} + 2.79 \times 10^{-2} \text{ mGy}$$
$$= 6.01 \text{ mGy } (\sim 0.6 \text{ rads})$$

Example 22-8 demonstrates that most of the dose delivered to an organ that concentrates the radionuclide arises from the radioactivity in the target organ itself [$\bar{D}(\mathrm{LI} \leftarrow \mathrm{LI})$].

EXAMPLE 22-9

An adult male patient is to be treated with ^{131}I for hyperthyroidism. It is determined by prior studies with a tracer dose of ^{131}I that the patient's thyroidal iodine uptake is 60% and the biologic half-life of iodine in the thyroid gland is 2 days. Assuming instantaneous uptake ($T_u \ll T_p = 8$ days), what is the dose to the thyroid (THY) from radioactivity contained in the thyroid for this patient, per MBq ^{131}I?

Answer

The effective half-life of ^{131}I in the thyroid for this patient is (Equation 22-10)

$$T_e = 8 \times 2/(8+2) = 16/10 \text{ days}$$
$$= 1.38 \times 10^5 \text{ sec}$$

Therefore the cumulated activity per MBq administered is (Equation 22-11)

$$\tilde{A} = 1.44 \times (1.38 \times 10^5 \text{ sec})$$
$$\times 0.60 \times 1 \text{ MBq}$$
$$= 1.19 \times 10^5 \text{ MBq} \bullet \text{sec/MBq administered}$$

The dose per MBq • sec is (see Table 22-4):

$$S(\mathrm{THY} \leftarrow \mathrm{THY}) = 1.57 \times 10^{-3} \text{ mGy/MBq} \bullet \text{sec}$$

Thus the average absorbed dose for the thyroid is

$$\bar{D}\,(\text{THY} \leftarrow \text{THY})$$
$$= (1.19 \times 10^5 \text{ MBq} \cdot \text{sec/MBq administered})$$
$$\times (1.57 \times 10^{-3} \text{ mGy/MBq} \cdot \text{sec})$$
$$= 187 \text{ mGy/MBq administered}$$
$$(\text{or } 692 \text{ rads/mCi})$$

One could include the radiation dose to the thyroid from activity in other organs in the calculation performed in Example 22-9; however, inspection of Table 22-4 reveals that in comparison to the thyroid as the source organ, other organs have much smaller values of S (by approximately a factor of 500). This, plus the fact that other organs concentrate much less of the activity than the thyroid, eliminates the need to consider them as source organs in this calculation.

Examples 22-8 and 22-9 represent simplified situations in which only a few organs are involved and where the cumulated activities of the organs are relatively easy to estimate. In many cases, the calculations are more involved, with complex time-activity curves and more widespread distribution of the radiopharmaceutical among different organs. To facilitate dosimetry calculations, a software program[8] has been developed to calculate the absorbed dose to major organs from commonly employed radionuclides using the Cristy and Eckerman[4] and Stabin[5] phantom models of human anatomy. This greatly simplifies dose calculations, although it still is necessary to provide the cumulated activity data for each organ for the radiopharmaceutical of interest. Estimated radiation doses for a large number of commonly used radiopharmaceuticals are available from the Oak Ridge Institute for Science and Education.[9] By way of example, radiation dose estimates for ^{18}F-fluorodeoxyglucose (FDG) PET studies based on the Cristy and Eckerman adult male phantom are reproduced in Table 22-6.

7. Whole-Body Dose and Effective Dose

The complete output of a dose calculation is an estimate of the radiation dose for all the major organs in the body. This provides a large amount of information that is difficult to assimilate into a perception of the risk of a specific radiopharmaceutical study, or for comparison of the dose from a nuclear medicine procedure with that from other medical procedures that use radiation sources. For these reasons, it would be convenient to condense radiation dose estimates such as those in Table 22-6 into a single number. There are two different approaches to doing this: *whole-body* (or *total-body*) *dose* and *effective dose*.

The whole-body or total-body dose is the *total energy deposited in the body* divided by the *total mass of the body*, or in terms of the S factor for the total body (TB):

$$\bar{D}(\text{TB} \leftarrow \text{TB}) = \tilde{A} \times S(\text{TB} \leftarrow \text{TB}) \tag{22-26}$$

This parameter was used for many years as the standard for evaluating the risks of different nuclear medicine procedures. However, the whole-body dose does not take into account the nonuniformity of dose distribution among the organs in the body, and its validity for comparing the risks of different nuclear medicine procedures is therefore questionable.

The effective dose, E, was introduced by the International Commission on Radiological Protection (ICRP)[1,10] as an attempt to characterize a nonuniform internal dose by a single number. This quantity was intended primarily for estimating radiation risks and doses received by radiation workers, although its extension to clinical nuclear medicine studies has been supported by the ICRP. The effective dose represents the whole-body dose that would result in the same overall risk as the nonuniform dose distribution actually delivered. This is achieved by assigning different *weighting factors* to the doses delivered to individual organs. The most recent recommended values for the tissue weighting factors, w_T, are shown in Table 22-7. The effective dose, which has units of sieverts, is calculated from

$$E = \sum_{T} w_T \times D_T \times w_R = \sum_{T} w_T \times H_T \tag{22-27}$$

where D_T is the average absorbed dose in organ T, w_T is the tissue weighting factor for organ T, and the summation is over all the organs listed in Table 22-7. H_T is the equivalent dose defined in Section A. As noted in Section A, w_R = 1 for all radiations used in diagnostic nuclear medicine procedures. An older quantity, *effective dose equivalent* (H_E), which uses slightly different tissue weighting factors, may be encountered in publications and in regulations established prior to 1991.

