Absorbed Dose Calculations in Haversian Canals for Several Beta-Emitting Radionuclides

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A mathematical model of a Haversian canal was used to calculate absorbed dose factors for ^{90}Sr, ^{90}Y, ^{45}Ca, ^{89}Sr, ^{32}P, ^{131}I and ^{153}Sm. The regions of interest considered in this study were the blood canal, the wall or bone surface and the bone matrix. The source regions were the blood canal and the bone surface. Absorbed dose calculations were performed with the EGS4-PRESTA Monte Carlo transport code. Dose factors were calculated for Haversian canals of 5-μm to 50-μm radius. These data are also tabulated so that dose factors can be evaluated for other radii. An example is given in which these data are used along with a biokinetic model of a radioactive material in bone to assess doses from diagnostic and radiotherapy procedures.

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The effects of internal irradiation of bone depend on the chemical, biological and physical characteristics of the radionuclide. It is customary to describe those radionuclides that are concentrated and retained in the skeleton as "bone seekers." This classification is further delineated when bone-seeking radionuclides are divided into "volume seekers" and "surface seekers." The chemical characteristics of bone-seeking radionuclides determine their behavior in the biological systems. The physical characteristics of bone-seeking radionuclides are based on their half-lives, the energy and the range of their emitted radiations and their decay products.

The alkaline earths, calcium, strontium, radium and barium, are considered volume-seekers. They are readily absorbed in bone regions where active mineralization is taking place and blood level is high (*1*). Calcium is the main constituent of mineral bone. Originally, it was thought that other alkaline earths might replace calcium and show an identical distribution in the skeleton. This is true for a short period of time after intake, however, there are important differences in the ways these radionuclides behave in the skeleton.

The metabolic behavior and skeletal distribution of these radionuclides vary. Experimental work in dogs shows that ^{45}Ca concentrates in all bone surfaces immediately after injection and in a matter of days it concentrates in sites of active accumulation and diffuses in much lower concentrations throughout mineral bone. A comparison between ^{45}Ca and ^{133}Ba uptake patterns shows that ^{133}Ba is retained largely on bone surfaces, especially around Haversian canals (*2*).

The radionuclides that concentrate on bone surfaces are americium, thorium, cerium, californium, plutonium and yttrium. Although these radionuclides are surface-seekers, the patterns of their distribution on surfaces are not the same.

Because Haversian canals are intimate parts of the skeletal system, a dosimetric model for the assessment of absorbed doses is of interest in diagnostic and radiotherapy applications. A Haversian canal consists of a central hole about 11–55 μm in radius, surrounded by concentric layers of a type of bone called lamella, which is composed largely of calcified bone. The canal contains blood vessels, nerves and connective tissue. Two types of tissue are present in the Haversian system: the blood cells and fixed tissues (the capillaries and the bone cells) (*3*).

METHODS

This work is part of a comprehensive task to develop and apply structure-specific dosimetry to beta-emitting radionuclides. For purposes of radiation dosimetry, the structure of a Haversian canal can be approximated by a long annular cylinder with radius r (Fig. 1). There are three regions of interest (ROI) in the structure of a Haversian canal: the cavity or blood canal, the bone surfaces or wall and the mineral bone. The interface between the canal and bone has been identified as the most radiosensitive. The term "bone surface" is a geographical, rather than a biological, term. A bone surface is made of osteogenic cells and the mineral matrix of the hard bone with density close to that of tissue. Similar models have been used to assess doses to the Haversian system and bone marrow cavities (*4–6*).

Irradiation of the Haversian canal can occur when radioactive material is distributed in the cavity and assimilated by the bone. Therefore, two source regions were considered for dose calculations: first, the canal itself with a uniform distribution of a radionuclide and second, the bone surface or wall. For purposes of dose calculations, the thickness of the wall was considered to be 10 μm.

