S Values for Radionuclides Localized Within the Skeleton

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Calculations of radiation absorbed dose to the active marrow are important to radionuclide therapies such as radioimmunotherapy and bone pain palliation. In diagnostic nuclear medicine, calculations of the effective dose for radiopharmaceutical procedures also require the assessment of radiation dose to the skeletal endosteum. We have previously reported the development of 2 3-dimensional electron transport models for assessing absorbed fractions to both marrow and endosteum in trabecular and cortical bone, respectively. Here, we extend these calculations to the assignment of radionuclide S values. **Methods:** Data published in International Commission on Radiological Protection *Publication 70* were used to develop tables of masses for total marrow space, active and inactive marrow, endosteum, and bone matrix within 22 skeletal sites in the adult. Using our site-specific tissue masses, along with electron absorbed fractions given by our 3-dimensional transport models, radionuclide S values (electron and β particle components only) were subsequently calculated using the MIRD schema for ^{32}P, ^{33}P, ^{89}Sr, ^{90}Sr, ^{90}Y, ^{117m}Sn, ^{153}Sm, ^{169}Er, ^{177}Lu, and ^{186}Re. Specific consideration was given to the trabecular active marrow as both a source and a target region. **Results:** Site-specific radionuclide S values are reported for 22 skeletal sites, for 9 source–target tissue combinations within trabecular bone, and for 6 source–target tissue combinations within cortical bone. Skeletal-averaged S values are also provided. **Conclusion:** A fully documented model is presented for the adult for use in radionuclide dosimetry of the skeleton. The model is based on both the latest international recommendations for skeletal tissue masses and results from three-dimensional electron transport calculations within the skeleton. Comparisons are additionally made against the radionuclide S values published in *MIRD Pamphlet No. 11* and those calculated using the MIRDOSE2 and MIRDOSE3 computer codes. Differences in these datasets vary with the source–target combination considered and may be attributed to 1 of 3 causes: (a) assumptions on reference target masses, (b) transport models used to assign absorbed fractions, and (c) implicit assumptions made in considering the trabecular active marrow as both a source and a target tissue.

Key Words: dosimetry; trabecular bone; cortical bone; S values, bone marrow

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In nuclear medicine, accurate skeletal dosimetry is important because of the high radiosensitivity of the hematopoietic cells contained within the marrow cavities of trabecular bone. Furthermore, in both radioimunotherapy and bone pain palliation, the red marrow is generally the dose-limiting organ (*1–3*).

Two models of electron transport in trabecular bone and cortical bone have been proposed for the adult (*4,5*). These models are based on 3-dimensional transport using chord length distributions measured by the research group of Spiers et al. for both trabecular (*6–8*) and cortical (*6,9*) bone. The EGS4-Parameter-Reduced Electron Step Transport Algorithm (PRESTA) Monte Carlo transport code (*10,11*) was used to simulate the physics of electron transport to derive absorbed fractions of energy. For trabecular regions of the skeleton, 7 bone sites were considered with 3 source and target regions: the trabecular marrow space (TMS), the trabecular bone endosteum (TBE), and the trabecular bone volume (TBV). For the cortical regions of the skeleton, 3 cortical bone sites were considered with 3 source and target regions: the cortical Haversian space (CHS), the cortical bone endosteum (CBE), and the cortical bone volume (CBV).

In this article, tabulations of the mean absorbed dose per unit cumulated activity (S value) are presented using these 2 transport models. Reference masses for an adult male are derived for 22 bone sites based on data given in International Commission on Radiological Protection *Publication 70* (ICRP 70) (*12*). These S values are given for all source–target combinations available from the transport models and for each of the 22 bone sites. Skeletal-averaged S values are also derived. The newly calculated S values are then compared with S values currently used in clinical medicine. The symbols used to both describe and calculate the various quantities in this article are given in Table 1 for ready reference.

PREVIOUS DOSIMETRIC MODELS OF CORTICAL AND TRABECULAR BONE

ORNL 5000/MIRD 11

The first calculation of S values for use in nuclear medicine skeletal dosimetry was performed in 1974 by

TABLE 1
Key to Terms and Symbols

Term or symbol	Explanation
TMS	Trabecular marrow space
TBE	Trabecular bone endosteum
TBV	Trabecular bone volume
TAM	Trabecular active marrow
CHS	Cortical Haversian space
CBE	Cortical bone endosteum
CBV	Cortical bone volume
BE	Bone endosteum (TBE + CBE)
BV	Bone volume (TBV + CBV)
AM	Active marrow
MS	Marrow space
IM	Inactive marrow
Δ_i	Mean energy emitted per nuclear transition
m_T	Mass of target region r_T
$m_{Skel,T}$	Mass of target region r_T throughout full skeleton
$m_{Skel,S}$	Mass of source region r_S throughout full skeleton
$m_{j,T}$	Mass of target region r_T in bone site j
$m_{j,S}$	Mass of source region r_S in bone site j
$S_{Skel}(r_T \leftarrow r_S)$	Skeletal-averaged S value from source region r_S to target region r_T
$S_j(r_T \leftarrow r_S)$	S value from source region r_S to target region r_T in bone site j
$D_{Skel}(r_T \leftarrow r_S)$	Skeletal-averaged dose from source region r_S to target region r_T
$D_j(r_T \leftarrow r_S)$	Dose from source region r_S to target region r_T in bone site j
$\tilde{A}_{Skel,S}$	Cumulated activity throughout full skeleton
$\tilde{A}_{j,S}$	Cumulated activity in bone site j
CF_j	Cellularity factor in trabecular bone site j
$\omega_{j,T}$	Mass fraction of target region r_T in bone site j
$\omega_{j,S}$	Mass fraction of source region r_S in bone site j
$\epsilon_j(r_T \leftarrow r_S)$	Energy deposited from source region r_S to target region r_T in bone site j
$\phi_j(r_T \leftarrow r_S)$	Electron absorbed fraction of energy from source region r_S to target region r_T in bone site j

Snyder et al. (*13*), who published Oak Ridge National Laboratory (ORNL) *Report Number 5000* (ORNL 5000), in which photon-specific absorbed fractions and radionuclide S values were given for combinations of source and target organs in an adult heterogeneous phantom. For the skeletal system, they performed calculations based mainly on the work of Spiers et al. at the University of Leeds, United Kingdom (*7,8,14*). To simulate electron transport in the skeleton, Spiers et al. had used chord length distributions measured in the cavities and bone matrix of both trabecular bone and cortical bone along with electron range–energy relationships in these tissues. Spiers et al. subsequently derived dose factors (dose per unit activity concentration in the bone matrix) for several radionuclides of interest in health physics (^{14}C, ^{18}F, ^{22}Na, ^{32}P, ^{45}Ca, ^{90}Sr, ^{90}Y), considering the red marrow and the endosteum (both trabecular and cortical) as target regions and the TBV and CBV as source regions (*7,8*). In ORNL 5000, Snyder et al. converted these dose factors to specific absorbed fractions of energy as a function of the average β particle energy. In their report, 4 source regions were considered: trabecular bone, cortical bone, red marrow, and yellow marrow. In addition, 4 target regions were examined: skeletal bone (both trabecular and cortical), red marrow, yellow marrow, and skeletal endosteum (both trabecular and cortical). For the skeletal source–target combinations not considered by Spiers et al., Snyder et al. applied 1 of the following 5 assumptions to estimate values of absorbed fraction: (a) no energy deposition in the target region, (b) full energy deposition in the target region, (c) conservation of energy within neighboring regions, (d) uniform energy deposited per unit mass in both the source and target regions, and/or (e) the reciprocity theorem (*15*) (defined as an equivalence in the specific absorbed fraction when the source and target region designations are reversed). Column 3 of Table 2 summarizes all methods and assumptions used by Snyder et al. to derive absorbed fractions and specific absorbed fractions of energy for the various combinations of source and target regions. In 1975, ORNL 5000 S values were also published by the MIRD Committee of the Society of Nuclear Medicine as *MIRD Pamphlet No. 11* (MIRD 11) (*16*). For the skeletal system, only 3 source regions were considered by the MIRD Committee (trabecular bone, cortical bone, and red marrow) along with 2 target regions (red marrow and skeletal bone tissue). These values are presumed to have come directly from ORNL 5000 as noted in the revised companion document *MIRD Pamphlet No. 5* (*17*). However, a 10% difference can be noted in the S values of ORNL 5000 and MIRD 11 in the case of the red marrow as both a source and a target region. No differences are found for the other source–target combinations within the skeleton.

ICRP 30/MIRDOSE2

In 1979, the ICRP published its *Report No. 30* (ICRP 30), which recommended absorbed fractions of energy for use in skeletal dosimetry (*18*). These recommended absorbed fractions are single-valued approximations to the data of Spiers et al. (*6–8,14*). Four source regions are considered (TBE, TBV, CBE, and CBV) along with 2 target regions (red marrow and skeletal endosteum). In the case of β particles originating in the bone volume, a single value of absorbed fraction is recommended and, in the case of β particles originating on the bone surface, one absorbed fraction is recommended for low-energy β particles (mean β energy < 0.2 MeV) and another value is recommended for high-energy β particles (mean β energy ≥ 0.2 MeV). These recommended absorbed fractions are listed in Table 2.

Subsequently, these rather energy-independent absorbed fractions of energy were implemented within the MIRDOSE2 program (*19*) for use in nuclear medicine dosimetry. Sources considered in MIRDOSE2 were the red marrow and the bone volume. Following the methodology used in the ICRP 30 bone model, radiopharmaceutical sources were located on the bone surface when the radionuclide physical half-life was less than 15 d or otherwise within the bone matrix. In the case of the red marrow as a source region, it was assumed that the full particle energy was deposited in the red marrow. This assumption was consistent with that suggested in ICRP 30 (*18*).

Eckerman/MIRDOSE3

In 1985, Eckerman (*20*) presented a 1-dimensional model of electron transport in trabecular bone based on the chord length distributions measured by the research group of Spiers (*6,14*). Using their approach (i.e., sampling chord length distributions and using electron range–energy relationships), Eckerman derived absorbed fractions of energy for monoenergetic electrons within the 7 trabecular bone sites considered earlier by Spiers et al.

According to Eckerman (*20*), these calculations were primarily intended to be used in radiation protection for photon sources within the ORNL mathematical phantoms (*21*) through the construction of photon fluence-to-dose conversion factors. In 1994, S values derived from these calculations were implemented within the MIRDOSE3 program to be used in nuclear medicine dosimetry (*19*). Target regions considered in MIRDOSE3 are the red marrow and the skeletal endosteum (both cortical and trabecular) and sources regions considered are the TBV, the red marrow, the CBV, the trabecular bone surface, and the cortical bone surface. The S values are given for 15 different bone sites in the skeletal system and for the 2 target and 4 source regions. Skeletal-averaged S values are also given based on site-specific S values for these 15 bone sites. The details of this computational model are only briefly documented by Eckerman (*20*). In this article, a transport model for electrons in trabecular bone is presented; no transport model for electrons in cortical bone is discussed. It is not clear how the bone surface (i.e., endosteum) was simulated as either a target or a source region. The source and target region combinations used in MIRDOSE3 are shown in Table 2.

Reference Masses

Another important aspect of the dosimetry of the skeletal system is the choice of reference masses for the different target regions. According to the MIRD formalism of dose calculation (*22*), radionuclide S values from a source region r_S to a target region r_T are calculated by performing a summation over the different radiations emitted by the radionuclide:

$$S(r_T \leftarrow r_S) = \sum_i \Delta_i \frac{\phi_i(r_T \leftarrow r_S)}{m_T}. \qquad \text{Eq. 1}$$

In this equation, Δ_i is the mean energy emitted per nuclear transition, $\phi_i(r_T \leftarrow r_S)$ is the absorbed fraction of energy in the target region for the ith radiation type originating in the source region r_S, and m_T is the mass of the target region r_T. Consequently, to derive radionuclide S values, skeletal bone reference masses are needed. In the ORNL 5000 (*13*) and the MIRD 11 (*16*) S value calculations, it was assumed that the reference mass for the red marrow was 1500 g as given in ICRP *Publication 23* (*23*). The latter publication indicated a reference red marrow mass of 1500 g. On the page following this statement, however, tabular data more accurately indicated that only 1045.7 g of the 1500 g was hematopoietically active within the trabecular region of the adult skeleton. The mass of active marrow in the adult was later revised to 1120 g by Cristy and Eckerman (*21*) and to 1170 g in ICRP Publication 70 (*12*). This 1500-g mass of red marrow is also recommended in the ICRP 30 bone model (*18*). In the MIRDOSE2 program, a mass of 1500 g was also reported (*19*). However, a value of 1120 g appears to be used when one considers the MIRDOSE2 S value for ^{32}P (9.91×10^{-5} mGy/MBq-s), an absorbed fraction of unity when the marrow is considered as both source and target, and a mean energy emitted per nuclear transition of 0.11 g-mGy/MBq-s (*24*). A red marrow mass of 1120 g corresponds to that used for the adult in the 1987 report by Cristy and Eckerman in their tabulations of dosimetric data for the ORNL mathematical phantom series (*21*). A mass of 1120 g also is used for the red marrow within the adult in the MIRDOSE3 program. Mass fractions of red marrow indexed by bone site can also be found in the documentation of the MIRDOSE3 program (*19*), although details and references for their derivation are not given. Other important skeletal masses used to calculate S values include 5000 g for total skeleton bone in both ORNL 5000 and MIRD 11, and 120 g for the total mass of skeletal endosteum in ICRP 30 and in both the MIRDOSE2 and MIRDOSE3 programs.

METHODS

Skeletal Absorbed Fractions of Energy

To calculate regional skeletal S values, the models of electron transport in trabecular and cortical bones developed by Bouchet et al. (*4,5*) are used. These 2 models are based on the chord length distribution measurements of Spiers et al. (*6–9,14*). The Monte Carlo transport code EGS4/PRESTA (*10,11*) was used for the transport of electrons, allowing full 3-dimensional transport of particles through both cortical and trabecular soft-tissue cavities and bone matrix. Three source and target regions are considered for trabecular bone: TBV, TBE, and TMS. Tabulations of absorbed fractions were given for all source and target combinations for 7 bone sites: cervical vertebra, femur head, femur neck, iliac crest, lumbar vertebra, parietal bone, and rib. Three source and target regions are considered for cortical bone: CBV, CBE, and the CHS. Absorbed fraction data were given for 3 cortical bone sites: humeral cortex, femoral cortex, and tibial cortex. A detailed description of these models has been reported previously (*4,5*).

Reference Skeletal Masses

Using these absorbed fractions of energy for trabecular and cortical bone, S values to the skeleton can be derived for various

TABLE 2

Summary of Absorbed Fraction Values and Assumptions Used to Estimate Specific Absorbed Fractions in ORNL 5000/MIRD 11 S Value Calculations, ICRP 30/MIRDOSE2 Skeletal Dosimetry Models, and MIRDOSE3 Skeletal Dosimetry Model

Source*	Target*	ORNL 5000/MIRD 11	ICRP 30/MIRDOSE2	MIRDOSE3
Red marrow	Red marrow	Values based on $\Phi(RM \leftarrow TB)$ and assuming uniform energy deposition per unit mass in TB, TBS, and RM	$\phi = 1$†	Values from Eckerman‡
	Yellow marrow	$\phi = 0$		
	Trabecular bone surface	Values based on $\Phi(TBS \leftarrow TB)$ and assuming uniform energy deposition per unit mass in TB, TBS, and RM	$\phi = 0.02$†	Values from Eckerman‡
	Cortical bone surface	$\phi = 0$	$\phi = 0$ (implied)	$\phi = 0$ (implied)
	Trabecular bone	Values based on reciprocity theorem: $\Phi(TB \leftarrow RM) = \Phi(RM \leftarrow TB)$		
	Cortical bone	$\phi = 0$		
Yellow marrow	Red marrow	$\phi = 0$		
	Yellow marrow	$\phi = 1$		
	Trabecular bone surface	$\phi = 0$		
	Cortical bone surface	Value based on $\Phi(CBS \leftarrow YM) = \Phi(YM \leftarrow YM)/2$		
	Trabecular bone	$\phi = 0$		
	Cortical bone	$\phi = 0$		
Trabecular bone	Red marrow	Values derived directly from Spiers§	$\phi = 0.35$	Values from Eckerman‡
	Yellow marrow	$\phi = 0$		
	Trabecular bone surface	Values derived directly from Spiers§	$\phi = 0.025$	Values from Eckerman‡
	Cortical bone surface	$\phi = 0$	$\phi = 0$ (implied)	$\phi = 0$ (implied)
	Trabecular bone	Values derived assuming $\phi(TB \leftarrow TB) + \phi(RM \leftarrow TB) = 1.0$		
	Cortical bone	$\phi = 0$		
Cortical bone	Red marrow	Values derived directly from Spiers§	$\phi = 0$	$\phi = 0$
	Yellow marrow	$\phi = 0$		
	Trabecular bone surface	Values derived directly from Spiers§	$\phi = 0$ (implied)	$\phi = 0$ (implied)
	Cortical bone surface	Values derived directly from Spiers§	$\phi = 0.015$	Values from Eckerman‡
	Trabecular bone	$\phi = 0$		
	Cortical bone	$\phi = 1$		
Trabecular bone surface	Red marrow	Sources on bone surfaces (endosteum) not considered	$\phi = 0.5$	No detailed model published
	Yellow marrow	Sources on bone surfaces (endosteum) not considered		
	Trabecular bone surface	Sources on bone surfaces (endosteum) not considered	$\phi = 0.25$ for $\bar{E}_\beta < 0.2$ MeV $\phi = 0.025$ for $\bar{E}_\beta \geq 0.2$ MeV	No detailed model published
	Cortical bone surface	Sources on bone surfaces (endosteum) not considered	$\phi = 0$ (implied)	$\phi = 0$ (implied)
	Trabecular bone	Sources on bone surfaces (endosteum) not considered		
	Cortical bone	Sources on bone surfaces (endosteum) not considered		
Cortical bone surface	Red marrow	Sources on bone surfaces (endosteum) not considered	$\phi = 0$	$\phi = 0$
	Yellow marrow	Sources on bone surfaces (endosteum) not considered		

TABLE 2 (*Continued*)

Source*	Target*	ORNL 5000/MIRD 11	ICRP 30/MIRDOSE2	MIRDOSE3
Cortical bone surface (*continued*)	Trabecular bone surface	Sources on bone surfaces (endosteum) not considered	$\phi = 0$ (implied)	$\phi = 0$ (implied)
	Cortical bone surface	Sources on bone surfaces (endosteum) not considered	$\phi = 0.25$ for $\bar{E}_\beta < 0.2$ MeV $\phi = 0.025$ for $\bar{E}_\beta \geq 0.2$ MeV	No detailed model published
	Trabecular bone	Sources on bone surfaces (endosteum) not considered		
	Cortical bone	Sources on bone surfaces (endosteum) not considered		

*Designation of source and target regions used in this table reflect nomenclature used in references *13,16,* and *18–20.* The terms trabecular bone surface and cortical bone surface in Table 1 are referred to within the present model as trabecular bone endosteum (TBE) and cortical bone endosteum (CBE), respectively.

