CONF-9406107--7

DOSIMETRIC METHODOLOGY OF THE ICRP

Keith F. Eckerman

Health Sciences Research Division

Oak Ridge National Laboratory

Oak Ridge, Tennessee 37831-6383

Research sponsored by the Office of Health and Environmental Research, U.S. Department of Energy, under contract DE-AC05-840R21400 with Martin Marietta Energy Systems, Inc.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DOSIMETRIC METHODOLOGY OF THE ICRP

Keith F. Eckerman

Oak Ridge National Laboratory

Oak Ridge, Tennessee

ABSTRACT

Establishment of guidance for the protection of workers and members of the public from radiation exposures necessitates estimation of the radiation dose to tissues of the body at risk. The dosimetric methodology formulated by the International Commission on Radiological Protection (ICRP) is intended to be responsive to this need. While developed for radiation protection, elements of the methodology are often applied in addressing other radiation issues; e.g., risk assessment. This chapter provides an overview of the methodology, discusses its recent extension to age-dependent considerations, and illustrates specific aspects of the methodology through a number of numerical examples.

INTRODUCTION

The radiation doses received by tissues of the body must be computed in assessments of the potential health detriment associated with exposures to ionizing radiations. It is the estimated organ or tissue dose from the exposure in question that enables an evaluation of the exposure in terms of information assembled from past studies of radiation health effects. For radionuclides taken into the body the dose typically varies greatly among the tissues of the body, which themselves are known to exhibit a range of sensitivities to the radiation insult. In the case of exposures to penetrating radiations emitted by radionuclides outside the body, the distribution of absorbed dose among the organs and tissues is rather uniform.

In radiation protection, it is the absorbed dose averaged over a tissue or organ and weighted for the radiation quality that is assumed to be correlated with biological effects. The primary radiation protection quantity, equivalent dose,[1] was defined to place all ionizing radiations on a common scale of biological harm, without regard to the particular tissues irradiated or biological endpoint involved. The total biological harm is given by the joint distribution of the equivalent dose in the irradiated tissues and their sensitivity to the radiation dose. The 1977 Recommendations of the International Commission on Radiological Protection (ICRP 1977) focused the dosimetric methodology on those organs and tissues at biological risk. The 1990 Recommendations extended the definition of health detriment to embody four components: the risk of fatal cancer, the risk of non-fatal cancer, the risk of hereditary defects, and the relative loss of life expectancy given a fatal cancer or severe genetic disorder (ICRP 1990a). Considerable judgement is involved in assigning measures of importance or weights to the component of detriment. The nature of the judgements are discussed, in some detail, in Publication 60 (ICRP 1990a).

DOSIMETRIC QUANTITIES

Absorbed Dose

Absorbed dose is the fundamental physical quantity used to characterize the radiation insult to tissues of the body from exposure to ionizing radiation. In the dosimetry of biological systems the absorbed dose D_T in tissue T is defined as

---

[1] Throughout the text, the less cumbersome names of the radiation protection quantities introduced by the ICRP in its 1990 recommendations are used. The new quantities entail some differences in definition, for the most part these difference are not of concern here.

$$D_T = \frac{E_{abs,T}}{M_T} \quad , \tag{1}$$

where $E_{abs,T}$ denotes the total energy absorbed in an irradiated (target) tissue of mass M_T. The SI unit of absorbed dose is joule per kg (J/kg), which has the special name gray (Gy); i.e., 1 Gy = 1 J/kg. The special name of the conventional unit of absorbed dose is the rad (1 rad = 0.01 Gy).

Equivalent Dose

It has long been known that biological effects from irradiation by various radiations (e.g., photons, electrons, alpha particles, and neutrons) do not correlate solely with absorbed dose. Radiobiological studies have provided information on the relative biological effectiveness (RBE) of various radiations with respect to specific biological endpoints; e.g, chromosome breaks, cell killing, and induction of cataracts. In radiation protection, the absorbed dose contribution of the radiations are weighted in a manner independent of the particular tissue or biological endpoint. This modification of the absorbed dose defines the equivalent dose quantity H_T (earlier called dose equivalent)

$$H_T = \sum_R w_R \, D_{T,R} \quad , \tag{2}$$

where w_R is the radiation weighting factor for radiation R and $D_{T,R}$ is the absorbed dose in tissue T due to radiation R. The unit of equivalent dose is the joule per kg (J/kg) with the special name sievert (Sv). The special name of the conventional unit of equivalent dose is the rem (1 rem = 0.01 Sv). The summation in eqn (2) extends over all radiations contributing to the absorbed dose in tissue T. The radiation weighting factors used earlier

in radiation protection, the quality factors Q, were taken to be a function of the linear energy transfer in water. The change in the name, in part, serves to heighten the judgmental nature of this parameter. Numerical values assigned to w_R, as a function of emitted radiation type and energy, are shown in Table 1.

Table 1. Radiation Weighting Factors[1]

Type and energy range	w_R
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons, energy < 10 keV	5
10 keV to 100 keV	10
> 100 keV to 2 MeV	20
> 2 MeV to 20 MeV	10
> 20 MeV	5
Protons, other than recoil protons, energies > 2 MeV	5
Alpha particles, fission fragments, and heavy nuclei	20

[1] All values relate to the radiation incident on the body or, for internal sources, emitted from the source.

Effective Dose

Radiation exposures generally result in several tissues of the body being irradiated. The effective dose quantity takes into account the contribution of irradiated tissues to the health detriment. The effective dose E is defined as

$$E = \sum_T w_T H_T \qquad (3)$$

where w_T is the tissue weighting factor (see Table 2) reflecting the relative contribution of tissue T to the total risk. In the 1990 recommendations, the ICRP assigned weighting factors

to a number of tissues that were not explicitly noted in the 1979 Recommendations; i.e., they were part of the remainder. In addition, the manner in which the remainder group of tissues is handled in the calculations has been further refined. Some details in the computation of the effective dose are discussed in Publication 61 (ICRP 1990b).

Table 2. Tissue weighting factors, w_R

	ICRP Recommendations	
Tissue or organ	1979	1990
Gonads	0.25	0.20
Red Marrow	0.12	0.12
Colon		0.12
Lung	0.12	0.12
Stomach		0.12
Bladder		0.05
Breast	0.15	0.05
Liver		0.05
Esophagus		0.05
Thyroid	0.03	0.05
Skin		0.01
Bone Surface	0.03	0.01
Remainder	0.30[1]	0.05[2]

[1] A value of 0.06 is applicable to each of the five remaining organs or tissues receiving the highest equivalent doses.
[2] The remainder is composed of the following tissues or organs: adrenals, brain, small intestine, kidney, muscle, pancreas, spleen, thymus, and uterus.

Activity

The activity, A, of a quantity of a radioactive nuclide is the average rate of spontaneous nuclear transformation occurring in the quantity at a particular time; i.e., the average rate of change in the number of radioactive atoms present. If N denotes the number of radioactive atoms then

$$A = \frac{dN}{dt} = \lambda N = \frac{\ln 2}{T_{1/2}} N \qquad (4)$$

where the decay constant λ is related to the physical half-life of the radionuclide, $T_{1/2}$, as indicated in eqn (4). The SI unit of activity is s^{-1} and has been given the special name becquerel (1 Bq = 1 s^{-1}), the conventional unit is the curie (1 Ci = 3.7 x 10^{10} Bq).

The time integral of rate of spontaneous nuclear transformation (activity) yields the total number of transformations (nt) occurring during the time period. Since each transformation results, on average, in the release of a fixed amount of energy, activity may be considered a surrogate measure of the rate of energy emission.

Illustrative Example 1. A number of radioisotopes of iodine exist with a wide range of physical half-lives. For example, I-131 has a half-life of 8.04 d while I-129 has a half-life of 1.57 x 10^7 y. Assume at time zero 1 Bq of each isotope is present. Compute the mass of each isotope at time zero and the number of nuclear transformations of each isotope occurring within the first day and over all time.

