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Dosage of Radiopharmaceuticals and Internal Dosimetry

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Dosage of Radiopharmaceuticals

Radiopharmaceuticals are widely used for diagnostic imaging and radiation therapy. Although radiation therapy uses damage to living tissue to the advantage of the patient, this damage, however, is a limitation for the diagnostic application. Radiation dosages for specific indications are optimized based on thorough studies performed on animals and through clinical trials on human subjects prior to approval for clinical applications. Proper dosages are derived through careful study of pharmacokinetics, the physical characteristics of the radionuclide, metabolism of the subject, and the pharmacodynamics of the radiopharmaceutical in animal and human subjects. The chemical- and radiotoxicities and adverse reactions are well understood before an optimal and safe dosage is recommended. Doses are typically scaled by weight, or total body surface area, and reduced for children. The recommended dosage for a specific indication and route of administration are stated by the drug manufacturers in the package insert, and are readily available online.

Internal Radiation Dosimetry

To assess the effects of radiation on a living organ, it is important to understand and quantify radiation energy deposited and absorbed by that organ. This deposition/absorption of energy is called *radiation absorbed dose*. Internal radiation dosimetry involves the studying of energy absorbed by the organs from an internally deposited radionuclide. It includes the study of physical characteristics of radionuclides, pharmacokinetics and biokinetics of the radiopharmaceutical, as well as establishing assumptions and models for calculating absorbed radiation energy.

Radiation Absorbed Dose

Radiation absorbed dose is defined as the quantity of radiation energy absorbed by a unit mass of absorber material (e.g., bone

marrow, body tissue, etc.). The SI unit for radiation absorbed dose is the *gray* (*Gy*).

1 Gy = 1 joule energy absorbed/kg of absorber medium

However, the traditional unit *rad*, is used more commonly in the United States.

1 rad = 100 erg energy absorbed/g of absorber medium

1 rad = 0.01 Gy

Radiation absorbed dose is proportional to several key estimated components. These components include (1) the amount of radioactivity in the source organ, (2) the residence time of radioactivity in the source organ, (3) the type and amount of radiation energy emitted by the radioactivity in the source organ, and (4) the fraction of the emitting energy from the source that is absorbed by the target organ. The fraction is dependent on the geometric and anatomic relationship of the source to target organs.

To calculate the radiation absorbed dose, we need to quantify each component discussed above. Quantifying each component that contributes to the radiation absorbed dose can be difficult due to the complex nature of metabolic systems and to differences in patient anatomy. Therefore, the calculation of radiation absorbed dose is really an estimate of quantity based on standard anatomic and kinetic models and reasonable assumptions.

Absorbed Dose

Cumulated Radioactivity $\tilde{A}$

The radiation dose delivered from a source organ to a target organ is dependent on the amount of radioactivity in the source organ and the length of time the radioactivity resides in the source organ. Due to the continuous uptake and elimination of the radiopharmaceutical administered to the living system, and physical decay of the radionuclide, the radioactivity in each organ is a function of time. Mathematically, the *cumulated radioactivity*, $\tilde{A}$, can be expressed as

$$\tilde{A} = \int_0^\infty A(t)dt \tag{1}$$

where $A(t)$ is the radioactivity in source organ at the time of t (Fig. 4.1). $\tilde{A}$ accounts for the radioactivity in the organ, and how long it resided in source organ (component 1 and 2 discussed above). The units for $\tilde{A}$ are μCi-hr.

$A(t)$ is different from organ to organ, and varies in individual living systems. However, it can be estimated from studying the pharmacokinetics of the radiopharmaceutical of the source organ. A time-radioactivity curve can be established for each source organ by following the uptake and excretion of the radionuclide in the organ. $A(t)$ is a function of the physical and biologic decay of the radiophar-

