Absorbed Dose Calculations to Blood and Blood Vessels for Internally Deposited Radionuclides

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At present, absorbed dose calculations for radionuclides in the human circulatory system used relatively simple models and are restricted in their applications. To determine absorbed doses to the blood and to the surface of the blood vessel wall, EGS4 Monte Carlo calculations were performed. Absorbed doses were calculated for the blood and the blood vessel wall (lumen) for different blood vessels sizes. The radionuclides chosen for this study were those commonly used in nuclear medicine. No penetration of the radionuclide into the blood vessel was assumed nor was cross fire between the vessel assumed. The results are useful in assessing the dose to blood and blood vessel walls for different nuclear medicine procedures.

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A number of radionuclides are used for purposes of medical imaging, radiation therapy, and in vivo determination of kinetic factors for modeling. Use of these radionuclides often delivers large doses to certain regions and organs of the body. When the material is injected intravenously, there is the possibility of delivering large doses to blood vessels. There have been several simplified attempts to estimate the dose to the blood and the vessel wall. For example, Cloutier and Watson (*1*) investigated the absorbed fraction for nonpenetrating radiation due to a few selected radionuclides in the blood. Hui and Poston (*2*) attempted to model the major features of the circulatory system in an adult human but focused primarily on photon-absorbed fractions. Explicit calculations of doses to the surface area of the vessel and to the blood containing the emitter are not available in the literature. The purpose of this paper is to report calculations of absorbed doses to the blood and to the surface of the blood vessel walls of the circulatory system for selected radionuclides.

The vascular system is important for the integrity and function of all tissues. Moreover, damage to the blood vessels may initiate, promote, or precipitate various types of damage in many organs. The main functions of the vascular system are to supply nutrients and oxygen and to remove metabolic products. Damage induced by irradiation of the vascular system may be expressed from several months to years after exposure. Late changes in blood vessels observed after irradiation include a reduction in number of endothelial cells, wall thickening and focal occlusion with subsequent decrease in blood flow. These changes may be important in the development of damage to other tissues.

Estimated absorbed doses to the organs of the body from radionuclides distributed in the blood depends on the assumptions used in the calculations. For nonpenetrating radiations in the blood, the absorbed fraction of energy has not been examined in detail. When considering radionuclides carried in the blood stream, the absorbed fraction depends on the geometry of the circulatory system. In large blood vessels, the self-absorbed fraction for nonpenetrating radiation approaches unity, and little of the energy reaches the organ through which the blood flows. The amount of energy reaching the organ depends on the distribution of the blood and the size of the blood vessels; other factors also must be taken into account. First, the radius of the vessel must be considered; second, the concentration of the radionuclide in the blood; third, the types of radiation and their spectral shapes; and fourth, the exposure time which is determined by the rate of injection, blood flow, retention time, etc.

The circulatory system comprises all structures concerned with the transportation of body fluids from one region of the body to another. The structures comprising the blood-vascular system are: the heart, which by contraction forces blood through the blood vessels; arteries, which conduct blood from the heart to tissues with their smaller branches called arterioles; veins, which conduct blood from tissues toward the heart with their smaller branches called venules; and capillaries, extremely small vessels which connect arteries and veins.

Figure 1 shows the average percentage distribution of blood in a resting man (*3*), and Table 1 presents representative dimensions of blood vessels in the circulatory system (*4*). As Figure 1 shows, only about 5% of the total amount of blood in the body is in the capillaries; however, this blood is exposed to a large surface area which facilitates the transfer of oxygen, carbon dioxide, nutrients and electrolytes through their walls.