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TABLE 22-3

S VALUES (mGy/MBq • sec) FOR Tc-99m IN THE ADULT MALE PHANTOM*

	Source Organs												
Target Organs	Adrenals	Brain	Breasts	Gallbladder Contents	Lower Large Intestine	Small Intestine	Stomach	Upper Large Intestine	Heart Contents	Heart Wall	Kidneys	Liver	Lungs	Muscle
Adrenals	1.80E-04	4.18E-10	5.05E-08	3.13E-07	2.25E-08	7.46E-08	2.73E-07	9.58E-08	2.53E-07	2.85E-07	7.24E-07	4.35E-07	2.33E-07	1.12E-07
Brain	4.18E-10	4.23E-06	3.17E-09	1.49E-10	1.57E-11	3.91E-11	4.27E-10	4.68E-11	3.14E-09	2.54E-09	1.58E-10	8.16E-10	7.63E-09	2.21E-08
Breasts	5.05E-08	3.17E-09	1.14E-05	3.33E-08	2.28E-09	7.35E-09	5.73E-08	8.00E-09	2.41E-07	2.61E-07	1.99E-08	6.82E-08	2.33E-07	4.25E-08
Gallbladder wall	3.57E-07	1.54E-10	3.41E-08	3.37E-05	6.49E-08	4.38E-07	3.05E-07	7.53E-07	1.03E-07	1.22E-07	4.09E-07	8.70E-07	7.46E-08	1.19E-07
Lower large intestine wall	1.98E-08	1.32E-11	2.42E-09	5.93E-08	1.23E-05	5.92E-07	9.10E-08	2.14E-07	4.06E-09	4.90E-09	5.50E-08	1.44E-08	3.29E-09	1.34E-07
Small intestine	7.46E-08	3.91E-11	7.35E-09	4.58E-07	7.16E-07	4.22E-06	2.08E-07	1.25E-06	1.57E-08	2.06E-08	2.13E-07	1.16E-07	1.35E-08	1.12E-07
Stomach wall	2.85E-07	2.52E-10	5.93E-08	2.93E-07	1.24E-07	2.13E-07	8.53E-06	2.86E-07	1.66E-07	2.65E-07	2.53E-07	1.48E-07	1.19E-07	1.09E-07
Upper large intestine wall	9.41E-08	4.76E-11	7.51E-09	7.78E-07	3.10E-07	1.36E-06	2.65E-07	8.37E-06	2.12E-08	2.65E-08	2.12E-07	1.88E-07	1.81E-08	1.10E-07
Heart wall	2.85E-07	2.54E-09	2.61E-07	1.04E-07	5.42E-09	2.06E-08	2.33E-07	2.97E-08	5.48E-06	1.19E-05	8.22E-08	2.33E-07	4.40E-07	9.20E-08
Kidneys	7.24E-07	1.58E-10	1.99E-08	3.89E-07	7.10E-08	2.13E-07	2.73E-07	2.12E-07	6.45E-08	8.22E-08	1.32E-05	2.93E-07	6.66E-08	9.79E-08
Liver	4.35E-07	8.16E-10	6.82E-08	8.20E-07	1.80E-08	1.16E-07	1.47E-07	1.87E-07	2.13E-07	2.33E-07	2.93E-07	3.16E-06	1.97E-07	7.52E-08
Lungs	2.33E-07	7.63E-09	2.33E-07	7.09E-08	4.50E-09	1.35E-08	1.10E-07	1.77E-08	4.59E-07	4.40E-07	6.66E-08	2.09E-07	3.57E-06	9.36E-08
Muscle	1.12E-07	2.21E-08	4.25E-08	1.14E-07	1.23E-07	1.12E-07	9.96E-08	1.07E-07	8.83E-08	9.20E-08	9.79E-08	7.52E-08	9.34E-08	1.93E-07
Ovaries	3.14E-08	1.52E-11	2.61E-09	1.11E-07	1.26E-06	9.23E-07	5.85E-08	7.71E-07	4.55E-09	6.15E-09	7.02E-08	3.81E-08	5.39E-09	1.44E-07
Pancreas	1.09E-06	4.15E-10	6.22E-08	6.75E-07	5.21E-08	1.42E-07	1.23E-06	1.62E-07	2.65E-07	3.57E-07	4.97E-07	3.86E-07	1.74E-07	1.24E-07
Red marrow	2.53E-07	1.01E-07	5.52E-08	1.02E-07	2.01E-07	1.79E-07	7.50E-08	1.43E-07	1.11E-07	1.11E-07	1.71E-07	8.32E-08	1.11E-07	9.07E-08
Bone surfaces	2.67E-07	2.99E-07	7.76E-08	1.14E-07	1.82E-07	1.49E-07	1.03E-07	1.27E-07	1.60E-07	1.60E-07	1.62E-07	1.24E-07	1.66E-07	1.84E-07
Skin	3.41E-08	3.97E-08	7.63E-08	3.09E-08	3.62E-08	3.01E-08	3.41E-08	3.09E-08	3.41E-08	3.70E-08	3.79E-08	3.62E-08	4.02E-08	5.72E-08
Spleen	4.58E-07	5.19E-10	4.37E-08	1.33E-07	6.53E-08	1.01E-07	7.83E-07	1.05E-07	1.24E-07	1.67E-07	6.63E-07	7.22E-08	1.64E-07	1.03E-07
Testes	1.54E-09	1.46E-12	0.00E+00	6.91E-09	1.40E-07	2.61E-08	2.90E-09	1.92E-08	5.16E-10	6.16E-10	3.10E-09	1.57E-09	3.67E-10	9.89E-08
Thymus	5.66E-08	6.88E-09	2.29E-07	1.43E-08	2.04E-09	4.66E-09	3.65E-08	5.43E-09	8.87E-07	7.35E-07	1.73E-08	5.93E-08	2.85E-07	1.06E-07
Thyroid	8.11E-09	1.35E-07	3.01E-08	2.45E-09	2.48E-10	4.87E-10	2.62E-09	7.69E-10	5.17E-08	4.33E-08	2.95E-09	8.64E-09	8.82E-08	1.16E-07
Urinary bladder wall	7.55E-09	6.02E-12	1.33E-09	4.22E-08	4.98E-07	2.12E-07	1.73E-08	1.61E-07	2.22E-09	2.17E-09	1.87E-08	1.16E-08	1.33E-09	1.40E-07
Uterus	1.89E-08	1.31E-11	2.62E-09	1.16E-07	5.17E-07	8.37E-07	5.05E-08	3.97E-07	4.87E-09	5.47E-09	6.42E-08	3.29E-08	4.10E-09	1.43E-07
Total body	1.72E-07	1.25E-07	1.03E-07	1.36E-07	1.49E-07	1.59E-07	1.17E-07	1.41E-07	1.17E-07	1.65E-07	1.58E-07	1.59E-07	1.44E-07	1.33E-07