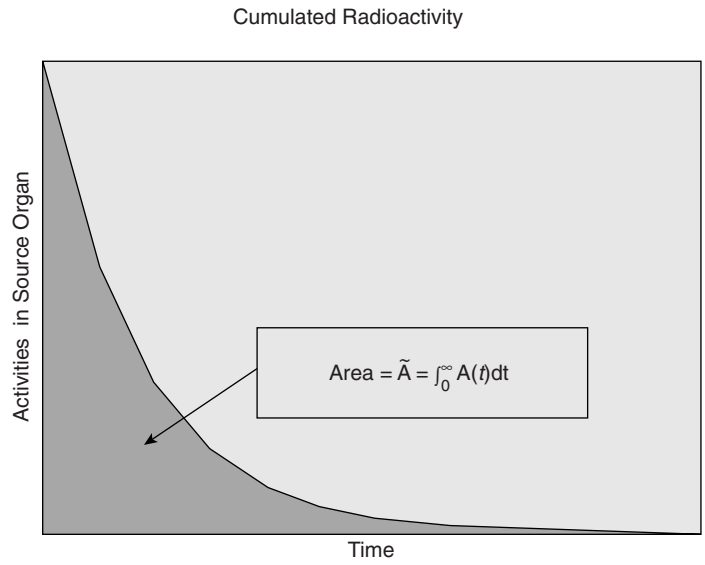

Figure 4.1. Time-activity curve. The area under is the curve is $\tilde{A}$, the accumulated radioactivity in the source organ.

maceutical. A simplified mathematical model of instantaneous and exponential elimination of the radiopharmaceutical in the source organ can be described as

$$A(t) = A_0 e^{-\lambda_e t} \tag{2}$$

and

$$\lambda_e = \lambda_p + \lambda_b \tag{3}$$

where λ_e is the effective decay constant, and λ_p and λ_b are the physical and biologic decay constants, respectively.

If the half-life is known, the decay constant can be calculated as

$$\lambda = \frac{0.693}{T_{1/2}}. \tag{4}$$

Therefore, equation 1 becomes

$$\tilde{A} = \frac{A_0}{\lambda_e} = 1.44 T_e A_0 \tag{5}$$

where T_e is the effective half-life.

Equilibrium Absorbed Dose Constant, Δ

The amount of radiation energy emitted per unit of accumulated radioactivity in the source organ can be calculated if the type, energy,

and frequency of each emission of the radionuclide are known. If we designate E_i as the energy of the i^{th} emission, n_i is the frequency of that emission. The amount of radiation energy emitted per unit of accumulated radioactivity can then be described as

$$\Delta_i = 2.13 n_i E_i \tag{6}$$

where E_i is in MeV and Δ_i is in (g-rad/μCi-hr). Δ_i is defined as *equilibrium absorbed dose constant* of the i^{th} emitter. The energy emitted from the i^{th} emission of the radionuclide in the source organ is a product of the equilibrium absorbed dose constant, Δ_i, and accumulated radioactivity, $\tilde{A}$. If a radionuclide deposited in the source organ has more than one emission, the equilibrium absorbed dose constant should be calculated for each emission and summated.

***Total Energy Absorbed by Target Organ,* D**

Due to the distance and attenuation between the source organ and target oranges, only a fraction of the energy emitted by the source organ is absorbed by the target organ. This fraction factor needs to be quantified so that the total absorbed dose by the target organ can be estimated.

***Absorbed Fraction* ϕ**

The absorbed fraction depends on the geometric relationship of the source and target organ, the emission energy of the radionuclide, and the composition of the source organs, the target organ, and those organs in between. Mathematically, the absorbed fraction of the i^{th} emission of the radionuclide can be expressed as $\phi_i(t_k \leftarrow s_j)$. The energy absorbed by the target organ, t_k, from the i^{th} emission of the radionuclide in source organ, s_j, is equal to $\tilde{A}_j \phi_i(t_k \leftarrow s_j)\Delta_i$. So the total energy absorbed by target organ, t_k, from all emissions in the source organ, s_j, is

$$\text{Energy Absorbed (g - rad)} = \tilde{A}_j \sum_i \phi_i(t_k \leftarrow s_j)\Delta_i. \tag{7}$$

