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RESPONSE FUNCTIONS FOR COMPUTING ABSORBED DOSE TO SKELETAL TISSUES FROM NEUTRON IRRADIATION

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Abstract

Spongiosa in the adult human skeleton consists of three tissues - active marrow (AM), inactive marrow (IM), and trabecularized mineral bone (TB). Active marrow is considered to be the target tissue for assessment of both long-term leukemia risk and acute marrow toxicity following radiation exposure. The total shallow marrow (TM₅₀), defined as all tissues laying within the first 50 μ m the bone surfaces, is considered to be the radiation target tissue of relevance for radiogenic bone cancer induction. For irradiation by sources external to the body, kerma to homogeneous spongiosa has been used as a surrogate for absorbed dose to both of these tissues, as direct dose calculations are not possible using computational phantoms with homogenized spongiosa. Recent microCT imaging of a 40-year-old male cadaver has allowed for the accurate modeling of the fine microscopic structure of spongiosa in many regions of the adult skeleton [Hough *et al* PMB (2011)]. This microstructure, along with associated masses and tissue compositions, was used to compute specific absorbed fractions (SAF) values for protons originating in axial and appendicular bone sites [Jokisch *et al* PMB (submitted)]. These proton SAFs, bone masses, tissue compositions, and proton production cross-sections, were subsequently used to construct neutron dose response functions (DRFs) for both AM and TM₅₀ targets in each bone of the reference adult male. Kerma conditions were assumed for other resultant charged particles. For comparison, active marrow, total shallow marrow, and spongiosa kerma coefficients were also calculated. At low incident neutron energies, AM kerma coefficients for neutrons correlate well with values of the AM DRF, while total marrow (TM) kerma coefficients correlate well with values of the TM₅₀ DRF. At high incident neutron energies, all kerma coefficients and DRFs tend to converge as charged particle equilibrium (CPE) is established across the bone site. In the range of 10 eV to 100 MeV,

substantial differences are observed among the kerma coefficients and DRF. As a result, it is recommended that the AM kerma coefficient be used to estimate the AM DRF, and that the TM kerma coefficient be used to estimate the TM₅₀ DRF below 10 eV. Between 10 eV and 100 MeV, the appropriate DRF should be used as presented in this study. Above 100 MeV, spongiosa kerma coefficients apply well for estimating skeletal tissue doses. DRF values for each bone site as a function of energy are provided in an electronic annex to this article.

Keywords

neutron dosimetry; bone dosimetry; dose-response functions; active marrow; total shallow marrow

1. Introduction

Exposure to neutrons occurs in a variety of environments. All humans are exposed to natural levels of background radiation which include neutrons from cosmic sources. Occupationally, radiation workers may be exposed to significant neutron doses above background levels in many nuclear facilities. Above an altitude of 10 km, neutrons can account for up to 50% of the ambient dose equivalent, indicating that neutron dose is a concern for astronauts (ICRU, 2000). Aircraft crews also receive elevated neutron doses, although to a lesser extent. Generally, dosimetry is performed for individuals in these professions to characterize the dose and subsequent biological risk incurred.

Neutron dose can also be significant in some medical applications. In methods of therapy using neutron beams, such as boron-neutron capture therapy, some neutrons will invariably interact within non-targeted regions of the patient's healthy tissues. In high-energy photon therapy, photoneutron production may be significant, exposing the patient to an unintended neutron dose (Allen and Chaudhri, 1988). Proton therapy may be performed on cancer patients when sharp distal fall-off is required due to the proximity of the planning tumor volume to organs-at-risk. Such therapies may create a significant secondary neutron dose to the patient from both (p,n) reactions within the treatment head or within the patient's body. Due to their large penetration distance and resulting secondary heavy-charged particles, neutrons are of special concern in proton therapy (Xu *et al.*, 2008).