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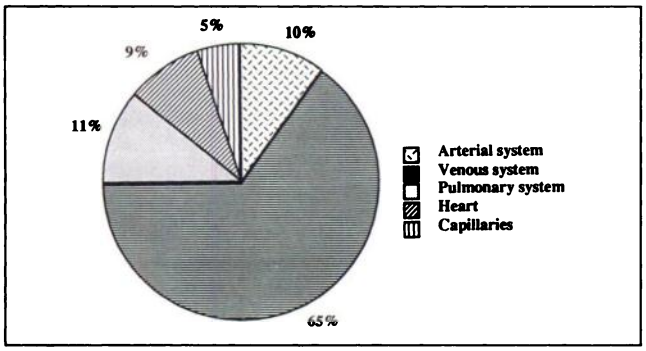

FIGURE 1. Distribution of blood volume in resting man.

METHODOLOGY

With the advent of Monte Carlo codes capable of simulating electron transport, it is possible to assess the energy deposition patterns of electrons. The code Electron Gamma Shower (EGS4) was used in this research because it is versatile and allows the manipulation of three-dimensional geometries (*5*). The EGS4 code is a general-purpose package for the simulation of electrons (+ or −) and photons in any element, compound or mixture.

TABLE 1
Representative Values of Blood Vessels for the Circulatory System (*4*)

	Sex	Thickness of wall (mm)	Diameter of lumen (cm)
		Adult arterial system	
Aorta			
Ascending	male	1.63	2.50
	female	1.48	2.50
Descending	male	1.20	2.50
	female	1.11	2.50
Abdominals	male	1.14	0.90–1.80
	female	1.08	0.90–1.80
Arteries			
Common iliac	male	0.93	0.90–1.80
	female	0.89	0.90–1.80
Common carotid	male	0.91	0.67
	female	0.81	0.67
Small arteries	both	0.80 and lower	0.40
Arterioles	both	20 μm	16–30 μm
Capillaries	both	1 μm	8–10 μm
		Adult venous system	
Venae cavae			
Superior	male	1.50	3.00
	female	1.50	3.00
Inferior	male	1.50	3.00
	female	1.50	3.00
Veins	male	0.50	0.50
	female	0.50	0.50
Venules	both	2 μm	20 μm
		Adult pulmonary system	
Arteries	male	1.27	2.40
	female	0.96	2.40

Data and cross sections are created by the preprocessor PEGS4 using cross sections for elements 1 through 100.

The code has shown to be acceptable for the energy range of 1 keV to 1 GeV for photons and 10 keV to 1 GeV electrons. The code can be used to simulate closely all electron interactions in matter such as Bremsstrahlung, backscatter, and knock-on electrons, which are transported if their energies are above a certain threshold. Electron transport was simulated by assuming that electrons are moved through the material in discrete steps. The electron step size was restricted not to exceed a maximum fraction of energy loss previously established. This fraction has the variable name ESTEPE in the EGS4 system code and was set equal to 1%. The lower cutoff energies were set to 10 keV and 1 keV for electrons and photons, respectively. Blood and blood vessel walls were considered to be tissue equivalent; thus, all transport calculations were made for tissue equivalent material (*4*).

In general, it is possible to assume that a blood vessel (arteries and veins) can be represented by a long annular cylinder, although actually the vessel nearly resembles an elongated circular cone. In these calculations it was assumed that the inner radius of the cylinder was R_0 and the outer radius was $2R_0$. The cylinder was subdivided arbitrarily into 100 annular regions with thickness ΔR (i.e., $2R_0/100$). A cross section of the cylinder is shown in Figure 2. The inner region of the cylinder, the lumen, of radius R_0 will contain the blood stream with a uniform distribution of radioactive material. The region between R_0 and $2R_0$ represents the wall of the blood vessel. Radiations crossing the boundary at $2R_0$ were followed because interactions, such as backscatter, would allow the return of energy to the regions of interest. However, energy deposited in the region greater than $2R_0$ was calculated but was not used in these dose estimates. Absorbed fractions of energy were calculated for selected monoenergetic photons and electrons generated in the source region (blood stream) for each subregion of the cylinder as shown in Figure 3. The radii of the different blood vessels were 0.02, 0.1, 0.5, and 1.0 cm. Calculations for 100,000 histories were made from which the mean absorbed fraction of energy to each annular region was determined for both electrons and photons. Since the distance between the large blood vessels is relatively large compared to the range of beta particles, it is possible to assume that little of the energy,