The number of atoms, N, of I-131 corresponding to an activity of 1 Bq is given by

$$N = \frac{A}{\lambda} = \frac{A\ T_{1/2}}{\ln(2)}$$

which yield $\frac{1/s\ 8.04\ d\ 8.64 \times 10^4 s/d}{0.693} = 1.00 \times 10^6\ atoms$. A mole of I-131, 6.02 x 10^{23} atoms, has a mass of about 131 g, thus the mass of 1 Bq of I-131 is $1.00 \times 10^6 \frac{131}{6.02 \times 10^{23}} = 2.18 \times 10^{-16}\ g$.

The activity at any time t is given by $A(t) = A(0)e^{-\lambda t}$. The number of nuclear transformations U during the period T is

$$U(T) = \int_0^T A(t)\ dt = A(0) \int_0^T e^{-\lambda t}\ dt = \frac{A(0)}{\lambda} [1 - e^{-\lambda T}]$$

which, for I-131 yields U(1 d) of $\frac{1\ /s}{9.98 \times 10^{-7}\ /s} [1. - e^{-9.98 \times 10^{-7}\ 8.64 \times 10^4}] = 8.28 \times 10^4$. Over all time, ($T = \infty$), the number of nuclear transformations is λ^{-1} or 1.00 x 10^6 (all the atoms initially present). For I-129 the initial number of atoms is 7.15 x 10^{14} with a mass of about 0.15 μg. Because of the long half-life we can neglect any change in I-129 activity during the

first day and thus the number of nuclear transformations in the first day is 8.64×10^4, and over all time is 7.15×10^{14}.

Committed dose

Exposure to radiation, either from a source external to the body or from the intake of a radionuclide, commits the individual to a health risk in future years. In the case of an external irradiation, the radiation dose is delivered during the period of exposure, while for the intake of a radionuclide, the dose is delivered at various rates as the material resides within the body. For purposes of planning in radiological protection it is assumed that the risk of a given biological effect is linearly related to equivalent dose. It then follows that the risk is determined by the total equivalent dose, averaged throughout the organ or tissue at risk, independent of the time over which it is delivered. The time integral of the equivalent dose rate following an intake of a radionuclide is the committed equivalent dose $H_T(\tau)$:

$$H_T(\tau) = \int_{t_0}^{t_0+\tau} \dot{H}_T(t)\, dt \qquad (5)$$

where $\dot{H}_T(t)$ is the equivalent dose rate in tissue T as a function of time and τ is the period of integration or commitment. Within ICRP documents, if the commitment period is not specified, it may be assumed to be 50 years for adults and from the age at intake to age 70 years for children. By extension, the committed effective dose, $E(\tau)$, is similarly defined. In ICRP Recommendations, when a reference is made to annual equivalent dose or annual effective dose, the annual dose is associated with the exposure period; it is implicit that committed doses from any intakes during the exposure period are included.

Dose coefficients

The dose per unit intake is referred to as a dose coefficient. The ICRP has not

introduced specific notation; however, in this chapter dose coefficients are denoted by the lower case symbol assigned to the dosimetric quantity. The committed equivalent dose in organ T resulting from an intake I is given by

$$H_T(\tau) = I\, h_T(\tau) \quad . \tag{6}$$

The coefficients are specific to the radionuclide and its route of intake; coefficients are normally presented for inhalation and ingestion intakes. In addition, it may be necessary to specify the age of the individual at the time of intake.

The dose coefficient quantity is assuming an increasingly important role in radiation protection. In ICRP's 1979 radiation protection system the annual limit on intake (ALI) was the secondary quantity; the ALI is defined as the activity which when inhaled or ingested would result in committed doses corresponding to the dose limits specified in the primary radiation protection guidance. The ALI is simply the quotient of the dose constraint and the dose coefficient (ICRP 1979). Because of aggressive numerical rounding of the ALIs, the tabulated values should not be used to compute dose from an intake estimate. In the U. S., two tabulations of dose coefficients have been published for use by federal agencies in the computation of dose (Eckerman et al. 1988 and Eckerman and Ryman 1993). The ICRP in its Publication 56 (ICRP 1989) has tabulated age-dependent dose coefficients and it may be anticipated that the revision of Publication 30 will provide dose coefficients for the worker.

DOSIMETRIC FORMULATION

The ICRP introduced, in Publication 30 (ICRP 1979), a new dosimetric formulation for estimation of the dose to tissues of the body. This formulation is similar, in structure, to that of the Medical Internal Radiation Dose (MIRD) Committee of the Society of Nuclear

Medicine (Loevinger and Berman 1968). In Publication 56 (ICRP 1989), the formulation was extended to address age-specific dosimetry. These publications present the dosimetric framework, provide biokinetics data (age-specific in the case of Publication 56) for selected nuclides, and include tabulations of the dose per unit intake (dose coefficient) for inhalation and ingestion intakes. We first introduce the formulations of Publication 30 and then extend the formulations to consider age as a variable.

Adult Worker

The committed equivalent dose in target organ or tissue T per unit intake is referred to as a dose coefficient and denoted as h_T. The dose coefficient is computed (ICRP 1989) as

$$h_T = \sum_S \sum_j U_{S,j}\, SEE(T \leftarrow S)_j \qquad (7)$$

where $U_{S,j}$ is the number of nuclear transformations of radionuclide j in source region S during the commitment period following the intake and $SEE(T \leftarrow S)_j$ is the specific effective energy deposited in T per nuclear transformation of radionuclide j in source region S. The number of transformations $U_{S,j}$ is given by $U_{S,j} = \int_0^\tau q_{S,j}(t)\, dt$ where $q_{S,j}(t)$ is the activity of radionuclide j in source region S at time t, assuming a unit activity inhaled, ingested, or injected at time zero. If a consistent set of units is not employed then a numerical constant may appear in eqn (7). For example, in Publication 30 SEE had units of $MeV\ (g\ nt)^{-1}$, the units of U_S were $nt\ Bq^{-1}$ and thus the constant of $1.6 \times 10^{-10}\ J\text{-}g\ (MeV\text{-}kg)^{-1}$ appeared in the

formulations.

Age-Specific Formulation

Consider the intake of a radionuclide by a child who continues to grow during the period the radionuclide resides in the body. The equivalent dose rate coefficient $\dot{h}_T(t)$ for organ T as a function of age t following an intake at age t_0 can be written (ICRP 1989)

$$\dot{h}_T(t) = \sum_S \sum_j q_{S,j}(t)\ SEE(T \leftarrow S; t)_j \tag{8}$$

where $q_{S,j}(t)$ is the activity of radionuclide j in source region S at age t assuming a unit intake at age t_0 and $SEE(T \leftarrow S; t)$ is the specific effective energy for the source/target pairs in an individual of age t. The committed equivalent dose coefficient is

$$\begin{aligned} h_T(\tau) &= \int_{t_0}^{t_0+\tau} \dot{h}_T(t)\ dt \\ &= \int_{t_0}^{t_0+\tau} \sum_S \sum_j q_{S,j}(t)\ SEE(T \leftarrow S; t)\ dt \quad . \end{aligned} \tag{9}$$

The dosimetric formulations focus attention on two parameters that represent: (1) the activity within the source regions and (2) the dose in the target tissues per unit activity in the source regions. While the biokinetics of the radionuclide in the body can be described in a manner that $q_{S,j}(t)$ can be computed as a continuous function of age, the *SEE* values are generally developed for individuals of a specified age; a finite set of reference individuals is used. These issues will be discussed further below.

