SEGMENTATION OF HEMATOPOIETIC SITES OF HUMAN SKELETON FOR CALCULATIONS OF DOSE TO ACTIVE MARROW EXPOSED TO BONE-SEEKING RADIONUCLIDES

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Abstract. The Techa River (the Urals, Russia) was heavily contaminated due to the release of radionuclides from the Mayak Production Association. The radioactive releases included bone-seeking beta-emitters such as ^{90}Sr and ^{89}Sr that contribute to doses to bone marrow. Moreover, ^{90}Sr is a long-lived isotope, the uptake of which leads to a chronic bone marrow exposure known to result in an increased risk of leukemias. Ongoing epidemiological studies of the long-term effects of chronic radiation exposure are being performed for the Techa River Cohort members. Radiation dosimetry is a part of this study, of which, the internal dose estimates for active bone marrow exposed to beta emission of Sr isotopes incorporated in calcified tissue is an important component. Internal dose calculations, which are based on electron-photon transport simulations, require geometrical descriptions of bone shapes and bone microstructures of the main hematopoietic sites of the human skeleton (ribs, vertebrae, pelvic bones, femur, humeri, bones of the skull, sternum, clavicle and scapula). For this purpose, the parametric approach for modeling bone geometry was elaborated. The proposed approach can be used to segment and define each of the bone sites as simple geometric shapes for which parameters can be derived. The aim of the paper is to present the principles of bone segmentation. Dose factors that convert the activity concentration of bone-seeking radionuclides into a corresponding bone marrow dose rate were calculated for each segment. The calculations were done with MCNP6. The bone segmentation allows optimizing the size of the computational phantom (in terms of voxel number), substituting the complex-shaped bone model with a set of simple stylized phantoms and taking into account the heterogeneity of bone microstructure.

Key words: Bone marrow dosimetry, computational phantoms, bone segmentation

1. INTRODUCTION

Bone-seeking $^{89,90}\text{Sr}$ was the main source of internal radiation exposure of the Urals residents in 1950 in the zone of influence of the Mayak plutonium Production Association (Russia). Thus, the releases of radioactive wastes from the Mayak into the Techa River in the 1950s resulted in internal and external radiation exposure of about 30,000 riverside residents [1].

A statistically significant dose-response association was estimated for leukemia incidence in the epidemiological study of the Techa River Cohort [2]. Evaluation of doses from ingested $^{89,90}\text{Sr}$ is of utmost importance in the dosimetry studies. Dose conversion factors (DFs) are used for calculation of absorbed dose rate (Gy/s) in active marrow (AM) due to bone-seeking radionuclides (Bq/g). DFs are calculated through Monte - Carlo simulations of electron-photon transport in bone media.

Bone dosimetry for B-emitter's is a complicated task because the source tissue (trabecular bone) and

target tissue (bone marrow) are inextricably linked and form common structure-spongiosa. The cortical layer covers the spongiosa and is the source of active bone marrow exposure.

Simulations of electron-photon transport are based on the geometrical modelling of bone structure geometry [3,4]. Geometric parameters are of main importance because the mean free paths of the electrons of the $^{90}\text{Sr}/^{90}\text{Y}$ (1-3 mm) in the bone media are comparable to the thickness of the cortical layer and the maximum free paths in a spongy bone (5-9 mm) are comparable to the linear dimensions of many bones of the skeleton. Thus, the model geometry should include an accurate description of the fine structure of spongiosa and cortical bone thickness, as well as descriptions of macro-dimensions of the bone.

For many years bone dosimetry model elaborated in Leeds University was used [4]. This model was based on the cadaver study. The latest achievements are related with the accurate description of bone trabecular structures with 3-D micro CT technics [3]. However, the principle one phantom=one cadaver doesn't allow

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taking into account significant biological variability of bone structures.

Recently, a parametric approach has been developed to generate bone segment phantoms with different bone microstructure and size variations simulating population variability [5]. The method is based on the fact that the bone parts (processes of vertebrae, femoral head, etc.) can be described by simple geometric shapes (hemisphere, box). Preliminary calculations showed that the simplification of the form does not significantly influence dose coefficients, in contrast to cortical layer thickness and micro structure parameters [6].

Implementation of this approach requires dividing the bones into segments in such a way as to describe the geometry of the bone as accurately as possible. Only hematopoietic sites of human skeleton were considered during modeling. Table 1 shows the main twelve hematopoietic sites used in ICRP [7]. Corresponding fractions of active bone marrow for hematopoietic sites have been recently obtained with the use of PET technique, they are also presented in the Table 1. Within the framework of modeling of skeletal hematopoietic sites, the aim of this study is to elaborate the principles of bone segmentation that can be used in calculations of dose factors for active marrow due to radiation exposure to $^{90}\text{Sr}/^{90}\text{Y}$ and ^{89}Sr incorporated either in trabecular bone or in cortical bone.

