**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 the blood source and hematopoietic stem cells (HSCs) to organs in the body, including the bone marrow and immune cells. Recent studies have revealed that HSCs and immune cells concentrate 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 the bone marrow was built using data from the adult Japanese male phantom. Doses absorbed by HSCs from blood and hard bone sources were calculated 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.
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), 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. 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.

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). Then energy transfers of bone tissues and blood vessels was built using the data assumed to be zero. For electron sources in the cortical bone to the RBM target is 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 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 (\(^{131}\text{I}\)), iodine-132 (\(^{132}\text{I}\)), and iodine-133 (\(^{133}\text{I}\)) in the blood source and from long-lived strontium-89 (\(^{89}\text{Sr}\)), strontium-90 (\(^{90}\text{Sr}\)), and its progeny, yttrium-90 (\(^{90}\text{Y}\)), in the cortical bone source.

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

| Source organ | Target organ | \(\beta^{\text{emitter uniform in volume}}\) | \(\beta^{\text{emitter on bone surfaces}}\) | \(E_{\text{th}} \geq 0.2 \text{ MeV}\) | \(E_{\text{th}} < 0.2 \text{ MeV}\) |
|--------------|--------------|-----------------|-----------------|-----------------|-----------------|
| 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 |

## 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. 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 89 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, 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. Material densities were set as 1.623 g/cm\(^3\) for the bone and 1 g/cm\(^3\) 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

[^2]: The table presents the electron AFs from the hard bone sources to the RBM in ICRP Publication 30. The AFs are provided for different source and target organs, showing the distribution of electrons from the bone to the RBM. The table includes columns for electron uniform distribution in volume and on bone surfaces, with specific values for different energy thresholds. The values indicate the proportion of energy absorbed in the RBM, highlighting the influence of different types of bone and blood sources on the dosimetry. This information is crucial for understanding the radiation exposure from bone-seeking radionuclides.

[^3]: The cervical vertebrae model was simplified to a 9 cm cylinder with an internal lattice structure, representing the trabecular bone, bone marrow, and blood vessels. This model was constructed using data on the mass distribution of bone and blood tissues from the Japanese phantom, JM-103. The model was designed to overcome the limitations of the ICRP 1990 model by incorporating detailed anatomical information and simplifying the distribution of blood vessels. Calculations were performed to determine the mass of blood in the RBM, the inner diameter of blood vessels, and the number of blood vessels, considering the cervical, thoracic, and lumbar spine proportions. The model was further refined by analyzing blood vessels at intervals, allowing for the examination of different scenarios involving the distribution of blood vessels within the cervical vertebrae. This approach provided a more accurate representation of the radiation exposure scenario, facilitating a better understanding of the impact of bone-seeking radionuclides on the cervical vertebrae.
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 \( t_{\text{deposit}} \) 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 less 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 generated 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 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 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

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**Table 2  Overview of analysis.**

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

\(^\ast\)/mass of total body tissue excluding contents of walled organs
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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 | Total body mass (g) | Cortical bone (g) | Trabecular bone (g) | Soft tissues (g) | RBM (g) | Soft tissues - RBM (g) | Blood (g) | 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 \( \frac{281.2 \times 4}{1,191.6 \times 7} \approx 100 \approx 13.5% \)
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 sinuoids 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 sinuoids 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, using RI-source function of PHITS ver. 3.02.

As shown in the bottom row of each dataset, the cervical vascular model SAFs (denoted SAF × 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 SAF × 2.2% to account for the fraction disintegrated in the cervical 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 (sinuoids) 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.

| Energy (MeV) | Weight of perivascular region (g) | Energy absorbed by perivascular region (MeV/Source) | AF     | SAF (kg\(^{-1}\)) | (perivascular region—whole blood)* | SAF/ICRP 1990 SAF |
|-------------|----------------------------------|----------------------------------------------------|--------|--------------------|------------------------------------|-------------------|
| 0.05        | 3.216-                             | 0.172                                              | 0.001  | 0.018              | 1.2                                |                   |
| 0.075       | 3.216-                             | 0.032                                              | 0.020  | 0.018              | 1.2                                |                   |
| 0.1         | 3.216-                             | 0.052                                              | 0.040  | 0.018              | 1.2                                |                   |
| 0.15        | 3.216-                             | 0.096                                              | 0.062  | 0.018              | 1.2                                |                   |
| 0.2         | 3.216-                             | 0.101                                              | 0.076  | 0.018              | 1.2                                |                   |
| 0.3         | 3.216-                             | 0.100                                              | 0.065  | 0.018              | 1.2                                |                   |
| 0.4         | 3.216-                             | 0.086                                              | 0.046  | 0.018              | 1.2                                |                   |
| 0.6         | 3.216-                             | 0.032                                              | 0.032  | 0.018              | 1.2                                |                   |
| 0.8         | 3.216-                             | 0.029                                              | 0.037  | 0.018              | 1.2                                |                   |
| 1.2         | 3.216-                             | 0.024                                              | 0.040  | 0.018              | 1.2                                |                   |
| 1.6         | 3.216-                             | 0.022                                              | 0.032  | 0.018              | 1.2                                |                   |
| 2.4         | 3.216-                             | 0.021                                              | 0.037  | 0.018              | 1.2                                |                   |