SPECIFIC EFFECTIVE ENERGY; SEE

The *SEE* quantity represents the equivalent dose rate in the target tissue per unit

activity in the source region. In the case of the adult, it may be advantageous to consider *SEE* to represent the equivalent dose in the target per nuclear transformation in the source region. The numerical values of *SEE* are dependent on the anatomical representation of the individual and the type, energy, and intensity of the radiations emitted by the radionuclide of interest. Consider the body to be divided into a set of geometric regions $\{S\}$ that might contain the radionuclide during its sojourn in the body. It is not necessary that members of $\{S\}$ be tissues; e.g., the contents of the gastrointestinal tract are potential members, nor is it necessary that the members correspond to volumes; e.g., the surfaces of bone mineral or the airways of the respiratory tract might be source regions. Consider a second partitioning of the body in terms of organs and tissues at risk; i.e., the target regions $\{T\}$. Unlike $\{S\}$ the members of $\{T\}$ are tissues. The principle biological effect of concern is cancer induction which is cellular in its origin. Specific information on the locations of cells at risk is reflected in the dosimetry of the gastrointestinal and respiratory tract, the skin, and the skeleton. In all other cases the location of the sensitive cells has not been specified. For these cases it is assumed that the cells at risk are uniformly distributed within the volume of the target tissues and thus the mass-averaged absorbed dose is a reasonable surrogate of the dose experienced by the cells at risk. The target and source organs typically considered in computations of SEE are listed in Table 3.

Table 3. Masses of organs and tissues of Reference Man used in Publication 30 (ICRP 1979)

Source Organ	Mass (g)	Target Organ	Mass (g)
Ovaries	11	Ovaries	11
Testes	35	Testes	35
Muscle	28,000	Muscle	28,000
Red Marrow	1,500	Red Marrow	1,500
Lungs	1,000	Lungs	1,000
Thyroid	20	Thyroid	20
St Content	250	Bone Surface	120
SI Content	400	St Wall	150
ULI Content	220	SI Wall	640
LLI Content	135	ULI Wall	210
Kidneys	310	LLI Wall	160
Liver	1,800	Kidneys	310
Pancreas	100	Liver	1,800
Cortical Bone	4,000	Pancreas	100
Trabecular Bone	1,000	Skin	2,600
Skin	2,600	Spleen	180
Spleen	180	Thymus	20
Adrenals	14	Uterus	80
Bladder Content	200	Adrenals	14
Total Body	70,000	Bladder Wall	45

Given an anatomical model describing the source and target regions in terms of their elemental composition, size, shape, and spatial relationships, then the transport of radiation between the source and target regions can be evaluated. This evaluation must be carried out for the types and energies of radiations emitted in the nuclear transformation of the radionuclide. The results of the radiation transport studies can be summarized as the fraction of the energy emitted with source region S that is absorbed in the target T; the

absorbed fraction AF is defined as

$$AF(T \leftarrow S) = \frac{\textit{Energy absorbed in } T}{\textit{Energy emitted in } S} \quad . \tag{10}$$

Note that the absorbed fractions depends on the anatomical model and the type and energy of radiation. For some source-target pairs, AF may be largely independent of energy while for other pairs the values are highly dependent on the energy. Since the evaluation of the radiation transport includes adoption of an anatomical model that specifies the mass of the target, the specific absorbed fraction, denoted by SAF or Φ, is frequently tabulated as

$$SAF(T \leftarrow S) = \frac{AF(T \leftarrow S)}{M_T} \tag{12}$$

where M_T is the mass of the target T.

The SEE for a particular radionuclide and individual of age t, is

$$SEE(T \leftarrow S;\ t) = \frac{1}{M_{T,t}} \sum_R E_R\, Y_R\, w_R\, AF(T \leftarrow S,\ E_R,\ t)_R \tag{13}$$

where $M_{T,t}$ is the mass of the target organ T at age t, E_R is the energy of the radiation R emitted with frequency Y_R per nuclear transformation, w_R is the radiation weighting factor applicable to radiation R, and $AF(T \leftarrow S,\ E_R,\ t)_R$ is the absorbed fraction for radiation R. The major feature of this dosimetric system is the applicability of eqn (13) to all types of radiations and source/target pairs. Evaluation of the energy deposition is reduced to assessment of the absorbed fractions for the radiations of concern.

Absorbed Fraction: Alpha Particles

The spontaneous transformation of some heavy nuclides results in the emission of alpha

particles.[2] Typically alpha particles are emitted with kinetic energies between 5 and 8 MeV and have ranges in tissue less than about 80 μm. Since the range is much smaller than the dimensions of the volumetric source regions, the emitted energy is locally absorbed within the source region, a situation referred to as self-dose. However, if a target tissue is in immediate contact with the source region, some fraction of the emitted alpha energy may be absorbed in the target. Such a cross-fire situation exists within the skeleton and the lung. For solid source-target regions, then

$$AF(T \leftarrow S) = \begin{cases} 1, \; if \; T = S \\ 0, \; if \; T \neq S \\ \dfrac{M_T}{M_{WB}}, \; if \; S = WB \end{cases} \tag{14}$$

If the source is uniformly distributed throughout the body (S is the *systemic region or whole body* of mass $M_{WB,t}$ for an individual of age t), then the fraction of the activity within the target region T is $M_{T,t}/M_{WB,t}$ and the absorbed fraction in T is $M_{T,t}/M_{WB,t}$.

For walled organs, the dose rate at the surface of the contents (or inner wall surface) is one-half the dose rate at the center of the contents. Using this relationship, the specific absorbed fraction, $SAF(Wall \leftarrow Cont)$, is

$$SAF(Wall \leftarrow Cont) = \frac{1}{2\,M_{Cont}} \nu \tag{15}$$

where M_{Cont} is the mass of the contents and ν is a factor between 0 and 1 representing the degree to which the radiation penetrates to the cells at risk; ν is taken to be 0.01 for alpha

[2] Sm-146 ($T_{1/2}$ = 1.03 x 10^8 y), alpha energy of 2.474 MeV is the lightest alpha emitter listed in Publication 38 (ICRP 1983).

particles (ICRP 1979).

The absorbed fractions for alpha emitters within the skeleton recommended in Publication 30 (ICRP 1979) are given in Table 3. This table considers sources associated with two mineral regions (trabecular and cortical bone) and further classified the source as residing primarily on the surface or within the volume of the region. The two skeletal tissues considered to be at risk are the osteogenic cells within 10 μm from mineral surfaces and the active (red) bone marrow. The red marrow is totally associated with trabecular bone and is beyond the range of alpha particles emitted within cortical bone.

Table 3. Recommended absorbed fraction of alpha emitters in bone

		Class of Alpha Emitter	
Source Region, S	Target Tissue, T	Volume	Surface
Trabecular	Bone Surface	0.025	0.25
Trabecular	Red Marrow	0.05	0.5
Cortical	Bone Surface	0.01	0.25
Cortical	Red Marrow	0.0	0.0

The absorbed fraction depends strongly on whether or not the alpha emitter is uniformly distributed in the volume of bone or along the surfaces.

Absorbed Fraction: Electrons

Many radionuclides undergo nuclear transformations by emission of a beta particle (an electron or positron). A sharing of the transition energy between the beta particle and the accompanying neutrino results in the beta particles having a continuous distribution in energy from zero to the maximum permitted by the transition. In addition, internal conversion of gamma transitions and processes involving atomic electrons result in the emission of electrons of discrete energy. The ranges, in tissue, for electrons of kinetic energy less than

0.2 MeV are comparable to those of alpha particles (6 - 8 MeV) while at 2.0 MeV the ranges approach 1 cm. Thus the ranges are small, relative to the dimensions of body organs, and one may consider the energy to be locally absorbed; i.e, eqn (14) applies. For walled organs, eqn (15) applies with ν taken as 1. The absorbed fraction for electrons in the skeleton recommended in Publication 30 (ICRP 1979) are given in Table 4.