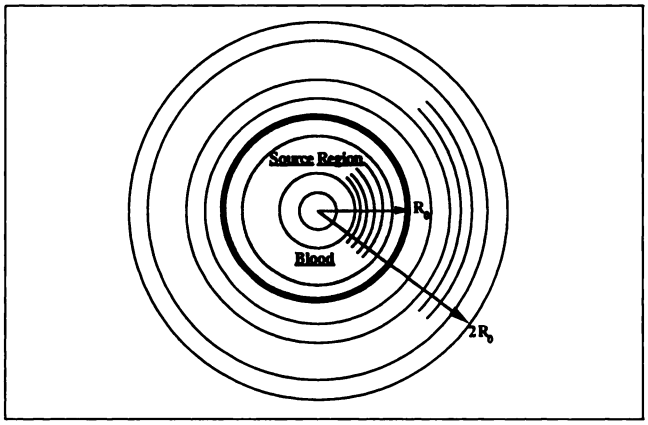

FIGURE 2. Cross section of an annular cylinder used to simulate a blood vessel. The inner cylinder with radius R_0 represents the source region which is the blood. The cylinder is divided into 100 inner cylinders to calculate absorbed fraction profiles throughout the source region and the wall.

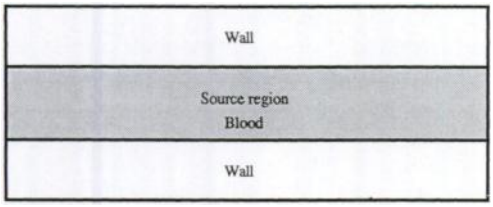

FIGURE 3. Model of a blood vessel used to obtain absorbed fraction profiles. The source region contains a uniform distribution of radioactive material.

lost from these vessels, is absorbed by other vessels. The dose delivered to i^{th} region of the cylinder with mass m_i is given by:

$$D_i = \frac{\epsilon_i}{m_i}, \qquad \text{Eq. 1}$$

where ϵ_i is the energy deposited in i^{th} shell.

The energy deposited, ϵ_i, in the i^{th} shell can be calculated using the following equation:

$$\epsilon_i = 1.602 \times 10^{-13}\pi R_0^2 \Delta X Q \sum_j \phi_{i,j} Y_j E_j \quad [J], \qquad \text{Eq. 2}$$

where πR_0^2 is the cross sectional area of the lumen or inner cylinder in which the blood stream flows, ΔX is the length of the cylinder in which energy is deposited, Q is the number of transformations per cm^3 in the source region (blood), $\phi_{i,j}$ is the absorbed fraction of type of radiation j and the i^{th} shell of the cylinder, Y_j is the yield per transformation for radiation type j, and E_j (MeV) is the energy for radiation type j. The mass of region i with length ΔX is:

$$m_i = \rho\pi(R_i^2 - R_{i-1}^2)\Delta X \quad [g], \qquad \text{Eq. 3}$$

where ρ is the density of the material.

The nuclear and atomic radiations associated with the radioactive decay of a radionuclide were calculated by using the computer code RADLST (*6*), this code also gives as an option the β^+ spectrum of each radionuclide which is broken into several energy bins. Thus, the beta spectrum for a particular radionuclide was represented by a histogram rather than as a continuum and was used in Equation 2. The total number of transformations in the inner radius R_0 is $\pi R_0^2 \Delta X Q$.

