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Absorbed fractions and dose factors for a model of the mouse skeleton

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Abstract A general model for skeletal dosimetry in mice is presented. Geometrical constructs were made for four general regions in the mouse skeleton, and dose factors for ^{90}Sr and ^{90}Y were calculated using the MCNP Monte Carlo transport code. Then, an overall skeletal dose factor for the whole skeleton was derived based on the individual values and the fraction of the total skeleton that they were assumed to represent. The whole skeleton average values were 1.56×10^{-11} Gy/dis for ^{90}Sr and 1.74×10^{-11} Gy/dis for ^{90}Y.

Keywords Skeleton · Mouse · Dose factors

1 Introduction

A generalized model of a mouse skeleton was developed with the purpose of generating absorbed fractions and dose factors for ^{90}Sr and ^{90}Y in the skeleton. The starting point was a model developed by Muthuswamy et al. [1]. In their model, four types of bone were described: (1) ribs, clavicle, sternum, pelvis; (2) limb bones; (3) vertebrae; and (4) skull. They used simplified geometric constructs, namely (1) a 300-µm-thick slab; (2) a 900-µm-diameter cylinder; (3) a 200-µm-diameter sphere; and (4) a 170-µm-diameter sphere, to represent the four structures. They then estimated electron absorption in these structures for ^{131}I, ^{186}Re, and ^{90}Y using a point kernel approach, numerically integrating absorption over the length of the particles' path.

We adopted their geometric model and performed similar calculations using the Monte Carlo transport code MCNP [2]. This simple study was performed to answer a specific question related to a study involving the injection of strontium chloride into mice. Xie et al. [3] developed a skeletal dosimetry model for a rat model and provided absorbed fractions for photons and electrons at discrete starting energies. Xie and Zaidi [4] developed dose factors for a series of mouse models. They treated the skeleton as a uniform mixture of bone and marrow. Keenan et al. [5] developed absorbed fractions and dose factors for several mouse and rat models and also modeled skeletal regions as a uniform mixture of bone and marrow, and the provided factors were averaged over all regions. We chose to adopt the region-specific descriptions developed by Muthuswamy et al. [1], using Monte Carlo method and employing the full beta spectra of ^{90}Sr and ^{90}Y to address the question posed.

2 Methods

Muthuswamy et al. [1] suggested that 47 % of the marrow is in the first bone type, 20 % in the second, 21 % in the third, and 12 % in the fourth. The geometric models were:

1. Ribs, clavicles, sternum, and pelvis (47 % of total marrow): this region was modeled as a uniform bone/marrow mixture in a slab with a 300 µm

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thickness, a length and width of 2 cm, and surrounded by a sphere of tissue-equivalent material with a 10 cm radius. The composition of the mixture will be described below.
2. Limb (20 % of total marrow): the 'limb' region was modeled as an inner cylinder with a radius of 450 µm, containing marrow and surrounded by a cylinder of thickness of 350 µm, containing bone, length: 2 cm. The source was assumed to be in the bone, and dose factors were calculated for the bone and marrow components separately. The length of the cylinder was set to an arbitrary value known to be longer than the range of the electrons and was surrounded by a sphere of tissue-equivalent material with a 10 cm radius.
3. Vertebrae (21 % of total marrow): this region was modeled as a uniform bone/marrow mixture, in a sphere with a 200 µm diameter, surrounded by a sphere of tissue-equivalent material with a 10 cm radius.
4. Skull (12 % of total marrow): this region was modeled as a uniform bone/marrow mixture, in a sphere with a 170 µm diameter, surrounded by a sphere of tissue-equivalent material with a 10 cm radius.

In cases 1, 3, and 4, as noted, bone and marrow regions were not treated separately. The bone was considered to be a uniform mixture of bone and marrow. The densities of the bone and marrow were 2.02 g/cm^3 and 1.04 g/cm^3, respectively. We used the values established in humans, as we did not find specific values for various animal models in the literature. The compositions and fractions [6] used in this simulation are given in Table 1.

Fractions of marrow in individual bones and fractions of bone in the whole skeleton of humans (detailed data for mice are not available) were taken from the MIRD mathematical phantom [6] and ICRP Publication 89 [7], to calculate the compositions of the mixtures, which are given in Tables 2 and 3. It is assumed that the mouse has the same composition for skeleton as humans and the composition data were used for the simulation.