The Electron Gamma Shower EGS4-PRESTA transport code (*7,8*) was used to calculate absorbed fractions of energy for monoenergetic electrons. Calculations were made for both source

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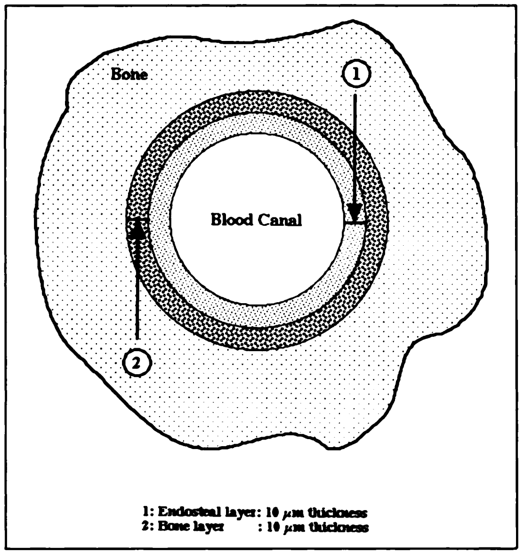

FIGURE 1. Schematic representation of a Haversian canal. The thickness of the endosteal layer and bone were considered to be 10 μm. The radius of the blood canal was assumed to be from 5 to 50 μm.

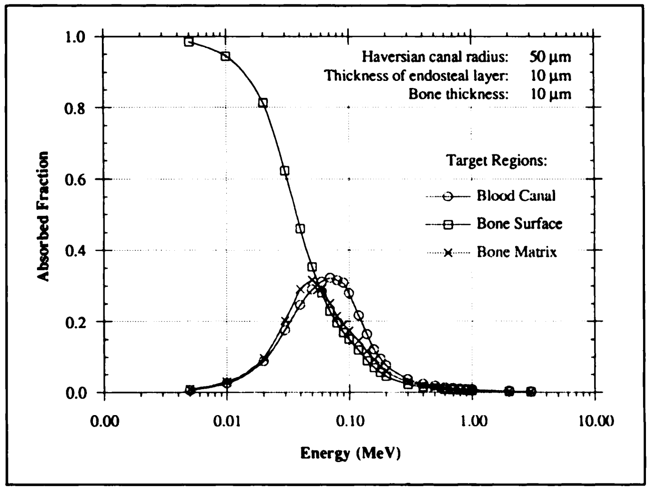

FIGURE 3. Absorbed fractions of energy for monoenergetic electrons. Source region is the wall. The target regions were the blood canal, the bone surface and the cortical bone. For purposes of absorbed dose calculations, the bone surface or wall and bone matrix are considered to be 10 μm thick.

regions and for Haversian canals of 5, 10, 20, 30, 40 and 50 μm radii. The total number of histories for each transport calculation was 50,000. The parameters used in the EGS4-PRESTA code were a maximum allowed energy loss per step, ESTEPE, of 2%, an electron cutoff energy, ECUT, of 1 keV and a photon cutoff energy, PCUT, of 1 keV. Radionuclide decay data were obtained by using the computer code RADLST (*9*). The associated errors for all transport calculations were less than 3%.

Figures 2 and 3 show absorbed fractions for monoenergetic electrons for a uniform source distribution in the blood canal and the wall (bone surface) for a Haversian system of 50 μm radius.

The absorbed energy can be expressed as:

$$\varepsilon(T \leftarrow S) = \sum n_i E_i \phi(T \leftarrow S)_i \text{ [Mev/Bq s]}, \qquad \text{Eq. 1}$$