### 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.

| Energy (MeV) | Weight of perivascular region (g) | Energy absorbed by perivascular region (MeV/Source) | AF     | SAF (kg\(^{-1}\)) | (perivascular region—whole blood)* | SAF/ICRP 1990 SAF |
|-------------|----------------------------------|----------------------------------------------------|--------|--------------------|------------------------------------|-------------------|
| 0.05        | 1.385-                             | 1.40E-                                             | 0.000  | 0.000              | 0.0                                |                   |
| 0.075       | 1.385-                             | 1.09E-                                             | 0.000  | 0.000              | 0.0                                |                   |
| 0.1         | 1.385-                             | 1.49E-                                             | 0.000  | 0.000              | 0.0                                |                   |
| 0.15        | 1.385-                             | 1.99E-                                             | 0.000  | 0.000              | 0.0                                |                   |
| 0.2         | 1.385-                             | 2.95E-                                             | 0.000  | 0.000              | 0.0                                |                   |
| 0.3         | 1.385-                             | 2.87E-                                             | 0.000  | 0.000              | 0.0                                |                   |
| 0.4         | 1.385-                             | 7.36E-                                             | 0.000  | 0.000              | 0.0                                |                   |
| 0.6         | 1.385-                             | 1.74E-                                             | 0.000  | 0.000              | 0.0                                |                   |
| 0.8         | 1.385-                             | 2.96E-                                             | 0.000  | 0.000              | 0.0                                |                   |
| 1.2         | 1.385-                             | 5.94E-                                             | 0.000  | 0.000              | 0.0                                |                   |
| 1.6         | 1.385-                             | 8.75E-                                             | 0.000  | 0.000              | 0.0                                |                   |
| 2.4         | 1.385-                             | 8.75E-                                             | 0.000  | 0.000              | 0.0                                |                   |

*SAF × 0.182%
compartment. With the blood within the RBM blood vessels (sinusoids) as the source, the SAF of $^{131}$I, adjusted for the fraction disintegrated in the blood in the RBM of the cervical ERQH, was $1/68.831$ kg–1.

### 3.4. Long-lived nuclides in the cortical bone source

Table 9 shows that the electron SAFs from $^{89}$Sr, $^{90}$Sr, and $^{90}$Y 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 source, were compared with the body tissue SAF of $1/68.831$ kg–1, because the SAF from the cortical bone source was defined as zero in the ICRP 1990 model.

Table 10 shows the absorbed doses in the perivascular region that were calculated for $^{89}$Sr, $^{90}$Sr, and $^{90}$Y, with the cortical and trabecular bones as the sources. The contribution of photons from $^{90}$Y was considered to be zero, due to its beta energy.