Table 4. Recommended absorbed fractions for electrons in bone

Source Region	Target Tissue	Volume Emitter	Surface Emitter	
			$\bar{E}_\beta \leq 0.2\ MeV$	$\bar{E}_\beta > 0.2\ MeV$
Trabecular	Bone Surface	0.025	0.25	0.025
Trabecular	Red Marrow	0.35	0.5	0.5
Cortical	Bone Surface	0.015	0.25	0.015
Cortical	Red Marrow	0.0	0.0	0.0

Absorbed Fraction: Photon

Unlike alpha particles and electrons, photons do not have a fixed range in tissue but rather a finite probability exists for the deposition of energy at any location in the body. This probability depends upon the elemental composition of intervening tissue and the initial energy of the photon, thus making the determination of the absorbed fractions a complex computational problem. The complex geometric shape of the body and its organs also adds to the difficulty. Recourse must be made to computational methods utilizing Monte Carlo techniques to solve the radiation transport equations under such complex geometries. Cristy (1980) has formulated age-specific mathematical representations of the body (referred to as phantoms), suitable for use in radiation transport calculations. The Cristy phantom series consists of six reference individuals of ages newborn, 1 year, 5 year, 10 year, 15 year, and the

adult. The photon absorbed fraction data for the phantom series have been published by Cristy and Eckerman (1987) and these data are currently used by the ICRP (ICRP 1990).

Nuclear Decay Data

Data on the radiations emitted during spontaneous nuclear transformations of radionuclides can be found in ICRP Publication 38 (ICRP 1983). The tabulation includes the yield and energy of internal conversion electrons, Auger electrons, x rays, gamma rays, beta and positron emissions, and annhiliation photons. The mean energy of each beta transition is included in the tabulations. These data, including the composite beta spectra for each beta emitter, are available in electronic form (Eckerman et al. 1993). As an example, Table 5 shows the radiations emitted in nuclear transformations of I-131. Note the multiple entries for beta particles (five different transitions) and the presence of conversion electrons (denoted by ce) in the tabulation. X rays associated with vacancies in the K-shell created by internal conversion of gamma transitions are also listed. As indicated at the bottom of the tabulation, some radiations are not included in the tabulation (these radiations represent less than 0.1% of the total energy for the radiation type).

Table 5. Radiation Emissions of I-131

Radiation	Y_i (Bq-s)$^{-1}$	E_i (MeV)	$Y_i E_i$
β^- 1	2.13×10^{-2}	6.935×10^{-2}	1.48×10^{-3}
β^- 2	6.20×10^{-3}	8.693×10^{-2}	5.39×10^{-4}
β^- 3	7.36×10^{-2}	9.660×10^{-2}	7.11×10^{-3}
β^- 4	8.94×10^{-1}	1.915×10^{-2}	1.71×10^{-1}
β^- 6	4.20×10^{-3}	2.832×10^{-2}	1.19×10^{-3}
γ 1	2.62×10^{-2}	8.018×10^{-2}	2.10×10^{-3}
ce-K, γ 1	3.63×10^{-2}	4.562×10^{-2}	1.66×10^{-3}
ce-L_1, γ 1	4.30×10^{-3}	7.473×10^{-2}	3.21×10^{-4}
γ 4	2.65×10^{-3}	1.772×10^{-1}	4.70×10^{-4}
γ 7	6.06×10^{-2}	2.483×10^{-1}	1.72×10^{-2}
ce-K, γ 7	2.48×10^{-3}	2.497×10^{-1}	6.20×10^{-4}
γ 12	2.51×10^{-3}	3.258×10^{-1}	8.18×10^{-4}
γ 13	8.12×10^{-1}	3.645×10^{-1}	2.96×10^{-1}
ce-K, γ14	1.55×10^{-2}	3.299×10^{-1}	5.10×10^{-3}
ce-L_1 , γ 14	1.71×10^{-3}	3.590×10^{-1}	6.13×10^{-4}
γ 16	3.61×10^{-3}	5.030×10^{-1}	1.82×10^{-3}
γ 17	7.27×10^{-2}	6.370×10^{-1}	4.63×10^{-2}
γ 18	2.20×10^{-3}	6.427×10^{-1}	1.41×10^{-3}
γ 19	1.80×10^{-2}	7.229×10^{-1}	1.30×10^{-2}
$K\alpha_1$ *X ray*	2.59×10^{-2}	2.978×10^{-2}	7.72×10^{-4}
$K\alpha_2$ *X ray*	1.40×10^{-2}	2.946×10^{-2}	4.12×10^{-4}
Listed X, γ, and γ $\pm$ radiations			3.80×10^{-1}
Omitted X, γ, and γ $\pm$ radiations			1.09×10^{-3}
Listed β, ce, and Auger radiations			1.90×10^{-1}
Omitted β, ce, and Auger radiations			1.86×10^{-3}
Listed radiations			5.70×10^{-1}
Omitted radiations			2.95×10^{-3}

Xe-131m daughter, yield 1.11×10^{-3}, is radioactive.
Xe-131 daughter, yield 9.889×10^{-1}, is stable.

Illustrative Example 2: In this example we calculate the SEE for irradiation of the thyroid gland by I-131 residing in the thyroid and systemic pool (the whole body). Specific absorbed fraction data for photons, from Eckerman and Cristy (1987), are tabulated below for the thyroid as the target region with the thyroid and whole body as source regions.

Specific Absorbed Fraction Data		
Energy Range (MeV)	$\Phi(Thy \leftarrow Thy)$ kg^{-1}	$\Phi(Thy \leftarrow WB)$ kg^{-1}
0.02 - 0.03	18.1 - 7.39	1.38 - 1.17 x 10^{-2}
0.05 - 0.10	2.54 - 1.46	8.43 - 5.98 x 10^{-3}
0.10 - 0.20	1.46 - 1.58	5.98 - 5.66 x 10^{-3}
0.20 - 0.50	1.58 - 1.71	5.66 - 5.57 x 10^{-3}
0.50 - 1.0	1.71 - 1.62	5.57 - 5.24 x 10^{-3}

First consider the thyroid being irradiated by I-131 within the gland. The total energy emitted by non-penetrating radiations (the listed β, ce, and Auger radiations) is 0.190 MeV/nt. If the thyroid mass is taken as 0.020 kg, then

$$SEE(Thy \leftarrow Thy) = 1.6 \times 10^{-13} \frac{J}{MeV} \, 0.19 \frac{MeV}{nt} \frac{1}{0.020\,kg} = 1.52 \times 10^{-12} \; Sv/nt \quad .$$

For systemic I-131 uniformly distributed in the whole body (the contents of the gastrointestinal tract, urinary bladder, and gall bladder are excluded; mass of 68.83 kg) the contribution of the nonpenetrating radiations to the thyroid dose would be

$$SEE(Thy \leftarrow WB) = 1.6 \times 10^{-13} \frac{0.020}{68.83} \frac{0.19}{0.020} = 4.42 \times 10^{-16} \; Sv/nt \quad .$$

where the factor 0.020 divided by 68.83 is the absorbed fraction in the thyroid for a source in the whole body. Tabulated below is a calculation of the photon contribution to the SEE for the thyroid for the two source regions. In computing the specific absorbed fraction for the various photons, linear interpolation was used.