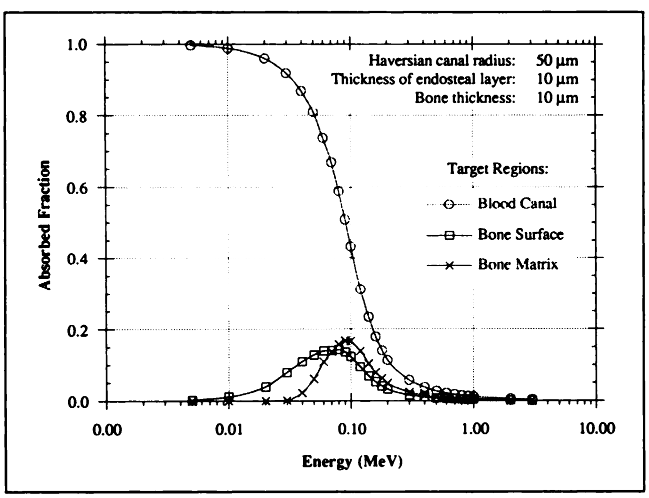

FIGURE 2. Absorbed fractions of energy for monoenergetic electrons. Source region is the blood canal. The target regions were the blood canal, bone surface and bone matrix. For purposes of absorbed dose calculations, the bone surface or wall and bone matrix are considered to be 10 μm thick.

where $\varepsilon(T \leftarrow S)$ is the energy deposited in the target region T, S represents the source region, n_i is the spectral yield per transformation of energy E_i for radiation type i and $\phi(T \leftarrow S)_i$ is the absorbed fraction for energy E_i and radiation type i.

Thus, the absorbed dose can be given by:

$$\bar{D}(T \leftarrow S) = \frac{\varepsilon(T \leftarrow S) q_S V_S}{m_T} \text{ [MeV/g]}, \qquad \text{Eq. 2}$$

where m_T is the mass of the target region, q_S is the total number of transformations per unit volume in source region S and V_S is the source volume. The value of q_S is dependent on the retention function(s) associated with a specific radionuclide. m_T can be expressed as:

$$m_T = \rho_T V_T, \qquad \text{Eq. 3}$$

where ρ_T and V_T are the density and volume of the target region, respectively.

As noted previously, the blood canal and the bone surface or wall were considered as source regions. Target regions were the blood canal of radius r, the wall surface with a thickness of 10 μm, and a region of the bone matrix with a thickness of 10 μm. The total absorbed dose to a target region will be that given by all source regions.

By considering the blood canal as a source region, absorbed doses are as follows:

Blood canal (BC) to Blood Canal (BC):

$$\frac{\bar{D}(BC \leftarrow BC)}{q_{BC}} = \frac{1.602 \times 10^{-10} \varepsilon(BC \leftarrow BC)}{\rho_{BC}} \text{ [Gy cm}^3\text{/Bq s]}. \qquad \text{Eq. 4}$$

Blood Canal (BC) to Bone Surface (BS):

$$\frac{\bar{D}(BS \leftarrow BC)}{q_{BC}} = \frac{1.602 \times 10^{-10} \varepsilon(BS \leftarrow BC) r^2}{(2r \times 10^{-3} + 10^{-6}) \rho_{BS}} \text{ [Gy cm}^3\text{/Bq s]}. \qquad \text{Eq. 5}$$

Blood Canal (BC) to Bone Matrix (BM):

$$\frac{\bar{D}(BM \leftarrow BC)}{q_{BC}} = \frac{1.602 \times 10^{-10}\varepsilon(BM \leftarrow BC)r^2}{(2r \times 10^{-3} + 3 \times 10^{-6})\rho_{BM}} \text{ [Gy cm}^3\text{/Bq s]}. \quad \text{Eq. 6}$$

When the bone surface is considered as a source region, absorbed doses are as follows:

Bone Surface (BS) to Blood Cavity (BC):

$$\frac{\bar{D}(BC \leftarrow BS)}{q_{BS}} = \frac{1.602 \times 10^{-10}\varepsilon(BC \leftarrow BS)(2r \times 10^{-3} + 10^{-6})}{r^2\rho_{BC}} \times \text{[Gy cm}^3\text{/Bq s]}. \quad \text{Eq. 7}$$

Bone Surface (BS) to Bone Surface (BS):

$$\frac{\bar{D}(BS \leftarrow BS)}{q_{BS}} = \frac{1.602 \times 10^{-10}\varepsilon(BS \leftarrow BS)}{\rho_{BS}} \text{ [Gy cm}^3\text{/Bq s]}. \quad \text{Eq. 8}$$