### Table 6

| Source | The number of vessels 25 | The number of vessels 49 | The number of vessels 121 |
|--------|-------------------------|-------------------------|-------------------------|
|        | Absorbed dose (Gy/source) | Blood/(RBM+Trabecular bone) | Blood/(RBM+Trabecular bone) | Blood/(RBM+Trabecular bone) |
|        | Blood | RBM | Trabecular bone | Blood | RBM | Trabecular bone | Blood | RBM | Trabecular bone |
| Energy (MeV) | 0.05 | 7.69E-14 | 1.34E-13 | 0.4 | 7.54E-14 | 1.37E-13 | 0.6 | 6.98E-14 | 1.37E-13 | 0.5 |
|     | 0.075 | 2.13E-13 | 1.93E-13 | 0.8 | 2.14E-13 | 2.05E-13 | 1.0 | 2.03E-14 | 1.97E-13 | 1.0 |
|     | 0.1 | 4.61E-13 | 2.50E-13 | 1.2 | 4.48E-13 | 2.79E-13 | 1.6 | 4.30E-13 | 2.62E-13 | 1.6 |
|     | 0.15 | 1.07E-12 | 3.95E-13 | 1.6 | 1.05E-12 | 4.03E-13 | 2.0 | 1.03E-12 | 3.96E-13 | 2.0 |
|     | 0.2 | 1.68E-12 | 5.54E-13 | 2.0 | 1.61E-12 | 5.43E-13 | 2.4 | 1.49E-12 | 5.28E-13 | 2.4 |
|     | 0.3 | 2.67E-12 | 8.19E-13 | 2.4 | 2.60E-12 | 8.31E-13 | 2.8 | 2.25E-12 | 7.85E-13 | 2.8 |
|     | 0.4 | 3.52E-12 | 1.07E-12 | 2.8 | 3.26E-12 | 1.11E-12 | 3.2 | 2.33E-12 | 1.07E-12 | 3.2 |
|     | 0.6 | 4.53E-12 | 1.61E-12 | 3.2 | 3.35E-12 | 1.59E-12 | 3.6 | 2.16E-12 | 1.54E-12 | 3.6 |
|     | 0.8 | 4.28E-12 | 2.11E-12 | 3.6 | 3.18E-12 | 2.13E-12 | 4.0 | 2.59E-12 | 2.08E-12 | 4.0 |
|     | 1.2 | 4.44E-12 | 2.91E-12 | 4.0 | 3.92E-12 | 2.13E-12 | 4.4 | 3.45E-12 | 2.95E-12 | 4.4 |
|     | 1.6 | 5.42E-12 | 3.70E-12 | 4.4 | 4.84E-12 | 3.76E-12 | 4.8 | 4.19E-12 | 3.72E-12 | 4.8 |
|     | 2.4 | 6.65E-12 | 5.00E-12 | 4.8 | 6.15E-12 | 5.00E-12 | 5.2 | 5.63E-12 | 4.95E-12 | 5.2 |

*SAF × 2.2%
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. 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.

### 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 model.

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

| 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.

| 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 ↔ whole blood) * | 0.091 | 0.074 | 0.080 |
| SAF/ICRP 1990 SAF | 6.360 | 5.212 | 5.619 |

* SAF × 0.182%

| 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) | 46.28 | 34.296 | 37.78 |
| SAF (perivascular region ↔ whole blood) * | 0.084 | 0.062 | 0.069 |
| SAF/ICRP 1990 SAF | 5.902 | 4.369 | 4.813 |

* SAF × 0.182%
Table 9  Comparison of the electron SAFs for $^{89}$Sr, $^{90}$Sr, and $^{90}$Y from the cortical bone source to the perivascular region of the RBM with the SAF in the ICRP 1990 model.

| 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 $^{89}$Sr, $^{90}$Sr, and $^{90}$Y absorbed to the perivascular region of the RBM from the cortical bone and trabecular bone sources.

| Source | Cortical bone volume | Trabecular bone volume | $^{89}$Sr | $^{90}$Sr | $^{90}$Y |
|--------|----------------------|------------------------|----------|----------|--------|
| Target | Perivascular region | Perivascular region | electron | photon | electron | photon | electron | photon |
| Gy/source | | | 5.74E-15 | 1.78E-13 | 0.000E+00 | 2.03E-13 | 9.12E-13 | 0.000E+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 | 0.000E+00 | 4.06E-14 | 1.82E-13 | 0.000E+00 | 3.71E-13 |
| Fraction | 0% | 38% | 0% | 11% | 49% | 0% | 100% |
| ICRP1990 SAF | 0 | 0 | 0 | 0.35 | 0.35 | 0 | 1.66 |
| Dose included in ICRP 1990 | 0 | 0 | 0 | 4.06E-14 | 1.82E-13 | 0 | 2.23E-13 |

| Source | Cortical bone volume | Trabecular bone volume | $^{90}$Sr |
|--------|----------------------|------------------------|----------|
| Target | Perivascular region | Perivascular region | electron |
| Gy/source | | | 8.38E-14 |
| 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 |
| Fraction | 36% | 64% | 100% |
| ICRP1990 SAF | 0 | 0.35 | 1.57 |
| Dose included in ICRP 1990 | 0 | 1.18E-13 | 1.18E-13 |
1990 model (1/68.831 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 ⁹⁰Sr and ⁹⁰Sr, 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 ⁹⁰Sr and ⁹⁰Sr/⁹⁰Y 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 ¹²⁵Te/¹²⁵I, 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). In the study of the skeletal dosimetry model based on micro CT images, 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

![Comparison of absorbed doses of electron and photon to the perivascular region.](image-url)

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

| Organ                | Mass (g) | Body tissue | RBM | Cortical bone | Trabecular bone | Soft tissues | Blood | RBM/ Body tissue | Blood/ Body tissue |
|----------------------|----------|-------------|-----|---------------|-----------------|--------------|-------|-----------------|-------------------|
| 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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