Photon	E(MeV)	Y	$\Phi(Thy \leftarrow Thy)$	$\Phi(Thy \leftarrow WB)$
γ 1	0.08	2.62 x 10^{-2}	1.89	6.96 x 10^{-3}
γ 4	0.1772	2.65 x 10^{-3}	1.53	5.73 x 10^{-3}
γ 7	0.2843	6.06 x 10^{-2}	1.61	5.63 x 10^{-3}
γ 12	0.3258	2.51 x 10^{-3}	1.63	5.62 x 10^{-3}
γ 13	0.3645	0.812	1.65	5.61 x 10^{-3}
γ 16	0.5030	3.61 x 10^{-3}	1.70	5.57 x 10^{-3}
γ 17	0.6370	7.27 x 10^{-2}	1.68	5.48 x 10^{-3}
γ 18	0.6427	2.20 x 10^{-3}	1.68	5.48 x 10^{-3}
γ 19	0.7229	1.80 x 10^{-2}	1.67	5.42 x 10^{-3}
$K\alpha_1$ *X ray*	0.0298	2.59 x 10^{-2}	7.60	0.0117
$K\alpha_2$ *X ray*	0.0295	1.40 x 10^{-2}	7.92	0.0118
		$\sum E_i \, Y_i \, \Phi_i =$	0.64	2.14 x 10^{-3}

The contribution of photons to the SEEs are thus

$$SEE(Thy \leftarrow Thy) = 1.6 \times 10^{-13}\ 0.64 = 1.02 \times 10^{-13}\ Sv/nt$$

$$SEE(Thy \leftarrow WB) = 1.64 \times 10^{-13}\ 2.14 \times 10^{-3} = 3.42 \times 10^{-16}\ Sv/nt \quad .$$

The total SEEs are

$$SEE(Thy \leftarrow Thy) = 1.52 \times 10^{-12} + 1.02 \times 10^{-13} = 1.62 \times 10^{-12}\ Sv/nt$$

$$SEE(Thy \leftarrow WB) = 4.42 \times 10^{-16} + 3.42 \times 10^{-16} = 7.84 \times 10^{-16}\ Sv/nt \quad .$$

Note the significance of the non-penetrating radiations in determining the SEEs. The SEECAL code of Cristy and Eckerman (1993) can be used to calculate SEE values for the six reference ages within the Cristy phantom series.

DYNAMIC MODELS OF RADIONUCLIDES IN THE BODY

Following intake of a radionuclide by inhalation or ingestion, the radionuclide may be absorbed into the systemic circulation and taken up by organs of the body. The retention of the activity will depending on the physiologic and metabolic processes associated with the material and the organ. For some radionuclides, the formation and decay of radioactive daughters is superimposed on the dynamics of uptake and retention of the parent radionuclide.

Figure 1 is a schematic representation of the general compartment model of movement of a radionuclide within the body. This schematic is similar to models adopted by ICRP in Publication 56 (ICRP 1989). The intake of the radionuclide may be as a result of inhalation, ingestion, or injection which results in an uptake to blood and/or body fluids (referred to as the transfer compartment in Publication 30) with a subsequent distribution among the systemic organs. While the biokinetics models of Publication 30 did not routinely address excretion of systemic activity, the inclusion of the urinary bladder as a tissue at risk (see Table 2) necessitates that newer models, e.g., those of Publication 56, include urinary and

fecal excretion. The activity in any compartment i of Fig. 1 can be described in terms of a system of linear ordinary differential equations

$$\begin{array}{l} \textit{Rate of change} \\ \textit{in compartment } i \end{array} = \begin{array}{l} \textit{inflow} \\ \textit{to } i \end{array} - \begin{array}{l} \textit{outflow} \\ \textit{from } i \end{array}$$

$$\frac{d}{dt} A_i = \sum_{\substack{j=1 \\ j \neq i}}^{n} \lambda_{ij} A_j - A_i \sum_{\substack{j=1 \\ j \neq i}}^{n} \lambda_{ji} \qquad (15)$$

where λ_{ij} denotes the fractional transfer of material from compartment j to compartment i. The system of equations is solved as an initial value problem; that is at time zero, nonzero activities are assigned to the intake compartments with all other compartments assigned a zero value. In ICRP Publication 56, the transfer coefficients between compartment λ_{ij} are dependent on age of the individual which, of course, changes during the period the radionuclide resides within the body.

Illustrative Example 3. Consider the biokinetic model for systemic iodine used in Publication 30 and shown in Fig. 2. This three-compartment model represents iodine in the transfer compartment, thyroid, and all remaining organs and tissues. Iodine deposited in the transfer compartment is removed with a biological half-time of 0.25 d, with 30% going to the thyroid and 70% to urinary excretion. Removal from the thyroid occurs with biological half-time of 120 d, and the iodine, in organic form, is deposited in a compartment representing other organs and tissues of the body. From the latter compartment, 10% goes to fecal excretion and 90% is returned to the transfer compartment, with biological half-time 12 d for both pathways.

The differential equations and initial conditions for an injection of 1 Bq are

$$\frac{d}{dt} q_0 = -(\lambda_0 + \lambda_R) q_0 + 0.9 \lambda_1 q_1 , \quad q_0(0) = 1$$

$$\frac{d}{dt} q_1 = -(\lambda_1 + \lambda_R) q_1 + 0.3 \lambda_0 q_0 , \quad q_1(0) = 0$$

$$\frac{d}{dt} q_2 = -(\lambda_2 + \lambda_R) q_2 + \lambda_1 q_1 , \quad q_2(0) = 0$$

where subscripts 0, 1, and 2 refer to the transfer compartment, thyroid, and "other tissue" compartments, respectively. From above we have $\lambda_0 = 0.693/0.25$ d $= 2.77$ d^{-1}, $\lambda_1 = 0.693/120$ d $= 5.78 \times 10^{-3}$ d^{-1}, and $\lambda_2 = 0.693/12$ d $= 5.78 \times 10^{-2}$ d^{-1}. One may solve the

system with $\lambda_R = 0$ to obtain the response for the stable element. Solutions for a particular radioiodine are obtained by multiplying the solutions for stable iodine by $e^{-\lambda_r t}$. The system of equations can be solved using Laplace transforms; however, the calculations can be tedious, particularly for large systems. Computer programs are available to solve such systems; for example see Killough and Eckerman (1984) and Leggett et al. (1993). The solutions for the iodine model are

$$q_0(t) = [e^{-2.77t} - 6.13x10^{-4}e^{-0.0595t} + 5.88x10^{-4}e^{-0.0041t}]e^{-\lambda_R t}$$
$$q_1(t) = [-0.301e^{-2.77t} + 0.00949e^{-0.0595t} + 0.291e^{-0.0041t}]e^{-\lambda_R t}$$
$$q_2(t) = [6.40x10^{-4}e^{-2.77t} - 0.032e^{-0.0595t} + 0.0313e^{-0.0041t}]e^{-\lambda_R t}.$$

The number of nuclear transformations of I-131 in the thyroid is

$$U_1 = 8.84x10^4 \int_0^\infty q_1(t)\,dt$$
$$= 8.64x10^4 \left[\frac{-0.301}{2.77+0.0862} + \frac{0.00949}{0.0595+0.0862} + \frac{0.291}{0.0041+0.0862}\right]$$
$$= 2.75 \times 10^5\ nt.$$

Similar calculations for blood and the other tissue compartments yield values of $3.21x10^4$ and $1.1x10^4$ nt, respectively.

Gastrointestinal Tract

The gastrointestinal tract is modeled in Publication 30 (ICRP 1979) as four discrete segments: stomach (St), small intestine (SI), upper large intestine (ULI), and lower large intestine (LLI) as shown in Fig. 3. Table 6 summarizes the basic data regarding the segments. Mathematically, each segment is viewed as a compartment whose contents clears into its successor by first-order kinetics, without feedback. It is assumed that absorption of material from the GI tract occurs in the small intestine, at a rate $\lambda_{ab}\ q_{SI}$, where λ_{ab} is the transfer coefficient (d^{-1}) and q_{SI} is the activity within the content of the small intestine. The equations describing the model are

$$
\begin{aligned}
\frac{d}{dt}q_{St} &= -(\lambda_{St}+\lambda_R)\, q_{St}\,, \quad q_{St}(0) = 1 \\
\frac{d}{dt}q_{SI} &= -(\lambda_{SI}+\lambda_{ab}+\lambda_R)\, q_{SI} + \lambda_{St}\, q_{St}\,, \quad q_{SI}(0) = 0 \\
\frac{d}{dt}q_{ULI} &= -(\lambda_{ULI}+\lambda_R)\, q_{ULI} + \lambda_{SI}\, q_{SI}\,, \quad q_{ULI}(0) = 0 \\
\frac{d}{dt}q_{LLI} &= -(\lambda_{LLI}+\lambda_R)\, q_{LLI} + \lambda_{ULI}\, q_{ULI}\,, \quad q_{LLI}(0) = 0.
\end{aligned}
\tag{16}
$$

Note the initial conditions of 1 Bq in the stomach at time 0. The transfer coefficients λ_{St}, λ_{SI}, λ_{ULI}, *and* λ_{LLI} govern clearance from the segment indicated by the subscript into the successor, or in case of the lower large intestine, out of the tract. The coefficients are the reciprocals of the mean residence times in Table 6.