Consequently, the dose D_i delivered to the i^{th} shell of the cylinder is given by:

$$D_i = \frac{1.602 \times 10^{-13}\pi R_0^2 \Delta Z Q \sum_j \phi_{i,j} Y_j E_j}{1.0 \times 10^{-3}\rho\pi(R_i^2 - R_{i-1}^2)\Delta X} \text{ [Gy]} \qquad \text{Eq. 4}$$

Equation 4 consequently can be expressed as:

$$\frac{D_i}{Q} = \frac{1.602 \times 10^{-10} R_0^2 \sum_j \phi_{i,j} Y_j E_j}{\rho(R_0^2 - R_{i-1}^2)} \left[\frac{\text{Gy cm}^3}{\text{Bq sec}}\right]. \qquad \text{Eq. 5}$$

Equation 5 gives the dose per unit transformation per cm^3 which is representative of the radionuclide used. Therefore, the dose profile can be calculated by using Equation 5 for every i^{th} shell of the cylinder.

RESULTS

Table 2 gives average absorbed doses to the blood per transformation per cm^3 for several radionuclides commonly used in medical imaging and radiation therapy for different blood vessel radii. As an example, the absorbed dose profile for ^{90}Y, ^{90}Sr, ^{11}C, and ^{133}Xe are shown in Figure 4 for a blood vessel radius of 0.02 cm. Figure 5 shows a plot of the data given in Table 2 for several radionuclides on which an interpolation method can be

TABLE 2
Average Absorbed Dose to Blood for Different Sizes of Blood Vessels

Average absorbed dose to blood (Gy cm^3/Bq sec)				
	Radius of blood vessel (cm)			
Radionuclide	0.02	0.10	0.50	1.00
^{13}N	1.05 E-11	4.26 E-11	7.23 E-11	7.82 E-11
^{11}C	1.36 E-11	3.98 E-11	5.88 E-11	6.28 E-11
^{14}C	7.29 E-12	7.82 E-12	7.94 E-12	7.96 E-12
^{18}F	1.75 E-11	3.82 E-11	4.29 E-11	4.73 E-11
^{15}O	7.84 E-12	4.41 E-11	9.89 E-11	1.11 E-10
^{24}Na	9.40 E-12	4.29 E-11	8.70 E-11	1.04 E-10
^{32}P	8.16 E-12	4.29 E-11	9.26 E-11	1.02 E-10
^{55}Fe	7.49 E-13	8.56 E-13	8.95 E-13	9.00 E-13
^{81m}Kr	6.71 E-12	8.62 E-12	9.64 E-12	1.10 E-11
^{90}Sr	1.62 E-11	2.60 E-11	3.03 E-11	3.08 E-11
^{90}Y	8.45 E-12	4.22 E-11	1.16 E-10	1.35 E-10
^{99m}Tc	2.07 E-12	2.39 E-12	2.74 E-12	3.08 E-12
^{99}Mo	1.21 E-11	3.68 E-11	5.81 E-11	6.17 E-11
^{123}I	3.69 E-12	4.29 E-12	5.04 E-12	5.86 E-12
^{124}I	2.49 E-12	1.17 E-11	2.96 E-11	3.69 E-11
^{125}I	2.67 E-12	2.83 E-12	3.39 E-12	4.12 E-12
^{126}I	6.10 E-13	1.20 E-12	2.46 E-12	3.65 E-12
^{130}I	1.42 E-11	3.30 E-11	5.07 E-11	5.69 E-11
^{131}I	1.61 E-11	2.64 E-11	3.22 E-11	3.40 E-11
^{111}In	4.10 E-12	5.31 E-12	6.98 E-12	8.61 E-12
^{114}In	8.07 E-12	4.18 E-11	9.88 E-11	1.11 E-10
^{127}Xe	4.00 E-12	4.91 E-12	6.11 E-12	7.33 E-12
^{131}Xe	1.83 E-11	2.17 E-11	2.28 E-11	2.32 E-11
^{133}Xe	1.77 E-11	2.08 E-11	2.19 E-11	2.22 E-11
^{133m}Xe	2.02 E-11	2.76 E-11	3.05 E-11	3.11 E-11
^{200}Tl	2.37 E-12	4.72 E-12	9.48 E-12	1.37 E-11
^{201}Tl	2.12 E-12	4.80 E-12	8.44 E-12	1.14 E-11
^{202}Tl	1.57 E-12	2.83 E-12	4.64 E-12	6.14 E-12