†Source: Preface to ICRP Publication 30, Part 3 (*18*).

‡Limited values are published in Eckerman (*20*) for $\phi(\text{RM} \leftarrow \text{TB})$, $\phi(\text{RM} \leftarrow \text{RM})$, $\phi(\text{TBS} \leftarrow \text{RM})$, and $\phi(\text{TBS} \leftarrow \text{TB})$ for parietal bone and lumbar vertebra. The model description does not indicate how endosteum is treated as a target region.

§Values of specific absorbed fraction were determined directly from dose factors of Spiers (*7,8*) using Bragg-Gray cavity theory, a constant value of 1.075 for ratio of electron stopping powers in bone and soft tissue, and reference masses of 1000, 4000, and 1500 g for trabecular bone, cortical bone, and red marrow, respectively.

RM = red marrow; YM = yellow marrow; TB = trabecular bone; CB = cortical bone; TBS = trabecular bone surface; CBS = cortical bone surface.

radionuclides, once reference masses are provided for each of the different targets within trabecular and cortical bone sites of the skeleton. In 1995, ICRP 70 provided anatomic and physiologic data on the human skeletal system for use in radiologic protection (*12*). This publication serves as an update to the skeletal chapters of ICRP 23 (*23*). In ICRP 70, reference masses are given for the total skeleton but not for specific bone sites. In addition, summaries of different quantitative data from the literature on the skeletal system are given in tabular form. These data can thus be used to derive bone site-specific masses for all sources and targets of interest in skeletal dosimetry.

From ICRP 70, 22 bone sites were first selected in 6 skeletal body regions to represent trabecular and cortical bone sites in the adult (Table 3). To calculate S values for all source–target combinations, the following masses were needed for each of the 22 bone sites: the TMS, the CHS, the active marrow, the inactive marrow, the cortical bone, the trabecular bone, the cortical endosteum, and the trabecular endosteum. The following sections explain how each of these masses is derived.

The mass for the total active marrow in Reference Man is given in ICRP 70 as 1170 g. In addition, ICRP 70, using data from a study by Cristy in 1981 (*25*), gives the percentage of active marrow in a given bone as a percentage of the total active marrow in the body (Table 4, column 2) (*12*). (Values in ICRP 70 are given for 2 adult ages: 25 and 40 y. In the work reported in this article, we have used the data for the 40-y-old adult because this age is more closely matched to the age [44 y] of the subject for whom trabecular chord length data are available). From these data, reference mass of active marrow in each of the 22 bone sites can be obtained (Table 4, column 3). Moreover, the percentage of total marrow space (both active and inactive) in individual adult bones was determined by Mechanik in 1926 (*26*) and later summarized by Woodard and Holoday in 1960 (*27*). These percentages were given in Table 30 of ICRP Report 23 (*23*) and are included here in column 4 of Table 4. Knowing that the ICRP 70 Reference Man mass for the total marrow is 3650 g (Reference Man mass of inactive

TABLE 3
Bone Sites Used in Calculations of S Values

Region	Bone sites
Head	Cranium
	Mandible
Vertebra	Cervical
	Thoracic
	Lumbar
Ribs, sternum, shoulders	Sternum
	Ribs
	Scapulae
	Clavicles
Pelvis	Os coxae
	Sacrum
Arms	Humeri, upper half*
	Humeri, lower half†
	Radii
	Ulnae
	Wrist and hands
Legs	Femora, upper half*
	Femora, lower half†
	Patellae
	Tibiae
	Fibulae
	Ankles and feet

*Proximal epiphysis and proximal half of diaphysis.
†Distal epiphysis and distal half of diaphysis.

TABLE 4
Derivation of Reference Masses for Active Marrow (AM), Marrow Space (MS), and Inactive Marrow (IM) in Adult Human Skeletal System and Verification Against Values Obtained Using the CF

Skeletal site	% AM	Mass AM (g)	% Total MS	Mass Total MS (g)	Mass IM (g)	Computed CF	CF	CF
	ICRP 70, Table 40; 40 y	% AM × 1170 g	ICRP 23, Table 30	% MS × 3650 g	Total − active	Active marrow/ total marrow	ICRP 70, Table 41; 25 y	ICRP 70, Table 41; 40 y
Head								
Cranium	7.6	89.0	6.3	231.2	142.2	0.39	0.42	0.38
Mandible	0.8	9.4	0.6	21.9	12.5	0.43	0.42	0.38
Vertebra								
Cervical	3.9	45.7	1.8	65.0	19.3	0.70	0.72	0.70
Thoracic	16.1	188.6	7.3	266.2	77.7	0.71	0.72	0.70
Lumbar	12.3	144.1	5.6	204.9	60.8	0.70	0.72	0.70
Ribs, sternum, shoulders								
Sternum	3.1	36.3	1.4	50.4	14.1	0.72	0.72	0.70
Ribs	16.1	188.6	7.3	268.0	79.5	0.70	0.72	0.70
Scapulae	2.8	32.8	2.4	86.9	54.1	0.38	0.42	0.38
Clavicles	0.8	9.4	0.8	27.8	18.4	0.34	0.37	0.33
Pelvis								
Os coxae	17.5	205.0	10.4*	379.7	174.8	0.54	0.58	0.48
Sacrum	9.9	115.9	5.9*	214.8	98.9	0.54	0.58	0.48
Arms								
Humeri, upper half	2.3	26.9	3.0†	109.2	82.3	0.25	0.30	0.25
Humeri, lower half	0.0	0.0	3.0†	109.2	109.2	0.00	0.00	0.00
Radii	0.0	0.0	1.3	48.9	48.9	0.00	0.00	0.00
Ulnae	0.0	0.0	1.4	50.4	50.4	0.00	0.00	0.00
Wrist and hands	0.0	0.0	2.7	100.1	100.1	0.00	0.00	0.00
Legs								
Femora, upper half	6.7	78.5	8.5‡	311.5	233.0	0.25	0.30	0.25
Femora, lower half	0.0	0.0	8.5‡	311.5	311.5	0.00	0.00	0.00
Patellae	0.0	0.0	0.8	29.9	29.9	0.00	0.00	0.00
Tibiae	0.0	0.0	10.9	398.8	398.8	0.00	0.00	0.00
Fibulae	0.0	0.0	1.5	56.2	56.2	0.00	0.00	0.00
Ankles and feet	0.0	0.0	8.4	307.5	307.5	0.00	0.00	0.00
Total	99.9%	1170.0	100.0%	3650.0	2480.0			

*For os coxae and sacrum, % MS was derived from % MS in pelvis (16.3%) by partitioning this value for each bone using their relative fractions of AM.
†Assumed half of % MS in full humerus (6.0%).
‡Assumed half of % MS in full femur (17.0%).

marrow is given as 2480 g in Table 47 of ICRP 70), it is then possible to derive the total mass of marrow per bone site (Table 4, column 5). The total mass of inactive marrow is obtained by subtraction (Table 4, column 6). To verify the derived masses of active, inactive, and total marrow, one may additionally calculate cellularity factors (CFs) for each of the trabecular bone sites and compare these values to data in ICRP 70 (*12*). The CF in trabecular bone site j (CF_j) is defined as the percentage of total marrow mass that is active and is thus calculated using the following expression (*25*):

$$CF_j = \frac{m_{j,TAM}}{m_{j,TMS}}, \qquad \text{Eq. 2}$$

where $m_{j,TAM}$ and $m_{j,TMS}$ are the mass of active marrow and total marrow space, respectively, in bone site j. Table 41 of ICRP 70 gives values of CFs for several bone sites and several ages originally given by Cristy (*25*). In Table 4, computed CFs are compared with these published data, and good agreement is seen.

To derive the mass of bone tissue within the trabecular and cortical regions of the skeleton, the relative weights of dry bones of adults as a percentage of the total dry skeleton given in Table 8 of ICRP 70 are used. (Corresponding data on the relative distribution of wet bone mass throughout the skeleton are not given in ICRP 70. It is thus assumed that percentages of dry and wet bone are equivalent when reference bone masses are derived.) These data were measured by Trotter and Hixon (*28*) in 1974 for 30 white men and are given in column 2 of Table 5. The total mass of bone tissue in Reference Man is given as 5500 g in ICRP 70 (*12*), and, therefore, the mass of bone tissue in each of the 22 skeletal regions can be calculated (Table 5, column 3). Next, using the percentages of cortical mass of bone tissue and of trabecular mass of bone tissue for the different bone sites as given in Table 10 of ICRP 70, one can calculate the mass of bone at a given skeletal

TABLE 5
Derivation of Reference Masses of Cortical and Trabecular Bone Matrix in Human Skeletal System

Skeletal site	% mass of total dry skeleton	Bone mass (g)	% Cortical	% Trabecular	Cortical mass of bone matrix (g)	Trabecular mass of bone matrix (g)
	ICRP 70, Table 8	% skeleton × 5500 g	ICRP 70, Table 10	ICRP 70, Table 10	Bone mass × % cortical	Bone mass × % trabecular
Head			From reference 38			
Cranium	15.7	865.2	95*	5*	822.0	43.3
Mandible	1.6	88.2	95*	5*	83.8	4.4
Vertebra			From reference 38			
Cervical	1.5	82.7	25	75	20.7	62.0
Thoracic	3.8	209.4	25	75	52.4	157.1
Lumbar	3.2	176.4	34	66	60.0	116.4
Ribs, sternum, shoulders			From reference 38			
Sternum	0.5	27.6	94	6	25.9	1.7
Ribs	6.0	330.7	94	6	310.8	19.8
Scapulae	3.1	170.8	94	6	160.6	10.3
Clavicles	1.0	55.1	94	6	51.8	3.3
Pelvis						
Os coxae	8.3	457.4	90†	10†	411.7	45.7
Sacrum	1.9	104.7	75	25	78.5	26.2
Arms			From references 39 and 38 for hands			
Humeri, upper half	3.4‡	187.4	90‡	10‡	168.6	18.7
Humeri, lower half	3.4‡	187.4	90‡	10‡	168.6	18.7
Radii	2.3	126.8	87	13	110.3	16.5
Ulnae	2.9	159.8	87	13	139.0	20.8
Wrist and hands	2.6	143.3	95	5	136.1	7.2
Legs			From references 39 and 38 for feet			
Femora, upper half	9.5‡	523.5	77‡	23‡	403.1	120.4
Femora, lower half	9.5‡	523.5	77‡	23‡	403.1	120.4
Patellae	0.6	33.1	80§	20§	26.5	6.6
Tibiae	11.1	611.7	83	17	507.7	104.0
Fibulae	2.3	126.8	89	11	112.8	13.9
Ankles and feet	5.6	308.6	95‖	5	293.2	15.4
Total mass (g)		5500.0			4547.2	952.8

*Indicated as "skull" in Table 10 of ICRP 70 (*12*).
†Indicated as "inominate" in Table 10 of ICRP 70 (*12*).
‡The % mass of total dry skeleton is assumed to be equally distributed in upper and lower halves of humeri and femora.
§The default reference value given in ICRP 70, page 20, is used (*12*).
‖This value was incorrectly listed as 65% in Table 10 of ICRP 70 (*12*).

site associated with its cortical or trabecular regions. Columns 4 and 5 of Table 5 give the mass percentages used for cortical and trabecular bone, and columns 6 and 7 of Table 5 give the resulting reference masses of cortical and trabecular bone tissue by skeletal site.

The calculations of reference masses for the endosteum in both cortical and trabecular bone are based on Tables 11 and 12 of ICRP 70, where surface-to-volume ratios are given for several bone sites. When surface-to-volume ratios were not available, the ICRP 70 default values were used: 3 mm^2/mm^3 for the cortical bone and 18 mm^2/mm^3 for the trabecular bone (*12*). Table 6 gives the values used for surface-to-volume ratios for both cortical and trabecular endosteum in the 22 cortical bone sites, respectively. To calculate the volume of endosteum, a thickness of 10 μm was assumed for the endosteum as recommended in ICRP 26 (*29*). The density of bone tissue was taken as 1.92 g/cm^3 (adult cortical bone) and the density of endosteum as 1.03 g/cm^3 (adult man, average soft tissue) from Appendix A of the International Commission on Radiation Units and Measurements (ICRU) Report 46 (*30*). The various steps in calculating endosteum masses are shown in Table 6.

Table 7 summarizes the various reference masses presented in Tables 4–6 that are needed for the calculation of radionuclide S values by skeletal site within the adult. Bone tissue and endosteal masses are obtained directly from corresponding columns in Tables 5 and 6, respectively. For the total marrow masses, columns 3 and 4 of Table 7 indicate the mass of total marrow space associated with either trabecular or cortical regions of a given skeletal site, respectively. More specifically, column 4 gives the mass of total

TABLE 6
Derivation of Masses of Endosteum in Cortical and Trabecular Bones Within Adult Human Skeleton

Skeletal site	Cortical bone Surf./vol. (mm²/mm³)	Bone matrix (g)	Bone matrix (cm³)	Endosteum (cm³)	Endosteum (g)	Trabecular bone Surf./vol. (mm²/mm³)	Bone matrix (g)	Bone matrix (cm³)	Endosteum (cm³)	Endosteum (g)
	ICRP 70, Table 11	Mass × % cort.	Mass/ 1.92 g/cm³	Vol. × (Surf./vol.) × 10 μm	Vol × 1.03 g/cm³	ICRP 70, Table 12	Mass × % trab.	Mass/ 1.92 g/cm³	Vol. × (Surf./vol.) × 10 μm	Vol × 1.03 g/cm³
Head										
Cranium	3.0*	822.0	428.1	12.8	13.2	7.8†	43.3	22.5	1.8	1.8
Mandible	3.0*	83.8	43.6	1.3	1.3	7.8†	4.4	2.3	0.2	0.2
Vertebra										
Cervical	3.0*	20.7	10.8	0.3	0.3	18.0*	62.0	32.3	5.8	6.0
Thoracic	3.0*	52.4	27.3	0.8	0.8	18.0*	157.1	81.8	14.7	15.2
Lumbar	3.0*	60.0	31.2	0.9	1.0	19.7†	116.4	60.6	11.9	12.3
Ribs, sternum, shoulders										
Sternum	3.0*	25.9	13.5	0.4	0.4	18.5†‡	1.7	0.9	0.2	0.2
Ribs	3.0*	310.8	161.9	4.9	5.0	18.5†	19.8	10.3	1.9	2.0
Scapulae	3.0*	160.6	83.6	2.5	2.6	18.5†‡	10.3	5.3	1.0	1.0
Clavicles	3.0*	51.8	27.0	0.8	0.8	18.5†‡	3.3	1.7	0.3	0.3
Pelvis										
Os coxae	3.0*	411.7	214.4	6.4	6.6	17.2†	45.74	23.8	4.1	4.2
Sacrum	3.0*	78.5	40.9	1.2	1.3	19.7†§	26.18	13.6	2.7	2.8
Arms										
Humeri, upper half	2.3†	168.6	87.8	2.0	2.1	18.0*	18.7	9.8	1.8	1.8
Humeri, lower half	2.3†	168.6	87.8	2.0	2.1	18.0*	18.7	9.8	1.8	1.8
Radii	2.3†‖	110.3	57.4	1.3	1.4	18.0*	16.5	8.6	1.5	1.6
Ulnae	2.3†‖	139.0	72.4	1.7	1.7	18.0*	20.8	10.8	1.9	2.0
Wrist and hands	2.3†‖	136.1	70.9	1.6	1.7	18.0*	7.2	3.7	0.7	0.7
Legs										
Femora, upper half	2.9†	403.1	210.0	6.1	6.3	17.3†	120.4	62.7	10.8	11.2
Femora, lower half	2.9†	403.1	210.0	6.1	6.3	17.3†	120.4	62.7	10.8	11.2
Patellae	3.0*	26.5	13.8	0.4	0.4	18.0*	6.6	3.4	0.6	0.6
Tibiae	1.9†	507.7	264.4	5.0	5.2	18.0*	104.0	54.2	9.7	10.0
Fibulae	1.9†¶	112.8	58.8	1.1	1.1	18.0*	13.9	7.3	1.3	1.3
Ankles and feet	3.0*	293.2	152.7	4.6	4.7	18.0*	15.4	8.0	1.4	1.5
Total		4547.2			65.6		952.8			89.7

*Default reference value from ICRP 70, page 23 (*12*).
†Data from Beddoe (*6,9*).
‡Assumed to equal that for ribs.
§Assumed to equal that for lumbar vertebra.
‖Assumed to equal that for humeri.
¶Assumed to equal that for tibiae.
Surf./vol. = surface/volume; cort. = cortical; Vol. = volume; trab. = trabecular.

marrow within the medullary cavities of the long bones of the appendicular skeleton (i.e., surrounded by cortical bone). Columns 5 and 6 of Table 7 indicate our partitioning of the total marrow space for each site into its active and inactive marrow masses. For the humeri and femora, data on CFs needed to make this partitioning are given only for their upper (proximal) and lower (distal) halves. Consequently, the CFs for the upper halves of these bones in the adult reflect both the portion of inactive marrow within the bone shaft and the fraction of partially active marrow contained within their proximal trabecular ends. As indicated in the notes to Table 7, we have approximated the distribution of active and inactive marrow in both the humeral and femoral shafts and in their trabecular ends using CFs from neighboring trabecular bone sites. As noted in Table 7, column 5, active marrow is found only in the proximal trabecular ends of the adult humerus and femur. At earlier ages, however, marrow with the medullary cavities is partially active (ICRP 70, Table 40 [*12*]), and thus this distinction will be important in future extensions of the skeletal model to pediatric patients.