Table 6. Parameters of the Gastrointestinal Tract Model

Segment	Mass of walls (g)	Mass of contents (g)	Mean residence time (d)
Stomach	150	250	1/24
Small intestine	640	400	4/24
Upper large intestine	210	220	13/24
Lower large intestine	160	135	24/24

Absorption from the GI tract is characterized by the parameter f_1 which denotes the fraction of ingested material absorbed into body fluids in the absence of radiological decay. Thus for the stable element, if one exists for the radionuclide, f_1 is the fraction of the total material clearing the small intestine that is cleared to blood:

$$
f_1 = \frac{\lambda_{ab}\, q_{SI}}{(\lambda_{SI}+\lambda_{ab})\, q_{SI}} \tag{17}
$$

which when solved for λ_{ab} yields:

$$\lambda_{ab} = \frac{f_1 \lambda_{SI}}{1 - f_1} \quad . \tag{18}$$

The model, as formulated above, does not permit total absorption of a nuclide ($f_1=1$). For such materials, in Publication 30, a different model was substituted where the material passed directly from the stomach to body fluids and the lower segments of the tract were not included in the kinetics. In Publication 56 this problem was avoided by substituting a value of 0.99 in eqn (18) when f_1 was stated to be 1.

When the residence time for biological removal of material from any segment is short, relative to the commitment period, the infinite time integral of the activity in the segment can be used to evaluate the number of nuclear transformations in the segment. Solving eqn (16) and integrating to infinite time, we obtain the expressions for the number of nuclear transformations in the segments, assuming 1 Bq presented in the stomach contents at time zero

$$\begin{aligned} U_{St} &= \frac{1}{\lambda_{St} + \lambda_R} \\ U_{SI} &= \frac{\lambda_{St} U_{St}}{\lambda_{ab} + \lambda_{SI} + \lambda_R} \\ U_{ULI} &= \frac{\lambda_{SI} U_{SI}}{\lambda_{ULI} + \lambda_R} \\ U_{LLI} &= \frac{\lambda_{ULI} U_{ULI}}{\lambda_{LLI} + \lambda_R} \end{aligned} \tag{19}$$

The transfer of ingested activity to blood is essentially complete within about a day and thus the activity transfered is $\lambda_{ab} U_{SI}$ or $\frac{\lambda_{St}\ \lambda_{ab}}{(\lambda_{ab} + \lambda_{SI} + \lambda_R)(\lambda_{St} + \lambda_R)}$. For a stable element; i.e.,

$\lambda_R = 0$, one can show that the transfer reduces to f_1 and for short-lived radionuclides, A_{ab}, diminishes asymptotically as $1/\lambda_R^2$.

Illustrative Example 4. Phosphorous-32 decays with a radiological half-life of 14.3 d and is readily absorbed from the small intestine, $f_1 = 0.8$. Compute the number of nuclear transformations in each segment of the GI tract assuming a unit intake. From above $\lambda_R = 0.0485\ d^{-1}$ and $\lambda_{ab} = 0.8\ 6/(1-0.8) = 24\ d^{-1}$ and thus

$$U_{St} = 1/(24+0.0485)\ 8.64x10^4\ s/d = 3.59x10^3$$
$$U_{SI} = (24)(3.59x10^3)/(24+6+0.0485) = 2.87x10^3$$
$$U_{ULI} = (6)(2.87x10^3)/(1.8+0.0485) = 9.31x10^3$$
$$U_{LLI} = (1.8)(9.57x10^3)/(1+0.0485) = 1.60x10^4\ .$$

Respiratory Tract

The respiratory tract model discussed here is the model used in ICRP Publication 30. This model will be superseded by a new model being published, in the near future, by the ICRP as Publication 66.

The lung model is applied to radionuclide-bearing aerosols introduced into the breathing passages by inhalation. The model is presented schematically in Fig. 4. The model identifies four major respiratory regions: nasopharynx (NP), tracheo-bronchial tree (TB), pulmonary region (P), and lymphatic tissue (L). Inhaled materials are assumed to belong to one of three discrete clearance classes, according to how rapidly they are removed from the pulmonary region. These clearance classes are designated as D (removal accomplished in days), W (weeks), and Y (years). Fractional depositions of inhaled particles in the first three of these regions are given by the fraction D_{NP}, D_{TB}, and D_P, respectively (the sum of these is less than one, with the shortfall being exhaled). The deposition fractions are functions of the activity median aerodynamic diameter (AMAD) of the inspired aerosol. The values of

the fractions shown in Fig. 4 correspond to AMAD = 1 μm.

Each major region is subdivided into compartments, and labeled with the letters *a, b, ..., j*. In the NP region, material deposited in compartment *a* is available for absorption into body fluids, while that deposited in compartment *b* is eventually swallowed and thus enters the GI tract. Similarly, material deposited in compartment *c* of the TB region is absorbed into body fluids, while compartment *d* represents material that is being moved upward by ciliary action, out of the lungs and into the GI tract. Material from compartments *f* and *g* of the pulmonary region also enters compartment *d* and is moved upward and into the GI tract, with material from *f* being cleared rapidly from the lungs and that from *g* progressing very slowly. Compartment *e* in the pulmonary regions represents absorption into body fluids, and material is removed from compartment *h* by lymphatic drainage. Lymphatic tissue is divided into two compartments (*i* and *j*), with material that leaves compartment *i* entering body fluids. Compartment *j* represents material that is tenaciously retained in lymph and is applied only in the case of Class Y material to 10% of the lymphatic burden. Fig. 4 gives, for each clearance class, the partition fraction F_ν and the biological half-time of removal, T_ν, for each compartment ν.

The system of differential equations, with initial conditions corresponding to the expected deposit of the aerosol into the compartment, may be solved by elementary methods. The solutions are:

$$
\begin{aligned}
q_v(t) &= F_v D_{NP} e^{-(\lambda_v+\lambda_R)t} \quad , v = a,b \\
q_c(t) &= F_c D_{TB} e^{-(\lambda_c+\lambda_R)t} \\
q_d(t) &= F_d D_{TB} e^{-(\lambda_d+\lambda_R)t} + \frac{\lambda_f F_f D_P}{\lambda_f-\lambda_d}[e^{-(\lambda_d+\lambda_R)t} - e^{-(\lambda_f+\lambda_R)t}] \\
&\quad + \frac{\lambda_g F_g D_P}{\lambda_g-\lambda_d}[e^{-(\lambda_d+\lambda_R)t} - e^{-(\lambda_g+\lambda_R)t}] \\
q_v(t) &= F_v D_P e^{-(\lambda_v+\lambda_R)t} \quad v = e,f,g,h \\
q_i(t) &= \begin{cases} \dfrac{F_h F_i \lambda_h D_P}{\lambda_v-\lambda_i}[e^{-(\lambda_i+\lambda_R)t} - e^{-(\lambda_h+\lambda_R)t}] & , \text{if } \lambda_h \neq \lambda_i \\ F_h F_i \lambda D_P t e^{-(\lambda+\lambda_R)t} & , \text{if } \lambda_h = \lambda_i = \lambda \end{cases} \\
q_j(t) &= (1-F_i) F_h D_P [\frac{1-e^{-\lambda_R t}}{\lambda_R} - \frac{1-e^{-(\lambda_h+\lambda_R)t}}{\lambda_h+\lambda_R}].
\end{aligned}
\tag{21}
$$