Because the absorbed dose is defined as energy absorbed in unit mass, the dose delivered from the source organ, s_j, to the target organ, t_k, is

$$D(t_k \leftarrow s_j)(rad) = \left(\frac{\tilde{A}_j}{m_k}\right)\sum_i \phi_i(t_k \leftarrow s_j)\Delta_i \tag{8}$$

where $\tilde{A}_j$ is the cumulated activity in source organ, s_j, and m_k is the mass of the target organ, t_k. The total dose to the target organ can be obtained by summing the doses from all the source organ of the body:

$$D(t_k)(rad) = \sum_j D(t_k \leftarrow s_j).$$

The calculation of absorbed fraction, ϕ, for each penetrating emission, for example, photons, is very complicated, as it is highly dependent on the energy of the radiation emission, the geometry between the target and source organs, and the characteristics of the tissue and organ. The range of ϕ is between 0 and 1 from the source organ to target

organ (target organ can be the source organ itself) for photons with emitting energy >10 keV. When the target organ is the same as the source organ, and electron or photon energy is <10 keV, $\phi = 1$. If the target organ is a different organ, then $\phi = 0$. This assumes that the source organ will attenuate and absorb within itself the entire radiation energy when the radiation emission is a low-energy photon or a non-penetrating particle, such as an electron.

Specific Absorbed Dose Fraction, Φ

A rearrangement of equation 8, gives us

$$D(t_k \leftarrow s_j)(rad) = \tilde{A}_j \sum_i \frac{\phi_i(t_k \leftarrow s_j)}{m_k} \Delta_i. \tag{9}$$

The term $\frac{\phi_i(t_k \leftarrow s_j)}{m_k}$, is defined as the specific absorbed fraction, $\Phi_i(t_k \leftarrow s_j)$. This is the fraction of the i^{th} radiation emitter that is given off by the radionuclide in the source organ, s_j, and absorbed, per unit mass, by target organ t_k. Equation 9 can then be written as

$$D(t_k \leftarrow s_j)(rad) = \tilde{A}_j \sum_i \Phi_i(t_k \leftarrow s_j) \Delta_i. \tag{10}$$

The specific absorbed fraction has been calculated using mathematical phantom models based on different age groups with complex mathematical simulations for source-target pairs. The results are a set of comprehensive tables of specific absorbed fractions for each reference age group. Table 4.1 is an example that was formulated by Oak Ridge National Lab (1). This example involves a 500 keV photon, the specific absorbed fraction from the kidney (source organ) to what could be considered the average liver of a 10-year-old (2.35E-2/kg or 2.35E-5/g).

A simplified quantity, *dose per cumulated activity*, or S value, has been calculated for the source-target organs for many radionuclides of interest. The S value of the source-target organs, pair j and k, is defined as $S(t_k \leftarrow s_j) = \sum_i \Phi_i(t_k \leftarrow s_j) \Delta_i$. This is calculated in the conventional units of rad/μCi-hr. **M**edical **I**nternal **R**adiation **D**ose (MIRD) committee pamphlet No. 11 tabulated many of the most commonly used radionuclides for the standard adult phantom (2). Now Equation 10 can be rewritten as

$$D(t_k \leftarrow s_j)(rad) = \tilde{A}_j S(t_k \leftarrow s_j). \tag{11}$$

The total dose $D(t_k)$ to target organ k is then described as

$$D(t_k) = \sum_j \tilde{A}_j S(t_k \leftarrow s_j). \tag{12}$$

If the accumulated radioactivity in each source organ is known, one can calculate the total dose to the target organ by using the S-value table and summing up the dose delivered to the target organ from each

Table 4.1. Specific absorbed fraction of photon energy in kg-1: recommended values for a 10-year-old