The total skeletal masses of the active marrow, inactive marrow, marrow space, and bone tissue are consistent with Reference Man masses given in Table 47 of ICRP 70 (*12*). The reference total surface areas for adult cortical bone and trabecular bone are given in ICRP 70 as 6.5 and 10.5 m^2, respectively. If one assumes a thickness of 10 μm for the endosteum (*29*) and a density of 1.03 g/cm^3, the approximate endosteal masses for cortical and trabecular bone are 67 and 108 g, respectively. These values are fairly consistent with the calculated masses given in Table 7 (62.0 and

TABLE 7
Summary of Reference Masses Derived for Calculation of Regional S Values Within Adult Skeleton

Skeletal site	Marrow mass (g) Total	Total MS associated with TB	Total MS associated with CB	Active marrow	Inactive marrow	Bone tissue mass (g) Cortical	Trabecular	Endosteum mass (g) Cortical	Trabecular
Head									
Cranium	231.2	231.2	0.0	89.0	142.2	822.0	43.3	13.2	1.8
Mandible	21.9	21.9	0.0	9.4	12.5	83.8	4.4	1.3	0.2
Vertebra									
Cervical	65.0	65.0	0.0	45.7	19.3	20.7	62.0	0.3	6.0
Thoracic	266.2	266.2	0.0	188.6	77.7	52.4	157.1	0.8	15.2
Lumbar	204.9	204.9	0.0	144.1	60.8	60.0	116.4	1.0	12.3
Ribs, sternum, shoulders									
Sternum	50.4	50.4	0.0	36.3	14.1	25.9	1.7	0.4	0.2
Ribs	268.0	268.0	0.0	188.6	79.5	310.8	19.8	5.0	2.0
Scapulae	86.9	86.9	0.0	32.8	54.1	160.6	10.3	2.6	1.0
Clavicles	27.8	27.8	0.0	9.4	18.4	51.8	3.3	0.8	0.3
Pelvis									
Os coxae	379.7	379.7	0.0	205.0	174.8	411.7	45.7	6.6	4.2
Sacrum	214.8	214.8	0.0	115.9	98.9	78.5	26.2	1.3	2.8
Arms									
Humeri, upper half	109.2	67.3*	41.8	26.9	82.3	168.6	18.7	2.1	1.8
Humeri, lower half	109.2	67.3*	41.8	0.0	109.2	168.6	18.7	2.1	1.8
Radii	48.9	29.4†	19.6	0.0	48.9	110.3	16.5	1.4	1.6
Ulnae	50.4	30.2†	20.2	0.0	50.4	139.0	20.8	1.7	2.0
Wrist and hands	100.1	100.1	0.0	0.0	100.1	136.1	7.2	1.7	0.7
Legs									
Femora, upper half	311.5	156.9*	154.6	78.5	233.0	403.1	120.4	6.3	11.2
Femora, lower half	311.5	156.9*	154.6	0.0	311.5	403.1	120.4	6.3	11.2
Patellae	29.9	29.9	0.0	0.0	29.9	26.5	6.6	0.4	0.6
Tibiae	398.8	199.4‡	199.4	0.0	398.8	507.7	104.0	5.2	10.0
Fibulae	56.2	28.1‡	28.1	0.0	56.2	112.8	13.9	1.1	1.3
Ankles and feet	307.5	307.5	0.0	0.0	307.5	293.2	15.4	4.7	1.5
Total	3650.0	2989.9	660.1	1170.0	2480.0	4547.2	952.8	65.6	89.7

*To assign marrow masses associated with only marrow contained within trabecular regions of epiphyses, we have assumed a CF of 0.4 for proximal ends of humeri (same as scapulae and clavicles) and a CF of 0.5 for proximal ends of femora (same as os coxae and sacrum). For example, mass of marrow space associated with proximal trabecular regions of humeri is estimated as (26.9 g active marrow/0.4) = 67.3 g total marrow. The remaining 41.8 g of marrow space within diaphyses is obtained by subtraction (109.2 g − 67.3 g) = 41.8 g. As before, we assume uniform distribution of total marrow space in both halves of humeri and femora.

†Distributions of trabecular MS and cortical MS in both radii and ulnae are assumed to be 60% and 40%, respectively, based on their fractional distribution estimated within humerus.

‡Distributions of trabecular MS and cortical MS in both tibiae and fibulae are assumed to be 50% and 50%, respectively, based on their fractional distribution estimated within femur.

MS = marrow space; TB = trabecular bone; CB = cortical bone.

89.9 g, respectively). The total calculated skeletal mass indicated in Table 7 is 9305 g. A total reference skeletal mass of 10,500 g is given in ICRP 70, Table 47, but this figure includes 1100 g of cartilage and a total of 250 g for the combined masses of endosteum, teeth, periosteum, and blood vessels within the skeleton.

Site-Specific S values

Twenty-two bone sites have been selected for the calculation of regional S values, and reference masses have been derived for all of these bone sites for the marrow space, the active marrow, the inactive marrow, the bone matrix, and the endosteum, considering both the cortical and trabecular regions of the skeleton. However, absorbed fractions of energy given by Bouchet et al. (*4*) and Bouchet and Bolch (*5*) have been calculated for only 7 trabecular bone sites and 3 cortical bone sites for which chord length distributions are available. For trabecular bone sites, weighted combinations of these 7 trabecular absorbed fractions are used as suggested by Whitwell (*7*), Spiers (*31*), and Eckerman (KF Eckerman, written communication, October 6, 1994). Table 8 gives the percent weights for the absorbed fractions used for all 22 trabecular bone sites. For the cortical bone regions, the cortex of the femur, tibia, and humerus were considered in the calculations of absorbed fraction of energy within these bones (*5*). For the other cortical bone sites, the relatively small variation in absorbed fractions with bone site justified the use of an average absorbed fraction to targets within cortical bone (*5*).

TABLE 8
Weights Used for Derivation of Bone Site-Specific Absorbed Fractions for Trabecular Bone for 7 Bone Sites

Skeletal site	CV (%)	FH (%)	FN (%)	IC (%)	LV (%)	PB (%)	RB (%)
Head							
Cranium						100	
Mandible						100	
Vertebra							
Cervical	100						
Thoracic	50				50		
Lumbar					100		
Ribs, sternum, shoulders							
Sternum							100
Ribs							100
Scapulae				60	40		
Clavicles				60	40		
Pelvis							
Os coxae				60	40		
Sacrum				60	40		
Arms							
Humeri, upper half		80	20				
Humeri, lower half		50	50				
Radii		50	50				
Ulnae		50	50				
Hands		50	50				
Legs							
Femora, upper half		80	20				
Femora, lower half		50	50				
Patellae		50	50				
Tibiae		50	50				
Fibulae		50	50				
Feet		50	50				

Data based on absorbed fractions of energy given by Bouchet et al. (*4*).
CV = cervical vertebra; FH = femur head; FN = femur neck; IC = iliac crest; LV = lumbar vertebra; PB = parietal bone; RB = rib.

Using the absorbed fractions of energy from Bouchet et al. (*4*) and Bouchet and Bolch (*5*) with the derived masses from Table 7, one can calculate bone site-specific S values to targets within trabecular bone and cortical bone. For trabecular bone, the source and target regions considered in the electron transport model are the TMS, TBV, and TBE (*4*). Consequently, S values can be tabulated for only these same source and target regions. In the same way, the source and target regions considered in the electron transport model in cortical bone are CHS, CBV, and CBE (*5*).

Skeletal-Averaged S values

It is also useful to derive a skeletal-averaged S value using these site-specific S values. Here as well, only source and target regions considered in the transport model can be considered. The absorbed dose to a target r_T from emission within source r_S is given as the total energy deposited in r_T per unit mass of r_T. Therefore, for the case of the skeletal system, one can sum the energy deposited $\varepsilon_j(r_T \leftarrow r_S)$ in all 22 bone sites j and divide by the total mass of target r_T within the skeleton $m_{Skel,T}$:

$$D_{Skel}(r_T \leftarrow r_S) = \frac{\sum_j^{\text{All Bone Sites}} \varepsilon_j(r_T \leftarrow r_S)}{m_{Skel,T}} = \frac{\sum_j^{\text{All Bone Sites}} m_{j,T}\, D_j(r_T \leftarrow r_S)}{m_{Skel,T}}, \quad \text{Eq. 3}$$

where $D_j(r_T \leftarrow r_S)$ is the dose to target r_T from source r_S in bone site j, and $m_{j,T}$ is the mass of r_T in bone site j. Therefore, by replacing the term $D_j(r_T \leftarrow r_S)$ within Equation 3 using the MIRD methodology of dose calculation (*22,32*), the following expression is obtained:

$$D_{Skel}(r_T \leftarrow r_S) = \sum_j^{\text{All Bone Sites}} \omega_{j,T}\, \tilde{A}_{j,S}\, S_j(r_T \leftarrow r_S), \text{ with} \quad \text{Eq. 4}$$

$$\omega_{j,T} = \frac{m_{j,T}}{m_{Skel,T}}, \quad \text{Eq. 5}$$

where $\omega_{j,T}$ is the relative mass fraction of target r_T in bone site j and $\tilde{A}_{j,S}$ is the cumulated activity in source region r_S in bone site j. If one now assumes that the activity in the source region is proportional to the volume (or mass) of the source, the cumulated activity in the source for bone site j is given as:

$$\tilde{A}_{j,S} = \frac{m_{j,S}}{m_{Skel,S}} \tilde{A}_{Skel,S}, \quad \text{Eq. 6}$$

where $\tilde{A}_{Skel,S}$ is the cumulative activity in source r_S throughout the entire skeleton. Substituting Equation 6 into Equation 4, one obtains:

$$D_{Skel}(r_T \leftarrow r_S) = \tilde{A}_{Skel,S} \sum_j^{\text{All Bone Sites}} \omega_{j,T}\, \omega_{j,S}\, S_j(r_T \leftarrow r_S), \text{ with} \quad \text{Eq. 7}$$

$$\omega_{j,S} = \frac{m_{j,S}}{m_{Skel,S}}, \quad \text{Eq. 8}$$

where $\omega_{j,S}$ is the relative mass fraction of source r_S in bone site j.

Using the definition of the S value given by the MIRD schema, one may relate the skeletal-averaged dose to the skeletal-averaged S value, $S_{Skel}(r_T \leftarrow r_S)$, as:

$$D_{Skel}(r_T \leftarrow r_S) = S_{Skel}(r_T \leftarrow r_S)\, \tilde{A}_{Skel,S}. \quad \text{Eq. 9}$$

Finally, the skeletal-averaged S value for a source region r_S and target region r_T is obtained through equating Equations 7 and 9:

$$S_{Skel}(r_T \leftarrow r_S) = \sum_j^{\text{All Bone Sites}} \omega_{j,T}\, \omega_{j,S}\, S_j(r_T \leftarrow r_S). \quad \text{Eq. 10}$$

The average S values to the skeleton for all source and target combinations are therefore calculated by using Equation 10, where each bone site-specific S value is weighted by the mass fractions of both the source region r_S and the target region r_T associated with bone site j.

Consideration of Trabecular Active Marrow as a Source or Target (or Both)

In the adult, the marrow space within trabecular bone is composed of several different tissues including (a) blood sinuses, blood vessels, and lymphatic vessels; (b) marrow tissue (marrow chords) containing the hematopoietic stem cells and their descendents within various stages of development; (c) connective tissue delineating the boundaries of the marrow chords and the adjacent sinuses; and (d) adipose cells. The endosteal cell layer separates this marrow space from the adjacent bone trabeculae. Target tissues of interest to radiation dosimetry of the skeleton have been defined by the ICRP as the endosteum (both trabecular and cortical) and the active (or red) marrow. Although precise histologic definitions of active (red) and inactive (yellow) marrow are lacking, one may consider the active marrow in the adult to be composed of all tissues within the marrow space, exclusive of the adipose cells. Consequently, in many trabecular bone regions of the adult, the active marrow may be considered to be a spatial subset of the total volume of marrow space (total marrow tissue minus adipose tissue). This distinction is made here because computational models for electron transport in trabecular bone, which are based on chord length distributions, allow one only to make estimates of absorbed fractions for the marrow space as either the source or the target region. Various assumptions must then be invoked when considering the active marrow as either the source or the target region.

Let us first consider the trabecular active marrow (TAM) only as the radiation target (i.e., not the radiation source). Because the location of the active marrow within the marrow space is not known, one may assume that for a source within the TMS, TBE, or TBV, the energy is uniformly deposited across the marrow space. If the dose is uniform within the marrow space, one may write for a bone site j:

$$S_j(\mathrm{TAM} \leftarrow r_S) = S_j(\mathrm{TMS} \leftarrow r_S), \qquad \text{Eq. 11}$$

where the source r_S can be the TMS, TBE, or TBV. Equation 11 can also be expressed in terms of absorbed fractions of energy:

$$\phi_j(\mathrm{TAM} \leftarrow r_S) = \frac{m_{j,\mathrm{TAM}}}{m_{j,\mathrm{TMS}}} \phi_j(\mathrm{TMS} \leftarrow r_S), \text{ or} \qquad \text{Eq. 12}$$

$$\phi_j(\mathrm{TAM} \leftarrow r_S) = \mathrm{CF}_j\, \phi_j(\mathrm{TMS} \leftarrow r_S), \qquad \text{Eq. 13}$$

where CF_j is the CF for bone site j.

Next, we consider the source region as the TAM and the target region as the TMS, TBE, or TBV. Because no geometric information is available on the location of the TAM within the TMS, one has to assume that the absorbed fractions of energy to a target region r_T, for either a TAM or a TMS source region, are equivalent:

$$\phi_j(r_T \leftarrow \mathrm{TAM}) = \phi_j(r_T \leftarrow \mathrm{TMS}). \qquad \text{Eq. 14}$$

In terms of S values, Equation 14 is equivalent to:

$$S_j(r_T \leftarrow \mathrm{TAM}) = S_j(r_T \leftarrow \mathrm{TMS}). \qquad \text{Eq. 15}$$

Because the TAM is contained within the TMS, Equation 14 may overestimate the true absorbed fraction for a TAM source. The error on the overestimation is a function of the percentage of TMS that is active. Consequently, this error will become smaller with increasing values of CF (i.e., a larger portion of the marrow space is active and thus serving as a radiation source). Exact statements on the degree of error cannot be made because the error is also a function of the spatial distribution of the TAM within the TMS (e.g., the TAM may be centrally or peripherally located within the TMS).

Finally, to consider the TAM as both the source and the target region, one must assume that the self-absorbed fractions for a TAM or a TMS region are the same:

$$\phi_j(\mathrm{TAM} \leftarrow \mathrm{TAM}) = \phi_j(\mathrm{TMS} \leftarrow \mathrm{TMS}). \qquad \text{Eq. 16}$$

In terms of S values, one can write:

$$S_j(\mathrm{TAM} \leftarrow \mathrm{TAM}) = \frac{m_{j,\mathrm{TMS}}}{m_{j,\mathrm{TAM}}} S_j(\mathrm{TMS} \leftarrow \mathrm{TMS}), \qquad \text{Eq. 17}$$

or

$$S_j(\mathrm{TAM} \leftarrow \mathrm{TAM}) = \frac{S_j(\mathrm{TMS} \leftarrow \mathrm{TMS})}{\mathrm{CF}_j}, \qquad \text{Eq. 18}$$

where the CF_j is the CF for bone site j. At very low electron energies, Equation 16 is nearly exact, as the electrons emitted within either the TAM or the TMS have short ranges, and thus the absorbed fraction approaches a value of unity with decreasing electron energy. With increasingly higher electron energies, a larger fraction of the electron energy may be deposited within the neighboring adipose cells of the marrow space (inactive marrow). Equation 16 then overestimates the true absorbed fraction because a TMS source or target simulation does not account for this loss of particle energy. The degree of the overestimation will again be a function of the mass fraction of TAM within the TMS (i.e., the CF) and the spatial distribution of the TAM within the TMS.

For the TAM as either a source or a target region, the skeletal-averaged S values are derived following Equation 10. Note that the summation can be limited to the trabecular bone sites that contain only active marrow.

Table 9 summarizes the different methodologies and assumptions in the calculations of absorbed fractions, bone site-specific S values, and skeletal-averaged S values. In this same table, the equations used for these calculations are reproduced.

RESULTS

Tables of bone site-specific S values are given in Appendix A for trabecular bone and in Appendix B for cortical bone. These S values were calculated using the radionuclide decay data files of Eckerman et al. (*33,34*), in which the β particle spectra are finely divided into logarithmic intervals. For trabecular bone, source and target regions considered are the TMS, TBE, TBV, and TAM. Note that S values for the TAM are only approximate because TAM cannot be considered explicitly in the transport model (*4*). For cortical bone, source regions are the CHS, CBE, and CBV, and target regions are the CBE and CBV (*5*).

TABLE 9

Summary of Calculations of Bone Site-Specific Absorbed Fractions and S Values and Skeletal-Averaged S Values for Various Source and Target Combinations

Source	Target	Absorbed fractions: ϕ	Bone site-specific S values: S_j	Skeletal-averaged S values: S_{skel}
TMS TBE TBV CHS CBE CBV	TMS TBE TBV CBE CBV CHS*	Derived directly from transport models	Use corresponding ϕ	Calculated using mass weighting $S_{Skel}(r_T \leftarrow r_S) = \sum_{j}^{\text{All bone sites}} \omega_{j,T}\omega_{j,S}S_j(r_T \leftarrow r_S)$
TMS TBE TBV	TAM	Assume uniform energy deposited across TMS $\phi_j(TAM \leftarrow r_S) = CF_j\phi_j(TMS \leftarrow r_S)$	Use corresponding ϕ $S_j(TAM \leftarrow r_S) = S_j(TMS \leftarrow r_S)$	Calculated using mass weighting $S_{Skel}(TAM \leftarrow r_S) = \sum_{j}^{\text{All bone sites with active marrow}} \omega_{j,TAM}\omega_{j,S}S_j(TAM \leftarrow r_S)$
TAM	TMS TBE TBV	Use ϕ results for TMS as source: $\phi_j(r_T \leftarrow TAM) = \phi_j(r_T \leftarrow TMS)$	Use corresponding ϕ $S_j(r_T \leftarrow TAM) = S_j(r_T \leftarrow TMS)$	Calculated using mass weighting $S_{Skel}(r_T \leftarrow TAM) = \sum_{j}^{\text{All bone sites with active marrow}} \omega_{j,T}\omega_{j,TAM}S_j(r_T \leftarrow TAM)$
TAM	TAM	Use ϕ results for TMS as both source and target $\phi_j(TAM \leftarrow TAM) = \phi_j(TMS \leftarrow TMS)$	Use corresponding ϕ $S_j(TAM \leftarrow TAM) = \dfrac{S_j(TMS \leftarrow TMS)}{CF_j}$	Calculated using mass weighting $S_{Skel}(TAM \leftarrow TAM) = \sum_{j}^{\text{All bone sites with active marrow}} \omega_{j,TAM}\omega_{j,TAM}S_j(TAM \leftarrow TAM)$

*S values for CHS as target region are not given because of lack of available data to derive their corresponding reference masses.