One can approximate the number of nuclear transformations as:

$$
\begin{aligned}
U_v &= \frac{D_{NP} F_v}{\lambda_v+\lambda_R} \quad , v = a, b \\
U_c &= \frac{D_{TB} F_c}{\lambda_c+\lambda_R} \\
U_d &= \frac{D_{TB} F_c}{\lambda_d+\lambda_R} + \frac{D_P}{\lambda_d+\lambda_R}[\frac{\lambda_f F_f}{\lambda_f+\lambda_R} + \frac{\lambda_g F_g}{\lambda_g+\lambda_r}] \\
U_v &= \frac{D_P F_v}{\lambda_v+\lambda_R} \quad , v = e,f,g,h \\
U_i &= \frac{D_P F_h \lambda_h F_i}{(\lambda_h+\lambda_R)(\lambda_i+\lambda_R)} \\
U_j &= \frac{D_P F_h \lambda_h F_j (1-e^{-\lambda_R \eta})}{(\lambda_h+\lambda_R)\lambda_R}.
\end{aligned}
\tag{22}
$$

Inhaled activity is cleared from the respiratory tract to the GI tract from compartments *b* and *d*. The fraction of the inhaled activity that cleared to the GI tract A_{GI} is

$$
A_{GI} = \lambda_b U_b + \lambda_d U_d \quad . \tag{23}
$$

Activity is cleared directly from the lung to body fluids via compartments *a, c, e,* and *i*, and thus the fraction of inhaled activity cleared in this manner is

$$A_{WB} = \lambda_a U_a + \lambda_c U_c + \lambda_e U_e + \lambda_i U_i. \quad (24)$$

Illustrative Example 5. We give an example involving a plutonium isotope to illustrate the model's treatment of Class Y materials. Pu-239 decays by alpha emission (energy of 5.23 MeV) with a half-life of 8.81 x 10^6 d. Publication 30 assigns PuO_2 to Class Y with GI-tract absorption parameter $f_1 = 10^{-5}$. For this example, assume an AMAD of 1 μm. Because of the low activity of the U-235 daughter formed per transformation of Pu-239, only the parent member of the decay chain is considered. The table below summarizes the calculation of the number of nuclear transformations in each compartment.

Compartment	F_v	Deposition	$\lambda_v(d^{-1})$	$\lambda_v + \lambda_R(d^{-1})$	U_v
a	0.01	0.30	69.3	69.3	3.74
b	0.99	0.30	1.73	1.73	1.48×10^4
c	0.01	0.08	69.3	69.3	0.994
d	0.99	0.08	3.47	3.47	6.96×10^3
e	0.05	0.25	1.39×10^{-3}	1.39×10^{-3}	7.77×10^5
f	0.4	0.25	0.693	0.693	1.24×10^4
g	0.4	0.25	1.39×10^{-3}	1.39×10^{-3}	6.21×10^6
h	0.15	0.25	1.39×10^{-3}	1.39×10^{-3}	2.33×10^6
i	0.9	-	6.93×10^{-4}	6.93×10^{-4}	4.21×10^6
j	0.1	-	0	7.87×10^{-8}	5.68×10^6
				$\sum_c^j$	$= 1.92 \times 10^7$ nt/Bq

Note the relatively large number of nuclear transformations occurring within the pulmonary and lymphatic regions, particularly compartments *g, h, i,* and *j*. The number of nuclear transformations and small mass of the lymph nodes (15 g) conspire to give a large dose to the lymphatic region. However, in Publication 30, the lung dose was defined to include the transformations in compartment *c* through *j* average over a mass of 1000 g. The dose coefficient for the lung for this example would be

$$\begin{aligned} h_{lung} &= U\ SEE(lung \leftarrow lung) \\ &= 1.6x10^{-10} J-g\ (MeV-kg)^{-1} 1.92x10^7\ nt\ Bq^{-1}\ \frac{20\ 5.23\ MeV\ nt^{-1}}{1000\ g} \\ &= 3.2x10^{-4}\ Sv\ Bq^{-1}\ . \end{aligned}$$

CALCULATION OF DOSE FROM OTHER TISSUE GROUP

We conclude with an illustration of how nuclear transformations in the source region *rest of the body*, a compartment frequently identified in the biokinetic models of ICRP Publication 30, are evaluated in the dosimetry. Although two approaches can be found in the literature, the consideration of sources distributed other than by volume, that is, activity distributed on the surfaces of bone mineral only arose with Publication 30. The approach is illustrated in calculating the dose coefficient for ingestion of radiophosphorus. The biokinetics and dosimetry are sufficiently simple that one can readily calculate the dose coefficient by hand. The ICRP briefly discussed their procedure for addressing the source region *rest of the body* (ROB) in the Supplements to Publication 30 and that discussion was incomplete, particularly regarding the bone surface compartments.

Consider an oral intake of phosphorous. The fraction of ingested phosphorus absorbed from the gastrointestinal tract is 0.8. The biokinetics of phosphorus is discussed in Publication 30 (ICRP 1979):

"Phosphorus entering the transfer compartment is assumed to be retained there with a half-life of 0.5 days. Of this phosphorus 0.15 is assumed to go directly to excretion, 0.15 to intracellular fluids where it is assumed to be retained with a half-life of 2 days, 0.40 to soft tissue where it is assumed to be retained with a half-life of 19 days and 0.30 to mineral bone where it is assumed to be permanently retained. ... Phosphorus going either to intracellular fluids or to soft tissue is, for the purposes of dosimetry, assumed to be uniformly distributed throughout all organs and tissues of the body excluding mineral bone."

The half-life of P-32, 14.29 d, is less than the 15 d value required in Publication 30 for a bone seeker to achieve a volume distribution in the skeleton. Thus P-32 is assumed to deposit uniformly on the surfaces of cortical and trabecular bone (both bone types are of equal area), where it is permanently retained. The fraction of phosphorous going directly to excretion leaves the transfer compartment at a rate corresponding to a half-time of 0.5 d.

The calculated number of nuclear transformations in the kinetic compartments for an oral intake of P-32 are tabulated below:

Compartment	U (nt Bq^{-1})
St Cont	3.59×10^{3}
SI Cont	2.87×10^{3}
ULI Cont	9.31×10^{3}
LLI Cont	1.60×10^{4}
Blood	4.80×10^{4}
C Bone-S	2.06×10^{5}
T Bone-S	2.06×10^{5}
ROB 1	2.52×10^{4}
ROB 2	3.13×10^{5}

The transformations in the transfer compartment, labeled above as blood, are assumed to be uniformly distributed throughout all organs and tissues of the body; the contents of the GI-tract segments are excluded, since these source regions are not applicable to systemic material. The number of transformations in an organ S, U_S', of mass M_S (kg) is

$$U_S' = U_S'' + \frac{M_S}{M_{T\ Body}} U_{TC} \tag{25}$$

where

U_S'' is the number of nuclear transformations in S indicated by the kinetics,

U_{TC} is the number of transformations in the transfer compartment, and

$M_{T\ Body}$ is the mass of the total body (70 kg).