Source = Kidneys	Energy (MeV)											
Target	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	4.84E − 03	5.22E − 02	1.29E − 01	1.57E − 01	1.06E − 01	7.46E − 02	6.89E − 02	6.69E − 02	6.74E − 02	6.21E − 02	5.67E − 02	4.40E − 02
UB Wall	0.0	0.0	5.85E − 07	2.95E − 04	2.08E − 03	2.49E − 03	2.91E − 03	3.29E − 03	3.33E − 03	3.23E − 03	3.09E − 03	2.64E − 03
Bone Sur	1.39E − 04	3.49E − 03	1.40E − 02	3.67E − 02	3.90E − 02	1.90E − 02	1.06E − 02	8.00E − 03	7.26E − 03	6.82E − 03	6.45E − 03	5.42E − 03
Brain	0.0	0.0	0.0	5.72E − 08	9.29E − 06	5.32E − 05	7.84E − 05	1.31E − 04	1.91E − 04	2.33E − 04	2.68E − 04	3.65E − 04
Breasts	0.0	0.0	3.85E − 07	7.36E − 04	2.82E − 03	2.59E − 03	3.19E − 03	3.63E − 03	3.53E − 03	3.36E − 03	3.21E − 03	2.82E − 03
St Wall	0.0	2.18E − 05	1.78E − 03	1.94E − 02	2.80E − 02	2.27E − 02	2.08E − 02	2.06E − 02	1.92E − 02	1.70E − 02	1.53E − 02	1.25E − 02
SI Wall	5.55E − 10	1.06E − 04	3.50E − 03	1.77E − 02	2.70E − 02	2.20E − 02	2.06E − 02	1.90E − 02	1.73E − 02	1.62E − 02	1.52E − 02	1.25E − 02
ULI Wall	0.0	1.70E − 05	1.61E − 03	1.43E − 02	2.70E − 02	2.13E − 02	1.76E − 02	1.79E − 02	1.64E − 02	1.54E − 02	1.45E − 02	1.17E − 02
LLI Wall	0.0	4.04E − 07	1.18E − 04	2.68E − 03	5.43E − 03	6.63E − 03	6.04E − 03	5.70E − 03	5.63E − 03	5.34E − 03	5.05E − 03	4.27E − 03
Kidneys	5.37E + 00	4.43E + 00	3.21E + 00	1.54E + 00	5.95E − 01	3.46E − 01	3.56E − 01	3.74E − 01	3.54E − 01	3.29E − 01	3.06E − 01	2.39E − 01
Liver	8.35E − 05	3.55E − 03	1.58E − 02	3.85E − 02	3.75E − 02	2.74E − 02	2.49E − 02	2.35E − 02	2.19E − 02	2.04E − 02	1.91E − 02	1.62E − 02
Lng Tiss	0.0	5.05E − 06	5.96E − 04	5.35E − 03	9.10E − 03	7.87E − 03	7.35E − 03	6.81E − 03	7.09E − 03	6.34E − 03	5.74E − 03	5.15E − 03
Muscle	3.13E − 03	8.91E − 03	1.43E − 02	1.59E − 02	1.16E − 02	8.53E − 03	8.27E − 03	8.39E − 03	8.04E − 03	7.58E − 03	7.14E − 03	5.88E − 03
Ovaries	0.0	1.55E − 08	4.97E − 05	2.30E − 03	7.47E − 03	8.85E − 03	8.20E − 03	8.49E − 03	7.53E − 03	6.96E − 03	6.66E − 03	6.24E − 03
Pancreas	5.22E − 10	3.99E − 04	1.26E − 02	6.20E − 02	6.58E − 02	4.69E − 02	3.98E − 02	4.04E − 02	3.44E − 02	3.02E − 02	2.77E − 02	2.36E − 02
R Marrow	6.38E − 05	1.33E − 03	4.91E − 03	1.23E − 02	1.51E − 02	1.38E − 02	1.37E − 02	1.35E − 02	1.23E − 02	1.14E − 02	1.08E − 02	8.81E − 03
Skin	1.14E − 04	7.68E − 04	2.97E − 03	5.28E − 03	4.27E − 03	3.41E − 03	3.68E − 03	4.08E − 03	3.89E − 03	3.94E − 03	3.93E − 03	3.31E − 03
Spleen	2.92E − 03	3.80E − 02	1.13E − 01	1.51E − 01	9.95E − 02	6.31E − 02	5.57E − 02	5.76E − 02	5.31E − 02	4.89E − 02	4.55E − 02	3.69E − 02
Testes	0.0	0.0	1.53E − 09	1.76E − 05	3.60E − 04	6.40E − 04	8.50E − 04	1.05E − 03	1.16E − 03	1.18E − 03	1.20E − 03	1.12E − 03
Thymus	0.0	0.0	7.94E − 08	1.13E − 04	7.80E − 04	1.89E − 03	2.30E − 03	2.50E − 03	2.60E − 03	2.64E − 03	2.57E − 03	2.21E − 03
Thyroid	0.0	0.0	1.36E − 10	5.08E − 06	2.18E − 04	6.20E − 04	7.04E − 04	7.71E − 04	8.36E − 04	9.48E − 04	1.01E − 03	9.37E − 04
GB Wall	0.0	3.31E − 05	3.69E − 03	2.55E − 02	5.26E − 02	3.56E − 03	2.48E − 02	2.40E − 02	2.00E − 02	1.86E − 02	1.80E − 02	1.66E − 02
Ht Wall	0.0	2.51E − 08	4.81E − 05	2.89E − 03	7.30E − 03	8.58E − 03	7.65E − 03	7.51E − 03	7.66E − 03	6.95E − 03	6.32E − 03	5.20E − 03
Uterus	0.0	1.26E − 09	1.72E − 05	1.78E − 03	6.39E − 03	8.05E − 03	6.87E − 03	6.99E − 03	7.56E − 03	7.10E − 03	6.57E − 03	5.48E − 03