TABLE 22-3 CONTINUED

	Source Organs													
Target Organs	Ovaries	Pancreas	Red Marrow	Cortical Bone Surfaces	Trabecular Bone Surfaces	Cortical Bone Volume	Trabecular Bone Volume	Spleen	Testes	Thymus	Thyroid	Urinary Bladder Contents	Uterus	Total Body
Adrenals	3.14E-08	1.09E-06	2.41E-07	1.07E-07	1.07E-07	1.07E-07	1.07E-07	4.58E-07	1.54E-09	5.66E-08	8.11E-09	8.41E-09	1.89E-08	1.67E-07
Brain	1.52E-11	4.15E-10	8.08E-08	1.17E-07	1.17E-07	1.17E-07	1.17E-07	5.19E-10	1.46E-12	6.88E-09	1.35E-07	5.94E-12	1.31E-11	1.21E-07
Breasts	2.61E-09	6.22E-08	5.12E-08	3.10E-08	3.10E-08	3.10E-08	3.10E-08	4.37E-08	0.00E+00	2.29E-07	3.01E-08	1.30E-09	2.62E-09	1.00E-07
Gallbladder wall	9.91E-08	8.14E-07	1.15E-07	4.41E-08	4.41E-08	4.41E-08	4.41E-08	1.35E-07	6.71E-09	2.65E-08	2.64E-09	3.45E-08	1.15E-07	1.77E-07
Lower large intestine wall	1.12E-06	4.17E-08	1.98E-07	7.25E-08	7.25E-08	7.25E-08	7.25E-08	4.65E-08	1.96E-07	1.61E-09	2.06E-10	5.78E-07	4.97E-07	1.73E-07
Small intestine	9.23E-07	1.42E-07	1.86E-07	5.74E-08	5.74E-08	5.74E-08	5.74E-08	1.01E-07	2.61E-08	4.66E-09	4.87E-10	2.24E-07	8.37E-07	1.77E-07
Stomach wall	5.85E-08	1.26E-06	8.23E-08	3.89E-08	3.89E-08	3.89E-08	3.89E-08	7.75E-07	4.43E-09	3.61E-08	3.71E-09	2.10E-08	5.53E-08	1.58E-07
Upper large intestine wall	8.29E-07	1.69E-07	1.55E-07	5.02E-08	5.02E-08	5.02E-08	5.02E-08	1.06E-07	1.78E-08	5.31E-09	7.69E-10	1.60E-07	4.17E-07	1.72E-07
Heart wall	6.15E-09	3.57E-07	1.09E-07	5.74E-08	5.74E-08	5.74E-08	5.74E-08	1.67E-07	6.16E-10	7.35E-07	4.33E-08	2.22E-09	5.47E-09	1.61E-07
Kidneys	7.02E-08	4.97E-07	1.70E-07	6.22E-08	6.22E-08	6.22E-08	6.22E-08	6.63E-07	3.10E-09	1.73E-08	2.95E-09	2.00E-08	6.42E-08	1.54E-07
Liver	3.81E-08	3.86E-07	8.96E-08	4.82E-08	4.82E-08	4.82E-08	4.82E-08	7.22E-08	1.57E-09	5.93E-08	8.64E-09	1.17E-08	3.29E-08	1.55E-07
Lungs	5.39E-09	1.76E-07	1.09E-07	6.67E-08	6.67E-08	6.67E-08	6.67E-08	1.65E-07	3.67E-10	2.97E-07	8.82E-08	1.04E-09	4.10E-09	1.41E-07
Muscle	1.44E-07	1.24E-07	9.07E-08	7.45E-08	7.45E-08	7.45E-08	7.45E-08	1.03E-07	9.89E-08	1.06E-07	1.16E-07	1.30E-07	1.43E-07	1.31E-07
Ovaries	3.22E-04	3.65E-08	2.13E-07	6.54E-08	6.54E-08	6.54E-08	6.54E-08	3.85E-08	0.00E+00	1.94E-09	2.29E-10	5.41E-07	1.57E-06	1.81E-07
Pancreas	3.65E-08	3.73E-05	1.48E-07	6.54E-08	6.54E-08	6.54E-08	6.54E-08	1.28E-06	2.58E-09	6.13E-08	7.28E-09	1.38E-08	3.73E-08	1.79E-07
Red marrow	2.13E-07	1.40E-07	1.79E-06	2.01E-07	6.38E-07	2.01E-07	3.88E-07	8.43E-08	2.69E-08	8.25E-08	7.94E-08	8.02E-08	1.39E-07	1.31E-07
Bone surfaces	1.66E-07	1.67E-07	1.01E-06	2.73E-06	3.15E-06	7.26E-07	1.21E-06	1.26E-07	1.02E-07	1.23E-07	1.97E-07	1.05E-07	1.30E-07	2.59E-07
Skin	3.09E-08	3.01E-08	4.20E-08	4.68E-08	4.68E-08	4.68E-08	4.68E-08	3.49E-08	1.03E-07	4.39E-08	4.38E-08	3.90E-08	3.01E-08	9.14E-08
Spleen	3.85E-08	1.28E-06	9.19E-08	4.94E-08	4.94E-08	4.94E-08	4.94E-08	2.24E-05	2.17E-09	3.89E-08	7.83E-09	8.40E-09	2.57E-08	1.54E-07
Testes	0.00E+00	2.58E-09	3.09E-08	4.09E-08	4.09E-08	4.09E-08	4.09E-08	2.17E-09	8.64E-05	1.91E-10	2.31E-11	3.73E-07	0.00E+00	1.28E-07
Thymus	1.94E-09	6.13E-08	8.45E-08	4.83E-08	4.83E-08	4.83E-08	4.83E-08	3.89E-08	1.91E-10	1.50E-04	1.62E-07	8.06E-10	1.81E-09	1.43E-07
Thyroid	2.29E-10	7.28E-09	7.54E-08	7.67E-08	7.67E-08	7.67E-08	7.67E-08	7.83E-09	2.31E-11	1.62E-07	1.49E-04	9.56E-11	2.14E-10	1.45E-07
Urinary bladder wall	5.49E-07	1.38E-08	9.18E-08	4.01E-08	4.01E-08	4.01E-08	4.01E-08	8.04E-09	3.85E-07	8.14E-10	9.65E-11	1.10E-05	1.28E-06	1.67E-07
Uterus	1.57E-06	3.73E-08	1.54E-07	4.89E-08	4.89E-08	4.89E-08	4.89E-08	2.57E-08	0.00E+00	1.81E-09	2.14E-10	1.24E-06	4.70E-05	1.83E-07
Total body	1.87E-07	1.85E-07	1.52E-07	1.40E-07	1.40E-07	1.40E-07	1.40E-07	1.59E-07	1.32E-07	1.48E-07	1.49E-07	1.18E-07	1.88E-07	1.39E-07

*Data from References 6 and 7.