Densities for the bone–marrow mixture of the three regions of mixtures were calculated to be 1.38 g/cm^3, 1.44 g/cm^3 and 1.67 g/cm^3, respectively.

The elemental compositions of the four bone types, as derived from humans [6, 7], are given in Table 4.

MCNP input files were prepared to represent various geometries, using the available appropriate combinatorial geometries. Beta spectra for ^{90}Sr and ^{90}Y were taken from the decay data compendium of Stabin and da Luz [8]. The material compositions from Tables 1 and 4 were coded into the MCNP materials cards, using the weight fraction option. An step value of 6 was used, with the F8 tally. From 25,000–15,0000 starting particles were employed. Reported tally uncertainties were under 1 %.

Table 1 Assumed elemental compositions and densities of bone and marrow

Element	Atomic number	Percent by weight	
		Marrow	Bone
H	1	0.10400	0.05600
C	6	0.22700	0.36750
N	7	0.02490	0.01750
O	8	0.63500	0.27250
Na	11	0.00112	–
Mg	12	0.00013	–
Si	14	0.00030	–
P	15	0.00134	0.09350
S	16	0.00204	–
Cl	17	0.00133	–
K	19	0.00208	–
Ca	20	0.00024	0.19100
Fe	26	0.00005	–
Zn	30	0.00003	–
Rb	37	0.00001	–
Zr	40	0.00001	–
Total		1.000	0.99800

3 Results

The MCNP simulation results are given in Table 5. Shown are the fractions of the whole skeleton assumed to be comprised by the components and the fractions of the total electron energy that was absorbed in that component, with comparisons to the values reported by Muthuswamy et al. [1] where possible.

Using the weight fractions from the human skeleton for the fraction of the total skeleton comprised by each bone type, and calculating the total fraction of ^{90}Sr and ^{90}Y energy absorbed in these bones, we obtain dose factors for the whole skeleton, which are 1.56×10^{-11} Gy/disintegration(dis) for ^{90}Sr and 1.74×10^{-11} Gy/dis for ^{90}Y. The calculated individual dose factors are given in Table 6.

4 Discussion

Bone and marrow dose models are some of the most difficult to characterize. Models for human bone and marrow have been evolving for decades [9] and are still under development by several groups. Anatomic models for rodents, and accompanying dose factors have been reported by Keenan et al. [5]. Dose factors for the whole skeleton were given, based on a simple model of the skeleton as a uniform bone/marrow mixture, which is

Table 2 Marrow percentage in the regions of human bones

Bone type	Mass (g)	Percentage (%)	Percentage from Ref. [1] (%)
Ribs, clavicle, sternum, pelvis	1173.0	33.51	47
Limb	1605.4	45.87	20
Vertebrae	477.2	13.64	21
Skull	244.3	6.98	12
Total	3499.9	100	100

Table 3 Bone percentage in the regions of human bones

Bone type	Mass (g)	Percentage (%)
Ribs, clavicle, sternum, pelvis	1226.2	17.90
Limb	4137.4	60.40
Vertebrae	643.9	9.40
Skull	849.4	12.40
Total	6856.7	100

widely used by researchers [3–5] and may lead to an error of 4 % at most for the results, with scoring of photon and electron energy in individual bones, and no characterization of bone microstructure. Their approximate values for the ^{90}Sr or ^{90}Y sources in the skeleton of a 30 g mouse were 1.0×10^{-11} Gy/dis and 2.1×10^{-11} Gy/dis, which agree reasonably well with our values. Our study extended the results of Muthuswamy et al. [1], using modern Monte Carlo method and the full beta spectra of the nuclides

