Original Paper

Evaluation of Doses Absorbed to a Bone Marrow Stem Cell Layer from Short-lived Radionuclides in the Blood Vessels and from Long-lived Radionuclides in the Cortical Bone

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The International Commission on Radiological Protection (ICRP) internal dose assessment model, currently adopted in Japanese regulation, assumes uniform distribution of radionuclides in bone marrow blood (ICRP Publication 60). Recent studies have revealed a localization of hematopoietic stem cells (HSCs) and immune cells in the perivascular region of the bone marrow sinusoids, suggesting a need to consider nonuniform distributions of the blood source and HSCs. To evaluate energy transfer to HSCs, a simplified model of cervical vertebrae with bone tissues and blood vessels was built using data from the adult Japanese male phantom. Doses absorbed by HSCs from blood and hard bone sources were calculated using a Monte Carlo simulation, and absorbed fractions (AFs) and specific absorbed fractions (SAFs) from electrons were compared with those in the ICRP 1990 model. In the cervical vascular model, electron SAFs from sinusoidal blood in the red bone marrow (RBM) to the target perivascular region were 1.2 to 6.9 times higher than the SAF in the ICRP 1990 model, suggesting an underestimation of the RBM dose. Electrons from the cortical bone source to the perisinusoidal target exhibited energy transfer. The ICRP 1990 model underestimates electron SAFs from radionuclides in sinusoidal blood and cortical bones. A more elaborate model is needed to examine doses for the RBM and effects on hematopoietic and immune functions.

KEY WORDS: ICRP internal dose assessment, absorbed fractions, specific absorbed fractions, PHITS, red bone marrow.

I INTRODUCTION

The International Commission on Radiological Protection (ICRP) model currently adopted in Japanese regulation (ICRP Publication 60, referred to hereafter as the ICRP 1990 model)¹⁾ postulates a uniform distribution of the blood source to organs in the body, including the bone marrow, based on the assumptions in ICRP Publication 30.²⁾ According to Part 1 of ICRP Publication 30, transformations occurring in the transfer compartment are assumed to be uniformly distributed throughout the whole body. Also, in a mathematical phantom based on the Medical Internal Radiation Dose method and used in the calculation of the photon specific absorbed fraction (SAF), each bone tissue is distinguished in its anatomical location only by weight, without any regard for its internal structure. As a result, it is assumed that the bone marrow and hematopoietic stem cells (HSCs) are uniformly distributed throughout the bone region.³⁾

Further, it is assumed that all the electrons from radionuclides in a source organ are absorbed to the source organ, except for organs with walls and the skeleton. For other areas, body tissue (the tissue of the whole body, excluding the contents of the esophagus, gallbladder, and bladder) is used as a surrogate for the blood source, and the electron absorbed fraction (AF) is defined as a ratio of the mass of the

target organ to the mass of the whole body.⁴⁾ The SAF that is obtained by dividing the AF by the mass of the target region of electrons from body tissue is defined to be $1/68.831 \text{ kg}^{-1}$, which means electron SAF of the blood source is $1/68.831 \text{ kg}^{-1}$ in any organ other than specific source and target combinations in the respiratory tract and the skeleton.⁵⁾

However, recent studies have revealed that HSCs and immune cells concentrate around the endothelium of bone marrow blood vessels.⁶⁾ Hematopoietic niches in the bone marrow have been considered to involve osteoblastic cells, endothelial cells, or stromal cells, but more recent studies using genetically modified mice have strongly supported a perivascular niche theory, with the niche consisting of mesenchymal stromal cells and endothelial cells.^{7, 8)} It has been reported that 85% of HSCs are located within $10 \mu\text{m}$ of the bone marrow sinusoids.⁹⁾ In mouse studies, the HSCs that were distinguished by a signaling lymphocytic activation molecule family constituted only a very small portion of the bone marrow cells (24 out of 488,400)¹⁰⁾; the number of HSCs within a mouse is estimated at $\sim 0.01\%$ of the bone marrow cellularity.¹¹⁾ If such scarce HSCs were localized around the sinusoids, doses from radiation emitted by radionuclides decaying in the blood, especially doses from electrons, could be underestimated by the ICRP 1990 model, which assumes a uniform distribution of the blood, bone marrow, and HSCs. It is thus necessary to evaluate energy transfer to the bone marrow stem cell layer using a model that considers the

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detailed internal structure of bone tissues.

According to the dose estimation model based on the ICRP 2007 recommendations (ICRP Publication 103, referred to hereafter as the ICRP 2007 model),¹²⁾ blood is allocated according to the mass of blood in each organ, and electron SAFs are calculated by a Monte Carlo code using a computational phantom. However, skeletal tissues cannot be geometrically represented in the computational phantom, which only identifies the cortical bone, medullary marrow, and trabecular spongiosa. The trabecular spongiosa is a mixture of the trabecular bone as well as the active and inactive marrow, and the absorbed dose is calculated by the sampling algorithm, based on the proportion of each component.¹³⁾ Thus, the ICRP 2007 model assumes a uniform distribution of the blood and HSCs. And even in a study that utilized micro CT images to recreate the cortical bone, trabecular bone, and active bone marrow within a phantom, no consideration was given to the blood vessels in the evaluation of electron SAFs.¹⁴⁾

Also, in the ICRP 1990 model, AFs for radionuclides in the hard bone are given specific numerical values, according to **Table 1** in ICRP Publication 30. When a bone-seeking nuclide is deposited on bone surfaces, it is distributed equally in the cortical and trabecular bone. When the nuclides move into the bone volume, they are distributed to the cortical and trabecular bone according to their proportions in the bone, that is, 0.8 for the cortical bone and 0.2 for the trabecular bone. The AF for electron sources in the cortical bone to the RBM target is assumed to be zero.