TABLE 22-4
S VALUES (mGy/MBq • sec) FOR I-131 IN THE ADULT MALE PHANTOM*

	Source Organs												
Target Organs	Adrenals	Brain	Breasts	Gallbladder Contents	Lower Large Intestine	Small Intestine	Stomach	Upper Large Intestine	Heart Contents	Heart Wall	Kidneys	Liver	Lungs	Muscle
Adrenals	1.97E-03	3.40E-09	1.65E-07	8.41E-07	7.95E-08	2.20E-07	7.93E-07	2.54E-07	6.95E-07	7.91E-07	2.05E-06	1.21E-06	6.71E-07	3.31E-07
Brain	3.40E-09	2.91E-05	1.43E-08	1.88E-09	2.62E-10	5.20E-10	3.50E-09	6.17E-10	1.68E-08	1.56E-08	1.47E-09	5.53E-09	3.34E-08	7.10E-08
Breasts	1.65E-07	1.43E-08	1.01E-04	1.09E-07	1.40E-08	3.33E-08	1.83E-07	3.85E-08	7.32E-07	7.97E-07	7.53E-08	2.18E-07	6.73E-07	1.36E-07
Gallbladder wall	9.04E-07	1.51E-09	1.15E-07	3.12E-04	1.79E-07	1.18E-06	8.17E-07	1.99E-06	2.79E-07	3.49E-07	1.09E-06	2.35E-06	2.16E-07	3.40E-07
Lower large intestine wall	7.68E-08	2.21E-10	1.42E-08	1.56E-07	1.19E-04	1.62E-06	2.52E-07	6.49E-07	1.91E-08	2.40E-08	1.67E-07	5.21E-08	1.65E-08	3.79E-07
Small intestine	2.20E-07	5.20E-10	3.33E-08	1.21E-06	1.94E-06	4.01E-05	5.41E-07	3.45E-06	5.72E-08	7.44E-08	5.93E-07	3.28E-07	5.05E-08	3.18E-07
Stomach wall	7.22E-07	2.68E-09	1.93E-07	7.80E-07	3.66E-07	5.96E-07	7.04E-05	7.97E-07	4.61E-07	7.00E-07	6.98E-07	4.24E-07	3.26E-07	3.13E-07
Upper large intestine wall	2.58E-07	6.23E-10	3.31E-08	2.07E-06	8.60E-07	3.80E-06	7.01E-07	7.57E-05	7.68E-08	9.14E-08	5.82E-07	5.16E-07	6.40E-08	3.11E-07
Heart wall	7.91E-07	1.56E-08	7.97E-07	2.88E-07	2.60E-08	7.44E-08	6.71E-07	9.44E-08	4.20E-05	1.09E-04	2.29E-07	6.37E-07	1.19E-06	2.64E-07
Kidneys	2.05E-06	1.47E-09	7.53E-08	1.03E-06	2.22E-07	5.93E-07	7.22E-07	5.85E-07	2.01E-07	2.29E-07	1.18E-04	8.19E-07	1.97E-07	2.89E-07
Liver	1.21E-06	5.53E-09	2.18E-07	2.20E-06	6.41E-08	3.28E-07	4.11E-07	5.29E-07	5.81E-07	6.37E-07	8.19E-07	2.15E-05	5.48E-07	2.21E-07
Lungs	6.71E-07	3.35E-08	6.74E-07	1.94E-07	2.19E-08	5.05E-08	3.07E-07	6.16E-08	1.25E-06	1.19E-06	1.97E-07	5.49E-07	3.40E-05	2.67E-07
Muscle	3.31E-07	7.10E-08	1.36E-07	3.27E-07	3.48E-07	3.18E-07	2.85E-07	3.03E-07	2.50E-07	2.64E-07	2.89E-07	2.21E-07	2.67E-07	1.42E-06
Ovaries	1.13E-07	2.65E-10	1.45E-08	2.99E-07	3.52E-06	2.47E-06	1.81E-07	2.08E-06	2.59E-08	3.16E-08	2.17E-07	1.20E-07	2.67E-08	4.07E-07
Pancreas	2.88E-06	4.18E-09	1.97E-07	1.83E-06	1.41E-07	3.98E-07	3.32E-06	4.46E-07	6.94E-07	9.41E-07	1.41E-06	1.03E-06	4.76E-07	3.53E-07
Red marrow	7.32E-07	2.77E-07	1.83E-07	3.07E-07	6.10E-07	5.14E-07	2.38E-07	4.27E-07	3.36E-07	3.36E-07	5.18E-07	2.63E-07	3.37E-07	2.75E-07
Bone surfaces	4.79E-07	5.34E-07	1.50E-07	1.90E-07	3.09E-07	2.46E-07	1.77E-07	2.14E-07	2.70E-07	2.70E-07	2.83E-07	2.17E-07	2.96E-07	3.28E-07
Skin	1.15E-07	1.40E-07	2.49E-07	1.02E-07	1.14E-07	9.94E-08	1.15E-07	1.02E-07	1.15E-07	1.20E-07	1.34E-07	1.18E-07	1.30E-07	1.89E-07
Spleen	1.25E-06	5.74E-09	1.51E-07	3.38E-07	1.77E-07	2.93E-07	2.09E-06	2.78E-07	3.26E-07	4.39E-07	1.87E-06	2.16E-07	4.54E-07	3.01E-07
Testes	1.02E-08	4.79E-11	0.00E+00	3.33E-08	4.43E-07	9.10E-08	1.86E-08	7.48E-08	4.30E-09	4.95E-09	1.91E-08	1.03E-08	3.16E-09	3.02E-07
Thymus	1.86E-07	3.52E-08	8.03E-07	5.65E-08	1.20E-08	2.20E-08	1.34E-07	2.73E-08	2.41E-06	1.98E-06	6.83E-08	1.77E-07	7.95E-07	3.11E-07
Thyroid	3.16E-08	4.21E-07	1.03E-07	1.50E-08	2.38E-09	3.04E-09	1.57E-08	5.97E-09	1.43E-07	1.36E-07	1.93E-08	3.51E-08	2.54E-07	3.38E-07
Urinary bladder wall	3.53E-08	1.34E-10	9.12E-09	1.60E-07	1.30E-06	5.76E-07	7.23E-08	4.55E-07	1.30E-08	9.31E-09	7.47E-08	5.03E-08	8.80E-09	3.97E-07
Uterus	8.02E-08	2.41E-10	1.70E-08	3.31E-07	1.39E-06	2.18E-06	1.51E-07	1.03E-06	2.53E-08	2.96E-08	2.00E-07	1.04E-07	2.03E-08	4.04E-07
Total body	8.01E-07	6.71E-07	6.33E-07	4.02E-07	6.01E-07	6.98E-07	4.26E-07	5.47E-07	4.33E-07	7.86E-07	7.71E-07	7.71E-07	7.22E-07	7.11E-07