The biokinetic model divides the systemic pool into two regions: bone mineral (mass of 5 kg) and the rest-of-body, *ROB* (mass of 65 kg). From the above data, U_{ROB}, is

$$
\begin{aligned}
U_{ROB} &= U_{ROB\text{-}1} + U_{ROB\text{-}2} + \frac{M_{ROB}}{M_{T\ Body}}\ U_{TC} \\
&= 2.52\ x\ 10^4 + 3.13\ x\ 10^5 + \frac{65}{70}\ 4.80\ x\ 10^4 \\
&= 3.83\ x\ 10^5\ .
\end{aligned}
\tag{26}
$$

The remaining transformations in the transfer compartment are distributed in the volume of cortical and trabecular bone as

$$
\begin{aligned}
U_{C\ Bone\text{-}V} &= \frac{M_{C\ Bone}}{M_{T\ Body}}\ U_{TC} \\
&= \frac{4}{70}\ 4.80\ x\ 10^4 \\
&= 2.75\ x\ 10^3 \\
U_{T\ Bone\text{-}V} &= \frac{M_{T\ Bone}}{M_{T\ Body}}\ U_{TC} \\
&= \frac{1}{70}\ 4.80\ x\ 10^4 \\
&= 6.86\ x\ 10^2.
\end{aligned}
\tag{27}
$$

Note that these transformations are not in the region indicated in the biokinetic model.

The rest-of-body *ROB* is not defined as a source region in the anatomical model. Two algorithms are available to evaluate the contribution of *ROB* to the dose in the target tissues. One approach computes SEEs for *ROB* as a source region from the tabulated *SEEs* for explicit source regions and the total body. The second approach, and the one used in Publication 30, creates a fictitious *Total Body* source with the density of nuclear transformations computed from the biokinetics for the *ROB* compartment. The fictitious source results in additional transformations within the source regions specified in the biokinetics and these transformation must be subtracted to conserve nuclear transformations. Thus, as outlined in the Supplement to Publication, Part 1, the number of nt in the fictitious *Total body* source, $U_{T\ Body}$, is

$$U_{T\ Body} = \frac{M_{T\ Body}}{M_{ROB}} U_{ROB} = \frac{70}{65} 3.83 \times 10^5 = 4.13 \times 10^5 \quad (28)$$

where U_{ROB} is the number of nuclear transformations in *ROB* of mass M_{ROB}. The transformations added by this fictitious source must be subtracted from the computed values for these regions. Thus, the number of transformations in source regions, U_S, is given by

$$U_S = U_S' - \frac{M_S}{M_{ROB}} U_{ROB} \quad (29)$$

where U_S' is given by eqn (25). Tabulated below are the number of nuclear transformations in the source regions, the *SEE* values for selected target tissues, and the committed equivalent dose in these targets. Since the biokinetic model excludes deposition of P-32 in volume of bone mineral, the correction for the fictitious total body source results in negative numbers of transformations in the volume mineral regions.

		SEE (T <- S) (MeV/g nt)			
Source	U (nt/Bq)	R Marrow	B Surface	LLI Wall	Breast
St Cont	3.59×10^3				
SI Cont	2.87×10^3				
ULI Cont	9.31×10^3			2.57×10^{-3}	
LLI Cont	1.60×10^4				
C-Bone-S	2.06×10^5		8.68×10^{-5}		
T-Bone-S	2.06×10^5	2.32×10^{-4}	1.45×10^{-4}		
C Bone-V	-2.08×10^4(1)		8.68×10^{-5}		
T Bone-V	-5.21×10^3(2)	1.62×10^{-4}	1.45×10^{-4}		
T Body	4.13×10^5(3)	9.92×10^{-6}	9.92×10^{-6}	9.92×10^{-6}	9.92×10^{-6}
	h_T (Sv/Bq) =	8.16×10^{-9}	7.88×10^{-9}	7.23×10^{-9}	6.54×10^{-10}

1. 4/70 U_{TC} - 4/65 U_{ROB}; mass of cortical bone = 4 kg.
2. 1/70 U_{TC} - 1/65 U_{ROB}; mass of trabecular bone = 1 kg.
3. 70/65 U_{ROB} + U_{TC}

SUMMARY

The basic concepts currently recommended by the ICRP for internal dosimetry calculations in radiation protection have been reviewed and illustrated through a number of numerical examples. We conclude by noting that tabulations of dose coefficients which can be of use in radiation protection are available for many radionuclides.

Fig. 1. Schematic representation of models of uptake and retention of radionuclides in the body. Note the series of systemic compartments exchanging material with blood and the explicit identification of excretion routes.

Fig. 2. The ICRP iodine model used in Publications 30 and 56.

Fig. 3. Schematic diagram of the model describing the movement of radionuclides through the gastrointestinal tract.

Fig. 4. The ICRP lung model as used in Publication 30.

REFERENCES

M. Cristy (1980). *Mathematical Phantoms Representing Children of Various Ages for use in Estimates of Internal Dose*, ORNL/TM-367, Oak Ridge National Laboratory, Oak Ridge, TN.

M. Cristy and K. F. Eckerman (1987). *Specific Absorbed Fractions of Energy at Various Ages from Internal Photon Sources*, ORNL/TM-8381/V1-7, Oak Ridge National Laboratory, Oak Ridge, TN.

M. Cristy and K. F. Eckerman (1993). *SEECAL: Program to Calculate Age-Dependent Specific Effective Energies*, ORNL/TM-12351 (Oak Ridge National Laboratory, Oak Ridge, TN)

K. F. Eckerman, A. B. Wolbarst, and A. C. B. Richardson (1988). *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestions*, Federal Guidance Report No. 11, EPA-520/1-88-020 (U.S. Environmental Protection Agency, Washington, DC).

K. F. Eckerman and J. C. Ryman (1993). *External Exposure to Radionuclides in Air, Water, and Soil*, Federal Guidance Report No. 12, EPA-402-R-93-081 (U.S. Environmental Protection Agency, Washington, DC).

K. F. Eckerman, R. J. Westfall, J. C. Ryman, and M. Cristy (1993). *Nuclear Decay Data Files of the Dosimetry Research Group*, ORNL/TM-12350 (Oak Ridge National Laboratory, Oak Ridge, TN).

G. G. Killough and K. F. Eckerman (1984). "A conversational eigenanalysis program for solving differential equations," p. 4.49 of *Computer Applications in Health Physics*, Proceedings of the Seventeenth Midyear Topical Sysmposium of the Health Physics Society (R. L. Kathren, D. P. Higby, and M. A. McKinney, eds) (Columbia Chapter of the Health Physics Society, Richland, Wa).

R. W. Leggett, K. F. Eckerman, and L. R. Williams (1993). "An elementary method for implementing complex biokinetic models," Health Phys. 64(3):260-271.

R. Loevinger and M. Berman (1976). *A revised schema for calculating the absorbed dose from biologically distributed radionuclides*, MIRD Pamphlet No. 1, Revised, Society of Nuclear Medicine, New York, NY.

ICRP (1977). International Commission on Radiological Protection, "Recommendations of the International Commission on Radiological Protection," ICRP Publication 26, *Annals of the ICRP Vol. 1*, No 3.

ICRP (1979). International Commission on Radiological Protection, "Limits for intakes of radionuclides by workers," ICRP Publication 30, *Annals of the ICRP Vol. 2*, Nos 3/4.

ICRP (1983). International Commission on Radiological Protection, "Radionuclide Transformation: Energy and Intensity of Emission," ICRP Publication 38, *Annals of the ICRP Vols. 11-13.*

ICRP (1989). International Commission on Radiological Protection, "Age-dependent Doses to Members of the Public from Intake of Radionuclide: Part 1," ICRP Publication 56, *Annals of the ICRP Vols. 20*, No. 2/3.

ICRP (1990a). International Commission on Radiological Protection, "1990 Recommendations of the International Commission on Radiological Protection," ICRP Publication 60, *Annals of the ICRP Vol. 21*, No. 1-3.

ICRP (1990b). International Commission on Radiological Protection, "Annual Limits on Intake of Radionuclides by Workers based on the 1990 Recommendations," ICRP Publication 61, *Annals of the ICRP Vol. 21*, No. 4.