To evaluate the dosimetry from the blood and cortical bone sources to the bone marrow stem cell layer in the ICRP 1990 model as well as in the ICRP 2007 model, a simplified model of bone tissues and blood vessels was built using the data of the Japanese phantom (JM-103).¹⁵⁾ Then energy transfers from the blood and cortical bone sources to the perivascular region of the RBM were calculated using PHITS code¹⁶⁾ and were compared to the electron AF in the ICRP 1990 model. To address the proportion of energies deposited from the source region with a nonuniform distribution to the target region of the perivascular stem cell layer, absorbed doses in the perivascular region were compared among three different source regions—in the blood in the RBM sinusoids, in all of the RBM, and in the whole bone.

To evaluate the extent of the effects of major nuclides in the actual exposure dose assessment, electron SAFs were also calculated from the short-lived iodine isotopes iodine-131 (¹³¹I), iodine-132 (¹³²I), and iodine-133 (¹³³I) in the blood source and from long-lived strontium-89 (⁸⁹Sr), strontium-90 (⁹⁰Sr), and its progeny, yttrium-90 (⁹⁰Y), in the cortical bone source.

II METHODS

2.1. Overview

A comparison between the ICRP 1990 model, the ICRP 2007 model, and the present study is shown in **Table 2**.

2.2. Building a simplified model of cervical vertebrae with bone tissues

To overcome the limitations of the ICRP 1990 model, which assumes a uniform distribution of nuclides, a simplified model of cervical vertebrae (hereafter called the cervical vascular model) was built using data on masses of bone tissues and blood from the Japanese phantom, JM-103.¹⁵⁾ This data was used because the weight of bone tissue and blood for each part of the bones was described in detail. Assuming the vertebral column length to be approximately three-tenths of 171 cm—the height of the JM-103—and the ratio of the cervical, thoracic, and lumbar spine to be 2:7:3, the cervical vertebrae were modeled as a 9 cm high cylinder with an internal lattice structure consisting of the trabecular bone, bone marrow, and blood vessels (**Fig. 1**). As the proportion of blood contained in each bone tissue was not available, proportions shown in ICRP Publication 89¹⁷⁾ were used, where blood distribution to the bone tissue and the RBM was 7% and 4%, respectively, of the total blood. The mass of the RBM blood was thus determined to be 13.5% of the mass of the RBM (**Table 3**). The weight of blood in the RBM of the cervical vertebrae was calculated as 6.09 g (13.5% of the bone marrow weight of 45.1 g), and the inner diameter of the blood vessel was calculated from the height (9 cm) and the number of blood vessels as a cylinder. As anatomical information on sinusoids is only available for mice,⁹⁾ blood vessels were modeled into cylinders arranged at equal intervals using a lattice structure, and they were analyzed for 25, 49 and 121 blood vessels by changing the inner diameters.

The internal radius of a blood vessel was determined from the mass of the blood, while the volume was calculated from the total mass of the cortical bone, trabecular bone, and soft tissues of the cervical vertebrae. These structures were arranged around the cervical vertebrae, assuming a neck circumference of 38 cm.¹⁸⁾ Material densities were set as 1.623 g/cm³ for the bone and 1 g/cm³ for the bone marrow, soft tissues, and blood. Although the central part of the bone marrow contains arteries and veins, all blood vessels were simplified as sinusoids, due to the use of the lattice structure. Also, because the estimation involved the blood source in the RBM, only blood in the RBM was considered, excluding blood in the cortical bone and trabecular bone as well as all

Table 1 Electron AFs from the hard bone sources to the RBM in ICRP Publication 30.²⁾

Source organ	Target organ	β emitter uniform in volume	β emitter on bone surfaces $E_{\beta} \geq 0.2$ MeV	β emitter on bone surfaces $E_{\beta} < 0.2$ MeV
Trabecular bone	Bone surfaces	0.025	0.025	0.25
Cortical bone	Bone surfaces	0.015	0.015	0.25
Trabecular bone	RBM	0.35	0.35	0.5
Cortical bone	RBM	0	0	0

Table 2 Overview of analysis.

	ICRP 1990 model	ICRP 2007 model	Present Study
Type	Mathematical phantom	Computational phantom	Cervical vertebral model
Identified bone tissues	None	Cortical bone, medullary marrow, spongiosa	Cortical bone, trabecular bone, RBM, blood vessels
Blood as the source organ in the bone	Uniformly distributed in bone	Uniformly distributed in RBM	Distributed in blood vessels in RBM
RBM as the target organ	Uniformly distributed in bone	Distributed in marrow cavities	Distributed between trabecular bone and blood vessels
HSCs	Uniformly distributed in bone	Uniformly distributed in bone marrow	Distributed in perivascular region
Electron SAF (blood source to RBM)	SAF of body tissue ($1/68.831 \text{ kg}^{-1}$)* is used as a surrogate	Calculated by a Monte Carlo simulation and sampling algorithm	—
Electron SAF (blood source to perivascular region)	—	—	Calculated with the cervical vascular model by a Monte Carlo simulation
Electron SAF (cortical bone source to RBM)	0	Calculated by a Monte Carlo simulation and sampling algorithm	—
Electron SAF (cortical bone source to perivascular region)	—	—	Calculated with the cervical vascular model by a Monte Carlo simulation

*1/mass of total body tissue excluding contents of walled organs

other soft tissues in the RBM. (Thus, the blood source in the cervical vascular model is essentially the sinusoidal blood in the RBM.)