TABLE 22-4 CONTINUED

	Source Organs													
Target Organs	Ovaries	Pancreas	Red Marrow	Cortical Bone Surfaces	Trabecular Bone Surfaces	Cortical Bone Volume	Trabecular Bone Volume	Spleen	Testes	Thymus	Thyroid	Urinary Bladder Contents	Uterus	Total Body
Adrenals	1.13E-07	2.88E-06	7.32E-07	3.31E-07	3.31E-07	3.31E-07	3.31E-07	1.25E-06	1.02E-08	1.86E-07	3.16E-08	4.16E-08	8.02E-08	8.00E-07
Brain	2.65E-10	4.18E-09	2.60E-07	3.74E-07	3.74E-07	3.74E-07	3.74E-07	5.74E-09	4.79E-11	3.52E-08	4.21E-07	1.33E-10	2.41E-10	6.71E-07
Breasts	1.45E-08	1.97E-07	1.78E-07	1.09E-07	1.09E-07	1.09E-07	1.09E-07	1.51E-07	0.00E+00	8.03E-07	1.03E-07	7.58E-09	1.70E-08	6.32E-07
Gallbladder wall	2.97E-07	2.07E-06	3.36E-07	1.34E-07	1.34E-07	1.34E-07	1.34E-07	3.46E-07	3.23E-08	9.17E-08	1.53E-08	1.20E-07	3.32E-07	8.28E-07
Lower large intestine wall	3.20E-06	1.30E-07	5.80E-07	2.23E-07	2.23E-07	2.23E-07	2.23E-07	1.34E-07	5.69E-07	9.83E-09	2.00E-09	1.54E-06	1.29E-06	8.16E-07
Small intestine	2.47E-06	3.98E-07	5.21E-07	1.67E-07	1.67E-07	1.67E-07	1.67E-07	2.93E-07	9.10E-08	2.20E-08	3.04E-09	5.77E-07	2.18E-06	8.28E-07
Stomach wall	1.86E-07	3.45E-06	2.46E-07	1.22E-07	1.22E-07	1.22E-07	1.22E-07	2.03E-06	2.27E-08	1.29E-07	2.17E-08	7.34E-08	1.73E-07	7.86E-07
Upper large intestine wall	2.23E-06	4.37E-07	4.42E-07	1.49E-07	1.49E-07	1.49E-07	1.49E-07	2.84E-07	6.84E-08	2.99E-08	5.97E-09	4.36E-07	1.09E-06	8.16E-07
Heart wall	3.16E-08	9.41E-07	3.23E-07	1.74E-07	1.74E-07	1.74E-07	1.74E-07	4.39E-07	4.95E-09	1.98E-06	1.36E-07	1.03E-08	2.96E-08	7.83E-07
Kidneys	2.17E-07	1.41E-06	5.16E-07	1.93E-07	1.93E-07	1.93E-07	1.93E-07	1.87E-06	1.91E-08	6.83E-08	1.93E-08	8.05E-08	2.00E-07	7.70E-07
Liver	1.20E-07	1.03E-06	2.68E-07	1.50E-07	1.50E-07	1.50E-07	1.50E-07	2.16E-07	1.03E-08	1.77E-07	3.51E-08	4.82E-08	1.04E-07	7.71E-07
Lungs	2.67E-08	4.76E-07	3.35E-07	2.06E-07	2.06E-07	2.06E-07	2.06E-07	4.55E-07	3.16E-09	7.96E-07	2.54E-07	6.19E-09	2.03E-08	7.22E-07
Muscle	4.07E-07	3.53E-07	2.75E-07	2.30E-07	2.30E-07	2.30E-07	2.30E-07	3.01E-07	3.02E-07	3.11E-07	3.38E-07	3.70E-07	4.04E-07	7.11E-07
Ovaries	3.63E-03	1.22E-07	5.99E-07	1.91E-07	1.91E-07	1.91E-07	1.91E-07	1.13E-07	0.00E+00	1.20E-08	2.36E-09	1.39E-06	3.99E-06	8.36E-07
Pancreas	1.22E-07	3.59E-04	4.44E-07	1.98E-07	1.98E-07	1.98E-07	1.98E-07	3.61E-06	1.52E-08	1.75E-07	3.22E-08	5.46E-08	1.24E-07	8.31E-07
Red marrow	5.99E-07	4.36E-07	1.55E-05	6.11E-07	6.91E-06	6.11E-07	5.08E-06	2.71E-07	9.62E-08	2.55E-07	2.38E-07	2.40E-07	4.07E-07	6.10E-07
Bone surfaces	2.79E-07	2.91E-07	8.20E-06	1.42E-05	1.83E-05	5.62E-06	1.05E-05	2.18E-07	1.86E-07	2.19E-07	3.42E-07	1.78E-07	2.13E-07	9.26E-07
Skin	1.02E-07	9.94E-08	1.46E-07	1.71E-07	1.71E-07	1.71E-07	1.71E-07	1.22E-07	3.29E-07	1.52E-07	1.45E-07	1.27E-07	9.94E-08	6.07E-07
Spleen	1.13E-07	3.61E-06	2.76E-07	1.50E-07	1.50E-07	1.50E-07	1.50E-07	1.95E-04	1.31E-08	1.05E-07	3.12E-08	4.30E-08	9.33E-08	7.71E-07
Testes	0.00E+00	1.52E-08	1.01E-07	1.32E-07	1.32E-07	1.32E-07	1.32E-07	1.31E-08	8.53E-04	2.02E-09	4.14E-10	1.03E-06	0.00E+00	7.10E-07
Thymus	1.20E-08	1.75E-07	2.57E-07	1.50E-07	1.50E-07	1.50E-07	1.50E-07	1.05E-07	2.02E-09	1.57E-03	4.42E-07	6.07E-09	1.14E-08	7.40E-07
Thyroid	2.36E-09	3.22E-08	2.33E-07	2.37E-07	2.37E-07	2.37E-07	2.37E-07	3.12E-08	4.14E-10	4.42E-07	1.57E-03	1.19E-09	2.22E-09	7.40E-07
Urinary bladder wall	1.45E-06	5.80E-08	2.56E-07	1.22E-07	1.22E-07	1.22E-07	1.22E-07	4.04E-08	1.03E-06	6.06E-09	1.19E-09	8.85E-05	3.45E-06	8.07E-07
Uterus	3.99E-06	1.24E-07	4.26E-07	1.48E-07	1.48E-07	1.48E-07	1.48E-07	9.33E-08	0.00E+00	1.14E-08	2.22E-09	3.28E-06	4.35E-04	8.42E-07
Total body	8.37E-07	8.31E-07	7.47E-07	7.14E-07	7.14E-07	7.14E-07	7.14E-07	7.71E-07	7.11E-07	7.41E-07	7.41E-07	3.65E-07	8.43E-07	7.16E-07

*Data from References 6 and 7.