Bone Surface (BS) to Bone Matrix (BM):

$$\frac{\bar{D}(BM \leftarrow BS)}{q_{BS}} = \frac{1.602 \times 10^{-10}\varepsilon(BM \leftarrow BS)(2r \times 10^{-3} + 10^{-6})}{(2r \times 10^{-3} + 3 \times 10^{-6})\rho_{BM}} \times \text{[Gy cm}^3\text{/Bq s]}. \quad \text{Eq. 9}$$

For Equations 4 through 9, the density, ρ, is expressed in units of g/cm^3, the radius, r, in units of cm, and the energy deposited, ε, in units of MeV and the total number of transformations per unit volume, q, in units of Bq s/cm^3. The value of q depends on the retention functions of the blood cavity and the bone surfaces of the Haversian system. Equations 4 through 9 are useful independent of the retention models used.

Let R_{BC} and R_{BS} be the retention functions for the blood and bone surfaces, respectively. The total number of transformations per cm^3 in blood, q_{BC}, can be given by:

$$q_{BC} = \frac{\rho_{BC}}{m_{BC}} \int_0^t A_0 e^{-\lambda t} R_{BC}(t)dt, \quad \text{Eq. 10}$$

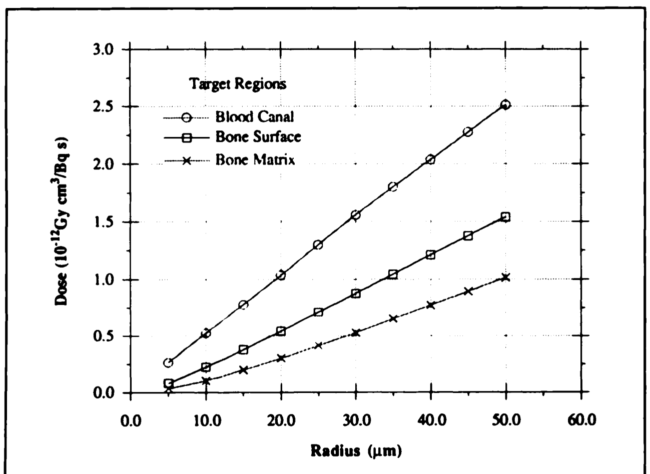

FIGURE 4. Absorbed dose factors for blood canal, wall and bone as a function of Haversian canal radius for a uniform distribution of ^{90}Sr in the blood canal.

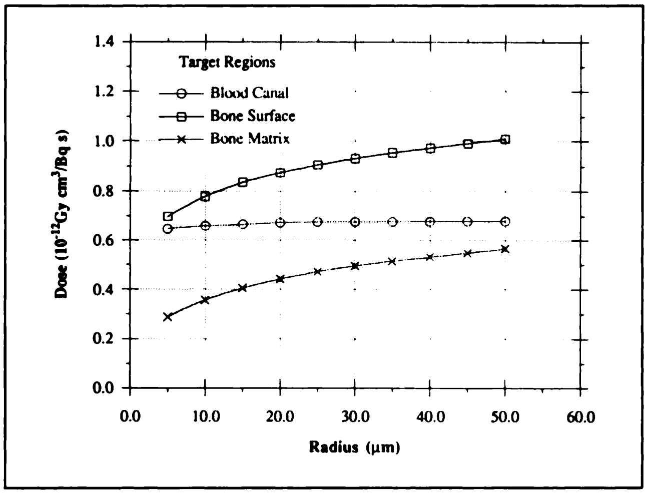

FIGURE 5. Absorbed dose factors for the blood canal, the bone surface or the wall and bone matrix as a function of Haversian canal radius for a uniform distribution of ^{90}Sr in the bone surface (10 μm thick).

where A_0 is the initial activity in blood, ρ_{BC} and m_{BC} are the density and total mass of the blood cavity, respectively, and λ is the radiological decay constant. q_{Wall} can be expressed by a similar equation.