2.3. Simulation of the electron transport through PHITS code and calculation of the AFs and SAFs

Based on the proposed model, the electron transport was simulated using a Monte Carlo method utilizing PHITS code ver. 2.91 as well as the EGS5 code,¹⁹⁾ and confirmed using PHITS code ver. 3.02. The source region was defined as the blood in the RBM and the cortical bone, and the target region was defined as the sinusoidal endothelium of the RBM blood vessels and of the perivascular region where the HSCs were localized. The perivascular region was set as an area with a thickness of 0.01 cm from the inner surface of the sinusoidal endothelium. Electrons were uniformly generated in the source region, and energy absorbed per decay in the target region was calculated using t_{deposit} tally in MeV/source to obtain electron energies deposited to each component of the bone tissues. Electrons were generated at 12 discrete energy points ranging from 0.05 MeV to 2.4 MeV. The number of trials in simulation for each settings were at least 10,000 times, with statistical errors in the target region generally lower than 0.05. The bremsstrahlung was considered as it is calculated using EGS mode for transportation of photons and electrons so that the bremsstrahlung photons are generate automatically. The AF was calculated as the fraction of the energy absorbed in the target region against the energy released, and the SAF was calculated by dividing the AF by the mass of the target region.

2.4. Comparison of electron SAFs in the cervical vascular model with SAFs in the ICRP 1990 model

The perivascular SAF, with the blood in the RBM blood vessels and cortical bone as the source, was compared with

the SAF in the ICRP 1990 model. The cervical vascular model SAF is based on the energy emitted by the disintegration in the cervical blood source, and comparison with the body tissue SAF in the ICRP 1990 model requires accounting for the proportion to energy emitted by the disintegration in the blood in the whole body, that is, the proportion of the cervical blood against the total amount of blood in the body. Thus, the cervical vascular model SAFs were multiplied by the mass ratio of the cervical vertebral RBM blood against the whole-body blood, 0.182% and were compared with the body tissue SAF ($1/68.831 \text{ kg}^{-1}$) in the ICRP 1990 model. Because the actual shape of sinusoids is unknown, calculations were conducted for 25, 49 and 121 blood vessels by changing the inner diameters to 0.093 cm, 0.066 cm and 0.042 cm, respectively.

In order to examine the validity of electron AFs from the cortical bone source, the cervical vascular model was used to calculate AFs and SAFs, with the cortical bone as the source and the perivascular region as the target (**Fig. 2**). The cervical vascular model SAFs were multiplied by the mass ratio of the cervical cortical bone to the whole-body cortical bone, i.e. 2.2%, to account for the fraction that disintegrated in the cortical bone of the cervical bone. As no comparison can be made with an SAF of zero, SAFs were compared with the body tissue SAF of $1/68.831 \text{ kg}^{-1}$. When a cortical bone is the source region, up to 570 million trials were required to reduce statistical errors in the perivascular region to less than 0.05.

2.5. Comparison with different settings in the cervical vascular model

As described previously, the phantom used in the ICRP 2007 model assumes that the trabecular spongiosa is a mixture of the trabecular bone as well as of the active and inactive marrow and blood, and that HSCs are uniformly distributed. In

Fig. 1 A simplified model of cervical vertebrae with bone tissues and blood vessels (cervical vascular model) (upper).
An enlarged view of the cervical vascular model (lower).

Table 3 Masses of bone tissues and blood in the cervical vertebrae of the Japanese phantom JM-103.

Organ ID and name used in JM-103	Mass (g)							
	Total body tissue	Cortical bone	Trabecular bone	Soft tissues	RBM	Soft tissues - RBM	Blood	Blood in RBM*
140 Cervical vertebra_01	0.8	—	0.2	0.6	0.5	0.1	0.1	0.1
141 Cervical vertebra_02	7.1	—	3.3	3.9	2.9	1.0	0.4	0.4
142 Cervical vertebra_03	40.7	13.7	8.6	18.3	13.7	4.6	2.2	1.8
143 Cervical vertebra_04	62.5	40.0	—	22.5	16.9	5.7	2.8	2.3
144 Cervical vertebra_05	47.5	36.1	—	11.4	8.5	2.9	1.6	1.2
145 Cervical vertebra_06	39.5	35.6	—	4.0	3.0	1.0	0.8	0.4
146 Cervical vertebra_07	8.6	8.6	—	—	—	—	—	—
Total	206.8	134.1	12.2	60.6	45.4	15.2	7.8	6.1

* Blood in RBM = RBM × 13.5%

Total volume in bone (ID 120–316), body tissue = 11,014.4 g, RBM = 1,191.6 g, blood in bone = 281.2 g

ICRP89 Blood distribution to the bone tissue = 7%, blood distribution to the RBM = 4%

Blood in RBM $\frac{281.2 \times 4}{1,191.6 \times 7} \times 100 \div 13.5\%$

Fig. 2 Electrons from the cortical bone source.

order to assess energies deposited to the perivascular stem cell layer in the target region from a non-uniform source tissue, perivascular AFs were compared between the source regions of the blood in the RBM blood sinusoids and in the entire RBM. Also, although the cervical vascular model was built using average values for bone tissue components of the cervical vertebrae, the actual shape of sinusoids is unknown as stated above. Thus, a sensitivity analysis was conducted by changing the thickness of the perivascular region from 0.00125 cm to 0.02 cm.