TABLE 22-5
S VALUES (mGy/MBq • sec) FOR F-18 IN THE ADULT MALE PHANTOM*

	Source Organs													
Target Organs	Adrenals	Brain	Breasts	Gallbladder Contents	Lower Large Intestine	Small Intestine	Stomach	Upper Large Intestine	Heart Contents	Heart Wall	Kidneys	Liver	Lungs	Muscle
Adrenals	2.59E-03	1.13E-08	4.60E-07	2.06E-06	2.06E-07	5.70E-07	2.06E-06	6.48E-07	1.74E-06	2.05E-06	5.22E-06	3.01E-06	1.74E-06	8.54E-07
Brain	1.13E-08	4.62E-05	3.99E-08	6.70E-09	9.01E-10	1.78E-09	1.06E-08	2.11E-09	4.95E-08	4.78E-08	4.84E-09	1.76E-08	9.70E-08	1.90E-07
Breasts	4.60E-07	3.99E-08	1.46E-04	3.01E-07	4.30E-08	9.55E-08	4.92E-07	1.13E-07	1.90E-06	2.06E-06	2.07E-07	5.85E-07	1.74E-06	3.64E-07
Gallbladder wall	2.21E-06	5.00E-09	3.17E-07	4.38E-04	4.59E-07	3.00E-06	2.06E-06	4.89E-06	6.98E-07	9.32E-07	2.84E-06	5.85E-06	5.54E-07	8.70E-07
Lower large intestine wall	2.06E-07	7.54E-10	4.30E-08	3.97E-07	1.64E-04	4.11E-06	6.64E-07	1.74E-06	5.57E-08	7.00E-08	4.28E-07	1.40E-07	4.93E-08	9.65E-07
Small intestine	5.70E-07	1.78E-09	9.55E-08	3.00E-06	4.74E-06	5.49E-05	1.34E-06	8.69E-06	1.59E-07	2.06E-07	1.50E-06	8.38E-07	1.40E-07	8.07E-07
Stomach wall	1.74E-06	9.18E-09	5.23E-07	1.90E-06	9.34E-07	1.52E-06	1.03E-04	2.06E-06	1.16E-06	1.74E-06	1.74E-06	1.11E-06	8.23E-07	8.07E-07
Upper large intestine wall	6.81E-07	2.11E-09	9.54E-08	5.21E-06	2.21E-06	9.64E-06	1.74E-06	1.07E-04	2.06E-07	2.38E-07	1.47E-06	1.31E-06	1.75E-07	7.91E-07
Heart wall	2.05E-06	4.78E-08	2.06E-06	7.29E-07	7.64E-08	2.06E-07	1.74E-06	2.38E-07	6.32E-05	1.53E-04	5.86E-07	1.58E-06	3.00E-06	6.80E-07
Kidneys	5.22E-06	4.84E-09	2.07E-07	2.68E-06	5.85E-07	1.50E-06	1.74E-06	1.47E-06	5.39E-07	5.86E-07	1.68E-04	2.06E-06	5.08E-07	7.44E-07
Liver	3.01E-06	1.76E-08	5.85E-07	5.53E-06	1.75E-07	8.38E-07	1.04E-06	1.36E-06	1.45E-06	1.58E-06	2.06E-06	3.40E-05	1.38E-06	5.70E-07
Lungs	1.74E-06	9.70E-08	1.74E-06	4.91E-07	6.36E-08	1.40E-07	7.92E-07	1.74E-07	3.16E-06	3.00E-06	5.08E-07	1.38E-06	4.69E-05	6.80E-07
Muscle	8.54E-07	1.90E-07	3.64E-07	8.38E-07	8.86E-07	8.07E-07	7.28E-07	7.75E-07	6.33E-07	6.80E-07	7.44E-07	5.70E-07	6.80E-07	2.21E-06
Ovaries	2.69E-07	9.16E-10	4.47E-08	7.75E-07	9.02E-06	6.17E-06	4.90E-07	5.22E-06	7.81E-08	9.21E-08	5.70E-07	3.17E-07	7.62E-08	1.04E-06
Pancreas	7.11E-06	1.39E-08	5.23E-07	4.73E-06	3.65E-07	1.03E-06	8.22E-06	1.12E-06	1.74E-06	2.37E-06	3.64E-06	2.53E-06	1.23E-06	9.02E-07
Red marrow	1.90E-06	6.96E-07	4.91E-07	7.91E-07	1.58E-06	1.31E-06	6.32E-07	1.12E-06	8.85E-07	8.85E-07	1.34E-06	6.96E-07	8.85E-07	7.12E-07
Bone surfaces	1.06E-06	1.20E-06	3.49E-07	3.95E-07	6.65E-07	5.22E-07	3.79E-07	4.58E-07	5.85E-07	5.85E-07	6.17E-07	4.74E-07	6.64E-07	7.28E-07
Skin	3.17E-07	3.81E-07	6.65E-07	2.70E-07	3.01E-07	2.70E-07	3.17E-07	2.70E-07	3.17E-07	3.17E-07	3.65E-07	3.18E-07	3.48E-07	5.07E-07
Spleen	3.16E-06	1.91E-08	4.12E-07	8.25E-07	4.59E-07	7.59E-07	5.21E-06	6.96E-07	8.07E-07	1.11E-06	4.75E-06	5.54E-07	1.14E-06	7.75E-07
Testes	3.19E-08	1.66E-10	0.00E+00	9.69E-08	1.18E-06	2.54E-07	5.73E-08	2.06E-07	1.39E-08	1.59E-08	5.88E-08	3.20E-08	1.03E-08	7.91E-07
Thymus	4.90E-07	1.03E-07	2.21E-06	1.59E-07	3.66E-08	6.20E-08	3.65E-07	7.94E-08	6.02E-06	4.91E-06	1.90E-07	4.60E-07	2.06E-06	8.07E-07
Thyroid	8.92E-08	1.11E-06	2.86E-07	4.62E-08	7.87E-09	9.46E-09	4.78E-08	1.92E-08	3.64E-07	3.64E-07	5.87E-08	9.67E-08	6.65E-07	8.70E-07
Urinary bladder wall	1.03E-07	4.63E-10	2.87E-08	4.43E-07	3.16E-06	1.44E-06	2.06E-07	1.17E-06	3.98E-08	2.71E-08	2.06E-07	1.43E-07	2.71E-08	1.01E-06
Uterus	2.21E-07	8.35E-10	5.26E-08	8.54E-07	3.47E-06	5.38E-06	3.97E-07	2.53E-06	7.48E-08	8.74E-08	5.23E-07	2.70E-07	5.88E-08	1.03E-06
Total body	1.49E-06	1.17E-06	1.10E-06	9.67E-07	1.21E-06	1.34E-06	9.19E-07	1.14E-06	9.10E-07	1.46E-06	1.43E-06	1.43E-06	1.30E-06	1.28E-06