TABLE 10

Radiation Characteristics of Radionuclides Used for Calculation of S Values

	Mode of decay	Average energy (MeV)*	Maximum energy (MeV)*	Half-life (d)*	Δ (electron) (g-mGy/MBq-s)†	Δ (photon) (g-mGy/MBq-s)†
^{32}P	β-	0.695	1.710	14.3	1.16E−01	0.00E+00
^{33}P	β-	0.077	0.249	25.3	1.28E−02	0.00E+00
^{89}Sr	β-	0.583	1.492	50.5	9.74E−02	1.35E−05
^{90}Sr	β-	0.196	0.546	10,416	3.30E−02	0.00E+00
^{90}Y	β-	0.934	2.282	2.67	1.56E−01	2.70E−07
^{117m}Sn	IT	0.135	0.159	13.6	2.58E−02	2.53E−02
^{153}Sm	β-	0.225	0.809	1.95	4.50E−02	9.91E−03
^{169}Er	β-	0.100	0.351	9.40	1.74E−02	1.52E−06
^{177}Lu	β-	0.133	0.498	6.71	2.46E−02	5.61E−03
^{186}Re	β- and EC	0.323	1.075	3.78	5.76E−02	3.29E−03

*From references 24 and 40.
†From references 33 and 34.
IT = isomeric transition; EC = electron capture.

For the tabulation of S values, 10 radionuclides are considered with radiation characteristics given in Table 10. In all but 3 of these radionuclides, the photon component of the emission spectrum is either very small or totally absent (i.e., pure β emitters). For ^{117m}Sn, ^{153}Sm, and ^{177}Lu, the S value reported here represents only the electron and β particle component of the total S value. As noted in Table 10, the ratios of the mean energies emitted per nuclear transition for the electron and photon emission components for these 3 radionuclides are 1.0, 4.5, and 4.4, respectively.

Skeletal-averaged S values were subsequently calculated for all source and target combinations and are given in Table 11 for all 10 radionuclides. Because masses were not available for the CHS, it was assumed that the volume of tissue within the Haversian canal space was proportional to the volume of cortical bone. Consequently, in determining skeletal-average S values for CHS sources, the mass fractions of cortical bone were used in the weighting expressions.

DISCUSSION

Comparison of Skeletal S Values with Previous Calculations

TAM as Both Source and Target. It is interesting to compare our calculated skeletal-averaged S values with those currently used in clinical medicine. Table 12 gives the different skeletal-averaged S values compiled from the MIRD 11, MIRDOSE2, and MIRDOSE3 datasets for 2 pure β emitters: ^{32}P and ^{90}Y.

When the TAM is considered as both the source and the target region, our calculated S values are found to be larger than those given in MIRD 11 and MIRDOSE3, yet smaller than those given by MIRDOSE2. Differences between the MIRD 11 S values and our values are attributed to the large change in the reference mass for the active marrow from 1500 to 1170 g. If the MIRD 11 S values are rescaled to an active marrow mass of 1170 g, differences of less than 5% are seen. Differences between our values and those of the MIRDOSE2 program (ratio of ~0.7 for both ^{32}P and ^{90}Y) are mainly the result of differences in the underlying models for the absorbed fraction. An absorbed fraction of unity is assumed within MIRDOSE2 for a TAM source and target, whereas our values obtained from 3-dimensional transport decrease with increasing particle energy.

Differences between our values and those of MIRDOSE3 may come from several sources: (a) reference masses for active marrow, (b) absorbed fraction values (1-dimensional versus 3-dimensional transport), and (c) weighting schemes for obtaining site-specific and skeletal-averaged S values. By using both a reference mass of 1120 g for the active marrow in the adult as well as absorbed fractions obtained from a 1-dimensional transport model (*4*) similar to that constructed by Eckerman (*20*), differences in methodology can be isolated to differences in the weighting schemes used. Using data for ^{32}P and ^{90}Y, very good agreement was found between MIRDOSE3 skeletal-averaged S values (4.41×10^{-5} and 5.87×10^{-5} mGy/MBq-s, respectively) and those

TABLE 11
Skeletal-Averaged S Values (mGy/MBq-s) for Different Combinations of Source and Target Regions for Trabecular and Cortical Bone

Skeletal region	^{32}P	^{33}P	^{89}Sr	^{90}Sr	^{90}Y	^{117m}Sn*	^{153}Sm*	^{169}Er	^{177}Lu*	^{186}Re
S_{Skel}(TAM ← TAM)	6.58E−05	9.57E−06	5.58E−05	2.11E−05	8.76E−05	1.88E−05	2.97E−05	1.24E−05	1.69E−05	3.50E−05
S_{Skel}(TMS ← TAM)	2.57E−05	3.75E−06	2.18E−05	8.25E−06	3.43E−05	7.34E−06	1.16E−05	4.86E−06	6.61E−06	1.37E−05
S_{Skel}(TBE ← TAM)	7.63E−05	4.83E−06	6.33E−05	1.75E−05	1.05E−04	1.06E−05	2.28E−05	7.15E−06	1.15E−05	3.46E−05
S_{Skel}(TBV ← TAM)	3.30E−05	1.22E−06	2.71E−05	6.66E−06	4.58E−05	2.99E−06	8.46E−06	2.20E−06	3.91E−06	1.41E−05
S_{Skel}(TAM ← TMS)	2.59E−05	3.76E−06	2.20E−05	8.28E−06	3.45E−05	7.36E−06	1.17E−05	4.88E−06	6.63E−06	1.38E−05
S_{Skel}(TMS ← TMS)	2.59E−05	3.76E−06	2.20E−05	8.28E−06	3.45E−05	7.36E−06	1.17E−05	4.88E−06	6.63E−06	1.38E−05
S_{Skel}(TBE ← TMS)	7.51E−05	4.68E−06	6.22E−05	1.70E−05	1.03E−04	1.03E−05	2.23E−05	6.94E−06	1.12E−05	3.39E−05
S_{Skel}(TBV ← TMS)	3.26E−05	1.20E−06	2.68E−05	6.59E−06	4.52E−05	2.95E−06	8.36E−06	2.17E−06	3.86E−06	1.40E−05
S_{Skel}(TAM ← TBE)	2.45E−05	1.82E−06	2.04E−05	5.97E−06	3.35E−05	3.88E−06	7.85E−06	2.61E−06	4.07E−06	1.14E−05
S_{Skel}(TMS ← TBE)	2.45E−05	1.82E−06	2.04E−05	5.97E−06	3.35E−05	3.88E−06	7.85E−06	2.61E−06	4.07E−06	1.14E−05
S_{Skel}(TBE ← TBE)	8.87E−05	2.49E−05	7.66E−05	3.51E−05	1.16E−04	3.81E−05	6.54E−05	3.21E−05	3.47E−05	5.39E−05
S_{Skel}(TBV ← TBE)	3.57E−05	5.35E−06	3.04E−05	1.21E−05	4.71E−05	1.10E−05	1.61E−05	6.82E−06	9.62E−06	1.94E−05
S_{Skel}(TAM ← TBV)	2.26E−05	7.69E−07	1.86E−05	4.42E−06	3.16E−05	1.89E−06	5.64E−06	1.41E−06	2.55E−06	9.59E−06
S_{Skel}(TMS ← TBV)	2.26E−05	7.69E−07	1.86E−05	4.42E−06	3.16E−05	1.89E−06	5.64E−06	1.41E−06	2.55E−06	9.59E−06
S_{Skel}(TBE ← TBV)	8.44E−05	9.03E−06	7.14E−05	2.54E−05	1.12E−04	1.98E−05	3.25E−05	1.25E−05	1.85E−05	4.34E−05
S_{Skel}(TBV ← TBV)	4.20E−05	1.02E−05	3.66E−05	1.79E−05	5.37E−05	1.92E−05	2.63E−05	1.25E−05	1.60E−05	2.62E−05
S_{Skel}(CBE ← CHS)	5.37E−05	1.83E−05	4.78E−05	2.73E−05	6.63E−05	3.15E−05	4.17E−05	2.05E−05	2.61E−05	3.72E−05
S_{Skel}(CBV ← CHS)	2.26E−05	1.27E−06	1.87E−05	5.19E−06	3.11E−05	3.02E−06	6.56E−06	2.01E−06	3.32E−06	1.02E−05
S_{Skel}(CBE ← CBE)	5.46E−05	2.98E−05	4.93E−05	3.18E−05	6.73E−05	4.27E−05	6.88E−05	3.74E−05	3.69E−05	4.30E−05
S_{Skel}(CBV ← CBE)	2.38E−05	2.08E−06	1.99E−05	6.26E−06	3.23E−05	4.48E−06	8.16E−06	2.91E−06	4.42E−06	1.14E−05
S_{Skel}(CBE ← CBV)	3.88E−05	3.24E−06	3.26E−05	1.03E−05	5.16E−05	7.11E−06	1.32E−05	4.63E−06	7.13E−06	1.88E−05
S_{Skel}(CBV ← CBV)	2.40E−05	2.73E−06	2.02E−05	6.84E−06	3.24E−05	5.46E−06	9.46E−06	3.66E−06	5.18E−06	1.20E−05

*S values for these radionuclides include only the electron or β component of emission spectrum.

TABLE 12

Comparison of Skeletal-Averaged S Values (mGy/MBq-s) Between MIRD 11, MIRDOSE 2, MIRDOSE3, and the Present Skeletal Dosimetry Model for Different Source–Target Combinations

	^{32}P				^{90}Y			
Target* ← Source	MIRD 11	MIRDOSE2	MIRDOSE3	New model	MIRD 11	MIRDOSE2	MIRDOSE3	New model
S_{Skel}(TAM ← TAM)	4.88E−05	9.91E−05	4.41E−05	6.58E−05	6.46E−05	1.34E−04	5.87E−05	8.76E−05
S_{Skel}(TAM ← TBE)	—	—	2.83E−05	2.45E−05	—	—	3.84E−05	3.35E−05
S_{Skel}(TAM ← TBV)	3.23E−05	4.96E−05	2.64E−05	2.26E−05	4.28E−05	6.67E−05	3.65E−05	3.16E−05
S_{Skel}(TAM ← CBV)	1.43E−06	0.00E+00	0.00E+00	0.00E+00	2.48E−06	0.00E+00†	0.00E+00†	0.00E+000
S_{Skel}(BE ← TAM)	—	1.85E−05	2.76E−05	4.41E−05‡	—	2.49E−05	3.71E−05	6.06E−05‡
S_{Skel}(BE ← TBE)	—	—	3.26E−05	5.12E−05‡	—	—	4.17E−05	6.70E−05‡
S_{Skel}(BE ← CBE)	—	—	4.89E−06	2.31E−05‡	—	—	4.74E−06	2.84E−05‡
S_{Skel}(BE ← TBV)	—	2.31E−05	2.75E−05	4.87E−05‡		3.12E−05	3.66E−05	6.47E−05‡
S_{Skel}(BE ← CBV)	—	1.39E−05	1.00E−06	1.64E−05‡	—	1.87E−05	9.69E−07	2.18E−05‡
S_{Skel}(BV ← TAM)	6.53E−06	—	—	5.72E−06‡	8.26E−06	—	—	7.93E−06‡
S_{Skel}(BV ← CBV)	2.25E−05	—	—	1.98E−05‡	3.00E−05	—	—	2.68E−05‡
S_{Skel}(BV ← TBV)	1.28E−05	—	—	7.28E−06‡	1.73E−05	—	—	9.30E−06‡

*In MIRD 11, MIRDOSE2, and MIRDOSE3 models, final target regions' designation did not separately consider trabecular and cortical region of both bone volume and endosteum regions.

†Only electron component.

‡Assume no cross-irradiation between trabecular and cortical bones.

In this table, bone endosteum (BE) and bone volume (BV) correspond to both cortical and trabecular regions. Note that for new model, cross-irradiation between cortical and trabecular bones is assumed to be null.

obtained using our 1-dimensional model data and the following weighting scheme:

$$S_{Skel}(\mathrm{TAM} \leftarrow \mathrm{TAM}) = \sum_{j}^{\substack{\text{All Bone Sites}\\ \text{with Active Marrow}}} \omega_{j,\mathrm{TAM}}\, \omega_{j,\mathrm{TAM}}\, S_j(\mathrm{TMS} \leftarrow \mathrm{TMS}), \quad \text{Eq. 19}$$

(4.5×10^{-5} and 6.0×10^{-5} mGy/MBq-s, respectively). Consequently, we deduce that the implicit assumption made in MIRDOSE3 is that:

$$S_j(\mathrm{TAM} \leftarrow \mathrm{TAM}) = S_j(\mathrm{TMS} \leftarrow \mathrm{TMS}). \quad \text{Eq. 20}$$

In terms of absorbed fractions, MIRDOSE3 thus assumes:

$$\phi_j(\mathrm{TAM} \leftarrow \mathrm{TAM}) = CF_j\, \phi_j(\mathrm{TMS} \leftarrow \mathrm{TMS}). \quad \text{Eq. 21}$$

This approximation greatly underestimates the absorbed fraction, particularly at low electron energies where the absorbed fraction should approach unity for a TAM source and target (all energy deposited within the source region). Consequently, the model assumption given by Equations 20 and 21 provides an explanation for the lower skeletal-averaged S values given in MIRDOSE3 when compared with those of the skeletal dosimetry model proposed here.

TAM as Only the Target Region. Other comparisons for TAM targets and TBE or TBV sources show that the new S values are ~15% lower than those from MIRDOSE3, due primarily to our consideration of the marrow space as defined as the marrow cavity minus its endosteal layers within the present model. MIRDOSE3 does not make this distinction. The large difference between our S values and those of MIRDOSE2 for trabecular bone volume sources may be traced to the use of the ICRP 30 bone model within MIRDOSE2. Here, MIRDOSE2 assigns both ^{32}P and ^{90}Y as surface-seekers, because their physical half-lives are less than 15 d (bone volume sources are not allowed for these radionuclides). An energy-independent absorbed fraction of 0.5 is thus used in MIRDOSE2. This value is considerably higher than our energy-dependent values of absorbed fractions for TBV sources (*4*). Finally, one can note that the dose contribution from the CBV to the TAM is assumed to be equal to zero for all models except that in MIRD 11.

TBE as Target Region. When one considers the bone endosteum (both cortical and trabecular) as the target region, higher S values are calculated using our model. The absorbed fraction values to the TBE were seen to be higher in our model for all sources than the absorbed fractions given by the model used in MIRDOSE3 (*4*). These increases in radionuclide S values occur even though the total reference mass of endosteum has increased from 120 to 155 g. For sources in cortical bone, S values determined by our model are roughly equivalent to those given by the MIRDOSE2 and ICRP 30 models but are substantially higher than those given in MIRDOSE3. Detailed explanations of these differences cannot be given because the cortical bone model of MIRDOSE3 has not yet been published.

Trabecular and Cortical Bone as Target Regions. The last possible comparison is for the bone volume as the target region. Only in MIRD 11 and in the present model are S values given for a bone volume target. Very good agreement is seen when the TAM or the CBV is considered source region, and, in these cases, the differences are mainly the result of the change in the reference mass for total bone (5000 g in MIRD 11 and 5500 g in both ICRP 70 and our model). In the case of a TBV source region and a BV target region, differences with MIRD 11 can be attributed to a difference in the absorbed fraction of energy. Using the data from MIRD 11, we estimate that Snyder et al. (*13*) used an effective absorbed fraction for self-irradiation of trabecular bone of ~0.55. This value exceeds values given in our model (~0.4 at 500 keV, ~0.3 at 1 MeV).

Assumptions and Limitations

The skeletal dosimetry model presented in this article, as well as the 2 preceding articles, is intended to provide more realistic estimates of marrow, endosteal, and bone tissue dose than previous models. Furthermore, the model has been presented in such a fashion as to make clear all underlying sources of input data and theoretic assumptions applied. Although already more than 25 y old, the chord length distributions measured by Spiers' group (*7*) still provide the most complete information available on the 3-dimensional microstructure of both trabecular and cortical bone (*7*). Thus, this information is used in the transport models for both trabecular and cortical bone. Reference tissue masses used in the model are derived from data taken from the most recent ICRP recommendations (*12*). These data in turn, however, are taken from studies made in the early part of the 1900s. Clearly, new sources of data on marrow mass and its fractional distribution within the skeleton are needed.

Because the location of the TAM within the marrow space is not known, various assumptions were also used to derive S values for this region. In the case of the TAM as a target region, it was assumed that the energy was uniformly distributed across the entire marrow space. For the case of a TAM source region, results of absorbed fractions to the TMS were used in the calculations of S values, giving an overestimate of the true S value. This overestimate is a function of the CF for the trabecular bone site considered (greater for bone sites with smaller percentages of active marrow), the spatial distribution of the active marrow within the marrow spaces, and the initial energy of the electron.

