Calculation of Skeletal Fluence-to-dose Response Functions for Korean Adults to Photon Exposures

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1. Introduction

Recently, a pair of new reference Korean phantoms, called mesh-type reference Korean phantoms (MRKPs), was developed for adult male and female in high-quality tetrahedral-mesh format to address the limitations of the voxel-type reference Korean phantoms due to the limited voxel resolution and the stair-stepped voxel geometry, thereby providing accurate organ absorbed doses and effective doses to Korean adults [1]. The MRKPs include most of the organs/tissues and micrometer-thick target and source regions required for the calculation of effective doses, with two exceptions. These exceptions are red bone marrow (RBM) and bone endosteum (BE), which were not directly defined in the phantoms due to the extremely complex skeletal structures. Instead, these skeletal tissues are defined as homogeneous regions (i.e., spongiosa and medullary cavity) in which RBM and BE doses can be approximated as the dose values multiplied by their mass fractions. This simple approach, however, can yield inaccurate dose values due to the inhomogeneous density and elemental composition distributions, especially in spongiosa regions, resulting in an overestimation of the absorbed dose to these skeletal target tissues at energies below ~200 keV [2]. To consider the skeletal structures for dose calculations, Shin *et al.* [3] modeled BE in medullary cavity region and incorporated site-specific spongiosa models developed based on the micro-CT data of Chinese adult cadavers into spongiosa regions of the MRKPs [3]. However, the micro voxel-based detailed spongiosa models coupled with MRKPs can be used for dose calculations only by parallel geometry feature provided by Geant4. Moreover, the MRKPs with incorporated spongiosa models require computer memory more than 120 GB and at least five times longer computational time for particle transportation.

In the present study, to enable accurate dose estimations of RBM and BE without the incorporation of spongiosa models, the fluence-to-dose response functions (DRFs), which is originally developed by Eckerman [4], were calculated for Korean adults. With DRFs, the photons and their secondary electrons can be decoupled and the dose to RBM and BE can be calculated using the photon fluence passing through the spongiosa and medullary cavity regions. To calculate DRFs, the MRKPs incorporating the detailed spongiosa models [3] were used to calculate electron absorbed fractions to skeletal target tissues. To validate the calculated DRFs for Korean, using the Geant4 Monte Carlo simulation code [5], the absorbed doses to RBM and BE calculated by using the DRFs were compared with those calculated by using the detailed spongiosa models and the homogeneous spongiosa models for photons in antero-posterior (AP) directions ranging from 0.01 to 10 MeV.

2. Materials and Methods

2.1 MRKPs incorporated with detailed spongiosa models

For the calculation of the DRFs, the electron absorbed fractions to skeletal tissues were first calculated for energies ranging from 1 keV to 10 MeV by using the MRKPs incorporated with the micro-CT images based site-specific detailed spongiosa voxel models developed by Shin *et al.* [3]. For spongiosa regions, the considered source tissues are yellow bone marrow, trabecular bone, and/or RBM and the considered target tissues are RBM and/or BE. For medullary cavity in long bones (*i.e.*, humeri, lower arm bones, femora, and lower leg bones), the electron absorbed fractions were calculated for yellow bone marrow as a source and BE as a target.

2.2 Calculation of dose response functions

The DRFs, which can be expressed as the absorbed dose in the target region per photon fluence in the spongiosa region, can be calculated using the following equation [4]:

$$R(r_T \leftarrow r_S, x, E) = \frac{D(r_T, x)}{\Phi(E, r_S, x)} = \sum_r \frac{m(r_S, x)}{m(r_T, x)} \times \sum_i \int_0^\infty \phi(r_T \leftarrow r_S, T_i, x) \left(\frac{\mu_i}{\rho}\right)_{r_S, E} T_i n_r(T_i, E) dT_i \quad (1)$$