TABLE 22-5 CONTINUED

	Source Organs													
Target Organs	Ovaries	Pancreas	Red Marrow	Cortical Bone Surface	Trabecular Bone Surface	Cortical Bone Volume	Trabecular Bone Volume	Spleen	Testes	Thymus	Thyroid	Urinary Bladder Contents	Uterus	Total Body
Adrenals	2.69E-07	7.11E-06	1.90E-06	8.70E-07	8.70E-07	8.70E-07	8.70E-07	3.16E-06	3.19E-08	4.90E-07	8.92E-08	1.19E-07	2.21E-07	1.49E-06
Brain	9.16E-10	1.39E-08	6.96E-07	9.97E-07	9.97E-07	9.97E-07	9.97E-07	1.91E-08	1.66E-10	1.03E-07	1.11E-06	4.63E-10	8.35E-10	1.17E-06
Breasts	4.47E-08	5.23E-07	4.91E-07	3.01E-07	3.01E-07	3.01E-07	3.01E-07	4.12E-07	0.00E+00	2.21E-06	2.86E-07	2.23E-08	5.26E-08	1.10E-06
Gallbladder wall	7.59E-07	5.21E-06	8.68E-07	3.48E-07	3.48E-07	3.48E-07	3.48E-07	8.71E-07	9.37E-08	2.38E-07	4.62E-08	3.17E-07	8.40E-07	1.57E-06
Lower large intestine wall	8.22E-06	3.32E-07	1.49E-06	5.85E-07	5.85E-07	5.85E-07	5.85E-07	3.48E-07	1.46E-06	3.03E-08	6.59E-09	3.79E-06	3.16E-06	1.54E-06
Small intestine	6.17E-06	1.03E-06	1.31E-06	4.27E-07	4.27E-07	4.27E-07	4.27E-07	7.59E-07	2.54E-07	6.20E-08	9.46E-09	1.44E-06	5.38E-06	1.57E-06
Stomach wall	5.07E-07	8.69E-06	6.33E-07	3.16E-07	3.16E-07	3.16E-07	3.16E-07	5.06E-06	6.52E-08	3.65E-07	6.36E-08	1.90E-07	4.60E-07	1.47E-06
Upper large intestine wall	5.54E-06	1.09E-06	1.11E-06	3.80E-07	3.80E-07	3.80E-07	3.80E-07	6.97E-07	1.90E-07	9.06E-08	1.92E-08	1.09E-06	2.69E-06	1.54E-06
Heart wall	9.21E-08	2.37E-06	8.38E-07	4.58E-07	4.58E-07	4.58E-07	4.58E-07	1.11E-06	1.59E-08	4.91E-06	3.64E-07	3.03E-08	8.74E-08	1.46E-06
Kidneys	5.70E-07	3.64E-06	1.34E-06	5.06E-07	5.06E-07	5.06E-07	5.06E-07	4.75E-06	5.88E-08	1.90E-07	5.87E-08	2.22E-07	5.23E-07	1.43E-06
Liver	3.17E-07	2.53E-06	6.96E-07	3.95E-07	3.95E-07	3.95E-07	3.95E-07	5.54E-07	3.20E-08	4.60E-07	9.67E-08	1.35E-07	2.70E-07	1.43E-06
Lungs	7.62E-08	1.23E-06	8.85E-07	5.53E-07	5.53E-07	5.53E-07	5.53E-07	1.14E-06	1.03E-08	2.06E-06	6.65E-07	1.92E-08	5.88E-08	1.30E-06
Muscle	1.04E-06	9.02E-07	7.12E-07	6.01E-07	6.01E-07	6.01E-07	6.01E-07	7.75E-07	7.91E-07	8.07E-07	8.70E-07	9.49E-07	1.03E-06	1.28E-06
Ovaries	4.72E-03	3.17E-07	1.53E-06	4.90E-07	4.90E-07	4.90E-07	4.90E-07	2.69E-07	0.00E+00	3.67E-08	7.87E-09	3.47E-06	9.96E-06	1.58E-06
Pancreas	3.17E-07	4.97E-04	1.15E-06	5.22E-07	5.22E-07	5.22E-07	5.22E-07	9.16E-06	4.62E-08	4.42E-07	8.90E-08	1.49E-07	3.17E-07	1.57E-06
Red marrow	1.53E-06	1.15E-06	2.04E-05	1.58E-06	1.04E-05	1.58E-06	8.44E-06	7.28E-07	2.69E-07	6.65E-07	6.17E-07	6.17E-07	1.06E-06	1.21E-06
Bone surfaces	5.85E-07	6.32E-07	1.14E-05	1.59E-05	1.98E-05	8.73E-06	1.31E-05	4.75E-07	4.12E-07	4.75E-07	7.59E-07	3.64E-07	4.42E-07	1.59E-06
Skin	2.70E-07	2.70E-07	3.96E-07	4.75E-07	4.75E-07	4.75E-07	4.75E-07	3.33E-07	8.71E-07	4.12E-07	3.81E-07	3.33E-07	2.70E-07	1.03E-06
Spleen	2.69E-07	9.16E-06	7.28E-07	3.96E-07	3.96E-07	3.96E-07	3.96E-07	2.81E-04	3.99E-08	2.71E-07	8.72E-08	1.27E-07	2.54E-07	1.43E-06
Testes	0.00E+00	4.62E-08	2.69E-07	3.48E-07	3.48E-07	3.48E-07	3.48E-07	3.99E-08	1.17E-03	6.76E-09	1.45E-09	2.53E-06	0.00E+00	1.28E-06
Thymus	3.67E-08	4.42E-07	6.65E-07	3.96E-07	3.96E-07	3.96E-07	3.96E-07	2.71E-07	6.76E-09	2.11E-03	1.11E-06	1.92E-08	3.51E-08	1.35E-06
Thyroid	7.87E-09	8.90E-08	6.17E-07	6.33E-07	6.33E-07	6.33E-07	6.33E-07	8.72E-08	1.45E-09	1.11E-06	2.11E-03	4.04E-09	7.39E-09	1.35E-06
Urinary bladder wall	3.63E-06	1.58E-07	6.47E-07	3.16E-07	3.16E-07	3.16E-07	3.16E-07	1.19E-07	2.53E-06	1.92E-08	4.04E-09	1.31E-04	8.69E-06	1.52E-06
Uterus	9.96E-06	3.17E-07	1.06E-06	3.79E-07	3.79E-07	3.79E-07	3.79E-07	2.54E-07	0.00E+00	3.51E-08	7.39E-09	8.21E-06	6.07E-04	1.60E-06
Total body	1.58E-06	1.57E-06	1.36E-06	1.28E-06	1.28E-06	1.28E-06	1.28E-06	1.43E-06	1.28E-06	1.35E-06	1.35E-06	8.66E-07	1.60E-06	1.28E-06

*Data from References 6 and 7.

EXAMPLE 22-10

Estimate the effective dose E for an adult male following the injection of 250 MBq of ^{18}F-FDG. Assume any organs or tissues not shown in Table 22-6 have a radiation dose of 1.5×10^{-2} mGy/MBq (approximately the average of those that are listed).

Answer

Using the available dose values in Table 22-6 and the tissue weighting factors in Table 22-7, and assuming that $w_R = 1$, then the effective dose is given by:

$$\begin{aligned}
E = {} & 0.12 \times (1.3 \times 10^{-2} \text{ mGy/MBq}) \\
& \times 250 \text{ MBq (red marrow)} \\
& + 0.12 \times (3 \times 10^{-2} \text{ mGy/MBq}) \\
& \times 250 \text{ MBq (colon, as sum of upper} \\
& \quad \text{and lower large intestine walls)} \\
& + 0.12 \times (1.7 \times 10^{-2} \text{ mGy/MBq}) \\
& \times 250 \text{ MBq (lung)} \\
& + 0.12 \times (1.3 \times 10^{-2} \text{ mGy/MBq}) \\
& \times 250 \text{ MBq (stomach)} \\
& + 0.12 \times (9.2 \times 10^{-3} \text{ mGy/MBq}) \\
& \times 250 \text{ MBq (breast)} \\
& + 0.08 \times (1.3 \times 10^{-2} \text{ mGy/MBq}) \\
& \times 250 \text{ MBq (gonads)} \\
& + 0.04 \times (1.9 \times 10^{-1} \text{ mGy/MBq}) \\
& \times 250 \text{ MBq (bladder)} \\
& + 0.04 \times (1.5 \times 10^{-2} \text{ mGy/MBq}) \\
& \times 250 \text{ MBq (esophagus)} \\
& + 0.04 \times (1.6 \times 10^{-2} \text{ mGy/MBq}) \\
& \times 250 \text{ MBq (liver)} \\
& + 0.04 \times (1.0 \times 10^{-2} \text{ mGy/MBq}) \\
& \times 250 \text{ MBq (thyroid)} \\
& + 0.01 \times (1.2 \times 10^{-2} \text{ mGy/MBq}) \\
& \times 250 \text{ MBq (bone surfaces)} \\
& + 0.01 \times (1.9 \times 10^{-2} \text{ mGy/MBq}) \\
& \times 250 \text{ MBq (brain)} \\
& + 0.01 \times (1.5 \times 10^{-2} \text{ mGy/MBq}) \\
& \times 250 \text{ MBq (salivary glands)} \\
& + 0.01 \times (8.4 \times 10^{-3} \text{ mGy/MBq}) \\
& \times 250 \text{ MBq (skin)} \\
& + 0.00923 \times (2.67 \times 10^{-1} \text{ mGy/MBq}) \\
& \times 250 \text{ MBq (sum of 13 listed} \\
& \quad \text{remainder tissues)} \\
= {} & 5.8 \text{ mSv (or 0.58 rem)}
\end{aligned}$$