The proposed model, like those underlying the radionuclide S values of MIRD 11, MIRDOSE2, and MIRDOSE3, is a Reference Man model developed to represent an average population. One may recall that the original work of Spiers was performed for radiation protection purposes (*6–9*), yet his data underlie skeletal dosimetry models currently used in clinical practice. Patients undergoing radionuclide therapy procedures for which these S values are generally applied have low marrow reserves as a result of previous chemotherapy treatments. Furthermore, these patients may be elderly and suffer from osteoporosis, thus displaying a trabecular microstructure very different from Spiers's original 44-y-old reference man. In these cases, patient-specific skeletal dosimetry would give improved correlations between marrow dose estimates and marrow toxicity effects. Techniques needed to calculate patient-specific S values for all skeletal sites, however, are currently unavailable. Instead, current efforts have been devoted to making patient-specific estimates of source activity (*2,3,35–37*) and using reference S values obtained from either MIRD 11, MIRDOSE2, or MIRDOSE3. Some of these activity quantification techniques attempt to estimate an activity concentration within the active marrow. If patient-specific marrow masses are not available, reference masses are then used to provide measures of total skeletal activity ($A_{Skel,S}$) as defined and used earlier in Equation 6. In this case, it is important that these reference masses be consistent with those used in the determination of both site-specific and skeletal-averaged S values. Furthermore, it is important that these skeletal masses be fully documented and referenced. The large change in the reference mass of active marrow from 1500 g in MIRD 11 to 1120 g in MIRDOSE3 is a noted example.

CONCLUSION

Skeletal S values have been derived on the basis of 2 new 3-dimensional electron transport models in both trabecular and cortical bone (*4,5*) and on new reference masses derived from ICRP 70 (*12*). These S values are tabulated for 22 different bone sites within the human skeletal system. A skeletal-averaged S value is also given based on these 22 site-specific S values. Source and target regions considered for the tabulation of S values are TAM, TMS, TBE, and TBV for the trabecular bone sites and the CHS, CBE, and CBV for the cortical bone sites.

Comparisons between the new calculated S values with other published data show that a greater number of source and target combinations are considered within the new model. A difference in methodology was also seen from the MIRDOSE3 data for the TAM as both a source and a target, in which the S value to the TAM was underestimated, particularly at low electron energies. Other differences were attributed to more accurate electron transport models in both trabecular and cortical bone and newer and more fully documented reference masses.

The S values presented in this paper will allow better estimates of the dose to the skeletal system. If regional skeletal activity concentration is available, it is advisable that tabulated bone site-specific S values are used rather than skeletal-averaged S values when considering the large variation in marrow and endosteal dose across the skeleton.

APPENDIX A

TABLE 1A

S Values (mGy/MBq-s) for TMS Target and Radionuclide Source Located Within TMS*

Skeletal region	^{32}P	^{33}P	^{89}Sr	^{90}Sr	^{90}Y	^{117m}Sn†	^{153}Sm†	^{169}Er	^{177}Lu†	^{186}Re
Cranium	1.43E−04	3.86E−05	1.25E−04	6.33E−05	1.84E−04	7.19E−05	9.56E−05	4.68E−05	5.85E−05	9.09E−05
Mandible	1.51E−03	4.08E−04	1.32E−03	6.68E−04	1.94E−03	7.59E−04	1.01E−03	4.94E−04	6.17E−04	9.59E−04
Cervical vertebra	1.11E−03	1.69E−04	9.40E−04	3.63E−04	1.47E−03	3.31E−04	5.15E−04	2.19E−04	2.95E−04	5.95E−04
Thoracic vertebra	2.91E−04	4.23E−05	2.47E−04	9.34E−05	3.88E−04	8.31E−05	1.32E−04	5.50E−05	7.48E−05	1.55E−04
Lumbar vertebra	4.06E−04	5.62E−05	3.44E−04	1.28E−04	5.41E−04	1.11E−04	1.79E−04	7.36E−05	1.01E−04	2.14E−04
Sternum	1.78E−03	2.36E−04	1.51E−03	5.52E−04	2.38E−03	4.68E−04	7.69E−04	3.12E−04	4.31E−04	9.33E−04
Ribs	3.35E−04	4.44E−05	2.84E−04	1.04E−04	4.47E−04	8.81E−05	1.45E−04	5.86E−05	8.10E−05	1.75E−04
Scapulae	8.90E−04	1.29E−04	7.54E−04	2.83E−04	1.19E−03	2.52E−04	4.00E−04	1.67E−04	2.27E−04	4.71E−04
Clavicles	2.78E−03	4.02E−04	2.36E−03	8.84E−04	3.71E−03	7.87E−04	1.25E−03	5.21E−04	7.08E−04	1.47E−03
Os coxae	2.04E−04	2.94E−05	1.73E−04	6.47E−05	2.72E−04	5.76E−05	9.14E−05	3.82E−05	5.19E−05	1.08E−04
Sacrum	3.60E−04	5.20E−05	3.05E−04	1.14E−04	4.81E−04	1.02E−04	1.62E−04	6.75E−05	9.17E−05	1.91E−04
Humeri, upper half	1.22E−03	1.70E−04	1.03E−03	3.81E−04	1.63E−03	3.34E−04	5.36E−04	2.21E−04	3.03E−04	6.40E−04
Humeri, lower half	1.24E−03	1.72E−04	1.05E−03	3.88E−04	1.65E−03	3.39E−04	5.45E−04	2.25E−04	3.08E−04	6.51E−04
Radii	2.83E−03	3.93E−04	2.40E−03	8.89E−04	3.78E−03	7.75E−04	1.25E−03	5.14E−04	7.04E−04	1.49E−03
Ulnae	2.76E−03	3.83E−04	2.33E−03	8.65E−04	3.68E−03	7.55E−04	1.21E−03	5.01E−04	6.85E−04	1.45E−03
Hands	8.32E−04	1.15E−04	7.04E−04	2.61E−04	1.11E−03	2.28E−04	3.66E−04	1.51E−04	2.07E−04	4.37E−04
Femora, upper half	5.23E−04	7.28E−05	4.42E−04	1.63E−04	6.99E−04	1.43E−04	2.30E−04	9.50E−05	1.30E−04	2.74E−04
Femora, lower half	5.31E−04	7.37E−05	4.49E−04	1.66E−04	7.08E−04	1.45E−04	2.34E−04	9.63E−05	1.32E−04	2.79E−04
Patellae	2.78E−03	3.87E−04	2.36E−03	8.74E−04	3.72E−03	7.62E−04	1.23E−03	5.06E−04	6.92E−04	1.46E−03
Tibiae	4.17E−04	5.80E−05	3.54E−04	1.31E−04	5.57E−04	1.14E−04	1.84E−04	7.58E−05	1.04E−04	2.20E−04
Fibulae	2.96E−03	4.11E−04	2.51E−03	9.30E−04	3.96E−03	8.11E−04	1.30E−03	5.38E−04	7.37E−04	1.56E−03
Feet	2.71E−04	3.76E−05	2.29E−04	8.50E−05	3.61E−04	7.41E−05	1.19E−04	4.92E−05	6.73E−05	1.42E−04

*These values are equivalent to those for TAM target and radionuclide source located within TMS.
†S values for these radionuclides include only the electron and β component of emission spectrum.

TABLE 2A

S Values (mGy/MBq-s) for TBE Target and Radionuclide Source Located Within TMS*

Skeletal region	^{32}P	^{33}P	^{89}Sr	^{90}Sr	^{90}Y	^{117m}Sn†	^{153}Sm†	^{169}Er	^{177}Lu†	^{186}Re
Cranium	4.10E−03	4.77E−04	3.45E−03	1.20E−03	5.48E−03	9.98E−04	1.59E−03	6.26E−04	9.10E−04	2.08E−03
Mandible	3.69E−02	4.30E−03	3.11E−02	1.08E−02	4.93E−02	8.98E−03	1.43E−02	5.63E−03	8.19E−03	1.87E−02
Cervical vertebra	1.27E−03	7.88E−05	1.05E−03	2.89E−04	1.74E−03	1.73E−04	3.78E−04	1.17E−04	1.89E−04	5.75E−04
Thoracic vertebra	4.67E−04	2.78E−05	3.87E−04	1.04E−04	6.41E−04	6.11E−05	1.36E−04	4.17E−05	6.78E−05	2.10E−04
Lumbar vertebra	5.34E−04	3.02E−05	4.41E−04	1.17E−04	7.35E−04	6.68E−05	1.53E−04	4.60E−05	7.54E−05	2.37E−04
Sternum	2.57E−02	1.36E−03	2.12E−02	5.46E−03	3.56E−02	3.01E−03	7.13E−03	2.09E−03	3.47E−03	1.12E−02
Ribs	2.57E−03	1.36E−04	2.12E−03	5.46E−04	3.56E−03	3.01E−04	7.13E−04	2.09E−04	3.47E−04	1.12E−03
Scapulae	7.64E−03	4.59E−04	6.33E−03	1.73E−03	1.05E−02	1.01E−03	2.26E−03	6.92E−04	1.13E−03	3.46E−03
Clavicles	2.55E−02	1.53E−03	2.11E−02	5.78E−03	3.49E−02	3.38E−03	7.53E−03	2.31E−03	3.75E−03	1.15E−02
Os coxae	1.82E−03	1.09E−04	1.51E−03	4.13E−04	2.49E−03	2.41E−04	5.38E−04	1.65E−04	2.68E−04	8.23E−04
Sacrum	2.73E−03	1.64E−04	2.26E−03	6.19E−04	3.74E−03	3.62E−04	8.07E−04	2.47E−04	4.02E−04	1.23E−03
Humeri, upper half	3.82E−03	2.10E−04	3.16E−03	8.29E−04	5.26E−03	4.66E−04	1.08E−03	3.20E−04	5.29E−04	1.69E−03
Humeri, lower half	3.48E−03	1.89E−04	2.87E−03	7.48E−04	4.81E−03	4.19E−04	9.80E−04	2.88E−04	4.77E−04	1.54E−03
Radii	3.92E−03	2.13E−04	3.23E−03	8.41E−04	5.41E−03	4.71E−04	1.10E−03	3.24E−04	5.36E−04	1.73E−03
Ulnae	3.13E−03	1.70E−04	2.59E−03	6.73E−04	4.33E−03	3.77E−04	8.82E−04	2.59E−04	4.29E−04	1.38E−03
Hands	8.95E−03	4.86E−04	7.39E−03	1.92E−03	1.24E−02	1.08E−03	2.52E−03	7.41E−04	1.23E−03	3.95E−03
Femora, upper half	6.14E−04	3.37E−05	5.07E−04	1.33E−04	8.45E−04	7.48E−05	1.74E−04	5.15E−05	8.50E−05	2.72E−04
Femora, lower half	5.60E−04	3.04E−05	4.62E−04	1.20E−04	7.73E−04	6.73E−05	1.57E−04	4.63E−05	7.66E−05	2.47E−04
Patellae	1.04E−02	5.67E−04	8.62E−03	2.24E−03	1.44E−02	1.26E−03	2.94E−03	8.64E−04	1.43E−03	4.61E−03
Tibiae	6.27E−04	3.40E−05	5.17E−04	1.35E−04	8.65E−04	7.54E−05	1.76E−04	5.19E−05	8.58E−05	2.77E−04
Fibulae	4.82E−03	2.62E−04	3.98E−03	1.04E−03	6.66E−03	5.80E−04	1.36E−03	3.99E−04	6.60E−04	2.13E−03
Feet	4.18E−03	2.27E−04	3.45E−03	8.97E−04	5.77E−03	5.03E−04	1.18E−03	3.46E−04	5.72E−04	1.84E−03

*These values are equivalent to those for TBE target and radionuclide source located within TAM.
†S values for these radionuclides include only the electron and β component of emission spectrum.

TABLE 3A

S Values (mGy/MBq-s) for TBV Target and Radionuclide Source Located Within TMS*

Skeletal region	^{32}P	^{33}P	^{89}Sr	^{90}Sr	^{90}Y	^{117m}Sn†	^{153}Sm†	^{169}Er	^{177}Lu†	^{186}Re
Cranium	1.72E−03	6.93E−05	1.42E−03	3.64E−04	2.38E−03	1.69E−04	4.60E−04	1.23E−04	2.16E−04	7.56E−04
Mandible	1.70E−02	6.82E−04	1.40E−02	3.58E−03	2.34E−02	1.67E−03	4.53E−03	1.21E−03	2.13E−03	7.44E−03
Cervical vertebra	5.76E−04	2.11E−05	4.74E−04	1.16E−04	7.99E−04	5.17E−05	1.48E−04	3.82E−05	6.82E−05	2.48E−04
Thoracic vertebra	1.95E−04	7.05E−06	1.60E−04	3.89E−05	2.71E−04	1.73E−05	4.95E−05	1.27E−05	2.27E−05	8.32E−05
Lumbar vertebra	2.19E−04	7.80E−06	1.80E−04	4.29E−05	3.06E−04	1.91E−05	5.48E−05	1.40E−05	2.51E−05	9.26E−05
Sternum	1.19E−02	3.70E−04	9.71E−03	2.15E−03	1.69E−02	9.04E−04	2.79E−03	6.74E−04	1.23E−03	4.85E−03
Ribs	1.02E−03	3.18E−05	8.34E−04	1.85E−04	1.45E−03	7.76E−05	2.39E−04	5.78E−05	1.06E−04	4.16E−04
Scapulae	2.93E−03	1.13E−04	2.42E−03	6.08E−04	4.06E−03	2.77E−04	7.69E−04	2.03E−04	3.59E−04	1.27E−03
Clavicles	9.16E−03	3.53E−04	7.55E−03	1.90E−03	1.27E−02	8.65E−04	2.40E−03	6.34E−04	1.12E−03	3.98E−03
Os coxae	6.61E−04	2.55E−05	5.45E−04	1.37E−04	9.15E−04	6.25E−05	1.73E−04	4.58E−05	8.09E−05	2.87E−04
Sacrum	1.15E−03	4.45E−05	9.51E−04	2.39E−04	1.60E−03	1.09E−04	3.02E−04	7.99E−05	1.41E−04	5.01E−04
Humeri, upper half	1.41E−03	5.31E−05	1.16E−03	2.90E−04	1.95E−03	1.30E−04	3.67E−04	9.60E−05	1.71E−04	6.11E−04
Humeri, lower half	1.38E−03	4.80E−05	1.13E−03	2.72E−04	1.91E−03	1.18E−04	3.47E−04	8.77E−05	1.58E−04	5.86E−04
Radii	1.56E−03	5.44E−05	1.28E−03	3.09E−04	2.17E−03	1.33E−04	3.93E−04	9.93E−05	1.79E−04	6.64E−04
Ulnae	1.24E−03	4.32E−05	1.02E−03	2.45E−04	1.72E−03	1.06E−04	3.12E−04	7.88E−05	1.42E−04	5.27E−04
Hands	3.57E−03	1.25E−04	2.94E−03	7.07E−04	4.96E−03	3.06E−04	9.01E−04	2.28E−04	4.10E−04	1.52E−03
Femora, upper half	2.19E−04	8.25E−06	1.80E−04	4.51E−05	3.03E−04	2.02E−05	5.70E−05	1.49E−05	2.65E−05	9.48E−05
Femora, lower half	2.14E−04	7.46E−06	1.76E−04	4.23E−05	2.97E−04	1.83E−05	5.39E−05	1.36E−05	2.45E−05	9.10E−05
Patellae	3.90E−03	1.36E−04	3.20E−03	7.71E−04	5.42E−03	3.34E−04	9.83E−04	2.48E−04	4.48E−04	1.66E−03
Tibiae	2.47E−04	8.63E−06	2.03E−04	4.90E−05	3.44E−04	2.12E−05	6.24E−05	1.58E−05	2.84E−05	1.05E−04
Fibulae	1.85E−03	6.46E−05	1.52E−03	3.66E−04	2.57E−03	1.58E−04	4.67E−04	1.18E−04	2.13E−04	7.89E−04
Feet	1.67E−03	5.83E−05	1.37E−03	3.31E−04	2.32E−03	1.43E−04	4.21E−04	1.06E−04	1.92E−04	7.12E−04

*These values are equivalent to those for TBV target and radionuclide source located within TAM.
†S values for these radionuclides include only the electron and β component of emission spectrum.