2.6. Application of the cervical vascular model

In order to evaluate the extent of effects from major nuclides in the actual exposure dose assessment, the electron SAFs were calculated for ^{131}I , ^{132}I , and ^{133}I in the blood source and for ^{89}Sr , ^{90}Sr , and ^{90}Y in the cortical bone source, using RI-source function of PHITS ver. 3.02.

Using the cervical vascular model, a β -ray spectrum was generated from ^{131}I , ^{132}I , and ^{133}I in the blood source, and AFs and SAFs in the perivascular region were calculated and compared with the SAF in ICRP Publication 30. In a similar manner, the β -ray spectrum was generated from ^{89}Sr , ^{90}Sr , and ^{90}Y in the cortical bone source, and AFs and SAFs in the perivascular region were calculated. As mentioned previously, the ICRP 1990 model assumes the electron SAF from the cortical bone source to the RBM to be zero. Calculations were performed to examine the extent of underestimation for the contributions of ^{89}Sr , ^{90}Sr , and ^{90}Y from the cortical bone source.

III RESULTS

3.1. Comparison between the electron SAFs in the cervical vascular model and the SAFs in the ICRP 1990 model

Assuming the blood in the sinusoids as the source and a cylindrical area with the thickness of 0.01 cm (including the

sinusoidal endothelium) in the perivascular region as the target, AFs and SAFs in the perivascular region were calculated. Comparisons were made of the SAF of the body tissue, used as a surrogate for the whole-body blood source, with the whole-body tissue ($1/68.831 \text{ kg}^{-1} = 0.01453 \text{ kg}^{-1}$) in the ICRP 1990 model (Table 4). Statistical errors in the perivascular region ranged from 0.01 to 0.075.

As shown in the bottom row of each dataset, the cervical vascular model SAFs (denoted $\text{SAF} \times 0.182\%$ to account for the fraction disintegrated in the blood in the RBM of the cervical bone) were 1.2 to 6.9 times higher than the SAF in the ICRP 1990 model (0.01453 kg^{-1}) for 49 blood vessels, with the maximum at the energy of 0.3 MeV. The degree of difference between the cervical vascular model SAFs and the SAF in the ICRP 1990 model was larger, with fewer blood vessels in the source and with a smaller thickness of the cylinder (i.e., a smaller perivascular region) in the target.

Table 5 shows the electron SAF from the cortical bone source to the perivascular region of the cervical vascular model (denoted $\text{SAF} \times 2.2\%$ to account for the fraction disintegrated in the cortical bone of the cervical bone). It shows that the energy is deposited to the perivascular region, beginning at 0.05 MeV. The ICRP 1990 model does not consider the electron energy from the cortical bone to the RBM, even though 80% of a bone-seeking nuclide is distributed to the cortical bone. Thus, the ICRP 1990 model underestimates the energy transfer for cortical bone sources.

3.2. Comparison with different settings for the cervical vascular model

a) With different source regions

Figure 3 shows absorbed doses per decay when the source region was the blood within blood vessels (sinusoids) or the RBM and trabecular bone when the target region was set as the perivascular region, with a thickness of 0.01 cm.

Absorbed doses in the perivascular region differed by a factor of 0.6 to 3.1 when a comparison was made between the blood and the RBM as sources for 49 blood vessels (Table 6). Thus, when hematopoietic cells are localized to the perivascular region, the ICRP 1990 model and the ICRP 2007 model, both of which assume a uniform distribution of HSCs throughout the entirety of bone tissues, underestimate doses.

b) With different thicknesses of the perivascular region

As shown in Fig. 4 and Table 7, absorbed doses increased when the thickness of the perivascular region was smaller. Comparisons between the thickness of 0.01 cm and 0.00125 cm show that the absorbed doses more than doubled at energies of 0.1 MeV or below. If the HSCs were concentrated in the perivascular region with smaller thicknesses, absorbed doses to the hematopoietic stem cell layer would increase.

3.3. Short-lived nuclides in the blood source

As shown in Table 8, the electron SAFs from the blood source to the perivascular region for ^{131}I , ^{132}I , and ^{133}I were 0.084 kg^{-1} , 0.062 kg^{-1} , and 0.069 kg^{-1} , respectively for 49 vessels. The SAF of ^{132}I , a daughter nuclide of ^{132}Te , is of special interest, due to its large decay proportion in the blood

Table 4 Comparison of the electron SAFs from the blood source in blood vessels to the perivascular region with the SAF in the ICRP 1990 model.