where $R(r_T \leftarrow r_S, x, E)$ is the DRFs, $D(r_T, x)$ is the absorbed dose in the target region, $\Phi(E, r_S, x)$ is the photon fluence in the spongiosa region, x is the site-specific bone sites in the phantom, r_S is the source tissue (i.e., yellow bone marrow, trabecular bone, and/or RBM), r_T is the target tissue (i.e., RBM and/or BE), E is the photon energy passing through the x, $m(r_S, x)$ is the mass of source tissue in the x, $m(r_T, x)$ is the mass of target tissue in the x, i is the type of photon interaction (i.e., photoelectric, Compton, and pair and triplet production) occurred in the source tissue, T_i is the secondary electron energy liberated in the source tissue

and absorbed in the target tissue, $\phi(r_T \leftarrow r_S, T_i, x)$ is the electron absorbed fraction liberated in the source tissue with the electron energy of T_i and absorbed in the target tissue in the x, $(\mu_i/\rho)_{r_S,E}$ is the mass attenuation coefficient for photon interaction i in the source tissue for photon energy E, and $n_r(T_i, E)dT_i$ is the number of secondary electrons of energy between T_i and $T_i + dT_i$ liberated in the source tissue for photon energy E.

For photon energies higher than 200 keV, where the charged-particle equilibrium is established across the bone sites, the kerma coefficients for spongiosa, which can be calculated by setting the $\phi(r_T \leftarrow r_S, T_i, x)$ as unity for self-irradiation, were taken as DRFs [2]. The absorbed dose to RBM and BE can be calculated by summing the product of the site-specific photon fluence in the spongiosa regions and the site-specific DRFs (see equation 2).

$$D(r_T, x) = \Phi(E, r_S, x) \times \mathrm{R}(r_T \leftarrow r_S, x, E) \qquad (2)$$

3. Results and Discussion

In the present study, the DRFs for Korean adult male and female were calculated for 17 bone groups, *i.e.*, humeri, lower arm bones, wrists and hands bones, clavicle, cranium, femora, lower leg bones, ankles and feet bones, mandible, pelvis, ribs, scapulae, cervical spine, thoracic spine, lumbar spine, sacrum, and sternum. Note that the DRFs for humeri, lower arm bones, femora, and lower leg bones are calculated for both spongiosa regions and medullary cavities.

Figure 1 shows the calculated DRFs which considered the charged-particle equilibrium and the DRFs-e which only considered the electrons escape from the spongiosa regions to the RBM and BE for ribs of Korean adult male as an example. It can be seen from the figure 1 that the DRFs and DRFs-e are in a good agreement at low energies. At energy ranges higher than 200 keV, on the other hand, DRFs-e are lower than DRFs. This tendency is due to the fact that the DRFs considered the

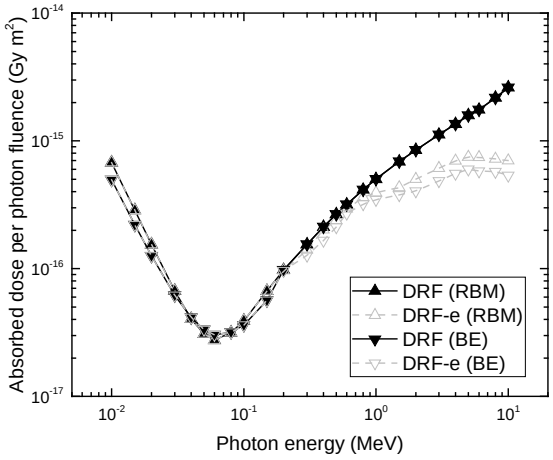

Figure 1. The calculated dose response functions (DRFs) to the red bone marrow (RBM) and bone endosteum (BE) for Korean adult male ribs.