Total doses to blood, wall and bone are as follows:

$$\bar{D}_{BC} = \bar{D}(BS \rightarrow BC) + \bar{D}(BC \rightarrow BC), \quad \text{Eq. 11}$$

$$\bar{D}_{BS} = \bar{D}(BS \rightarrow BS) + \bar{D}(BC \rightarrow BS), \quad \text{Eq. 12}$$

$$\bar{D}_{BM} = \bar{D}(BS \rightarrow BM) + \bar{D}(BC \rightarrow BM). \quad \text{Eq. 13}$$

RESULTS

Figure 4 shows absorbed dose factors for blood, wall and bone as a function of radius for a uniform distribution of ^{90}Sr in blood. Similarly, Figure 5 shows absorbed dose factors for a uniform distribution of ^{90}Sr in the wall. Tables 1 through 7 present absorbed dose factors as a function of Haversian canal radius for ^{90}Sr, ^{90}Y, ^{45}Ca, ^{89}Sr, ^{32}P, ^{131}I and ^{153}Sm, respectively.

As an example of how these tables can be used to evaluate absorbed doses, consider calcium. Radioisotopes of calcium are assumed to be distributed and retained in the body as established in the model developed by the Task Group on Alkaline Earth Metabolism in Adult Man (*1*). With a biokinetic model for calcium, the dose to Haversian canals can be assessed. Table 8 shows the residence times per unit activity administered intravenously, τ, for ^{45}Ca in cortical bone (*10*). If this biokinetic model is used, q_{wall} and q_{Blood} can be expressed approximately as:

$$q_{BS} \cong \tau_S A_0 \rho_{BS}/m_{BS}, \quad \text{Eq. 14}$$

$$q_{Blood} \cong \tau_S A_0 \rho_{Blood}/m_{Blood}. \quad \text{Eq. 15}$$

Let A_0 be 1 MBq. Thus, assuming the mass of the bone surfaces, m_{BS}, in an adult man to be 120 g; and the density of bone surfaces, ρ_{BS}, to be 1.04 g/cm^3; q_{BS} is approximately:

TABLE 1
Absorbed Dose Factors for Blood Canal, Bone Surface and Bone Matrix for ^{90}Sr in Haversian System

^{90}Sr radius (μm)	Absorbed dose (10^{-12} Gy cm^3/Bq s)					
	Source in blood			Source in bone surface		
	Blood	Wall	Bone	Blood	Wall	Bone
5	0.26	0.08	0.03	0.65	0.70	0.29
10	0.52	0.22	0.11	0.66	0.78	0.36
15	0.78	0.38	0.20	0.66	0.83	0.41
20	1.03	0.54	0.30	0.67	0.87	0.44
25	1.30	0.71	0.41	0.67	0.91	0.47
30	1.56	0.88	0.53	0.68	0.93	0.50
35	1.80	1.04	0.65	0.68	0.96	0.51
40	2.04	1.21	0.77	0.69	0.97	0.53
45	2.27	1.38	0.89	0.68	0.99	0.55
50	2.51	1.54	1.01	0.69	1.01	0.57

TABLE 2
Absorbed Doses Factors for Blood Canal, Bone Surface and Bone Matrix for ^{90}Y in Haversian System

^{90}Y radius (μm)	Absorbed dose (10^{-12} Gy cm^3/Bq s)					
	Source in blood			Source in bone surface		
	Blood	Wall	Bone	Blood	Wall	Bone
5	0.21	0.07	0.03	0.56	0.59	0.24
10	0.43	0.19	0.09	0.56	0.64	0.31
15	0.64	0.33	0.17	0.56	0.68	0.35
20	0.86	0.46	0.26	0.57	0.72	0.38
25	1.10	0.61	0.36	0.57	0.76	0.41
30	1.34	0.76	0.46	0.57	0.79	0.43
35	1.54	0.91	0.57	0.57	0.80	0.44
40	1.73	1.05	0.68	0.58	0.82	0.45
45	1.93	1.19	0.79	0.58	0.84	0.47
50	2.13	1.33	0.89	0.59	0.86	0.50

TABLE 3
Absorbed Dose Factors for Blood Canal, Bone Surface and Bone Matrix for ^{45}Ca in Haversian System