Cristy M, Eckerman KF, Specific absorbed fraction of energy at various ages from internal photon source. IV. Ten-year-old. Oak Ridge National Laboratory Report ORNL/TM-8381:Vol. 4, 1987

Bone Sur: Bone Surface; GB Wall: Gall Bladder Wall; Ht Wall: Heart Wall; LLI Wall: Lower Large Intestine Wall; Long Tiss: Lung Tissue; R Marrow: Red Marrow; SI Wall: Small Intestine Wall; St. Wall: Stomach Wall; UB wall: Urinary Bladder Wall; ULI Wall: Upper Large Intestine Wall.

source organ. In absence of the S-value tables for other age groups, the S value can be calculated using tabulated Φ and Δ values, as discussed earlier.

Pediatric Dose Estimate

For pediatric patients, radiopharmaceutical dosages are based on a pediatric dosing schedule. There are many different dosing schedules. The most common ones are those using body weight or body surface areas as guides to scale the dose. Pediatric dose schedules consider many factors to scale down the dosage from that of adult to child, including organ doses, effective dose, and image quality.

However, absorbed radiation dose and effective dose to pediatric patients are not as simple as the dosing schedule. They are not just simple linear scaled-down doses of those for adult patients. As we discussed before, radiation doses to patients depend on geometric and anatomic relationships of source to target organs. Differences in pediatric organ size, density, and composition significantly change the geometric and anatomic relationships that were established for adult patient (or phantom). Differences of biokinetics, due to age-related differences in uptakes (e.g., thyroid uptake of iodine), and excretion (e.g., bladder voiding interval), must be considered when estimate radiation doses for pediatric patients.

Mathematical phantoms for age groups considering the geometric and anatomic variables have been well developed. They are typically for infants, and 1-, 5-, 10-, and 15-year-olds. Specific absorbed fraction has been calculated and tabulated (e.g., Table 4.1) for each age-specific phantom group. Combined with dose schedule, age-adjusted uptake and excretion parameters, pediatric radiation doses can then be estimated according to Equation 10.

Practical Approach to Internal Dose Estimate

The estimation of internal dose from a radionuclide in a human is rather a complicated process. Studies of biokinetic models of a particular radiopharmaceutical normally begin through investigations of the model in animals. Modeling data are collected starting with the initial amount of the radiopharmaceutical of interest that is injected into the animal. The percentage of the radionuclide that is taken up by the source organ is determined through imaging. Other pertinent data are collected through assays of blood and urine. These data points are then carefully plotted or fitted to an established mathematical model that describes the biokinetics of the radionuclides in each source organ. Complex regulatory requirements regarding human research subjects dictate that dose estimates in human subjects should conducted after successful animal studies. Many radiopharmaceuticals are not directly studied for pediatric applications because of complicated social and ethical issues related to conducting radiation research in children.