TABLE 4A

S Values (mGy/MBq-s) for TMS Target and Radionuclide Source Located Within TBE*

Skeletal region	^{32}P	^{33}P	^{89}Sr	^{90}Sr	^{90}Y	^{117m}Sn†	^{153}Sm†	^{169}Er	^{177}Lu†	^{186}Re
Cranium	1.24E−04	1.60E−05	1.05E−04	3.78E−05	1.66E−04	3.25E−05	5.09E−05	2.05E−05	2.94E−05	6.40E−05
Mandible	1.31E−03	1.69E−04	1.10E−03	3.99E−04	1.75E−03	3.43E−04	5.38E−04	2.17E−04	3.10E−04	6.76E−04
Cervical vertebra	1.01E−03	7.85E−05	8.43E−04	2.49E−04	1.38E−03	1.66E−04	3.29E−04	1.11E−04	1.72E−04	4.74E−04
Thoracic vertebra	2.66E−04	2.00E−05	2.21E−04	6.50E−05	3.64E−04	4.24E−05	8.55E−05	2.85E−05	4.44E−05	1.24E−04
Lumbar vertebra	3.70E−04	2.70E−05	3.08E−04	8.98E−05	5.07E−04	5.75E−05	1.18E−04	3.89E−05	6.09E−05	1.72E−04
Sternum	1.61E−03	1.15E−04	1.34E−03	3.88E−04	2.22E−03	2.47E−04	5.08E−04	1.67E−04	2.62E−04	7.45E−04
Ribs	3.04E−04	2.16E−05	2.52E−04	7.30E−05	4.17E−04	4.64E−05	9.55E−05	3.14E−05	4.93E−05	1.40E−04
Scapulae	8.27E−04	6.31E−05	6.89E−04	2.05E−04	1.13E−03	1.34E−04	2.69E−04	9.01E−05	1.40E−04	3.88E−04
Clavicles	2.59E−03	1.97E−04	2.15E−03	6.41E−04	3.53E−03	4.20E−04	8.40E−04	2.82E−04	4.39E−04	1.21E−03
Os coxae	1.89E−04	1.44E−05	1.58E−04	4.69E−05	2.58E−04	3.07E−05	6.15E−05	2.06E−05	3.21E−05	8.88E−05
Sacrum	3.35E−04	2.55E−05	2.79E−04	8.29E−05	4.57E−04	5.43E−05	1.09E−04	3.65E−05	5.68E−05	1.57E−04
Humeri, upper half	1.13E−03	8.30E−05	9.38E−04	2.74E−04	1.54E−03	1.77E−04	3.60E−04	1.19E−04	1.87E−04	5.24E−04
Humeri, lower half	1.14E−03	8.30E−05	9.45E−04	2.74E−04	1.56E−03	1.76E−04	3.61E−04	1.19E−04	1.86E−04	5.27E−04
Radii	2.60E−03	1.90E−04	2.16E−03	6.28E−04	3.57E−03	4.04E−04	8.27E−04	2.72E−04	4.27E−04	1.21E−03
Ulnae	2.53E−03	1.85E−04	2.11E−03	6.11E−04	3.47E−03	3.93E−04	8.05E−04	2.65E−04	4.15E−04	1.17E−03
Hands	7.65E−04	5.58E−05	6.36E−04	1.84E−04	1.05E−03	1.19E−04	2.43E−04	7.99E−05	1.25E−04	3.54E−04
Femora, upper half	4.84E−04	3.56E−05	4.02E−04	1.18E−04	6.62E−04	7.57E−05	1.55E−04	5.11E−05	8.00E−05	2.25E−04
Femora, lower half	4.88E−04	3.56E−05	4.05E−04	1.18E−04	6.68E−04	7.57E−05	1.55E−04	5.10E−05	7.99E−05	2.26E−04
Patellae	2.56E−03	1.87E−04	2.13E−03	6.18E−04	3.51E−03	3.97E−04	8.13E−04	2.68E−04	4.20E−04	1.19E−03
Tibiae	3.84E−04	2.80E−05	3.19E−04	9.26E−05	5.26E−04	5.96E−05	1.22E−04	4.01E−05	6.29E−05	1.78E−04
Fibulae	2.72E−03	1.99E−04	2.26E−03	6.57E−04	3.73E−03	4.23E−04	8.65E−04	2.85E−04	4.46E−04	1.26E−03
Feet	2.49E−04	1.82E−05	2.07E−04	6.01E−05	3.41E−04	3.86E−05	7.90E−05	2.60E−05	4.08E−05	1.15E−04

*These values are equivalent to those for TAM target and radionuclide source located within TBE.
†S values for these radionuclides include only the electron and β component of emission spectrum.

TABLE 5A
S Values (mGy/MBq-s) for TBE Target and Radionuclide Source Located Within TBE

Skeletal region	^{32}P	^{33}P	^{89}Sr	^{90}Sr	^{90}Y	^{117m}Sn*	^{153}Sm*	^{169}Er	^{177}Lu*	^{186}Re
Cranium	4.35E−03	1.30E−03	3.75E−03	1.71E−03	5.72E−03	1.96E−03	3.29E−03	1.63E−03	1.75E−03	2.64E−03
Mandible	3.91E−02	1.17E−02	3.37E−02	1.54E−02	5.15E−02	1.77E−02	2.97E−02	1.47E−02	1.58E−02	2.38E−02
Cervical vertebra	1.44E−03	3.77E−04	1.23E−03	5.40E−04	1.90E−03	5.77E−04	1.00E−03	4.86E−04	5.29E−04	8.47E−04
Thoracic vertebra	5.47E−04	1.50E−04	4.71E−04	2.14E−04	7.17E−04	2.31E−04	3.95E−04	1.93E−04	2.10E−04	3.30E−04
Lumbar vertebra	6.50E−04	1.86E−04	5.63E−04	2.65E−04	8.46E−04	2.89E−04	4.87E−04	2.40E−04	2.61E−04	4.02E−04
Sternum	3.38E−02	1.14E−02	2.96E−02	1.52E−02	4.33E−02	1.75E−02	2.86E−02	1.45E−02	1.55E−02	2.22E−02
Ribs	3.38E−03	1.14E−03	2.96E−03	1.52E−03	4.33E−03	1.75E−03	2.86E−03	1.45E−03	1.55E−03	2.22E−03
Scapulae	8.72E−03	2.28E−03	7.49E−03	3.31E−03	1.15E−02	3.51E−03	6.07E−03	2.94E−03	3.22E−03	5.16E−03
Clavicles	2.91E−02	7.58E−03	2.50E−02	1.10E−02	3.83E−02	1.17E−02	2.02E−02	9.81E−03	1.07E−02	1.72E−02
Os coxae	2.08E−03	5.42E−04	1.78E−03	7.87E−04	2.73E−03	8.36E−04	1.45E−03	7.00E−04	7.66E−04	1.23E−03
Sacrum	3.11E−03	8.13E−04	2.68E−03	1.18E−03	4.10E−03	1.25E−03	2.17E−03	1.05E−03	1.15E−03	1.84E−03
Humeri, upper half	4.47E−03	1.22E−03	3.86E−03	1.74E−03	5.87E−03	1.86E−03	3.24E−03	1.58E−03	1.71E−03	2.70E−03
Humeri, lower half	4.15E−03	1.21E−03	3.59E−03	1.67E−03	5.43E−03	1.84E−03	3.15E−03	1.56E−03	1.67E−03	2.55E−03
Radii	4.67E−03	1.36E−03	4.04E−03	1.88E−03	6.11E−03	2.07E−03	3.55E−03	1.75E−03	1.88E−03	2.87E−03
Ulnae	3.74E−03	1.09E−03	3.23E−03	1.50E−03	4.88E−03	1.65E−03	2.84E−03	1.40E−03	1.50E−03	2.30E−03
Hands	1.07E−02	3.11E−03	9.24E−03	4.30E−03	1.40E−02	4.72E−03	8.11E−03	4.01E−03	4.30E−03	6.57E−03
Femora, upper half	7.19E−04	1.96E−04	6.20E−04	2.80E−04	9.43E−04	2.99E−04	5.21E−04	2.54E−04	2.75E−04	4.33E−04
Femora, lower half	6.67E−04	1.95E−04	5.77E−04	2.69E−04	8.72E−04	2.95E−04	5.07E−04	2.51E−04	2.69E−04	4.10E−04
Patellae	1.25E−02	3.63E−03	1.08E−02	5.01E−03	1.63E−02	5.51E−03	9.46E−03	4.68E−03	5.02E−03	7.66E−03
Tibiae	7.47E−04	2.18E−04	6.46E−04	3.01E−04	9.77E−04	3.31E−04	5.68E−04	2.81E−04	3.01E−04	4.60E−04
Fibulae	5.75E−03	1.68E−03	4.97E−03	2.31E−03	7.51E−03	2.54E−03	4.37E−03	2.16E−03	2.32E−03	3.54E−03
Feet	4.98E−03	1.45E−03	4.31E−03	2.01E−03	6.51E−03	2.20E−03	3.78E−03	1.87E−03	2.01E−03	3.06E−03

*S values for these radionuclides include only the electron and β component of emission spectrum.

TABLE 6A
S Values (mGy/MBq-s) for TBV Target and Radionuclide Source Located Within TBE

Skeletal region	^{32}P	^{33}P	^{89}Sr	^{90}Sr	^{90}Y	^{117m}Sn*	^{153}Sm*	^{169}Er	^{177}Lu*	^{186}Re
Cranium	1.82E−03	1.55E−04	1.52E−03	4.78E−04	2.47E−03	3.34E−04	6.23E−04	2.19E−04	3.35E−04	8.75E−04
Mandible	1.79E−02	1.53E−03	1.50E−02	4.71E−03	2.43E−02	3.29E−03	6.13E−03	2.16E−03	3.30E−03	8.61E−03
Cervical vertebra	6.58E−04	8.74E−05	5.58E−04	2.11E−04	8.76E−04	1.82E−04	2.78E−04	1.14E−04	1.63E−04	3.48E−04
Thoracic vertebra	2.30E−04	3.31E−05	1.96E−04	7.64E−05	3.04E−04	6.82E−05	1.01E−04	4.24E−05	6.01E−05	1.24E−04
Lumbar vertebra	2.70E−04	4.27E−05	2.31E−04	9.36E−05	3.54E−04	8.73E−05	1.25E−04	5.37E−05	7.53E−05	1.49E−04
Sternum	1.59E−02	2.77E−03	1.37E−02	5.86E−03	2.06E−02	5.62E−03	7.87E−03	3.45E−03	4.79E−03	9.11E−03
Ribs	1.37E−03	2.38E−04	1.18E−03	5.03E−04	1.77E−03	4.83E−04	6.76E−04	2.97E−04	4.11E−04	7.82E−04
Scapulae	3.36E−03	4.88E−04	2.86E−03	1.11E−03	4.46E−03	1.00E−03	1.48E−03	6.22E−04	8.79E−04	1.80E−03
Clavicles	1.05E−02	1.52E−03	8.92E−03	3.47E−03	1.39E−02	3.13E−03	4.62E−03	1.94E−03	2.74E−03	5.63E−03
Os coxae	7.57E−04	1.10E−04	6.44E−04	2.50E−04	1.01E−03	2.26E−04	3.33E−04	1.40E−04	1.98E−04	4.07E−04
Sacrum	1.32E−03	1.92E−04	1.12E−03	4.37E−04	1.75E−03	3.94E−04	5.82E−04	2.44E−04	3.46E−04	7.09E−04
Humeri, upper half	1.67E−03	2.68E−04	1.43E−03	5.86E−04	2.20E−03	5.49E−04	7.80E−04	3.38E−04	4.72E−04	9.25E−04
Humeri, lower half	1.67E−03	2.68E−04	1.43E−03	5.92E−04	2.19E−03	5.52E−04	7.86E−04	3.41E−04	4.76E−04	9.30E−04
Radii	1.89E−03	3.04E−04	1.62E−03	6.71E−04	2.48E−03	6.25E−04	8.91E−04	3.86E−04	5.40E−04	1.05E−03
Ulnae	1.50E−03	2.41E−04	1.28E−03	5.33E−04	1.97E−03	4.96E−04	7.06E−04	3.06E−04	4.28E−04	8.36E−04
Hands	4.33E−03	6.97E−04	3.71E−03	1.54E−03	5.69E−03	1.43E−03	2.04E−03	8.84E−04	1.24E−03	2.42E−03
Femora, upper half	2.60E−04	4.16E−05	2.22E−04	9.10E−05	3.42E−04	8.53E−05	1.21E−04	5.24E−05	7.33E−05	1.44E−04
Femora, lower half	2.59E−04	4.17E−05	2.22E−04	9.20E−05	3.40E−04	8.57E−05	1.22E−04	5.29E−05	7.40E−05	1.44E−04
Patellae	4.73E−03	7.61E−04	4.05E−03	1.68E−03	6.20E−03	1.56E−03	2.23E−03	9.65E−04	1.35E−03	2.63E−03
Tibiae	3.00E−04	4.83E−05	2.57E−04	1.07E−04	3.94E−04	9.92E−05	1.41E−04	6.12E−05	8.57E−05	1.67E−04
Fibulae	2.24E−03	3.61E−04	1.92E−03	7.97E−04	2.95E−03	7.42E−04	1.06E−03	4.58E−04	6.41E−04	1.25E−03
Feet	2.03E−03	3.26E−04	1.73E−03	7.19E−04	2.66E−03	6.70E−04	9.54E−04	4.14E−04	5.79E−04	1.13E−03

*S values for these radionuclides include only the electron and β component of emission spectrum.

TABLE 7A
S Values (mGy/MBq-s) for TMS Target and Radionuclide Source Located Within TBV*

Skeletal region	^{32}P	^{33}P	^{89}Sr	^{90}Sr	^{90}Y	^{117m}Sn†	^{153}Sm†	^{169}Er	^{177}Lu†	^{186}Re
Cranium	1.15E−04	4.38E−06	9.46E−05	2.39E−05	1.57E−04	1.07E−05	3.02E−05	7.89E−06	1.40E−05	5.01E−05
Mandible	1.21E−03	4.62E−05	9.98E−04	2.52E−04	1.66E−03	1.13E−04	3.19E−04	8.33E−05	1.48E−04	5.29E−04
Cervical vertebra	9.58E−04	3.30E−05	7.88E−04	1.90E−04	1.33E−03	8.09E−05	2.42E−04	6.06E−05	1.10E−04	4.09E−04
Thoracic vertebra	2.49E−04	8.45E−06	2.05E−04	4.85E−05	3.48E−04	2.07E−05	6.20E−05	1.55E−05	2.80E−05	1.05E−04
Lumbar vertebra	3.44E−04	1.15E−05	2.82E−04	6.59E−05	4.82E−04	2.82E−05	8.44E−05	2.10E−05	3.81E−05	1.44E−04
Sternum	1.45E−03	4.24E−05	1.18E−03	2.56E−04	2.06E−03	1.04E−04	3.33E−04	7.83E−05	1.45E−04	5.86E−04
Ribs	2.73E−04	7.97E−06	2.22E−04	4.82E−05	3.88E−04	1.95E−05	6.26E−05	1.47E−05	2.73E−05	1.10E−04
Scapulae	7.81E−04	2.83E−05	6.43E−04	1.58E−04	1.08E−03	6.94E−05	2.00E−04	5.14E−05	9.20E−05	3.36E−04
Clavicles	2.44E−03	8.83E−05	2.01E−03	4.93E−04	3.39E−03	2.17E−04	6.26E−04	1.61E−04	2.88E−04	1.05E−03
Os coxae	1.79E−04	6.47E−06	1.47E−04	3.61E−05	2.48E−04	1.59E−05	4.58E−05	1.18E−05	2.11E−05	7.68E−05
Sacrum	3.16E−04	1.14E−05	2.60E−04	6.38E−05	4.39E−04	2.81E−05	8.10E−05	2.08E−05	3.72E−05	1.36E−04
Humeri, upper half	1.07E−03	3.83E−05	8.81E−04	2.15E−04	1.49E−03	9.41E−05	2.74E−04	7.00E−05	1.26E−04	4.60E−04
Humeri, lower half	1.07E−03	3.53E−05	8.78E−04	2.07E−04	1.49E−03	8.65E−05	2.64E−04	6.51E−05	1.19E−04	4.51E−04
Radii	2.45E−03	8.07E−05	2.01E−03	4.73E−04	3.42E−03	1.98E−04	6.05E−04	1.49E−04	2.72E−04	1.03E−03
Ulnae	2.38E−03	7.86E−05	1.96E−03	4.60E−04	3.33E−03	1.93E−04	5.89E−04	1.45E−04	2.64E−04	1.01E−03
Hands	7.19E−04	2.37E−05	5.90E−04	1.39E−04	1.00E−03	5.81E−05	1.78E−04	4.37E−05	7.98E−05	3.03E−04
Femora, upper half	4.60E−04	1.64E−05	3.78E−04	9.24E−05	6.39E−04	4.04E−05	1.17E−04	3.00E−05	5.38E−05	1.97E−04
Femora, lower half	4.59E−04	1.51E−05	3.76E−04	8.86E−05	6.40E−04	3.71E−05	1.13E−04	2.79E−05	5.09E−05	1.94E−04
Patellae	2.41E−03	7.94E−05	1.98E−03	4.65E−04	3.36E−03	1.95E−04	5.95E−04	1.46E−04	2.67E−04	1.02E−03
Tibiae	3.61E−04	1.19E−05	2.96E−04	6.97E−05	5.04E−04	2.92E−05	8.92E−05	2.20E−05	4.01E−05	1.52E−04
Fibulae	2.56E−03	8.44E−05	2.10E−03	4.95E−04	3.58E−03	2.07E−04	6.33E−04	1.56E−04	2.84E−04	1.08E−03
Feet	2.34E−04	7.72E−06	1.92E−04	4.52E−05	3.27E−04	1.89E−05	5.79E−05	1.42E−05	2.60E−05	9.88E−05

*These values are equivalent to those for TAM target and radionuclide source located within TBV.
†S values for these radionuclides include only the electron and β component of emission spectrum.

TABLE 8A
S Values (mGy/MBq-s) for TBE Target and Radionuclide Source Located Within TBV

Skeletal region	^{32}P	^{33}P	^{89}Sr	^{90}Sr	^{90}Y	^{117m}Sn*	^{153}Sm*	^{169}Er	^{177}Lu*	^{186}Re
Cranium	3.96E−03	2.84E−04	3.30E−03	9.94E−04	5.36E−03	6.34E−04	1.27E−03	4.23E−04	6.67E−04	1.87E−03
Mandible	3.56E−02	2.56E−03	2.97E−02	8.94E−03	4.82E−02	5.71E−03	1.14E−02	3.80E−03	6.01E−03	1.68E−02
Cervical vertebra	1.38E−03	1.33E−04	1.16E−03	3.98E−04	1.84E−03	2.94E−04	5.08E−04	1.89E−04	2.84E−04	6.93E−04
Thoracic vertebra	5.20E−04	5.41E−05	4.39E−04	1.54E−04	6.91E−04	1.18E−04	1.98E−04	7.52E−05	1.12E−04	2.65E−04
Lumbar vertebra	6.13E−04	6.87E−05	5.19E−04	1.88E−04	8.10E−04	1.49E−04	2.41E−04	9.38E−05	1.38E−04	3.18E−04
Sternum	3.11E−02	3.65E−03	2.64E−02	9.70E−03	4.07E−02	7.85E−03	1.26E−02	4.91E−03	7.21E−03	1.64E−02
Ribs	3.11E−03	3.65E−04	2.64E−03	9.70E−04	4.07E−03	7.85E−04	1.26E−03	4.91E−04	7.21E−04	1.64E−03
Scapulae	8.33E−03	8.72E−04	7.03E−03	2.46E−03	1.11E−02	1.91E−03	3.15E−03	1.20E−03	1.79E−03	4.23E−03
Clavicles	2.78E−02	2.91E−03	2.34E−02	8.20E−03	3.71E−02	6.35E−03	1.05E−02	4.02E−03	5.97E−03	1.41E−02
Os coxae	1.98E−03	2.08E−04	1.67E−03	5.86E−04	2.65E−03	4.54E−04	7.51E−04	2.87E−04	4.27E−04	1.01E−03
Sacrum	2.97E−03	3.11E−04	2.51E−03	8.79E−04	3.97E−03	6.81E−04	1.13E−03	4.30E−04	6.40E−04	1.51E−03
Humeri, upper half	4.32E−03	4.85E−04	3.66E−03	1.33E−03	5.73E−03	1.06E−03	1.70E−03	6.66E−04	9.83E−04	2.25E−03
Humeri, lower half	3.97E−03	4.44E−04	3.37E−03	1.23E−03	5.27E−03	9.71E−04	1.57E−03	6.11E−04	9.04E−04	2.07E−03
Radii	4.47E−03	4.99E−04	3.79E−03	1.38E−03	5.92E−03	1.09E−03	1.77E−03	6.88E−04	1.02E−03	2.33E−03
Ulnae	3.58E−03	3.99E−04	3.03E−03	1.11E−03	4.74E−03	8.74E−04	1.41E−03	5.50E−04	8.13E−04	1.86E−03
Hands	1.02E−02	1.14E−03	8.66E−03	3.16E−03	1.35E−02	2.50E−03	4.04E−03	1.57E−03	2.32E−03	5.33E−03
Femora, upper half	6.94E−04	7.79E−05	5.88E−04	2.14E−04	9.20E−04	1.71E−04	2.74E−04	1.07E−04	1.58E−04	3.61E−04
Femora, lower half	6.39E−04	7.13E−05	5.41E−04	1.98E−04	8.46E−04	1.56E−04	2.52E−04	9.83E−05	1.45E−04	3.33E−04
Patellae	1.19E−02	1.33E−03	1.01E−02	3.69E−03	1.58E−02	2.91E−03	4.71E−03	1.83E−03	2.71E−03	6.22E−03
Tibiae	7.15E−04	7.99E−05	6.06E−04	2.21E−04	9.48E−04	1.75E−04	2.83E−04	1.10E−04	1.63E−04	3.73E−04
Fibulae	5.50E−03	6.14E−04	4.66E−03	1.70E−03	7.29E−03	1.34E−03	2.17E−03	8.47E−04	1.25E−03	2.87E−03
Feet	4.77E−03	5.32E−04	4.04E−03	1.48E−03	6.32E−03	1.16E−03	1.88E−03	7.34E−04	1.08E−03	2.49E−03

*S values for these radionuclides include only the electron and β component of emission spectrum.