Direct measurement of dose resulting from neutron irradiation is not practical, and for the skeletal tissues, characterization of neutron dose through computational models is complicated greatly by the heterogeneous and microscopic nature of this organ system. Human skeletal tissues are comprised of different regions and elements. Blood cell production takes place in hematopoietically active (or red) marrow, which is one constituent of bone spongiosa. Inactive (or yellow) marrow and trabecularized mineral bone also comprise spongiosa. Depending on the bone site, different amounts of these three constituents are present. Irradiation of the active marrow is associated with leukemia risk, while irradiation of total shallow marrow, defined as the layer extending 50 μm from the bone surfaces into the marrow cavity, is associated with the risk of osteosarcoma (Eckerman *et al.*, 2008). It should be noted that previously, the target tissue for osteoprogenitor irradiation was taken to be a 10- μm thick cell layer extending from the bone surfaces into the

marrow cavities. Recently, however, the osteoprogenitor cells have been found to reside up to 50 μm into the marrow cavities, and so the total shallow marrow is now the target tissue for osteoprogenitor irradiation. The structure of spongiosa is complex and is not easily represented using simplified geometric definitions. Currently, kerma to the spongiosa is used as a surrogate for absorbed dose to both active marrow and total shallow marrow.

The geometric structure and bone region composition differences can lead to a lack of charged particle equilibrium (CPE) in the marrow cavities (Eckerman *et al.*, 2008), calling into question the accuracy of using spongiosa kerma as a surrogate dosimetric quantity. A lack of CPE can occur in spongiosa for both photon and neutron irradiation, but for different yet complementary reasons. During photon irradiation of spongiosa at energies below about 200 keV, a greater number of photoelectric events will occur in bone trabeculae than in bone marrow. As a result, an *enhancement* of the absorbed dose to both active marrow and total shallow marrow will result as photoelectrons emerge from bone trabeculae and deposit energy to adjacent marrow tissues (Johnson *et al.*, 2011). In contrast, elastic collisions of neutrons in spongiosa will result in a greater number of recoil protons created within the marrow tissues than in the bone trabeculae (owing to a higher hydrogen content in the former), and these recoil particles will, in many cases, traverse the marrow spaces with their residual energy being lost to surrounding trabeculae. The net result for neutron irradiation is then a *suppression* of the absorbed dose to marrow tissues from that predicted under a kerma approximation.

To consider these non-equilibrium conditions, as well as to avoid having to explicitly model the complex microstructure of the skeletal tissues within a computational whole-body phantom, dose response functions (DRF) can be utilized. Instead of performing full secondary particle transport, the user can record energy-dependent neutron fluence over the spongiosa of a particular bone site and implement the appropriate DRF to return the desired quantity – the absorbed dose to active marrow or total shallow marrow. This method requires the calculation of the secondary charged particle absorbed fractions (AF) defined as the ratio of the energy absorbed in the target tissue per unit energy emitted in the source tissue. Previously, DRFs for photon irradiation of the skeleton have been calculated by Johnson *et al.* (2011) using electron AFs given in Hough *et al.* (2011) for the University of Florida (UF) adult male hybrid phantom. Additionally, skeletal DRFs for neutrons have been calculated previously for the DS86 project for the atomic bomb survivors at Hiroshima and Nagasaki (Kerr and Eckerman, 1985). These calculations, however, considered only active marrow in a homogeneous skeletal model, and therefore did not separately calculate DRFs for the total shallow marrow. In addition, only recoil protons with energies less than 20 MeV were evaluated, and anisotropic scattering was not considered (Kerr and Eckerman, 1985).

Kerma response functions (also referred to as “kerma coefficients”) have been previously calculated for neutrons. Brenner calculated kerma coefficients for neutrons above 15 MeV (Brenner, 1984). Due to a lack of experimental values at high energies, nuclear interaction data are based on models of the nucleus. However, the nuclear models used prior to this study were “general purpose” in nature, and not acceptable for lighter mass nuclides such as those present in human tissues (due to the lack of statistical behavior of nuclides with mass numbers less than 20) (Brenner, 1984). Brenner used the intra-nuclear cascade model

followed by Fermi breakup for these lighter nuclei, and obtained good results for incident neutron energies ranging from 16 to 80 MeV for carbon, nitrogen, and oxygen. Neutron kerma coefficients have also been calculated for incident neutron energies less than 30 MeV using cross-section data from the Evaluated Nuclear Data File (ENDF) (Caswell *et al.*, 1980). An important caveat was included in this investigation: below neutron energies around 30 eV, molecular interactions are significant, but are not addressed by the kerma coefficient (Caswell *et al.*, 1980).