^{45}Ca radius (μm)	Absorbed dose (10^{-12} Gy cm^3/Bq s)					
	Source in blood			Source in bone surface		
	Blood	Wall	Bone	Blood	Wall	Bone
5	0.83	0.21	0.07	1.67	1.90	0.61
10	1.49	0.52	0.20	1.56	2.03	0.71
15	2.08	0.83	0.35	1.47	2.10	0.77
20	2.60	1.12	0.51	1.40	2.14	0.81
25	3.08	1.40	0.65	1.33	2.15	0.84
30	3.52	1.64	0.80	1.27	2.16	0.85
35	3.93	1.86	0.93	1.21	2.17	0.86
40	4.30	2.07	1.05	1.16	2.18	0.87
45	4.64	2.25	1.17	1.11	2.18	0.87
50	4.96	2.42	1.28	1.06	2.18	0.87

TABLE 4
Absorbed Doses Factors for Blood Canal, Bone Surface and Bone Matrix for ^{89}Sr in Haversian System

^{89}Sr radius (μm)	Absorbed dose (10^{-12} Gy cm^3/Bq s)					
	Source in blood			Source in bone surface		
	Blood	Wall	Bone	Blood	Wall	Bone
5	0.26	0.08	0.03	0.65	0.70	0.29
10	0.52	0.22	0.11	0.66	0.78	0.36
15	0.78	0.38	0.20	0.66	0.83	0.41
20	1.03	0.54	0.30	0.67	0.87	0.44
25	1.30	0.71	0.41	0.67	0.91	0.47
30	1.56	0.88	0.53	0.68	0.93	0.50
35	1.80	1.04	0.65	0.68	0.96	0.51
40	2.04	1.21	0.77	0.68	0.97	0.53
45	2.27	1.38	0.89	0.68	0.99	0.55
50	2.51	1.54	1.01	0.68	1.02	0.57

TABLE 5
Absorbed Doses Factors for Blood Canal, Bone Surface and Bone Matrix for ^{32}P in Haversian System

^{32}P radius (μm)	Absorbed dose (10^{-12} Gy cm^3/Bq s)					
	Source in blood canal			Source in bone surface		
	Blood	Wall	Bone	Blood	Wall	Bone
5	0.22	0.07	0.03	0.58	0.61	0.26
10	0.45	0.20	0.10	0.59	0.68	0.32
15	0.68	0.34	0.18	0.60	0.73	0.73
20	0.91	0.49	0.28	0.61	0.77	0.41
25	1.16	0.65	0.38	0.61	0.81	0.43
30	1.40	0.80	0.49	0.61	0.83	0.46
35	1.62	0.96	0.61	0.62	0.85	0.47
40	1.84	1.12	0.72	0.62	0.87	0.49
45	2.06	1.27	0.84	0.63	0.89	0.51
50	2.28	1.43	0.96	0.63	0.91	0.53

TABLE 6
Absorbed Dose Factors for Blood Canal, Bone Surface and Bone Matrix for ^{131}I in Haversian System

^{131}I radius (μm)	Absorbed dose (10^{-12} Gy cm^3/Bq s)					
	Source in blood			Source in bone surface		
	Blood	Wall	Bone	Blood	Wall	Bone
5	0.54	0.15	0.05	1.17	1.32	0.48
10	1.01	3.86	0.17	1.16	1.44	0.58
15	1.45	0.64	0.31	1.12	1.53	0.64
20	1.87	0.90	0.45	1.11	1.57	0.69
25	2.29	1.14	0.61	1.11	1.61	0.73
30	2.68	1.38	0.77	1.08	1.63	0.75
35	3.05	1.62	0.92	1.06	1.66	0.77
40	3.40	1.85	1.08	1.04	1.68	0.79
45	3.74	2.06	1.23	1.02	1.69	0.80
50	4.07	2.26	1.37	1.00	1.71	0.82

TABLE 7
Absorbed Doses Factors for Blood Canal, Bone Surface and Bone Matrix for ^{153}Sm in Haversian System