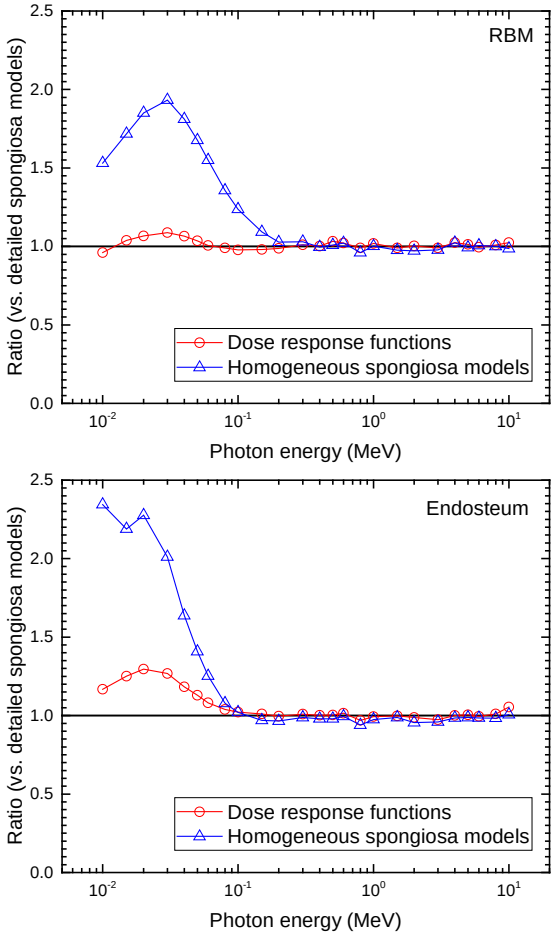

Figure 2. Ratio of the absorbed doses calculated by using the dose response functions (DRFs) and homogeneous spongiosa models to those calculated by using the detailed spongiosa models for red bone marrow (RBM) (upper) and Endosteum (lower).

establishment of charged-particle equilibrium across the spongiosa regions at energies exceeding 200 keV in which the electrons that escape the spongiosa regions are compensated for by the electrons that enter the spongiosa regions created in the surrounding organs/tissues.

Figure 2 shows the ratio of the absorbed RBM and BE doses calculated by using the homogeneous spongiosa models with DRFs and original simple mass fraction approach to those calculated by using the detailed spongiosa models for external photon in AP irradiation geometry for Korean adult male. Note that the absorbed doses calculated with the detailed spongiosa models incorporated in MRKPs, which directly defined the RBM and BE, were set as reference values. At energies higher than 200 keV, the absorbed doses calculated with DRFs and homogeneous spongiosa models are generally in a good agreement due to the charged-particle equilibrium; the differences are within ~6%. At energies less than 200 keV, however, the values calculated with the homogeneous spongiosa models showed relatively large differences compared with the reference values; the maximum differences are 93% at 0.03 MeV and 134% at

0.01 MeV for the RBM and BE, respectively. On the other hand, the values calculated with the DRFs showed similar results compared with the reference values; the maximum differences are 9% at 0.03 MeV and 30% at 0.03 MeV for the RBM and BE, respectively.

The computer memory and the computational time required for the calculation of doses to RBM and BE were compared between the MRKPs with the DRFs and the MRKPs incorporating the detailed spongiosa models. The computer memory required for the calculation of doses to skeletal tissues were much smaller with the DRFs, which requires 10 GB of memory, than the MRKPs incorporating the detailed spongiosa models, which requires 122 GB of memory. At photon energies ranging from 0.01 MeV to 10 MeV, the computational time was decreased by up to 5 to 20 times with the DRFs compared with the MRKPs incorporating the detailed spongiosa models when the simulations were performed on the Intel® Xeon® CPU E5-2698 v4 @ 2.20 GHz CPU processor and 512 GB memory.

4. Conclusion

In the present study, the skeletal fluence-to-dose response functions (DRFs) were calculated for Korean adult male and female exposed to photons. For this, the electron absorbed fractions to the red bone marrow (RBM) and bone endosteum (BE) were calculated by using the mesh-type reference Korean phantoms (MRKPs) incorporating the detailed spongiosa models developed in Shin *et al.* [3]. The results of the present study show that the accurate doses to these skeletal tissues can be provided with the Korean adult DRFs without incorporating the detailed spongiosa models. With DRFs, absorbed doses to RBM and BE can be calculated without installing the detailed spongiosa models, which is available in general-purpose Monte Carlo codes (i.e., Geant4, MCNP6 and PHITS). Korean adult DRFs will be used for the calculation of comprehensive dataset of accurate doses to the skeletal tissues of Korean in the near future.

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