ICRU Report 63, *Nuclear Data for Neutron and Proton Radiotherapy and for Radiation Protection*, presents cross-sections and kerma coefficients for elements of interest in radiotherapy (ICRU, 2000). While previous neutron data were driven by weapons research and considered neutron energies up to 15–20 MeV, this report includes neutron data up to 150 MeV. To determine the cross-sections and kerma coefficients, the generated values from the GNASH code (Young *et al.*, 1992) were compared with existing measurements (ICRU, 2000). It is important to emphasize that the cross-section and kerma coefficient values stated in ICRU Report 63 are evaluated, meaning that they are a combination of experimental and theoretically derived data. Thus, if one calculates a kerma coefficient based upon the reported cross-sections, there will likely be some difference with the corresponding kerma coefficient as stated in this report.

In the present study, skeletal neutron DRFs for active marrow and total shallow marrow are calculated for all skeletal sites within the UF adult male hybrid phantom as constructed by Hough *et al.* (2011). The active marrow DRF and total shallow marrow DRF are compared to kerma coefficients for active marrow, total marrow, and spongiosa. Based upon these comparisons, guidance is provided regarding the evaluation of dose to the two target tissues of interest. This protocol addresses incident neutron energies ranging from thermal to 150 MeV.

2. Materials and Methods

2.1 Specific absorbed fraction data

As previously stated, the calculation of a neutron DRF requires the AF of secondary charged particles to the target tissue of interest. AFs can be calculated from the specific absorbed fraction (SAF), which is simply the quotient of the AF and the target mass. The SAFs for active marrow and total shallow marrow as a target were previously calculated for protons using path-length distributions from microCT scans of spongiosa samples from a 40-year-old male cadaver (Jokisch *et al.*, submitted) using the continuously slowing down approximation (CSDA) for proton transport (Jokisch *et al.*, 2011). CSDA data were retrieved from the National Institute for Standards and Technology (NIST) and scaled to each bone region composition. The compositions for the three bone regions of interest (active marrow, trabecular mineral bone, and inactive marrow) were taken from ICRU Report 46 (ICRU, 1992), and are shown in Table 1. These compositions were also used directly in the calculation of the neutron DRF. In addition, the neutron DRF calculation used a skeletal mass set that was entirely consistent with that used to compile the SAF data. These masses were based on the same 40-year-old male cadaver used to generate the path-length distributions (Hough *et al.*, 2011).

2.2 Photon DRF and the Three-Factor Method

Photon DRF have also been calculated using electron AF data generated from simulations based on the spongiosa microstructure of the 40-year-old male cadaver (Johnson *et al.*, 2011). An alternative to explicitly calculating the photon DRF is to use the *three-factor method*, in which the absorbed dose to active marrow, D_{AM} is given by the following expression:

$$D_{AM} = K_{SP} \left[\frac{\mu_{en}}{\rho} \right]_{SP}^{AM} S(E) \quad [1]$$

where K_{SP} is the kerma to homogeneous spongiosa, $\left[\frac{\mu_{en}}{\rho} \right]_{SP}^{AM}$ is the ratio of mass-energy absorption coefficients of active marrow and homogeneous spongiosa, and $S(E)$ is a dose enhancement factor which accounts for additional energy deposition to active marrow from photoelectrons created within neighboring bone trabeculae (Lee *et al.*, 2006). Energy dependence is implicit in the dose terms and the mass-energy absorption coefficients. Since the properties of DRF follow the properties of absorbed dose, the dose terms in Equation 1 can be replaced by the DRF (dose per unit fluence). Therefore, for each bone, if the photon active marrow DRF is known, the dose enhancement factor can be found as well.

The primary advantage to using the three-factor method is its ease of use. If the dose to AM from photons is required, one can simply record kerma over a homogeneous spongiosa volume and apply the corrections of Equation 1. An easily-implemented analogous method does not exist when addressing the neutron dose. In order to use a method similar to the three-factor method with neutron dose and DRF, one would need to know the fraction of dose in the homogeneous spongiosa volume due to interactions from each resultant charged particle, with its unique and corresponding dose enhancement factor. Thus, the large number of neutron-produced charged particle types (protons, deuterons, tritons, ^3He nuclei, alphas, and recoil nuclei) precludes the use of a “neutron three-factor method”. Instead, a dose-to-kerma ratio may be calculated as the quotient of the calculated DRF and the spongiosa kerma coefficient of the corresponding bone site. This approach yields a dimensionless factor which can be applied to spongiosa kerma to yield absorbed dose to the target tissue of interest for a given bone site.