^{153}Sm radius (μm)	Absorbed dose (10^{-12} Gy cm^3/Bq s)					
	Source in blood			Source in bone surface		
	Blood	Wall	Bone	Blood	Wall	Bone
5	0.47	0.13	0.05	1.05	1.17	0.44
10	0.89	0.35	0.16	1.05	1.29	0.53
15	1.29	0.58	0.29	1.02	1.37	0.60
20	1.68	0.82	0.43	1.01	1.41	0.64
25	2.06	1.055	0.58	1.01	1.45	0.68
30	2.43	1.28	0.73	1.00	1.48	0.71
35	2.78	1.51	0.89	0.99	1.50	0.73
40	3.11	1.73	1.04	0.97	1.52	0.75
45	3.44	1.94	1.19	0.96	1.54	0.76
50	3.76	2.15	1.33	0.95	1.56	0.78

TABLE 8
Residence Times for Intravenous Administration of ^{45}Ca

Organ (S)	τ_S
Total body	9.5×10^6 sec
Cortical bone	4.6×10^6 sec
Trabecular bone	3.9×10^6 sec

$$q_{BS} \cong 4.0 \times 10^{10} (\text{Bq s/cm}^3).$$

Similarly,

$$q_{Blood} \cong 1.4 \times 10^8 (\text{Bq s/cm}^3),$$

where on the mass of blood in the body, m_{Blood}, is 5410 g; and the average density, ρ_{Blood}, is 1.03 g/cm^3. The dose to bone surfaces, using Equation 12 and dose factors from Table 7 for a Haversian canal of 50 μm radius, is:

$$\bar{D}_{BS} = 4.0 \times 10^{10} \left(\frac{\text{Bq s}}{\text{cm}^3}\right) 1.56 \times 10^{-12} \left(\frac{\text{Gy cm}^3}{\text{Bq s}}\right) + 1.4 \times 10^8 \left(\frac{\text{Bq s}}{\text{cm}^3}\right) 2.15 \times 10^{-12} \left(\frac{\text{Gy cm}^3}{\text{Bq s}}\right),$$

$$\bar{D}_{BS} = 6.3 \text{ (cGy)}.$$

Therefore, the dose to bone surface is 6.3 cGy per administered MBq. Similar methods can be used to assess doses based on other biokinetic models.

Johnson et al. (*6*) recently used the same Monte Carlo transport code (EGS4) to assess dose profiles in a bone-to-marrow slab interface. Their results were expressed in terms of units of surface activity (cGy cm^2/μCi-hr). For ^{153}Sm, Johnson's paper gave a dose factor of about 60 (cGy cm^2/μCi-hr) at the bone marrow interface for a uniform distribution at the endosteum. The Haversian model provides a value of 1.56×10^{-12} (Gy cm^3/Bq s). Assuming the same concentration of activity in a slab interface and in the bone surface of a Haversian system, it is possible to compare both results. A surface activity can be converted into a volume activity by taking the thickness of the endosteal layer into consideration. However, this approach does not consider any cross-fire among surfaces. Therefore:

$$60(\text{cGycm}^2/\mu\text{Ci} - \text{hr}) 10 \times 10^{-4} (\text{cm}) = 0.06 (\text{cGycm}^3/\mu\text{Ci} - \text{hr}).$$

This value is close to that calculated in a Haversian system of 50-μm radius, which is approximately 0.02 (cGy cm^3/μCi-hr).

CONCLUSIONS

Biokinetic models predicting the distribution of radionuclides in blood are used for substances that remain largely in circulation, including labeled blood cells and radionuclides attached to macromolecules. These biokinetic models, along with the dosimetric model for Haversian canals, can be used to assess absorbed doses by calculating the specific cumulated activity in blood and bone surfaces. The precise pattern of tissue injury that results from any radiation exposure is dependent upon a number of variables besides radiation dose. These variables are time of exposure, whether the exposure is acute, continuous, or fractionated; and the type of tissue being irradiated. There are many other factors that can affect the response to radiation, such as age, gender, metabolic activity and diet. However, the dose factors provided in this work will help researchers assess and compare absorbed doses to Haversian canals and other bone regions.

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