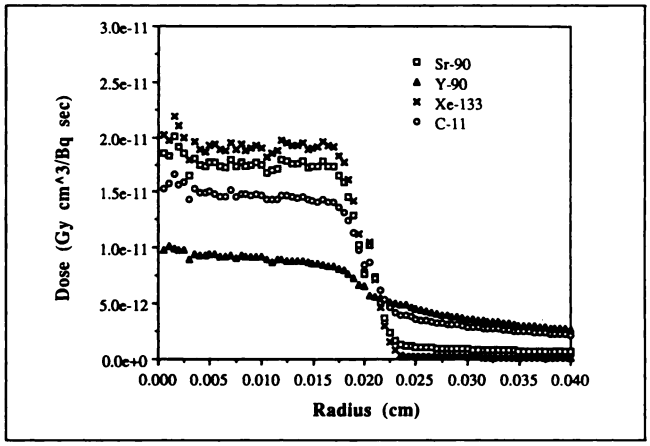

FIGURE 4. Absorbed dose profile for ^{90}Y, ^{11}C, ^{90}Sr, and ^{133}Xe for a blood vessel of 0.02 cm radius.

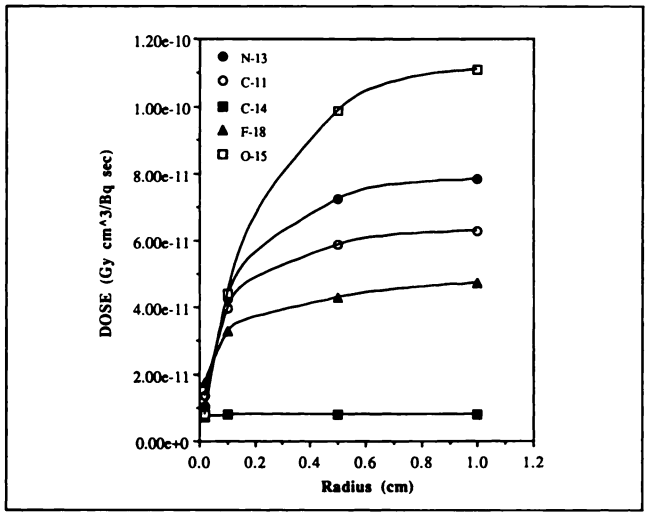

FIGURE 5. Average absorbed dose per transformation per cm^3 to blood as a function of blood vessel radius for different radionuclides.

used to assess the average dose (Gy cm^3/Bq sec) to the blood for different blood vessel radii. The absorbed dose to capillaries was obtained by extrapolation from 0.02 cm radius, using the assumption that as the radius of the blood vessel tends to zero the absorbed dose to the blood will approach zero.

Table 3 gives the absorbed dose (Gy cm^3/Bq sec) to the surface of the blood vessel wall (i.e., the surface of the inner cylinder with radius R_0). Figure 6 shows a plot of the data given in Table 3, and again an interpolation method can be used to assess the surface dose to the blood vessel wall for other radii. The surface dose is assumed to be the average of the absorbed doses obtained for the last region in the source (blood) and the first region in the blood vessel wall. The usefulness of the data obtained for the different radionuclides varies according to the application. Individual organ doses can be assessed by defining their vascular system and the amount of blood in different blood vessel sizes.