Table 1. Distribution of bone marrow in adults (% of the total active marrow mass) [8]

Nº	Site	% bone marrow
1	Head (cranium+ mandible)	6.2
2	Cervical spine	3.5
3	Thoracic spine	17.5
4	Lumbar spine	15.5
5	Sternum	1.8
6	Pelvic bones	23.2
7	Sacrum	7.4
8	Proximal femur	5.9
9	Proximal humeri	3.6
10	Scapulae	4.8
11	Clavicles	0.8
12	Ribs	9.8

Specific tasks:

- Describe the general steps for dose factor estimation;
- Illustrate the principles of bone segmentation using: rib, lumbar vertebra, proximal femur as the examples;
- Present the results of DF calculations in terms of sources in the cortical and trabecular bone for an adult male.

2. TERMS AND DEFINITIONS

Basic parameters of bone microstructure model were fixed as follows:

- Spongiosa – in the current study, an entire integrated source and target region combining bone

trabeculae and the inter-trabecular spaces occupied by bone marrow and blood vessels.

- Tb.Th – trabecular thickness (μm);
- BV/TV – bone volume fraction of spongiosa (%)
- TBV-trabecular bone volume
- CBV-cortical bone volume
- BM-bone marrow
- DF(BM $\leftarrow$ TBV)-dose factor reflecting the dose rate in bone marrow per unit of radionuclide activity concentration in the trabecular bone volume
- DF(BM $\leftarrow$ CBV)- dose factor reflecting the dose rate in bone marrow per unit of radionuclide activity concentration in the cortical bone volume

3. THE GENERAL STEPS FOR DOSE FACTORS ESTIMATION

The development of bone phantoms and estimation of dose factors and their uncertainties includes the following general steps:

1. analysis of anatomical data on the size and microstructure of the bone in order to be able to describe it with simple geometric shapes.
2. segmentation of each bone site and their description by simple geometric figures
3. evaluation of average values for micro- and macro-parameters and their uncertainties due to intra-specimen and individual variability for each segment;
4. generation and voxelization of a population-average sized phantom of each segment;
5. generation of a set of supplementary phantoms simulating individual variability of bone size and shapes in population.
6. calculation of bone phantom-specific energy depositions by simulating ^{89}Sr and $^{90}\text{Sr}+^{90}\text{Y}$ electron emission and estimation of DF(BM $\leftarrow$ TBV) and DF(BM $\leftarrow$ CBV); Calculations were provided by using MCNP 6.1, isotropic sources of $^{90}\text{Sr}+^{90}\text{Y}$ and ^{89}Sr homogeneously distributed in the bone media; NPS was used more than $4 \cdot 10^5$ to achieve the statistical error $<1\%$.
7. calculation of DFs typical for each of segment and estimation of coefficient of variation (δvar , %) for DF(BM $\leftarrow$ TBV) and DF(BM $\leftarrow$ CBV);
8. calculation of skeletal-average dose factors DF(BM $\leftarrow$ TBV) and DF(BM $\leftarrow$ CBV) and their coefficient of variation (δvar , %) by averaging the segment-specific results.

4. PRINCIPLES OF BONE SEGMENTATION

There is a number of limitations related to the computational phantoms. First, the size of computational phantoms (in terms of voxel number) is restricted by computing capabilities. Specifically, the software MCNP6, which was used for Monte - Carlo simulation of electron-photon transport, can operate with no more than $50 \cdot 10^7$ voxels. On the other hand, the accurate description of bone microstructure requires high voxel resolution (ideally, it should be equal to $1/2$ of the mean Tb.Th, viz., 50-80 μm). Such a

resolution can result in extremely large voxel numbers exceeding the MCNP capacity. Besides the software limitation, there exists a computer limitation. For example, if a model consists of >35 million voxels, then the Monte - Carlo histories treated with MCNP 6.1 may take more than 35 hours to run on a computer with 32 cores and 64GB RAM.

The complex shape of the bones and heterogeneous microstructure complicates modeling of bone geometry. Therefore, segmentation of bones is required for optimization of the modelling

The principles of bone segmentation can be formulated as follows:

1. the number of voxels should be as small as possible, while still yielding meaningful results;
2. each complex-shaped bone site should be subdivided into a set of simple geometric figures;
3. each segment should consist of a uniform microstructure.