The number of vessels 25												
Energy (MeV)	0.05	0.075	0.1	0.15	0.2	0.3	0.4	0.6	0.8	1.2	1.6	2.4
Weight of perivascular region (g)	1.385	1.385	1.385	1.385	1.385	1.385	1.385	1.385	1.385	1.385	1.385	1.385
Energy absorbed by perivascular region (MeV/Source)	6.65E-04	1.84E-03	3.99E-03	9.26E-03	1.45E-02	2.31E-02	3.04E-02	3.92E-02	3.70E-02	3.84E-02	4.69E-02	5.75E-02
AF	0.013	0.025	0.040	0.062	0.073	0.077	0.076	0.065	0.046	0.032	0.029	0.024
SAF (kg ⁻¹)	9.597	17.689	28.779	44.579	52.429	55.616	54.892	47.113	33.396	23.096	21.161	17.302
SAF (perivascular region←whole blood)*	0.018	0.032	0.052	0.081	0.096	0.101	0.100	0.086	0.061	0.042	0.039	0.032
SAF/ICRP 1990 SAF	1.2	2.3	3.7	5.6	6.6	7.1	7.0	6.0	4.3	2.9	2.7	2.2
The number of vessels 49												
Energy (MeV)	0.05	0.075	0.1	0.15	0.2	0.3	0.4	0.6	0.8	1.2	1.6	2.4
Weight of perivascular region (g)	1.967	1.967	1.967	1.967	1.967	1.967	1.967	1.967	1.967	1.967	1.967	1.967
Energy absorbed by perivascular region (MeV/Source)	9.26E-04	2.62E-03	5.50E-03	1.28E-02	1.97E-02	3.20E-02	4.00E-02	4.12E-02	3.91E-02	4.81E-02	5.94E-02	7.55E-02
AF	0.019	0.035	0.055	0.086	0.099	0.107	0.100	0.069	0.049	0.040	0.037	0.031
SAF (kg ⁻¹)	9.416	17.776	27.969	43.535	50.114	54.182	50.808	34.875	24.837	20.391	18.869	15.986
SAF (perivascular region←whole blood)*	0.017	0.032	0.051	0.079	0.091	0.099	0.093	0.064	0.045	0.037	0.034	0.029
SAF/ICRP 1990 SAF	1.2	2.3	3.6	5.6	6.4	6.9	6.5	4.5	3.1	2.6	2.4	2.0
The number of vessels 121												
Energy (MeV)	0.05	0.075	0.1	0.15	0.2	0.3	0.4	0.6	0.8	1.2	1.6	2.4
Weight of perivascular region (g)	3.216	3.216	3.216	3.216	3.216	3.216	3.216	3.216	3.216	3.216	3.216	3.216
Energy absorbed by perivascular region (MeV/Source)	1.40E-03	4.08E-03	8.64E-03	2.06E-02	3.00E-02	4.51E-02	4.68E-02	4.33E-02	5.20E-02	6.92E-02	8.40E-02	1.13E-01
AF	0.028	0.054	0.086	0.137	0.150	0.150	0.117	0.072	0.065	0.058	0.053	0.047
SAF (kg ⁻¹)	8.713	16.899	26.862	42.729	46.589	46.733	36.409	22.438	20.215	17.931	16.332	14.637
SAF (perivascular region←whole blood)*	0.016	0.031	0.049	0.078	0.085	0.085	0.066	0.041	0.037	0.033	0.030	0.027
SAF/ICRP 1990 SAF	1.1	2.2	3.4	5.5	5.9	5.9	4.6	2.9	2.6	2.3	2.1	1.9

* SAF × 0.182%

Table 5 Comparison of the electron SAFs from the cortical bone source to the perivascular region of the RBM with the SAF in the ICRP 1990 model.

The number of vessels 25												
Energy (MeV)	0.05	0.075	0.1	0.15	0.2	0.3	0.4	0.6	0.8	1.2	1.6	2.4
Weight of perivascular region (g)	1.385	1.385	1.385	1.385	1.385	1.385	1.385	1.385	1.385	1.385	1.385	1.385
Energy absorbed by perivascular region (MeV/Source)	1.40E-08	3.17E-08	5.58E-08	1.09E-07	1.49E-07	6.35E-07	2.95E-05	2.87E-04	7.36E-04	1.74E-03	2.96E-03	5.94E-03
AF	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002	0.002
SAF (kg ⁻¹)	0.000	0.000	0.000	0.000	0.001	0.002	0.053	0.345	0.664	1.044	1.334	1.778
SAF (perivascular region←whole blood)*	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.008	0.014	0.023	0.029	0.039
SAF/ICRP 1990 SAF	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.5	1.0	1.6	2.0	2.7
The number of vessels 49												
Energy (MeV)	0.05	0.075	0.1	0.15	0.2	0.3	0.4	0.6	0.8	1.2	1.6	2.4
Weight of perivascular region (g)	1.967	1.967	1.967	1.967	1.967	1.967	1.967	1.967	1.967	1.967	1.967	1.967
Energy absorbed by perivascular region (MeV/Source)	2.30E-08	4.38E-08	7.91E-08	8.02E-08	8.44E-06	1.06E-04	2.97E-04	8.26E-04	1.50E-03	2.89E-03	4.52E-03	8.75E-03
AF	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002	0.002	0.003	0.004
SAF (kg ⁻¹)	0.000	0.000	0.000	0.000	0.021	0.180	0.378	0.699	0.953	1.224	1.435	1.854
SAF (perivascular region←whole blood)*	0.000	0.000	0.000	0.000	0.000	0.002	0.008	0.015	0.021	0.027	0.031	0.040
SAF/ICRP 1990 SAF	0.0	0.0	0.0	0.0	0.0	0.3	0.6	1.1	1.5	1.9	2.2	2.8