2.3 Neutron DRF generalized formulation

A general formulation for the neutron DRF should allow for consideration of all types of secondary charged particles resulting from neutron interactions. Neutron interactions are not represented by simple mathematical expressions. Instead, the calculation of neutron DRFs relies on interaction probabilities, similar to the way in which kerma coefficients are calculated. In contrast with kerma coefficients, and similar to the photon DRF formulation, fractional energy deposition by recoil secondaries must be considered (Eckerman *et al.*, 2008; Johnson *et al.*, 2011).

For neutrons, the DRF formulation for a given skeletal site is given as:

$$\frac{D(T)}{\Phi(E_n)} = \sum_j \frac{\lambda}{m(T)} \frac{N_A}{A_j} \sum_r f_j(r) m(r) \sum_i \int_0^\infty \phi_i(T \leftarrow r; \varepsilon) \times \sigma_{ij}^{prod}(E_n) n_{ij}(\varepsilon, E_n) \varepsilon d\varepsilon, \quad [2]$$

where E_n is the incident neutron energy, λ is a conversion factor to obtain the desired DRF units, N_A is Avogadro's number, A_j is the atomic mass of nuclide j , $m(T)$ is the mass of the target region, $m(r)$ is the mass of the source region, $f_j(r)$ is the percent mass abundance of nuclide j in the source region r , $\phi_i(T \leftarrow r; \varepsilon)$ is the absorbed fraction for secondary charged particles with energy ε of type i from source region r to target region T , $\sigma_{ij}^{prod}(E_n)$ is the secondary charged-particle production cross-section for nuclide j and secondary charged particle i , and $n_{ij}(\varepsilon, E_n)$ is the distribution of secondary charged particles of type i from a neutron interaction with nuclide j . In this formulation, three summations occur: (1) over all secondary charged particles i ; (2) over all source regions, r ; and (3) over all nuclides, j , comprising the source regions.

The value of the conversion factor λ is dependent upon the units used for the equation variables to calculate the neutron DRF. In general, mass will be expressed in grams, energy will be expressed in electron-volts, and cross-section will be expressed in barns. Therefore, after all operations excluding multiplication by the conversion factor are performed, the units are left in the product of electron-volts and barns per gram. The desired units are gray-square meters. Therefore, the conversion factor is given as

$$\lambda = \frac{1 \text{ m}^2}{10^{28} \text{ b}} \cdot \frac{1.6022 \times 10^{-19} \text{ J}}{1 \text{ eV}} \cdot \frac{1000 \text{ g}}{1 \text{ kg}} = 1.6022 \times 10^{-44} \frac{\text{Gy m}^2}{\text{b eV g}^{-1}}.$$

A myriad of charged particles can result from neutron interactions with a constituent nucleus. Theoretically, if AF data existed for all of these particles, a neutron DRF in pure form could be calculated.

2.4 Hydrogen neutron DRF formulation

Since skeletal SAFs are currently limited to protons only, a DRF in pure form is not practically calculated. As the only resultant charged particle from a neutron interaction with hydrogen is a recoil proton, it is the simplest element to address. Furthermore, the linear ranges of protons will be higher than other recoil nuclei in marrow and bone, and thus their consideration will dominate the conditions of charge particle disequilibrium. In addition, due to the low relative abundance of deuterium and tritium, the neutron DRF formulation for hydrogen is simplified greatly by assuming that ^1H comprises all of the hydrogen in the skeletal tissues. The equation used to find the hydrogen component of the neutron DRF for each skeletal site is

$$\left[\frac{D(T)}{\Phi(E_n)} \right]_H = \frac{\lambda}{m(T)} \frac{N_A}{A_H} \sum_r f_H(r) m(r) \int_0^\infty \phi_p(T \leftarrow r; \varepsilon) \times \sigma_{n,n}(E_n) n_p(\varepsilon, E_n) \varepsilon d\varepsilon, \quad [3]$$

where $\sigma_{n,n}(E_n)$ is the cross-section for neutron scatter on hydrogen, and $n_p(\varepsilon, E_n)$ is the energy distribution for the recoil proton.

To derive the energy distribution of protons resulting from neutron scatter on hydrogen, the angular distribution of neutrons after interaction with hydrogen must be used. These data are part of the ENDF files, and are readily available from the US Department of Energy's National Nuclear Data Center (NNDC, 2006). The angular distribution of neutrons resulting from scatter on hydrogen is displayed in Figure 1. It is evident from this figure that the assumption of isotropic scattering of neutrons on hydrogen is only valid up to incident neutron energy of 20 MeV. The anisotropy of scatter must be considered when calculating the hydrogen component of the neutron DRF.