TABLE 9A
S Values (mGy/MBq-s) for TBV Target and Radionuclide Source Located Within TBV

Skeletal region	^{32}P	^{33}P	^{89}Sr	^{90}Sr	^{90}Y	^{117m}Sn*	^{153}Sm*	^{169}Er	^{177}Lu*	^{186}Re
Cranium	1.88E−03	2.60E−04	1.59E−03	5.83E−04	2.53E−03	5.11E−04	8.23E−04	3.39E−04	4.63E−04	9.83E−04
Mandible	1.85E−02	2.56E−03	1.57E−02	5.74E−03	2.49E−02	5.03E−03	8.09E−03	3.34E−03	4.56E−03	9.67E−03
Cervical vertebra	7.20E−04	1.59E−04	6.23E−04	2.88E−04	9.35E−04	3.02E−04	4.21E−04	1.97E−04	2.53E−04	4.31E−04
Thoracic vertebra	2.60E−04	6.19E−05	2.27E−04	1.10E−04	3.33E−04	1.17E−04	1.62E−04	7.65E−05	9.76E−05	1.62E−04
Lumbar vertebra	3.20E−04	8.24E−05	2.81E−04	1.44E−04	4.02E−04	1.56E−04	2.12E−04	1.02E−04	1.29E−04	2.07E−04
Sternum	2.11E−02	5.84E−03	1.88E−02	1.04E−02	2.56E−02	1.11E−02	1.51E−02	7.26E−03	9.26E−03	1.45E−02
Ribs	1.81E−03	5.01E−04	1.61E−03	8.93E−04	2.19E−03	9.57E−04	1.29E−03	6.23E−04	7.95E−04	1.25E−03
Scapulae	3.78E−03	9.19E−04	3.29E−03	1.59E−03	4.87E−03	1.73E−03	2.36E−03	1.13E−03	1.43E−03	2.34E−03
Clavicles	1.18E−02	2.87E−03	1.03E−02	4.97E−03	1.52E−02	5.40E−03	7.38E−03	3.52E−03	4.46E−03	7.30E−03
Os coxae	8.53E−04	2.07E−04	7.42E−04	3.59E−04	1.10E−03	3.90E−04	5.33E−04	2.54E−04	3.22E−04	5.27E−04
Sacrum	1.49E−03	3.61E−04	1.29E−03	6.26E−04	1.91E−03	6.80E−04	9.29E−04	4.43E−04	5.62E−04	9.20E−04
Humeri, upper half	1.89E−03	4.99E−04	1.65E−03	8.37E−04	2.41E−03	9.36E−04	1.25E−03	6.08E−04	7.64E−04	1.20E−03
Humeri, lower half	1.93E−03	5.15E−04	1.69E−03	8.79E−04	2.44E−03	9.72E−04	1.30E−03	6.31E−04	7.96E−04	1.25E−03
Radii	2.18E−03	5.83E−04	1.92E−03	9.96E−04	2.76E−03	1.10E−03	1.47E−03	7.15E−04	9.03E−04	1.42E−03
Ulnae	1.73E−03	4.63E−04	1.52E−03	7.90E−04	2.19E−03	8.74E−04	1.17E−03	5.67E−04	7.16E−04	1.12E−03
Hands	5.01E−03	1.34E−03	4.40E−03	2.28E−03	6.33E−03	2.52E−03	3.37E−03	1.64E−03	2.07E−03	3.25E−03
Femora, upper half	2.93E−04	7.76E−05	2.57E−04	1.30E−04	3.74E−04	1.45E−04	1.94E−04	9.44E−05	1.19E−04	1.87E−04
Femora, lower half	2.99E−04	7.99E−05	2.63E−04	1.37E−04	3.78E−04	1.51E−04	2.02E−04	9.79E−05	1.24E−04	1.94E−04
Patellae	5.46E−03	1.46E−03	4.80E−03	2.49E−03	6.90E−03	2.75E−03	3.68E−03	1.79E−03	2.26E−03	3.54E−03
Tibiae	3.47E−04	9.25E−05	3.05E−04	1.58E−04	4.38E−04	1.75E−04	2.33E−04	1.13E−04	1.43E−04	2.25E−04
Fibulae	2.59E−03	6.92E−04	2.28E−03	1.18E−03	3.28E−03	1.31E−03	1.75E−03	8.48E−04	1.07E−03	1.68E−03
Feet	2.34E−03	6.25E−04	2.06E−03	1.07E−03	2.96E−03	1.18E−03	1.58E−03	7.66E−04	9.67E−04	1.52E−03

*S values for these radionuclides include only the electron and β component of emission spectrum.

TABLE 10A
S Values (mGy/MBq-s) for TAM Target and Radionuclide Source Located Within TAM

Skeletal region	^{32}P	^{33}P	^{89}Sr	^{90}Sr	^{90}Y	^{117m}Sn*	^{153}Sm*	^{169}Er	^{177}Lu*	^{186}Re
Cranium	3.72E−04	1.00E−04	3.25E−04	1.64E−04	4.78E−04	1.87E−04	2.48E−04	1.22E−04	1.52E−04	2.36E−04
Mandible	3.53E−03	9.50E−04	3.08E−03	1.56E−03	4.53E−03	1.77E−03	2.35E−03	1.15E−03	1.44E−03	2.24E−03
Cervical vertebra	1.57E−03	2.41E−04	1.34E−03	5.17E−04	2.09E−03	4.71E−04	7.32E−04	3.11E−04	4.19E−04	8.47E−04
Thoracic vertebra	4.11E−04	5.97E−05	3.49E−04	1.32E−04	5.47E−04	1.17E−04	1.86E−04	7.76E−05	1.06E−04	2.19E−04
Lumbar vertebra	5.77E−04	7.99E−05	4.89E−04	1.81E−04	7.69E−04	1.58E−04	2.54E−04	1.05E−04	1.43E−04	3.04E−04
Sternum	2.47E−03	3.28E−04	2.10E−03	7.66E−04	3.30E−03	6.50E−04	1.07E−03	4.33E−04	5.98E−04	1.30E−03
Ribs	4.76E−04	6.31E−05	4.03E−04	1.47E−04	6.35E−04	1.25E−04	2.05E−04	8.33E−05	1.15E−04	2.49E−04
Scapulae	2.36E−03	3.41E−04	2.00E−03	7.49E−04	3.15E−03	6.67E−04	1.06E−03	4.42E−04	6.00E−04	1.25E−03
Clavicles	8.23E−03	1.19E−03	6.97E−03	2.61E−03	1.10E−02	2.33E−03	3.69E−03	1.54E−03	2.09E−03	4.35E−03
Os coxae	3.77E−04	5.45E−05	3.20E−04	1.20E−04	5.04E−04	1.07E−04	1.69E−04	7.07E−05	9.60E−05	2.00E−04
Sacrum	6.67E−04	9.64E−05	5.66E−04	2.12E−04	8.91E−04	1.89E−04	3.00E−04	1.25E−04	1.70E−04	3.53E−04
Humeri, upper half	3.05E−03	4.25E−04	2.58E−03	9.53E−04	4.07E−03	8.35E−04	1.34E−03	5.54E−04	7.57E−04	1.60E−03
Humeri, lower half	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Radii	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ulnae	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hands	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Femora, upper half	1.04E−03	1.46E−04	8.84E−04	3.27E−04	1.40E−03	2.86E−04	4.60E−04	1.90E−04	2.60E−04	5.48E−04
Femora, lower half	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Patellae	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tibiae	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Fibulae	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Feet	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

*S values for these radionuclides include only the electron and β component of emission spectrum.

APPENDIX B

TABLE 1B

S Values (mGy/MBq-s) for CBE Target and Radionuclide Source Located Within CHS

Skeletal region	^{32}P	^{33}P	^{89}Sr	^{90}Sr	^{90}Y	^{117m}Sn*	^{153}Sm*	^{169}Er	^{177}Lu*	^{186}Re
Cranium	2.65E−04	9.00E−05	2.36E−04	1.34E−04	3.28E−04	1.55E−04	2.05E−04	1.01E−04	1.29E−04	1.83E−04
Mandible	2.70E−03	9.14E−04	2.40E−03	1.37E−03	3.33E−03	1.57E−03	2.09E−03	1.03E−03	1.31E−03	1.86E−03
Cervical vertebra	1.17E−02	3.96E−03	1.04E−02	5.92E−03	1.44E−02	6.82E−03	9.04E−03	4.44E−03	5.66E−03	8.07E−03
Thoracic vertebra	4.38E−03	1.49E−03	3.90E−03	2.22E−03	5.41E−03	2.56E−03	3.39E−03	1.67E−03	2.12E−03	3.03E−03
Lumbar vertebra	3.50E−03	1.19E−03	3.12E−03	1.78E−03	4.33E−03	2.05E−03	2.71E−03	1.33E−03	1.70E−03	2.42E−03
Sternum	8.76E−03	2.97E−03	7.80E−03	4.44E−03	1.08E−02	5.11E−03	6.78E−03	3.33E−03	4.25E−03	6.05E−03
Ribs	7.01E−04	2.38E−04	6.24E−04	3.55E−04	8.66E−04	4.09E−04	5.42E−04	2.67E−04	3.40E−04	4.84E−04
Scapulae	1.35E−03	4.57E−04	1.20E−03	6.83E−04	1.67E−03	7.87E−04	1.04E−03	5.13E−04	6.53E−04	9.31E−04
Clavicles	4.38E−03	1.49E−03	3.90E−03	2.22E−03	5.41E−03	2.56E−03	3.39E−03	1.67E−03	2.12E−03	3.03E−03
Os coxae	5.31E−04	1.80E−04	4.73E−04	2.69E−04	6.56E−04	3.10E−04	4.11E−04	2.02E−04	2.57E−04	3.67E−04
Sacrum	2.70E−03	9.14E−04	2.40E−03	1.37E−03	3.33E−03	1.57E−03	2.09E−03	1.03E−03	1.31E−03	1.86E−03
Humeri, upper half	1.52E−03	5.11E−04	1.35E−03	7.47E−04	1.90E−03	8.44E−04	1.17E−03	5.68E−04	7.19E−04	1.03E−03
Humeri, lower half	1.52E−03	5.11E−04	1.35E−03	7.47E−04	1.90E−03	8.44E−04	1.17E−03	5.68E−04	7.19E−04	1.03E−03
Radii	2.50E−03	8.49E−04	2.23E−03	1.27E−03	3.09E−03	1.46E−03	1.94E−03	9.52E−04	1.21E−03	1.73E−03
Ulnae	2.06E−03	6.99E−04	1.83E−03	1.04E−03	2.55E−03	1.20E−03	1.59E−03	7.84E−04	9.99E−04	1.42E−03
Hands	2.06E−03	6.99E−04	1.83E−03	1.04E−03	2.55E−03	1.20E−03	1.59E−03	7.84E−04	9.99E−04	1.42E−03
Femora, upper half	5.74E−04	2.07E−04	5.13E−04	2.99E−04	7.06E−04	3.48E−04	4.65E−04	2.29E−04	2.90E−04	4.04E−04
Femora, lower half	5.74E−04	2.07E−04	5.13E−04	2.99E−04	7.06E−04	3.48E−04	4.65E−04	2.29E−04	2.90E−04	4.04E−04
Patellae	8.76E−03	2.97E−03	7.80E−03	4.44E−03	1.08E−02	5.11E−03	6.78E−03	3.33E−03	4.25E−03	6.05E−03
Tibiae	7.10E−04	2.29E−04	6.32E−04	3.61E−04	8.77E−04	4.18E−04	5.27E−04	2.62E−04	3.38E−04	4.90E−04
Fibulae	3.19E−03	1.08E−03	2.84E−03	1.61E−03	3.94E−03	1.86E−03	2.46E−03	1.21E−03	1.54E−03	2.20E−03
Feet	7.46E−04	2.53E−04	6.64E−04	3.78E−04	9.21E−04	4.35E−04	5.77E−04	2.84E−04	3.61E−04	5.15E−04

*S values for these radionuclides include only the electron and β component of emission spectrum.

TABLE 2B

S Values (mGy/MBq-s) for CBV Target and Radionuclide Source Located Within CHS

Skeletal region	^{32}P	^{33}P	^{89}Sr	^{90}Sr	^{90}Y	^{117m}Sn*	^{153}Sm*	^{169}Er	^{177}Lu*	^{186}Re
Cranium	1.25E−04	7.00E−06	1.04E−04	2.86E−05	1.72E−04	1.66E−05	3.62E−05	1.11E−05	1.83E−05	5.65E−05
Mandible	1.23E−03	6.87E−05	1.02E−03	2.80E−04	1.69E−03	1.63E−04	3.55E−04	1.09E−04	1.79E−04	5.54E−04
Cervical vertebra	4.96E−03	2.78E−04	4.11E−03	1.13E−03	6.82E−03	6.59E−04	1.44E−03	4.40E−04	7.25E−04	2.24E−03
Thoracic vertebra	1.96E−03	1.10E−04	1.62E−03	4.48E−04	2.70E−03	2.60E−04	5.67E−04	1.74E−04	2.86E−04	8.86E−04
Lumbar vertebra	1.71E−03	9.60E−05	1.42E−03	3.91E−04	2.35E−03	2.27E−04	4.95E−04	1.52E−04	2.50E−04	7.73E−04
Sternum	3.97E−03	2.22E−04	3.29E−03	9.07E−04	5.45E−03	5.27E−04	1.15E−03	3.52E−04	5.79E−04	1.79E−03
Ribs	3.30E−04	1.85E−05	2.74E−04	7.56E−05	4.54E−04	4.39E−05	9.56E−05	2.93E−05	4.83E−05	1.49E−04
Scapulae	6.40E−04	3.59E−05	5.30E−04	1.46E−04	8.80E−04	8.50E−05	1.85E−04	5.67E−05	9.34E−05	2.89E−04
Clavicles	1.98E−03	1.11E−04	1.64E−03	4.53E−04	2.73E−03	2.63E−04	5.74E−04	1.76E−04	2.90E−04	8.96E−04
Os coxae	2.49E−04	1.40E−05	2.07E−04	5.70E−05	3.43E−04	3.31E−05	7.22E−05	2.21E−05	3.64E−05	1.13E−04
Sacrum	1.31E−03	7.33E−05	1.08E−03	2.99E−04	1.80E−03	1.74E−04	3.79E−04	1.16E−04	1.91E−04	5.91E−04
Humeri, upper half	6.03E−04	3.25E−05	4.99E−04	1.34E−04	8.33E−04	7.65E−05	1.71E−04	5.13E−05	8.50E−05	2.69E−04
Humeri, lower half	6.03E−04	3.25E−05	4.99E−04	1.34E−04	8.33E−04	7.65E−05	1.71E−04	5.13E−05	8.50E−05	2.69E−04
Radii	9.31E−04	5.22E−05	7.71E−04	2.13E−04	1.28E−03	1.24E−04	2.70E−04	8.26E−05	1.36E−04	4.21E−04
Ulnae	7.39E−04	4.14E−05	6.12E−04	1.69E−04	1.02E−03	9.82E−05	2.14E−04	6.55E−05	1.08E−04	3.34E−04
Hands	7.55E−04	4.23E−05	6.25E−04	1.73E−04	1.04E−03	1.00E−04	2.18E−04	6.69E−05	1.10E−04	3.41E−04
Femora, upper half	2.58E−04	1.54E−05	2.14E−04	6.06E−05	3.54E−04	3.63E−05	7.66E−05	2.40E−05	3.92E−05	1.18E−04
Femora, lower half	2.58E−04	1.54E−05	2.14E−04	6.06E−05	3.54E−04	3.63E−05	7.66E−05	2.40E−05	3.92E−05	1.18E−04
Patellae	3.88E−03	2.17E−04	3.21E−03	8.86E−04	5.33E−03	5.15E−04	1.12E−03	3.44E−04	5.66E−04	1.75E−03
Tibiae	2.01E−04	1.10E−05	1.67E−04	4.62E−05	2.77E−04	2.64E−05	5.82E−05	1.77E−05	2.93E−05	9.12E−05
Fibulae	9.11E−04	5.10E−05	7.54E−04	2.08E−04	1.25E−03	1.21E−04	2.64E−04	8.07E−05	1.33E−04	4.11E−04
Feet	3.50E−04	1.96E−05	2.90E−04	8.01E−05	4.82E−04	4.65E−05	1.01E−04	3.11E−05	5.12E−05	1.58E−04

*S values for these radionuclides include only the electron and β component of emission spectrum.