The number of vessels 121												
Energy (MeV)	0.05	0.075	0.1	0.15	0.2	0.3	0.4	0.6	0.8	1.2	1.6	2.4
Weight of perivascular region (g)	3.216	3.216	3.216	3.216	3.216	3.216	3.216	3.216	3.216	3.216	3.216	3.216
Energy absorbed by perivascular region (MeV/Source)	1.55E-04	2.30E-04	3.04E-04	4.36E-04	5.80E-04	9.68E-04	1.40E-03	2.28E-03	3.01E-03	5.44E-03	8.05E-03	1.49E-02
AF	0.003	0.003	0.003	0.003	0.003	0.003	0.004	0.004	0.004	0.005	0.005	0.006
SAF (kg ⁻¹)	0.965	0.954	0.945	0.903	0.902	1.003	1.091	1.179	1.169	1.410	1.565	1.931
SAF (perivascular region←whole blood)*	0.021	0.021	0.021	0.020	0.020	0.022	0.024	0.026	0.025	0.031	0.034	0.042
SAF/ICRP 1990 SAF	1.5	1.5	1.4	1.4	1.4	1.5	1.7	1.8	1.8	2.1	2.4	2.9

* SAF × 2.2%

Fig. 3 Comparison of doses absorbed to the perivascular region from the blood and from the RBM and trabecular bone sources.

compartment. With the blood within the RBM blood vessels (sinusoids) as the source, the SAF of ¹³²I, adjusted for the fraction disintegrated in the blood in the RBM of the cervical bone (SAF × 0.182%), was 4.4 times higher than the SAF in the ICRP 1990 model, 1/68.831 kg⁻¹.

3.4. Long-lived nuclides in the cortical bone source

Table 9 shows that the electron SAFs from ⁸⁹Sr, ⁹⁰Sr, and ⁹⁰Y in the cortical bone source were 0.020 kg⁻¹, 0.004 kg⁻¹ and 0.026 kg⁻¹, respectively, when the number of blood vessels was set at 49. For the comparison with the ICRP 1990 model, the electron SAFs, adjusted for the fraction disintegrated in the cortical bone of the cervical bone, i.e. SAF × 2.2%, were compared with the body tissue SAF of 1/68.831 kg⁻¹ (0.01453 kg⁻¹), because the SAF from the cortical bone source to the bone marrow is defined as zero in the ICRP 1990 model.

Table 10 shows the absorbed doses in the perivascular region that were calculated for ⁸⁹Sr, ⁹⁰Sr, and ⁹⁰Y, with the cortical and trabecular bones as the sources. The contribution of photons from ⁹⁰Y was considered to be zero, due to its low emission ratio of 1.4E-6 %.²⁰ The ICRP 1990 model sets the electron AF from the trabecular bone as 0.5 for the bone

Table 6 Comparison of dose absorbed to the perivascular region from the blood and from the RBM and trabecular bone sources.

The number of vessels 25				The number of vessels 49			The number of vessels 121		
Source	Absorbed dose (Gy/source)			Absorbed dose (Gy/source)			Absorbed dose (Gy/source)		
	Blood	Blood/(RBM +Trabecular bone)		Blood	Blood/(RBM +Trabecular bone)		Blood	Blood/(RBM +Trabecular bone)	
		RBM	+Trabecular bone		RBM	+Trabecular bone		RBM	+Trabecular bone
Energy (MeV)	0.05	7.69E-14	1.34E-13	0.6	7.54E-14	1.37E-13	0.6	6.98E-14	1.37E-13
	0.075	2.13E-13	1.93E-13	1.1	2.14E-13	2.05E-13	1.0	2.03E-14	1.97E-13
	0.1	4.61E-13	2.50E-13	1.8	4.48E-13	2.79E-13	1.6	4.30E-13	2.62E-13
	0.15	1.07E-12	3.95E-13	2.7	1.05E-12	4.03E-13	2.6	1.03E-12	3.96E-13
	0.2	1.68E-12	5.54E-13	3.0	1.61E-12	5.43E-13	3.0	1.49E-12	5.28E-13
	0.3	2.67E-12	8.19E-13	3.3	2.60E-12	8.31E-13	3.1	2.25E-12	7.85E-13
	0.4	3.52E-12	1.07E-12	3.3	3.26E-12	1.11E-12	2.9	2.33E-12	1.07E-12
	0.6	4.53E-12	1.61E-12	2.8	3.35E-12	1.59E-12	2.1	2.16E-12	1.54E-12
	0.8	4.28E-12	2.11E-12	2.0	3.18E-12	2.13E-12	1.5	2.59E-12	2.08E-12
	1.2	4.44E-12	2.91E-12	1.5	3.92E-12	2.13E-12	1.8	3.45E-12	2.95E-12
	1.6	5.42E-12	3.70E-12	1.5	4.84E-12	3.76E-12	1.3	4.19E-12	3.72E-12
	2.4	6.65E-12	5.00E-12	1.3	6.15E-12	5.00E-12	1.2	5.63E-12	4.95E-12

Fig. 4 Comparison of absorbed doses to the perivascular region with different perivascular thicknesses.

surface and as 0.35 for the bone content. For a comparison of absorbed doses, the cervical vascular model was used for the absorbed doses in the perivascular region, with whole bone as the source.

It is assumed that ^{90}Y remains in the bone indefinitely.⁴⁾ The ICRP 1990 model sets the electron AF from the cortical bone source as zero, excluding it from the dose estimation for the RBM. Thus, neither ^{90}Sr nor ^{89}Sr is assessed for the dose from the cortical bone source, which comprises about 30% of the dose from the hard bone source.