4.1. Approach to modelling of bone with relatively uniform micro- and macrostructures

Figure 1. Bone size optimization on the example of the rib

Large bones with a relatively uniform micro- and macro structure can be modeled as a set of small repeating segments to reduce the number of voxels and speed up the modeling process. The size of a segment (one or two dimensions) was chosen as 3 maximal pathlengths of $^{90}\text{Sr}+^{90}\text{Y}$ electrons =30 mm. Therefore, the increase in the model length will not influence the DF value. Figure 1 illustrates the example of the rib segmentation. The model of the whole rib (about 10 segments) with the voxel size of 0.006 mm, consists of $24\cdot 10^7$ voxels. This value is comparable to the MCNP6 limitation and calculation of such a model requires large computing resources. Similar approach was provided for: flat bones of skull, iliac ala, iliac crest, etc.

4.2. Approach to modeling of complex-shaped bones

Complex-shaped bones were modeled as a set of simple geometric shapes. Most of the segments are described by boxes and elliptic cylinders (see Table 2).

Table 2. Geometric shapes used in hematopoietic sites modelling

Nº	Shape	Number of segments
1	Box	37
2	Elliptic cylinder	18
3	Truncated elliptic cone	6
4	Pyramid	3
5	Hemi ellipse	2
6	Elliptic-based tube	1

The examples of segmentation of complex-shaped bones (vertebra and femur) are presented in Figure 2 and 3.

Figure 2. Complex-shaped bone simplification using the example of lumbar vertebra: (a) lateral view; (b) posterior view (c) superior view, (d) Bone Phantom Segments (BPS) describing vertebra segments: (1) body; (2) pedicle; (3) lamina; (4) spinous process; (5) transverse process; (6) superior and (7) inferior articular process

As shown in Figure 2, to describe the complex structure of the vertebra, 7 segments were required, despite the fact that the microstructure of the segments was assumed to be the same.

Figure 3. Separation of segments with different microstructure using the example of proximal femur

Parts of proximal femur have very different microstructure, that determined its segmentation. As

shown in Figure 3, segments of proximal femur have different microstructure parameters and cortical bone thickness. Thus, after segmentation, each segment is a simple geometric figure with a small voxel count and a uniform microstructure.

5. RESULTS OF DOSE FACTORS CALCULATION

Dose factors were calculated for each from 67 segments with the use of Monte - Carlo simulation of electron-photon transport [9]. The obtained values were averaged within the hematopoietic site, taking into account segment-specific bone marrow mass.

Table 3 presents preliminary estimates of ^{90}Sr DFs for main hematopoietic sites and skeletal-average DF obtained according to percent-contribution of bone marrow (Table 1). Similar calculations were provided for ^{89}Sr .

Table 3. DFs of $^{90}\text{Sr}/^{90}\text{Y}$ for main hematopoietic sites of an adult male

№	Site	N*	$^{90}\text{Sr}/^{90}\text{Y}$ DF* 10^{-11} , Gy/s per Bq/g (individual variability %).	
			DF AM←TBV	DF AM←CBV
1	Head (cranium+mandibula)	7	8.7 (25)	3.7 (39)
2	Cervical spine	11	4.6 (13)	2.4 (16)
3	Thoracic spine	6	3.3 (16)	1.4 (28)
4	Lumbar spine	7	3.4 (12)	0.9 (20)
5	Sternum	2	3.5 (19)	1.7 (16)
6	Pelvic bones	8	4.7 (8)	1.2 (17)
7	Sacrum	10	3.3 (12)	1.4 (17)
8	Proximal femur	3	4.2 (5)	1.1 (15)
9	Proximal humeri	2	2.3 (31)	0.7 (18)
10	Scapulae	4	3.7 (13)	2.0 (16)
11	Clavicles	3	4.4 (23)	1.7 (19)
12	Ribs	4	3.3 (28)	2.9 (14)
Overall skeleton		67	4.1 (25)	1.6 (28)

*-number of segments

As for cortical DFs, maximal site-specific DF was obtained for head. The main reason is that flat-cranial bones segments have very thin trabecular and thick cortical layers that resulted in significant contribution of source in cortical bone in AM exposure Minimum DF(BM←CBV) was calculated for proximal humeri, where a huge volume of spongiosa was covered by a relatively thin cortical layer.

The DF(BM←TBV) depends on the spongiosa microstructure, mainly on BV/TV value. For example, DFs(BM←TBV) calculated for thoracic and cervical vertebrae, which were described with similar shape parameters and different BV/TV parameters (32% difference), differed by 40%.

Thus, differences between site-specific DFs(BM←CBV) are sensitive to cortical bone thickness; DFs(BM←TBV) are sensitive to BV/TV.

The results obtained in the study will be combined with biokinetic model of strontium [10] and could later be used in calculations of bone marrow doses for residents of the contaminated area of the Urals region.

6. CONCLUSIONS

The proposed method allows:

1. Optimization of the size of the computation phantom (in terms of voxel number);
2. Substitution of the complex-shaped bone model with a set of simple stylized phantoms, which can be described analytically.
3. Accounting for the heterogeneity of the bone microstructure.

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