It is further necessary to convert the angular distribution of resultant neutrons to the energy distribution of its recoil protons. First, the proton energy for a given incident energy and cosine of center-of-mass (CM) neutron scattering angle must be calculated. For the generalized case of scatter on any stationary body, the energy of the recoil nucleus is given as (Shultis and Faw, 2000)

$$T = \frac{1}{2} E (1 - \alpha) [1 - \omega_c \sqrt{1 + \Delta}] + \frac{Q}{A + 1}, \quad [4]$$

with

$$\alpha \equiv \left[\frac{A - 1}{A + 1} \right]^2, \quad [5]$$

and

$$\Delta = \frac{Q(1 + A)}{AE}. \quad [6]$$

Here, E is the incident neutron energy, ω_c is the cosine of the CM scattering angle, Q is the Q -value for the scattering interaction, and A is the ratio of masses of the stationary body and the scattering particle. Clearly, for elastic scattering of a neutron on a hydrogen nucleus, the Q -value is zero, and so equals zero. Also, A can be approximated as unity, as a neutron and a proton are of nearly equal mass, yielding a value of zero for α . After considering these simplifications, the energy of the recoil proton is given as

$$T = \frac{1}{2}E(1 - \omega_c). \quad [7]$$

Next, the angular distribution of scattered neutrons must be modified to yield the energy distribution of recoil protons. To do so, the chain rule must be applied as:

$$n(T, E) = \frac{dn(E)}{dT} = \frac{dn(E)}{d\omega_c} \cdot \frac{d\omega_c}{dT} = n(\omega_c, E) \cdot \frac{d\omega_c}{dT}. \quad [8]$$

Differentiating Equation 7 with respect to ω_c yields

$$\frac{dT}{d\omega_c} = -\frac{1}{2}E. \quad [9]$$

Combining Equations 8 and 9, the energy distribution for recoil protons is given as

$$n(T, E) = -\frac{2}{E} \cdot n(\omega_c, E). \quad [10]$$

The negative sign in Equation 10 is a result of the inverse relationship between the cosine of the CM scattering angle and the recoil proton energy. To avoid negative values in a distribution, which are mathematically appropriate but not physically realizable, one may “flip” the distribution and the recoil proton energy, while leaving the incident neutron energy unaltered. This operation is numerically equivalent to interchanging the limits of integration.

To ensure that the proper result is obtained, one can inspect the relative probabilities as a function of recoil proton energy for incident neutron energy of 150 MeV. For this energy, the most probable CM scattering angle cosine is -1 , corresponding to a direct collision of the neutron with the hydrogen nucleus. This results in maximal energy transfer to the recoil proton. Thus, after the conversion of the angular distribution of resultant neutrons to the energy distribution of recoil protons, the relative probability of a recoil proton with maximal energy should be greater than the relative probability of a recoil proton with zero energy, which results from a glancing collision (i.e., $\omega_c = 1$).

To perform the neutron DRF calculation, a in-house computer program was written in MATLAB® version 7.10.0 (The Mathworks Inc., Natick, MA). Since the proton data from the study of Jokisch et al (submitted) is presented in SAF form, it was determined that the equations used to evaluate the neutron DRF should be modified accordingly. Also, the equation was modified to minimize the number of numerical integrations performed, and the maximum proton energy is assumed to be the incident neutron energy. For hydrogen, the actual equation used to calculate the hydrogen component of the neutron DRF is

$$\left[\frac{D(T)}{\Phi(E_n)} \right]_H = \lambda \frac{N_A}{A_H} \int_0^{E_n} \left\{ \sum_r f_H(r) m(r) \Phi_p(T \leftarrow r; \varepsilon) \right\} \times \sigma_{n,n}(E_n) n_p(\varepsilon, E_n) \varepsilon d\varepsilon. \quad [11]$$

where $\Phi_p(T \leftarrow r; \varepsilon)$ is the SAF for protons of energy ε from source region r to target region T , and all other variables are as designated in Equation 3 above.

To perform the integration, first the energy range was split into logarithmically-equidistant divisions. Next, the summation was performed for the three source regions (active marrow, inactive marrow, trabecular bone). The product of the summation, the scattering cross-section, and the recoil proton energy distribution was calculated for each incident neutron energy and recoil proton energy. The result was numerically integrated using the trapezoidal method. Finally, the conversion factor was applied to obtain a result in Gy m².