A wealth of information concerning internal dosimetry for the most commonly used radionuclides in nuclear medicine has been established and published, including dosimetry data for radionuclides used in positron emission tomography (PET) scanning (3–6). Pediatric dose estimates have also been calculated for different age groups based on adult biokinetics of radiopharmaceuticals and anatomic phantom models. Researchers have observed the differences between pediatric biokinetic models and those of an adult, especially in regard to infants, and so improvements in dosimetry data for pediatric patients continue. The Annals of **I**nternational **C**ommission on **R**adiological **P**rotection (ICRP) Publication 53 provides biokinetic models and lists radiation doses to patients from the most commonly used radiopharmaceuticals in nuclear medicine (7). ICRP Publication 80 recalculated 19 of the most frequently used radiopharmaceuticals from ICRP 53 and added 10 more new radiopharmaceuticals (8). Tables 4.2 to 4.4 are absorbed-dose tables of several radiopharmaceuticals used for PET imaging, adapted from ICRP 80.

Table 4.2. Absorbed dose of ^{18}F-FDG (2-fluoro-2-deoxy-D-glucose)

^{18}F 109.77 min	Absorbed dose per unit activity administered (mGy/MBq)				
Organ	**Adult**	**15 years**	**10 years**	**5 years**	**1 year**
Adrenals	1.2E – 02	1.5E – 02	2.4E – 02	3.8E – 02	7.2E – 02
Bladder	1.6E – 01	2.1E – 01	2.8E – 01	3.2E – 01	5.9E – 01
Bone surfaces	1.1E – 02	1.4E – 02	2.2E – 02	3.5E – 02	6.6E – 02
Brain	2.8E – 02	2.8E – 02	3.0E – 02	3.4E – 02	4.8E – 02
Breast	8.6E – 03	1.1E – 02	1.8E – 02	2.9E – 02	5.6E – 02
Gall bladder	1.2E – 02	1.5E – 02	2.3E – 02	3.5E – 02	6.6E – 02
GI-tract					
Stomach	1.1E – 02	1.4E – 02	2.2E – 02	3.6E – 02	6.8E – 02
SI	1.3E – 02	1.7E – 02	2.7E – 02	4.1E – 02	7.7E – 02
Colon	1.3E – 02	1.7E – 02	2.7E – 02	4.0E – 02	7.4E – 02
(ULI	1.2E – 02	1.6E – 02	2.5E – 02	3.9E – 02	7.2E – 02)
(LLI	1.5E – 02	1.9E – 02	2.9E – 02	4.2E – 02	7.6E – 02)
Heart	6.2E – 02	8.1E – 02	1.2E – 01	2.0E – 01	3.5E – 01
Kidneys	2.1E – 02	2.5E – 02	3.6E – 02	5.4E – 02	9.6E – 02
Liver	1.1E – 02	1.4E – 02	2.2E – 02	3.7E – 02	7.0E – 02
Lungs	1.0E – 02	1.4E – 02	2.1E – 02	3.4E – 02	6.5E – 02
Muscles	1.1E – 02	1.4E – 02	2.1E – 02	3.4E – 02	6.5E – 02
Oesophagus	1.1E – 02	1.5E – 02	2.2E – 02	3.5E – 02	6.8E – 02
Ovaries	1.5E – 02	2.0E – 02	3.0E – 02	4.4E – 02	8.2E – 02
Pancreas	1.2E – 02	1.6E – 02	2.5E – 02	4.0E – 02	7.6E – 02
Red marrow	1.1E – 02	1.4E – 02	2.2E – 02	3.2E – 02	6.1E – 02
Skin	8.0E – 03	1.0E – 02	1.6E – 02	2.7E – 02	5.2E – 02
Spleen	1.1E – 02	1.4E – 02	2.2E – 02	3.6E – 02	6.9E – 02
Testes	1.2E – 02	1.6E – 02	2.6E – 02	3.8E – 02	7.3E – 02
Thymus	1.1E – 02	1.5E – 02	2.2E – 02	3.5E – 02	6.8E – 02
Thyroid	1.0E – 02	1.3E – 02	2.1E – 02	3.5E – 02	6.8E – 02
Uterus	2.1E – 02	2.6E – 02	3.9E – 02	5.5E – 02	1.0E – 01
Remaining organs	1.1E – 02	1.4E – 02	2.2E – 02	3.4E – 02	6.3E – 02
Effective dose (mSv/MBq)	1.9E – 02	2.5E – 02	3.6E – 02	5.0E – 02	9.5E – 02

Source: ICRP Publication 80 Radiation Dose to Patients from Radiopharmaceutical. Annals of ICRP 1998;28(3):10–49, with permission from the ICRP.