IV DISCUSSION

The cervical vascular model revealed that electron SAFs, with the blood in the bone marrow blood vessels as the source, are 1.2 to 6.9 times larger than the electron SAF in the ICRP 1990 model. In comparison with the electron SAF in the ICRP 2007 model, the SAF's were larger by a factor of 0.6 to 3.1. When the electron SAFs from ^{131}I , ^{132}I , and ^{133}I in the blood source were calculated considering the β -ray spectrum for 49 blood vessels, the SAFs were larger than the SAF in the ICRP

Table 7 Comparison of doses absorbed to the perivascular region for different perivascular thicknesses.

		Absorbed dose (Gy/source)					
Thickness of perivascular region		0.02 cm	0.01 cm	0.005 cm	0.0025 cm	0.00125 cm	0.00125 cm/0.02 cm
Energy (MeV)	0.05	3.52E-14	7.54E-14	1.56E-13	3.09E-13	4.61E-13	13.1
	0.075	9.97E-14	2.14E-13	4.27E-13	6.21E-13	7.96E-13	8.0
	0.1	2.12E-13	4.48E-13	7.37E-13	9.31E-13	1.05E-12	5.0
	0.15	6.18E-13	1.05E-12	1.36E-12	1.53E-12	1.66E-12	2.7
	0.2	1.15E-12	1.61E-12	1.90E-12	2.11E-12	2.20E-12	1.9
	0.3	2.12E-12	2.60E-12	2.91E-12	3.00E-12	3.03E-12	1.4
	0.4	2.81E-12	3.26E-12	3.42E-12	3.54E-12	3.70E-12	1.3
	0.6	3.11E-12	3.35E-12	3.53E-12	3.63E-12	3.67E-12	1.2
	0.8	2.95E-12	3.18E-12	3.38E-12	3.42E-12	3.55E-12	1.2
	1.2	3.68E-12	3.92E-12	4.04E-12	4.14E-12	4.31E-12	1.2
	1.6	4.53E-12	4.84E-12	4.88E-12	5.04E-12	5.01E-12	1.1
	2.4	5.85E-12	6.15E-12	6.13E-12	6.28E-12	6.37E-12	1.1

Table 8 Comparison of the electron SAFs for ^{131}I , ^{132}I , and ^{133}I from the blood source to the perivascular.

The number of vessels 25			
Radionuclide	^{131}I	^{132}I	^{133}I
Weight of perivascular region (g)	1.385	1.385	1.385
Energy absorbed by perivascular region (MeV/Source)	1.25E-02	2.62E-02	2.42E-02
AF	0.069	0.057	0.061
SAF (kg^{-1})	49.923	40.910	44.103
SAF (perivascular region $\leftarrow$ whole blood) *	0.091	0.074	0.080
SAF/ICRP 1990 SAF	6.360	5.212	5.619
* SAF $\times$ 0.182%			
The number of vessels 49			
Radionuclide	^{131}I	^{132}I	^{133}I
Weight of perivascular region (g)	1.967	1.967	1.967
Energy absorbed by perivascular region (MeV/Source)	1.66E-02	3.13E-02	2.94E-02
AF	0.091	0.067	0.074
SAF (kg^{-1})	46.328	34.296	37.78
SAF (perivascular region $\leftarrow$ whole blood) *	0.084	0.062	0.069
SAF/ICRP 1990 SAF	5.902	4.369	4.813
* SAF $\times$ 0.182%			

The number of vessels 121			
Radionuclide	¹³¹ I	¹³² I	¹³³ I
Weight of perivascular region (g)	3.216	3.216	3.216
Energy absorbed by perivascular region (MeV/Source)	2.27E-02	3.97E-02	3.63E-02
AF	0.127	0.089	0.096
SAF (kg ⁻¹)	39.558	27.764	29.814
SAF (perivascular region ← whole blood) *	0.072	0.051	0.054
SAF/ICRP 1990 SAF	5.04	3.537	3.798

* SAF × 0.182%

Table 9 Comparison of the electron SAFs for ⁸⁹Sr, ⁹⁰Sr, and ⁹⁰Y from the cortical bone source to the perivascular region of the RBM with the SAF in the ICRP 1990 model.

The number of vessels 49			
Radionuclide	⁸⁹ Sr	⁹⁰ Sr	⁹⁰ Y
Weight of perivascular region (g)	1.967	1.967	1.967
Energy absorbed by perivascular region (MeV/Source)	1.03E-03	8.78E-05	2.18E-03
AF	0.0018	0.0004	0.0024
SAF (kg ⁻¹)	0.915	0.203	1.220
SAF (perivascular region ← whole blood) *	0.020	0.004	0.026
SAF/ICRP 1990 SAF	1.409	0.313	1.879

* SAF × 2.2%

Table 10 Comparison of doses of ⁸⁹Sr, ⁹⁰Sr, and ⁹⁰Y absorbed to the perivascular region of the RBM from the cortical bone and trabecular bone sources.