As an example, let 3.7×10^7 Bq (1.0 mCi) of ^{90}Y be uniformly distributed in the blood of the circulatory system. Assuming no biologic elimination of the material from the body (non-dynamic problem), the total number of transformations is 1.23×10^{13}. The average amount of blood in a Reference Man can be given as 5200 ml (*4*); assuming that the number of transformations per unit volume remains constant throughout the circulatory system, this will give a total number of transformation per cubic centimeter of 2.37×10^9. By using an interpolation method, it is possible to calculate the dose to the blood and to the surface of the blood vessel wall for the different blood vessels of the circulatory system given in Table 1. Table 4 gives the doses to the blood in different regions of the circulatory system and Table 5 gives the doses delivered to the surface of the blood vessel walls. As can be seen in

TABLE 3
Absorbed Dose to the Surface of the Blood Vessel Wall for Different Sizes of Blood Vessels

	Absorbed dose to the surface of the blood vessel (Gy cm^3/Bq sec)			
	Radius of blood vessel (cm)			
Radionuclide	0.02	0.10	0.50	1.00
^{13}N	7.19 E-12	2.77 E-11	3.79 E-11	4.06 E-11
^{11}C	8.59 E-12	2.46 E-11	3.04 E-11	3.27 E-11
^{14}C	3.80 E-12	3.93 E-12	4.02 E-12	3.96 E-12
^{18}F	9.95 E-12	1.88 E-11	2.23 E-11	2.55 E-11
^{15}O	5.93 E-12	3.09 E-11	5.40 E-11	5.81 E-11
^{24}Na	6.64 E-12	2.87 E-11	4.88 E-11	5.88 E-11
^{32}P	6.03 E-12	2.98 E-11	5.01 E-11	5.28 E-11
^{55}Fe	3.95 E-13	4.34 E-13	4.51 E-13	4.54 E-13
^{81m}Kr	3.64 E-12	4.52 E-12	4.99 E-12	5.30 E-12
^{90}Sr	8.98 E-12	1.43 E-11	1.52 E-11	1.58 E-11
^{90}Y	6.13 E-12	2.98 E-11	6.79 E-11	7.10 E-11
^{99m}Tc	1.10 E-12	1.23 E-12	1.48 E-12	1.73 E-12
^{99}Mo	7.62 E-12	2.32 E-11	3.02 E-11	3.17 E-11
^{123}I	1.96 E-12	2.22 E-12	2.79 E-12	3.26 E-12
^{124}I	1.75 E-12	8.06 E-12	1.74 E-11	2.06 E-11
^{125}I	1.36 E-12	1.45 E-12	1.94 E-12	2.28 E-12
^{126}I	3.41 E-13	7.30 E-13	1.50 E-12	2.26 E-12
^{130}I	8.43 E-12	1.99 E-11	2.73 E-11	3.32 E-11
^{131}I	8.95 E-12	1.47 E-11	1.65 E-11	1.78 E-11
^{111}In	2.20 E-12	2.84 E-12	3.95 E-12	4.96 E-12
^{114}In	5.91 E-12	2.94 E-11	5.47 E-11	5.77 E-11
^{127}Xe	2.13 E-12	2.58 E-12	3.39 E-12	4.15 E-12
^{131}Xe	9.83 E-12	1.11 E-11	1.17 E-11	1.17 E-11
^{133}Xe	9.38 E-12	1.07 E-11	1.11 E-11	1.12 E-11
^{133m}Xe	1.10 E-11	1.47 E-11	1.54 E-11	1.59 E-11
^{200}Tl	1.33 E-12	2.85 E-12	5.73 E-12	8.75 E-12
^{201}Tl	1.27 E-12	2.89 E-12	4.86 E-12	6.76 E-12
^{202}Tl	8.75 E-13	1.64 E-12	2.65 E-12	3.65 E-12

Table 4, the blood in the aorta will receive an average absorbed dose of 31.6 rad and the wall of the aorta will receive a maximum absorbed dose of 16.7 rad. The average absorbed dose to the blood will be the absorbed doses in