Table 4.3. Absorbed dose [methyl-^{11}C]thymidine

^{11}C 20.38 min	Absorbed dose per unit activity administered (mGy/MBq)				
Organ	Adult	15 years	10 years	5 years	1 year
Adrenals	2.9E – 03	3.7E – 03	5.8E – 03	9.3E – 03	1.7E – 02
Bladder	2.3E – 03	2.7E – 03	4.3E – 03	7.1E – 03	1.3E – 02
Bone surfaces	2.4E – 03	3.0E – 03	4.7E – 03	7.6E – 03	1.5E – 02
Brain	1.9E – 03	2.4E – 03	4.0E – 03	6.7E – 03	1.3E – 02
Breast	1.8E – 03	2.3E – 03	3.6E – 03	5.9E – 03	1.1E – 02
Gall bladder	2.8E – 03	3.4E – 03	5.2E – 03	7.9E – 03	1.5E – 02
GI-tract					
Stomach	2.4E – 03	2.9E – 03	4.6E – 03	7.3E – 03	1.4E – 02
SI	2.4E – 03	3.1E – 03	4.9E – 03	7.8E – 03	1.5E – 02
Colon	2.4E – 03	2.9E – 03	4.7E – 03	7.4E – 03	1.4E – 02
(ULI	2.4E – 03	3.0E – 03	4.8E – 03	7.7E – 03	1.4E – 02)
(LLI	2.3E – 03	2.7E – 03	4.5E – 03	7.1E – 03	1.3E – 02)
Heart	3.4E – 03	4.3E – 03	6.8E – 03	1.1E – 02	2.0E – 02
Kidneys	1.1E – 02	1.3E – 02	1.9E – 02	2.8E – 02	5.1E – 02
Liver	5.2E – 03	6.8E – 03	1.0E – 02	1.6E – 02	2.9E – 02
Lungs	3.0E – 03	3.9E – 03	6.2E – 03	9.9E – 02	1.9E – 02
Muscles	2.1E – 03	2.6E – 03	4.1E – 03	6.6E – 03	1.3E – 02
Oesophagus	2.2E – 03	2.8E – 03	4.3E – 03	6.9E – 03	1.3E – 02
Ovaries	2.4E – 03	3.0E – 03	4.8E – 03	7.6E – 03	1.4E – 02
Pancreas	2.7E – 03	3.4E – 03	5.3E – 03	8.3E – 03	1.6E – 02
Red marrow	2.5E – 03	3.1E – 03	4.8E – 03	7.6E – 03	1.4E – 02
Skin	1.7E – 03	2.1E – 03	3.4E – 03	5.6E – 03	1.1E – 02
Spleen	3.0E – 03	3.7E – 03	5.9E – 03	9.6E – 03	1.8E – 02
Testes	2.0E – 03	2.5E – 03	3.9E – 03	6.2E – 03	1.2E – 02
Thymus	2.2E – 03	2.8E – 03	4.3E – 03	6.9E – 03	1.3E – 02
Thyroid	2.3E – 03	2.9E – 03	4.7E – 03	7.8E – 03	1.5E – 02
Uterus	2.4E – 03	3.0E – 03	4.8E – 03	7.6E – 03	1.4E – 02
Remaining organs	2.1E – 03	2.6E – 03	4.2E – 03	6.8E – 03	1.3E – 02
Effective dose (mSv/MBq)	2.7E – 03	3.4E – 03	5.3E – 03	8.4E – 03	1.6E – 02

Source: ICRP Publication 80 Radiation Dose to Patients from Radiopharmaceutical. Annals of ICRP 1998;28(3):10–49, with permission from the ICRP.