Although effective dose is regarded as a better indicator of overall radiation risk than whole-body dose for radiation protection purposes, there still is debate about its relevance, and care should be taken in its use and interpretation. In particular, effective dose is not recommended for use in radionuclide therapy applications, nor should it be used to evaluate the risk from a radionuclide study to a specific individual. This is because calculations of E are based on an "average" human, whereas the actual dose can vary considerably with body shape and size, as well as the specific distribution of the radionuclide in the individual. This, along with some other general limitations of internal radiation dose estimates, is discussed in the next section.

8. Limitations of the MIRD Method

There are a number of important limitations in the MIRD approach for calculating radiation dose. Although Equation 22-18 is fundamentally correct, the values of ϕ are currently based on simplistic models of human anatomy that assume specific relationships in the shape, size, and location of various organs (see Fig. 22-5). More realistic models of the human body, based on medical imaging data and advanced computer modeling, are currently under development for dosimetry purposes. The MIRD formulation also implicitly assumes that activity is distributed uniformly within each organ and, furthermore, that energy is uniformly deposited throughout the organ. The assumption can cause a significant error in the calculated dose from nonpenetrating radiation (e.g., Auger electrons) when the activity is taken up in specific regions or cell types within an organ. Local radionuclide concentrations and, hence, the absorbed dose can be much higher than organ average calculations might suggest.

Calculation of cumulated activity, $\tilde{A}$, also is problematic. Initially, with a new radiopharmaceutical, this must be determined from animal studies. There can be significant differences between the kinetics of a tracer in an animal model and in the human. Once a radiopharmaceutical is approved for human use, it is possible to obtain human data to estimate $\tilde{A}$. However, values for healthy subjects may differ widely from those for patients and from one patient to the next because of pathophysiologic effects on uptake, clearance, and excretion of the radiopharmaceutical.

Despite these limitations, the MIRD method is a useful tool for comparing the average dose to various organs in patients for

TABLE 22-6
RADIATION DOSE ESTIMATES FOR ^{18}F-FLUORODEOXYGLUCOSE IN AN ADULT SUBJECT*

Organ Dose	mGy/MBq Administered	Organ Dose	mGy/MBq Administered
Adrenals	1.3×10^{-2}	Muscle	1.1×10^{-2}
Brain	1.9×10^{-2}	Ovaries	1.7×10^{-2}
Breasts	9.2×10^{-3}	Pancreas	2.6×10^{-2}
Gallbladder wall	1.4×10^{-2}	Red marrow	1.3×10^{-2}
Lower large intestine wall	1.7×10^{-2}	Bone surfaces	1.2×10^{-2}
Small intestine	1.4×10^{-2}	Skin	8.4×10^{-3}
Stomach	1.3×10^{-2}	Spleen	3.7×10^{-2}
Upper large intestine wall	1.3×10^{-2}	Testes	1.3×10^{-2}
Heart wall	6.0×10^{-2}	Thymus	1.2×10^{-2}
Kidneys	2.0×10^{-2}	Thyroid	1.0×10^{-2}
Liver	1.6×10^{-2}	Urinary bladder wall	1.9×10^{-1}
Lungs	1.7×10^{-2}	Uterus	2.3×10^{-2}

*Data from reference 9.

TABLE 22-7
TISSUE WEIGHTING FACTORS USED FOR CALCULATION OF EFFECTIVE DOSE (*E*)*

Organ	w_T
Red marrow, colon, lungs, stomach, breast	0.12 each
Gonads	0.08
Bladder, liver, esophagus, thyroid	0.04 each
Brain, skin, salivary glands, bone surfaces	0.01 each
Remainder tissues (adrenals, extrathoracic region, gallbladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate [males], small intestine, spleen, thymus, uterus/cervix [females])	0.12 total (0.00923 each)

*From reference 1.

a wide variety of nuclear medicine procedures. It also is an essential tool in the approval process for new radiopharmaceuticals. In circumstances in which the assumptions on which the MIRD approach is based are unacceptable, more complex and involved methods can be used. For example, microdosimetric (cellular level) calculations should be done for radiopharmaceuticals that have very nonuniform uptake in radiosensitive organs. As well, radiation dose estimates for therapeutic applications should incorporate data acquired on the specific patient, as described in Example 22-9.

REFERENCES

Society of Nuclear Medicine (MIRD) and ICRP publications, along with data available from references 6 and 9, provide the basic data for calculating absorbed doses:

1. International Commission on Radiological Protection: Recommendations of the International Commission on Radiological Protection. *ICRP Publication 103; Ann ICRP* 37(2-4), 2007.
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10. International Commission on Radiological Protection: 1990 Recommendations of the International Commission on Radiological Protection (ICRP Publication No. 60), New York, 1991, Pergamon Press.

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An excellent overview of the topics in this chapter is provided by the following detailed text:

Stabin MG: *Fundamentals of Nuclear Medicine Dosimetry*, New York, 2008, Springer.

A comprehensive collection of materials and data can be found at the Radiation Dose Assessment Resource website:

http://www.doseinfo-radar.com [accessed December 17, 2011].

A general guide for performing internal dosimetry calculations with the MIRD approach is the following:

Loevinger R, Budinger T, Watson E: *MIRD Primer for Absorbed Dose Calculations*, New York, 1991, Society of Nuclear Medicine.

The following book is useful for MIRD calculations at the cellular level:

Goddu SM, Howell RW, Bouchet LG, et al: *MIRD Cellular S Values*, New York, 1997, Society of Nuclear Medicine.

Recommended textbooks on basic radiation biology are the following:

Hall EJ: *Radiobiology for the Radiologist*, ed 7, New York, 2011, Lippincott, Williams & Wilkins.
Forshier S: *Essentials of Radiation Biology and Protection*, ed 2, Clifton Park, NY, 2008, Delmar Cengage Learning.