Table 4 Composition of the bone/marrow mixtures

Nuclide	Atomic number	Percentage by weight			
		Ribs, clavicle	Limb	Vertebrae	Skull sternum, pelvis
H	1	7.97E−02	6.96E−02	7.67E−02	6.68E−02
C	6	2.99E−01	3.28E−01	3.08E−01	3.36E−01
N	7	2.11E−02	1.96E−02	2.07E−02	1.92E−02
O	8	4.50E−01	3.74E−01	4.27E−01	3.54E−01
Na	11	5.48E−04	3.13E−04	4.77E−04	2.50E−04
Mg	12	6.36E−05	3.63E−05	5.53E−05	2.90E−05
Si	14	1.47E−04	8.39E−05	1.28E−04	6.70E−05
P	15	4.84E−02	6.77E−02	5.43E−02	7.29E−02
S	16	9.97E−04	5.70E−04	8.68E−04	4.56E−04
Cl	17	6.50E−04	3.72E−04	5.66E−04	2.97E−04
K	19	1.02E−03	5.81E−04	8.85E−04	4.65E−04
Ca	20	9.77E−02	1.38E−01	1.10E−01	1.48E−01
Fe	26	2.44E−05	1.40E−05	2.13E−05	1.12E−05
Zn	30	1.47E−05	8.39E−06	1.28E−05	6.70E−06
Rb	37	4.89E−06	2.80E−06	4.26E−06	2.23E−06
Zr	40	4.89E−06	2.80E−06	4.26E−06	2.23E−06

Table 5 Fractional energy absorption, ^{90}Sr and ^{90}Y

Componet	^{90}Y			^{90}Sr	
	% Total	Skeleton	Marrow [1]	% Total	Skeleton
Ribs, clavicle, sternum, pelvis	47	0.153	0.14	47	0.568
Vertebrae	21	0.022	0.017	21	0.174
Skull	12	0.021	0.014	12	0.170
Limb	20	0.284[a]	0.12	20	0.804[b]

[a] 0.284 equals the sum of absorptions in marrow (0.054) and bone (0.23)

[b] 0.804 equals the sum of absorptions in marrow (0.094) and bone (0.710)

Table 6 Region-specific dose actors (Gy/dis)

	^{90}Sr	^{90}Y
Limb[a]	8.26E−13	1.41E−12
Ribs, clavicle, sternum, pelvis[b]	1.04E−11	1.33E−11
Vertebrae[b]	2.51E−12	1.51E−12
Skull[b]	1.85E−12	1.11E−12
Total	1.56E−11	1.74E−11

[a] Source in the bone component only

[b] Source in the bone/marrow mixture

instead of mean values. Ours was a fairly simplified treatment of bone and marrow dosimetry. Advanced techniques such as small animal modeling and three-dimensional modeling of electron transport in individual bone cavities can extend or confirm these results, but this is a very big undertaking.

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References

1. M.S. Muthuswamy, P.L. Roberson, D.J. Buchsbaum, A mouse bone marrow dosimetry model. J. Nucl. Med. **39**, 1243–1247 (1998)
2. J.F. Briesmeister (ed.), *MCNP-A General Monte Carlo N-Particle Transport Code, Version 4C. LA-13709-M* (Los Alamos National Laboratory, 2000)
3. T. Xie, D. Han, Y. Liu et al., Skeletal dosimetry in a voxel-based rat phantom for internal exposures to photons and electrons. Med. Phys. **37**, 2167–2178 (2010). doi:10.1118/1.3380223
4. T. Xie, H. Zaidi, Monte Carlo-based evaluation of S-values in mouse models for positron-emitting radionuclides. Phys. Med. Biol. **58**, 169–182 (2013). doi:10.1088/0031-9155/58/1/169
5. M.A. Kennan, M.G. Stabin, W.P. Segars et al., RADAR realistic animal model series for dose assessment. J. Nucl. Med. **51**, 471–476 (2010). doi:10.2967/jnumed.109.070532
6. Description of the mathematical phantoms. http://crpk.ornl.gov/resources/Mird.pdf
7. ICRP, *Basic Anatomical and Physiological Data for Use in Radiological Protection: Reference Values* (ICRP Publication 89, Elsevier Health, 2003)
8. M.G. Stabin, C.Q.P.L. da Luz, Decay data for internal and external dose assessment. Health Phys. **83**, 471–475 (2002). doi:10.1097/00004032-200210000-00004
9. F.W. Spiers, Beta dosimetry in trabecular bone, in *Delayed Effects of Bone-Seeking Radionuclides*, ed. by C.W. Mays (University of Utah Press, Salt Lake City, 1969), pp. 95–108