2.5 DRF neutron formulation for other elements

The equation for the neutron DRF proton component associated with each target element is similar to Equation 11 – the equation for the hydrogen component of the neutron DRF. For neutrons incident on an arbitrary element X , the proton component of the total neutron DRF is given as

$$\left[\frac{D(T)}{\Phi(E_n)} \right]_X = \lambda \frac{N_A}{A_X} \int_0^{E_n} \left\{ \sum_r f_X(r) m(r) \Phi_p(T \leftarrow r; \varepsilon) \right\} \times \sigma_{xp}(\varepsilon, E_n) \varepsilon d\varepsilon, \quad [12]$$

where $\sigma_{xp}(\varepsilon, E_n)$ is the differential proton production cross-section.

The cross-sections and kerma coefficients listed in ICRU Report 63 are for the major isotopes of elements considered important for biological or shielding reasons. These data are tabulated for incident neutron energies from 20 MeV to 150 MeV. The elements contained in ICRU Report 63, corresponding major isotopes, and natural abundances of the major isotopes are displayed in Table 2. According to ICRU Report 63 recommendations (ICRU, 2000), when natural abundances of isotopes are assumed, the data for the major isotopes may be used as representative of the element. The data included on the ICRU Report 63 data CD was used for the constituent elements of skeletal tissue. It should be noted that for iron, the kerma coefficients for the four major isotopes were included on the data CD, and so these were combined according to natural abundance in order to yield an elemental iron kerma coefficient.

With the exception of protons, SAF data do not exist for charged particles resulting from neutron interactions in the skeletal tissues. Therefore, partial kerma coefficients must be used for these resultant charged particles. Partial kerma coefficients for deuterons, ³He nuclei, alphas, and recoil nuclei are listed for the elements in ICRU Report 63. These were weighted by the appropriate percent mass abundances and summed to yield the contribution of non-proton resultant charged particles. Assuming kerma conditions for charged particles

other than protons will lead to some error in the estimation of the neutron DRF. However, the error is not expected to be substantial since the heavier charged particles have ranges in skeletal tissues that are much smaller than those for protons.

2.6 Complete neutron DRF definition

The final neutron DRF for each skeletal site was taken to be the hydrogen-only DRF for incident neutron energies up to 20 MeV. Above 20 MeV, the neutron DRF was calculated for hydrogen and ICRU Report 63 elements. Any element not listed in ICRU Report 63 was not included in the calculation of the skeletal neutron DRF, primarily due to a lack of cross-section data. However, these elements make up less than one percent of the composition of active marrow, inactive marrow, and trabecular mineral bone, and so their exclusion is not expected to cause appreciable error in the calculations.

3. Results

Neutron dose-response functions were calculated for both AM and TM₅₀ targets within bone sites representing the axial skeleton of the ICRP 89 reference adult male. For each of the 13 bone sites of the distal appendicular skeleton, only response functions to TM₅₀ were calculated, as no active marrow resides in these sites. Note that for the medullary cavities of the long bones, the kerma approximation is assumed and thus the DRF for medullary marrow is simply taken to be the kerma coefficient for inactive marrow. These DRFs are shown in both graphical and tabular format for both the axial and appendicular skeleton in Annexes A and B, respectively.

For comparison purposes, the neutron kerma coefficients for AM, total marrow (TM), and spongiosa were also calculated for each axial bone site. Since the composition of AM for each axial bone site is the same, the AM kerma coefficients are all equal. Due to differences in marrow cellularity and the percentage of spongiosa comprised of trabecular bone, the TM kerma coefficients and spongiosa kerma coefficients vary by skeletal site. Figures 2A and 3A show the kerma coefficients for AM, TM, and spongiosa, as well as the dose-response functions for AM and TM₅₀, for the thoracic vertebrae and proximal humeri, respectively. The thoracic vertebra is a bone site where the differences among the kerma coefficients and DRFs are relatively small, while the proximal humerus is a bone site where these differences among kerma coefficients and DRFs are much more prominent. Corresponding tabular data for the DRFs in these two bone sites are Tables 3 and 4, respectively.