Table 4.4. Absorbed dose ^{15}O-abeled water

^{15}O 2.04 min	Absorbed dose per unit activity administered (mGy/MBq)				
Organ	Adult	15 years	10 years	5 years	1 year
Adrenals	1.4E – 03	2.2E – 03	3.1E – 03	4.3E – 03	6.6E – 03
Bladder	2.6E – 04	3.1E – 04	5.0E – 04	8.4E – 04	1.5E – 03
Bone surfaces	6.2E – 04	8.0E – 04	1.3E – 03	2.3E – 03	5.5E – 03
Brain	1.3E – 03	1.3E – 03	1.4E – 03	1.6E – 03	2.2E – 03
Breast	2.8E – 04	3.5E – 04	6.0E – 04	9.9E – 04	2.0E – 03
Gall bladder	4.5E – 04	5.5E – 04	8.6E – 04	1.4E – 03	2.7E – 03
GI-tract					
Stomach	7.8E – 04	2.2E – 03	3.1E – 03	5.3E – 03	1.2E – 02
SI	1.3E – 03	1.7E – 03	3.0E – 03	5.0E – 03	9.9E – 03
Colon	1.0E – 03	2.1E – 03	3.7E – 03	6.2E – 03	1.2E – 02
(ULI	1.0E – 03	2.1E – 03	3.7E – 03	6.2E – 03	1.2E – 02)
(LLI	1.1E – 03	2.1E – 03	3.7E – 03	6.2E – 03	1.2E – 02)
Heart	1.9E – 03	2.4E – 03	3.8E – 03	6.0E – 03	1.1E – 02
Kidneys	1.7E – 03	2.1E – 03	3.0E – 03	4.5E – 03	8.1E – 03

Table 4.4. Absorbed dose ^{15}O-abeled water (*Continued*)

^{15}O 2.04 min	Absorbed dose per unit activity administered (mGy/MBq)				
Organ	**Adult**	**15 years**	**10 years**	**5 years**	**1 year**
Liver	**1.6E − 03**	**2.1E − 03**	**3.2E − 03**	**4.8E − 03**	**9.3E − 03**
Lungs	**1.6E − 03**	**2.4E − 03**	**3.4E − 03**	**5.2E − 03**	**1.0E − 02**
Muscles	**2.9E − 04**	**3.7E − 04**	**6.1E − 04**	**1.0E − 03**	**2.0E − 03**
Oesophagus	**3.3E − 04**	**4.2E − 04**	**6.7E − 04**	**1.1E − 03**	**2.1E − 03**
Ovaries	**8.5E − 04**	**1.1E − 03**	**1.8E − 03**	**2.8E − 03**	**5.8E − 03**
Pancreas	**1.4E − 03**	**2.0E − 03**	**4.2E − 03**	**5.4E − 03**	**1.2E − 02**
Red marrow	**8.5E − 04**	**9.7E − 04**	**1.6E − 03**	**3.0E − 03**	**6.1E − 03**
Skin	**2.5E − 04**	**3.1E − 04**	**5.2E − 04**	**8.8E − 04**	**1.8E − 03**
Spleen	**1.6E − 03**	**2.3E − 03**	**3.7E − 03**	**5.8E − 03**	**1.1E − 02**
Testes	**7.4E − 04**	**9.3E − 04**	**1.5E − 03**	**2.6E − 03**	**5.1E − 03**
Thymus	**3.3E − 04**	**4.2E − 04**	**6.7E − 04**	**1.1E − 03**	**2.1E − 03**
Thyroid	**1.5E − 03**	**2.5E − 03**	**3.8E − 03**	**8.5E − 03**	**1.6E − 02**
Uterus	**3.5E − 04**	**4.4E − 04**	**7.2E − 04**	**1.2E − 03**	**2.3E − 03**
Remaining organs	**4.0E − 04**	**5.6E − 04**	**9.4E − 04**	**1.7E − 03**	**2.9E − 03**
Effective dose (mSv/MBq)	**9.3E − 04**	**1.4E − 03**	**2.3E − 03**	**3.8E − 03**	**7.7E − 03**

Source: ICRP Publication 80 Radiation Dose to Patients from Radiopharmaceutical. Annals of ICRP 1998;28(3):10–49, with permission from the ICRP.

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