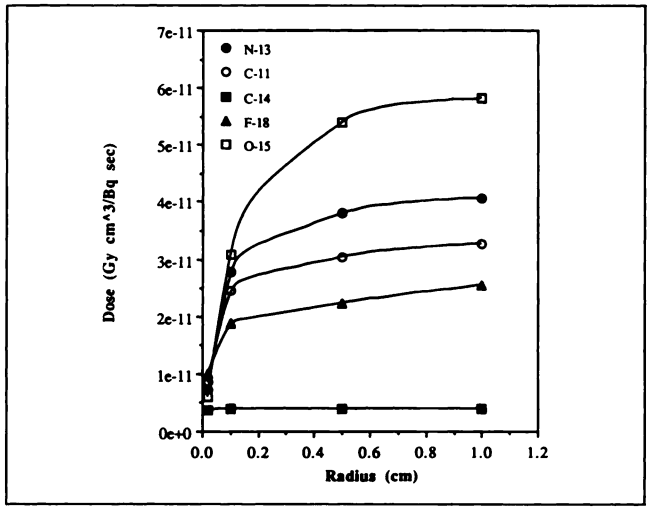

FIGURE 6. Absorbed dose per transformation per cm^3 to the surface of the blood vessel wall as a function of blood vessel radius for different radionuclides.

TABLE 4
Average Absorbed Dose to Blood for Different Blood Vessels in the Circulatory System

Radionuclide: ^{90}Y 1.23×10^{13} dis.	Blood amount (ml)	Radius (cm)	Dose (Gy cm^3/ Bq sec)	Dose (Gy)
Arterial system				
Aorta	140	1.0000	1.34 E-10	3.17 E-01
Arteries	420	0.5000	1.22 E-10	2.88 E-01
Arterioles	70	0.0025	1.51 E-11	3.56 E-02
Capillaries	280	0.0010	6.10 E-12	1.44 E-02
Venous system				
Venae Cavae	300	1.5000	1.43 E-10	3.37 E-01
Veins	2600	0.2500	1.17 E-10	2.77 E-01
Venuoles	300	0.0020	1.21 E-11	2.86 E-02
Pulmonary system				
Arteries	200	1.2000	1.38 E-10	3.26 E-01
Veins	230	0.2500	1.17 E-10	2.77 E-01
Capillaries	100	0.0010	6.10 E-12	1.44 E-02

TABLE 5
Absorbed Dose to the Surface of the Blood Vessel Wall for Different Blood Vessels in the Circulatory System

Radionuclide: ^{90}Y 1.23×10^{13} dis.	Blood amount (ml)	Radius (cm)	Dose (Gy cm^3/ Bq sec)	Dose (Gy)
Arterial system				
Aorta	140	1.0000	7.10 E-11	1.68 E-01
Arteries	420	0.5000	6.31 E-11	1.49 E-01
Arterioles	70	0.0025	7.68 E-12	1.82 E-02
Capillaries	280	0.0010	3.11 E-12	7.36 E-03
Venous system				
Venae Cavae	300	1.5000	7.71 E-11	1.82 E-01
Veins	2600	0.2500	6.01 E-11	1.42 E-01
Venuoles	300	0.0020	6.17 E-12	1.46 E-02
Pulmonary system				
Arteries	200	1.2000	7.36 E-11	1.74 E-01
Veins	230	0.2500	6.01 E-11	1.42 E-01
Capillaries	100	0.0010	3.11 E-12	7.36 E-03

every vessel weighted by the amount of blood contained in each. For this specific case, the average absorbed dose to the blood is 27.2 rad.

It is important to notice that the total number of transformations that occurred in the blood are dependent on the half-life of the radionuclide and other physiologic and metabolic parameters. So far, it has been assumed that the total number of transformations per cm^3, Q (Bq sec/cm^3), is a constant which is not dependent of the point of intake. The parameter Q in real life is dependent on time and is analogous to the retention function used in internal dosimetry calculations. It must be emphasized that a dynamic model of the circulatory system is necessary for future work in nuclear medicine.

CONCLUSIONS

The methodology described above can be applied to any radionuclide of interest in nuclear medicine and will provide estimates of the absorbed doses to the blood and blood vessels of the circulatory system for different medical procedures such as tumor therapy using radiolabeled antibodies. The results shown in Figures 4 and 5 can be used in dynamic processes of blood circulation by determining the total number of transformations per unit volume in different regions of the circulatory system.

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