TABLE 3B
S Values (mGy/MBq-s) for CBE Target and Radionuclide Source Located Within CBE

Skeletal region	^{32}P	^{33}P	^{89}Sr	^{90}Sr	^{90}Y	^{117m}Sn*	^{153}Sm*	^{169}Er	^{177}Lu*	^{186}Re
Cranium	2.67E−04	1.46E−04	2.41E−04	1.56E−04	3.29E−04	2.10E−04	3.38E−04	1.84E−04	1.81E−04	2.11E−04
Mandible	2.71E−03	1.49E−03	2.45E−03	1.58E−03	3.35E−03	2.13E−03	3.43E−03	1.86E−03	1.84E−03	2.14E−03
Cervical vertebra	1.18E−02	6.45E−03	1.06E−02	6.86E−03	1.45E−02	9.22E−03	1.49E−02	8.08E−03	7.97E−03	9.27E−03
Thoracic vertebra	4.41E−03	2.42E−03	3.98E−03	2.57E−03	5.44E−03	3.46E−03	5.58E−03	3.03E−03	2.99E−03	3.48E−03
Lumbar vertebra	3.53E−03	1.93E−03	3.19E−03	2.06E−03	4.35E−03	2.77E−03	4.46E−03	2.42E−03	2.39E−03	2.78E−03
Sternum	8.82E−03	4.83E−03	7.97E−03	5.15E−03	1.09E−02	6.92E−03	1.12E−02	6.06E−03	5.98E−03	6.95E−03
Ribs	7.06E−04	3.87E−04	6.37E−04	4.12E−04	8.70E−04	5.53E−04	8.92E−04	4.85E−04	4.78E−04	5.56E−04
Scapulae	1.36E−03	7.44E−04	1.23E−03	7.92E−04	1.67E−03	1.06E−03	1.72E−03	9.32E−04	9.20E−04	1.07E−03
Clavicles	4.41E−03	2.42E−03	3.98E−03	2.57E−03	5.44E−03	3.46E−03	5.58E−03	3.03E−03	2.99E−03	3.48E−03
Os coxae	5.35E−04	2.93E−04	4.83E−04	3.12E−04	6.59E−04	4.19E−04	6.76E−04	3.67E−04	3.62E−04	4.21E−04
Sacrum	2.71E−03	1.49E−03	2.45E−03	1.58E−03	3.35E−03	2.13E−03	3.43E−03	1.86E−03	1.84E−03	2.14E−03
Humeri, upper half	1.56E−03	9.14E−04	1.42E−03	9.42E−04	1.93E−03	1.29E−03	2.08E−03	1.14E−03	1.12E−03	1.26E−03
Humeri, lower half	1.56E−03	9.14E−04	1.42E−03	9.42E−04	1.93E−03	1.29E−03	2.08E−03	1.14E−03	1.12E−03	1.26E−03
Radii	2.52E−03	1.38E−03	2.28E−03	1.47E−03	3.11E−03	1.98E−03	3.19E−03	1.73E−03	1.71E−03	1.99E−03
Ulnae	2.08E−03	1.14E−03	1.87E−03	1.21E−03	2.56E−03	1.63E−03	2.62E−03	1.43E−03	1.41E−03	1.64E−03
Hands	2.08E−03	1.14E−03	1.87E−03	1.21E−03	2.56E−03	1.63E−03	2.62E−03	1.43E−03	1.41E−03	1.64E−03
Femora, upper half	5.76E−04	3.10E−04	5.20E−04	3.32E−04	7.09E−04	4.43E−04	7.16E−04	3.88E−04	3.84E−04	4.51E−04
Femora, lower half	5.76E−04	3.10E−04	5.20E−04	3.32E−04	7.09E−04	4.43E−04	7.16E−04	3.88E−04	3.84E−04	4.51E−04
Patellae	8.82E−03	4.83E−03	7.97E−03	5.15E−03	1.09E−02	6.92E−03	1.12E−02	6.06E−03	5.98E−03	6.95E−03
Tibiae	7.06E−04	3.71E−04	6.36E−04	4.05E−04	8.72E−04	5.38E−04	8.64E−04	4.68E−04	4.64E−04	5.50E−04
Fibulae	3.21E−03	1.76E−03	2.90E−03	1.87E−03	3.95E−03	2.52E−03	4.06E−03	2.20E−03	2.17E−03	2.53E−03
Feet	7.51E−04	4.11E−04	6.78E−04	4.38E−04	9.25E−04	5.89E−04	9.49E−04	5.16E−04	5.09E−04	5.92E−04

*S values for these radionuclides include only the electron and β component of emission spectrum.

TABLE 4B
S Values (mGy/MBq-s) for CBV Target and Radionuclide Source Located Within CBE

Skeletal region	^{32}P	^{33}P	^{89}Sr	^{90}Sr	^{90}Y	^{117m}Sn*	^{153}Sm*	^{169}Er	^{177}Lu*	^{186}Re
Cranium	1.30E−04	1.14E−05	1.09E−04	3.42E−05	1.77E−04	2.45E−05	4.47E−05	1.59E−05	2.42E−05	6.26E−05
Mandible	1.27E−03	1.12E−04	1.07E−03	3.36E−04	1.73E−03	2.40E−04	4.38E−04	1.56E−04	2.37E−04	6.14E−04
Cervical vertebra	5.16E−03	4.53E−04	4.31E−03	1.36E−03	7.01E−03	9.73E−04	1.77E−03	6.31E−04	9.61E−04	2.48E−03
Thoracic vertebra	2.04E−03	1.79E−04	1.70E−03	5.37E−04	2.77E−03	3.84E−04	7.01E−04	2.49E−04	3.80E−04	9.81E−04
Lumbar vertebra	1.78E−03	1.56E−04	1.49E−03	4.69E−04	2.42E−03	3.36E−04	6.12E−04	2.18E−04	3.32E−04	8.57E−04
Sternum	4.13E−03	3.62E−04	3.45E−03	1.09E−03	5.60E−03	7.77E−04	1.42E−03	5.05E−04	7.68E−04	1.99E−03
Ribs	3.44E−04	3.02E−05	2.87E−04	9.06E−05	4.67E−04	6.48E−05	1.18E−04	4.21E−05	6.40E−05	1.65E−04
Scapulae	6.65E−04	5.83E−05	5.56E−04	1.75E−04	9.04E−04	1.25E−04	2.29E−04	8.14E−05	1.24E−04	3.20E−04
Clavicles	2.06E−03	1.81E−04	1.72E−03	5.43E−04	2.80E−03	3.89E−04	7.09E−04	2.52E−04	3.84E−04	9.93E−04
Os coxae	2.60E−04	2.28E−05	2.17E−04	6.84E−05	3.53E−04	4.89E−05	8.92E−05	3.17E−05	4.83E−05	1.25E−04
Sacrum	1.36E−03	1.19E−04	1.14E−03	3.59E−04	1.85E−03	2.57E−04	4.68E−04	1.66E−04	2.53E−04	6.55E−04
Humeri, upper half	6.38E−04	5.72E−05	5.34E−04	1.70E−04	8.67E−04	1.23E−04	2.21E−04	7.93E−05	1.20E−04	3.08E−04
Humeri, lower half	6.38E−04	5.72E−05	5.34E−04	1.70E−04	8.67E−04	1.23E−04	2.21E−04	7.93E−05	1.20E−04	3.08E−04
Radii	9.69E−04	8.50E−05	8.10E−04	2.55E−04	1.32E−03	1.83E−04	3.33E−04	1.18E−04	1.80E−04	4.66E−04
Ulnae	7.69E−04	6.74E−05	6.43E−04	2.03E−04	1.04E−03	1.45E−04	2.64E−04	9.40E−05	1.43E−04	3.70E−04
Hands	7.85E−04	6.89E−05	6.56E−04	2.07E−04	1.07E−03	1.48E−04	2.70E−04	9.60E−05	1.46E−04	3.78E−04
Femora, upper half	2.66E−04	2.34E−05	2.22E−04	7.02E−05	3.61E−04	5.04E−05	9.15E−05	3.26E−05	4.97E−05	1.28E−04
Femora, lower half	2.66E−04	2.34E−05	2.22E−04	7.02E−05	3.61E−04	5.04E−05	9.15E−05	3.26E−05	4.97E−05	1.28E−04
Patellae	4.03E−03	3.54E−04	3.37E−03	1.06E−03	5.48E−03	7.60E−04	1.39E−03	4.93E−04	7.51E−04	1.94E−03
Tibiae	2.08E−04	1.78E−05	1.74E−04	5.43E−05	2.83E−04	3.83E−05	7.08E−05	2.50E−05	3.81E−05	9.97E−05
Fibulae	9.47E−04	8.31E−05	7.92E−04	2.50E−04	1.29E−03	1.79E−04	3.26E−04	1.16E−04	1.76E−04	4.56E−04
Feet	3.64E−04	3.20E−05	3.05E−04	9.60E−05	4.95E−04	6.87E−05	1.25E−04	4.46E−05	6.78E−05	1.75E−04

*S values for these radionuclides include only the electron and β component of emission spectrum.

TABLE 5B
S Values (mGy/MBq-s) for CBE Target and Radionuclide Source Located Within CBV

Skeletal region	^{32}P	^{33}P	^{89}Sr	^{90}Sr	^{90}Y	^{117m}Sn*	^{153}Sm*	^{169}Er	^{177}Lu*	^{186}Re
Cranium	1.92E-04	1.61E-05	1.61E-04	5.09E-05	2.56E-04	3.53E-05	6.56E-05	2.30E-05	3.54E-05	9.33E-05
Mandible	1.95E-03	1.63E-04	1.64E-03	5.17E-04	2.59E-03	3.58E-04	6.66E-04	2.33E-04	3.59E-04	9.47E-04
Cervical vertebra	8.45E-03	7.06E-04	7.10E-03	2.24E-03	1.12E-02	1.55E-03	2.89E-03	1.01E-03	1.56E-03	4.10E-03
Thoracic vertebra	3.17E-03	2.65E-04	2.66E-03	8.40E-04	4.22E-03	5.82E-04	1.08E-03	3.79E-04	5.84E-04	1.54E-03
Lumbar vertebra	2.53E-03	2.12E-04	2.13E-03	6.72E-04	3.37E-03	4.66E-04	8.66E-04	3.03E-04	4.67E-04	1.23E-03
Sternum	6.34E-03	5.30E-04	5.32E-03	1.68E-03	8.43E-03	1.16E-03	2.17E-03	7.58E-04	1.17E-03	3.08E-03
Ribs	5.07E-04	4.24E-05	4.26E-04	1.34E-04	6.75E-04	9.31E-05	1.73E-04	6.07E-05	9.34E-05	2.46E-04
Scapulae	9.75E-04	8.15E-05	8.19E-04	2.59E-04	1.30E-03	1.79E-04	3.33E-04	1.17E-04	1.80E-04	4.74E-04
Clavicles	3.17E-03	2.65E-04	2.66E-03	8.40E-04	4.22E-03	5.82E-04	1.08E-03	3.79E-04	5.84E-04	1.54E-03
Os coxae	3.84E-04	3.21E-05	3.23E-04	1.02E-04	5.11E-04	7.05E-05	1.31E-04	4.60E-05	7.08E-05	1.87E-04
Sacrum	1.95E-03	1.63E-04	1.64E-03	5.17E-04	2.59E-03	3.58E-04	6.66E-04	2.33E-04	3.59E-04	9.47E-04
Humeri, upper half	1.13E-03	9.77E-05	9.49E-04	3.06E-04	1.50E-03	2.13E-04	3.95E-04	1.39E-04	2.14E-04	5.55E-04
Humeri, lower half	1.13E-03	9.77E-05	9.49E-04	3.06E-04	1.50E-03	2.13E-04	3.95E-04	1.39E-04	2.14E-04	5.55E-04
Radii	1.81E-03	1.51E-04	1.52E-03	4.80E-04	2.41E-03	3.33E-04	6.19E-04	2.17E-04	3.34E-04	8.79E-04
Ulnae	1.49E-03	1.25E-04	1.25E-03	3.96E-04	1.98E-03	2.74E-04	5.09E-04	1.78E-04	2.75E-04	7.24E-04
Hands	1.49E-03	1.25E-04	1.25E-03	3.96E-04	1.98E-03	2.74E-04	5.09E-04	1.78E-04	2.75E-04	7.24E-04
Femora, upper half	4.07E-04	3.41E-05	3.42E-04	1.07E-04	5.41E-04	7.50E-05	1.38E-04	4.87E-05	7.48E-05	1.97E-04
Femora, lower half	4.07E-04	3.41E-05	3.42E-04	1.07E-04	5.41E-04	7.50E-05	1.38E-04	4.87E-05	7.48E-05	1.97E-04
Patellae	6.34E-03	5.30E-04	5.32E-03	1.68E-03	8.43E-03	1.16E-03	2.17E-03	7.58E-04	1.17E-03	3.08E-03
Tibiae	5.14E-04	4.15E-05	4.32E-04	1.34E-04	6.84E-04	9.16E-05	1.72E-04	5.98E-05	9.25E-05	2.48E-04
Fibulae	2.30E-03	1.93E-04	1.94E-03	6.11E-04	3.07E-03	4.23E-04	7.87E-04	2.76E-04	4.25E-04	1.12E-03
Feet	5.39E-04	4.51E-05	4.53E-04	1.43E-04	7.18E-04	9.91E-05	1.84E-04	6.46E-05	9.94E-05	2.62E-04

*S values for these radionuclides include only the electron and β component of emission spectrum.

TABLE 6B
S Values (mGy/MBq-s) for CBV Target and Radionuclide Source Located Within CBV

Skeletal region	^{32}P	^{33}P	^{89}Sr	^{90}Sr	^{90}Y	^{117m}Sn*	^{153}Sm*	^{169}Er	^{177}Lu*	^{186}Re
Cranium	1.33E-04	1.51E-05	1.12E-04	3.78E-05	1.79E-04	3.02E-05	5.23E-05	2.03E-05	2.86E-05	6.65E-05
Mandible	1.30E-03	1.48E-04	1.10E-03	3.71E-04	1.76E-03	2.96E-04	5.13E-04	1.99E-04	2.81E-04	6.53E-04
Cervical vertebra	5.28E-03	5.99E-04	4.43E-03	1.50E-03	7.12E-03	1.20E-03	2.08E-03	8.05E-04	1.14E-03	2.64E-03
Thoracic vertebra	2.08E-03	2.37E-04	1.75E-03	5.93E-04	2.81E-03	4.74E-04	8.21E-04	3.18E-04	4.49E-04	1.04E-03
Lumbar vertebra	1.82E-03	2.07E-04	1.53E-03	5.18E-04	2.46E-03	4.14E-04	7.17E-04	2.78E-04	3.92E-04	9.11E-04
Sternum	4.22E-03	4.79E-04	3.54E-03	1.20E-03	5.69E-03	9.59E-04	1.66E-03	6.44E-04	9.09E-04	2.11E-03
Ribs	3.51E-04	3.99E-05	2.95E-04	1.00E-04	4.74E-04	7.99E-05	1.38E-04	5.36E-05	7.57E-05	1.76E-04
Scapulae	6.80E-04	7.72E-05	5.72E-04	1.94E-04	9.18E-04	1.55E-04	2.68E-04	1.04E-04	1.47E-04	3.41E-04
Clavicles	2.11E-03	2.39E-04	1.77E-03	6.00E-04	2.85E-03	4.79E-04	8.30E-04	3.22E-04	4.54E-04	1.06E-03
Os coxae	2.65E-04	3.01E-05	2.23E-04	7.55E-05	3.58E-04	6.03E-05	1.04E-04	4.05E-05	5.72E-05	1.33E-04
Sacrum	1.39E-03	1.58E-04	1.17E-03	3.96E-04	1.88E-03	3.16E-04	5.48E-04	2.12E-04	3.00E-04	6.97E-04
Humeri, upper half	6.51E-04	7.38E-05	5.48E-04	1.85E-04	8.79E-04	1.48E-04	2.56E-04	9.94E-05	1.40E-04	3.26E-04
Humeri, lower half	6.51E-04	7.38E-05	5.48E-04	1.85E-04	8.79E-04	1.48E-04	2.56E-04	9.94E-05	1.40E-04	3.26E-04
Radii	9.90E-04	1.12E-04	8.32E-04	2.82E-04	1.34E-03	2.25E-04	3.90E-04	1.51E-04	2.13E-04	4.96E-04
Ulnae	7.86E-04	8.92E-05	6.60E-04	2.24E-04	1.06E-03	1.79E-04	3.09E-04	1.20E-04	1.69E-04	3.93E-04
Hands	8.02E-04	9.11E-05	6.74E-04	2.28E-04	1.08E-03	1.82E-04	3.16E-04	1.22E-04	1.73E-04	4.02E-04
Femora, upper half	2.72E-04	3.08E-05	2.28E-04	7.73E-05	3.67E-04	6.16E-05	1.07E-04	4.14E-05	5.85E-05	1.36E-04
Femora, lower half	2.72E-04	3.08E-05	2.28E-04	7.73E-05	3.67E-04	6.16E-05	1.07E-04	4.14E-05	5.85E-05	1.36E-04
Patellae	4.12E-03	4.68E-04	3.46E-03	1.17E-03	5.56E-03	9.37E-04	1.62E-03	6.29E-04	8.88E-04	2.06E-03
Tibiae	2.13E-04	2.43E-05	1.79E-04	6.07E-05	2.88E-04	4.86E-05	8.41E-05	3.26E-05	4.60E-05	1.07E-04
Fibulae	9.68E-04	1.10E-04	8.14E-04	2.76E-04	1.31E-03	2.20E-04	3.81E-04	1.48E-04	2.09E-04	4.85E-04
Feet	3.72E-04	4.23E-05	3.13E-04	1.06E-04	5.03E-04	8.47E-05	1.47E-04	5.68E-05	8.03E-05	1.87E-04

*S values for these radionuclides include only the electron and β component of emission spectrum.

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