90Sr							
Source	Cortical bone volume			Trabecular bone volume			Total
Target	Perivascular region			Perivascular region			
Radionuclide	90Sr	90Y	90Y	90Sr	90Y	90Y	
	electron	electron	photon	electron	electron	photon	
Gy/source	5.74E-15	1.78E-13	0.00E+00	2.03E-13	9.12E-13	0.00E+00	
Distribution of nuclide in the bone	0.8	0.8	0.8	0.2	0.2	0.2	1.0
Gy/source × distribution in the bone	4.59E-15	1.42E-13	0.00E+00	4.06E-14	1.82E-13	0.00E+00	3.71E-13 a
Fraction	1%	38%	0%	11%	49%	0%	100%
ICRP1990 SAF	0	0	—	0.35	0.35	—	
Dose included in ICRP 1990	0	0	0	4.06E-14	1.82E-13	0	2.23E-13 b

89Sr							
Source	Cortical bone volume			Trabecular bone volume			Total
Target	Perivascular region			Perivascular region			
Radionuclide	89Sr			89Sr			
	electron			electron			
Gy/source	8.38E-14			5.90E-13			
Distribution of nuclide in the bone	0.8			0.2			1.0
Gy/source × distribution in the bone	6.70E-14			1.18E-13			1.85E-13 c
Fraction	36%			64%			100%
ICRP1990 SAF	0			0.35			
Dose included in ICRP 1990	0			1.18E-13			1.18E-13 d

a/b

1.66

c/d

1.57

1990 model ($1/68.831 \text{ kg}^{-1}$) by factors of 5.9, 4.4, and 4.8, respectively.

In the calculation of the electron SAFs from the cortical bone source using the cervical vascular model, the energy depositions began at the energy of 0.05 MeV or above. The ICRP model defines electron AFs from the cortical bone source as zero, and any contribution from the cortical bone source is not included in the dose assessment of the RBM. Thus, for ^{90}Sr and ^{89}Sr , the doses absorbed from the cortical bone source, which are nearly 30% of the dose from the hard bone source, are not considered in the dose assessment. Further, if the electron SAFs from the cortical bone source are added to those from the trabecular bone source, the doses absorbed from ^{89}Sr and $^{90}\text{Sr}/^{90}\text{Y}$ will be larger by a factor of 1.57 and 1.66, respectively.

The absorbed doses to perivascular region from the electron sources and the photon sources in blood vessels were compared in **Fig. 5** for 49 blood vessels. It shows that the absorbed dose from radionuclides in blood sources are largely from electrons. With the cervical vascular model revealing the possibility of underestimation of the bone marrow dose from blood source, considerations are due in assessing validity of the current dose assessment, especially for short-lived radionuclides such as $^{132}\text{Te}/^{132}\text{I}$, as the proportion of the number of decay in the blood compartment is relatively large.

Regarding the limitations of the cervical vascular model in evaluating the electron SAFs, several issues are raised. The cervical vascular model, designed with an average mass of bone tissues in the cervical vertebrae (JM-103 ID 140-146), does not reflect differences in the mass of bone tissues according to location. The shape of bone tissues also varies widely according to location in the bone (**Table 11**).¹⁵⁾ In the study of the skeletal dosimetry model based on micro CT

images,¹⁴⁾ AFs from the trabecular and cortical bones to the active marrow vary by bone location. The shape and blood volume of the sinusoids and other blood vessels are also unclear. An accurate dose estimation requires an evaluation with a more elaborate model using micro CT images.

V CONCLUSION

The current ICRP internal dose assessment model underestimates the RBM dose from the blood and cortical bone electron sources. A more sensitive model should be used

Fig. 5 Comparison of absorbed doses of electron and photon to the perivascular region.

Table 11 Masses of bone tissues and blood by anatomical location.

Organ	Mass (g)						RBM/ Body tissue	Blood/ Body tissue
	Body tissue	RBM	Cortical bone	Trabecular bone	Soft tissues	Blood		
Cranium	1,346.1	91.2	773.8	308.1	264.2	27.5	6.8%	2.0%
Mandible	164.9	9.2	79.8	52.4	32.7	3.4	5.6%	2.1%
Cervical vertebra	206.8	45.3	134.1	12.2	60.6	7.9	21.9%	3.8%
Thoracic vertebra	653.7	187.3	315.2	76.7	261.8	31.8	28.7%	4.9%
Lumbar vertebra	589.8	143.1	221.9	118.4	249.2	30.0	24.3%	5.1%
Sacrum	260.7	115.1	128.0	12.2	120.4	14.2	44.2%	5.5%
Clavicles	111.5	9.5	52.0	27.9	31.7	2.6	8.6%	2.3%
Scapulae	310.3	34.0	142.9	70.2	97.1	8.3	11.0%	2.7%
Sternum	107.3	36.4	39.3	20.8	47.2	5.6	33.9%	5.2%
Ribs	945.0	186.7	324.6	226.1	394.3	47.6	19.8%	5.0%
Os coxae	1,057.0	220.7	388.4	257.5	411.5	38.1	20.9%	3.6%
Humeri	589.4	28.6	282.4	121.7	193.3	10.0	4.9%	1.7%
Forearm	360.6	0.0	205.3	55.2	100.2	3.2	0.0%	0.9%
Wrist-hand	220.1	0.0	115.2	35.8	69.1	2.2	0.0%	1.0%
Femora	1,652.7	84.1	665.1	440.4	547.1	24.4	5.1%	1.5%
Tibiae-fibulae-patellae	1,563.2	0.0	669.0	367.3	526.6	15.6	0.0%	1.0%
Ankle-foot	871.7	0.0	298.7	261.8	313.3	8.7	0.0%	1.0%
Os hyoideum	3.8	0.3	1.8	0.9	1.1	0.1	8.2%	2.3%
Total	11,014.4	1,192.6	4,837.4	2,465.7	3,721.5	281.2		

to evaluate the bone marrow dose assessment and the effects on hematopoietic and immune functions, and the validity of the current dose evaluation of short-lived radionuclides which decay in the blood compartment in relatively large proportion should be assessed.

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