Tables 5 and 6 give dose-to-kerma ratios for AM and TM₅₀ targets in the thoracic vertebrae and proximal humeri, respectively. Here, the dose-to-kerma ratios were calculated using the DRFs reported in this study and kerma coefficients to homogeneous spongiosa as calculated using data in ICRU Report 63. Ratios less than unity indicate that the kerma to homogeneous spongiosa over-predicts the absorbed dose to the relevant target tissue (AM or TM₅₀). Conversely, ratios exceeding unity indicate that the kerma to homogeneous spongiosa under-predicts the desired target tissue dose. If dose-to-kerma ratios are to be implemented in instances where the incident neutron energy exceeds 150 MeV, it is important that the user calculate kerma coefficients based upon the particular cross-section library used for neutron transport. Furthermore, the data given in Tables 5 and 6 are unique

to the materials and elemental compositions of spongiosa in the UF hybrid reference adult male phantom (Hough *et al.*, 2011).

While the differences between the thoracic vertebra and proximal humerus represent variation in terms of the spread among the kerma coefficients and DRFs in the human skeleton, there are several similarities that are characteristic of every bone site. At very low energies (less than 10 meV), the kerma coefficients and DRFs change very little with incident neutron energy; an approximate value for the AM DRF is 3.1×10^{-17} Gy m², while the TM₅₀ DRFs ranges from a minimum 6.3×10^{-18} Gy m² for the appendicular skeletal sites to a maximum of 2.4×10^{-17} Gy m² for sites of high cellularity such as the vertebrae. The values then decrease to a minimum at energies between 10 and 100 eV, and then increase with incident neutron energy. The maximum for values observed for the AM DRFs are around 1.3×10^{-14} Gy m², while the maximum values for the TM₅₀ DRFs are between 1.2×10^{-14} to 1.4×10^{-14} Gy m².

At low incident neutron energies, the AM kerma coefficient accurately represents the AM DRFs for all axial bone sites, while the TM kerma coefficient corresponds well with the TM₅₀ DRFs for both axial and appendicular bone sites. The convergence of these values at low incident neutron energies is expected, since secondary charged particles are unlikely to have sufficient energy to escape the region of their creation, imposing static CPE. At high incident neutron energies, all kerma coefficients and DRFs converge, as dynamic CPE is established within the spongiosa of each bone site. In the mid-range incident neutron energies (100 eV to 100 MeV), neither static nor dynamic CPE exist due to the interplay between the size and shape of the bone trabeculae and marrow cavities and the ranges of the recoil protons resulting from neutron interactions. This is manifest in the large differences between the kerma coefficients and DRFs when compared with the differences observed at energies outside of this range.

4. Discussion

To quantitatively evaluate the use of a particular kerma coefficient for a DRF, the relative difference as a function of incident neutron energy was calculated. Explicitly, the relative difference, or RD, is calculated as

$$RD(E_n) = \frac{k(E_n) - \frac{D(T)}{\Phi(E_n)}}{\frac{D(T)}{\Phi(E_n)}}, \quad [13]$$

where $k(E_n)$ is the kerma coefficient for a chosen bone region as a function of incident

neutron energy and $\frac{D(T)}{\Phi(E_n)}$ is the DRF for a chosen bone region as a function of incident neutron energy. Therefore, a positive RD value indicates that the kerma coefficient overestimates the DRF, while a negative RD value indicates that the kerma coefficient underestimates the DRF. The RD values in this study are reported as percentages.

For the axial skeleton, the RD of the kerma coefficient values with respect to the AM DRF and TM₅₀ DRF were found, while the RD of the kerma coefficient values with respect to the TM₅₀ DRF were calculated for the appendicular skeleton. The most pertinent comparisons for the axial skeletal sites are between

- AM kerma coefficient and AM DRF,
- TM kerma coefficient and TM₅₀ DRF,
- Spongiosa kerma coefficient and AM DRF, and
- Spongiosa kerma coefficient and TM₅₀ DRF.

The first two comparisons are important for evaluating differences due to charged particle disequilibrium, while the last two comparisons indicate differences resulting from approximating dose to AM and TM₅₀ by kerma to homogeneous spongiosa as might be seen in a whole-body computational phantom. Similarly, the most pertinent comparisons for the appendicular skeleton are between

- TM kerma coefficient and TM₅₀ DRF, and
- Spongiosa kerma coefficient and TM₅₀ DRF.

Plots of the RD as a function of incident neutron energy for the thoracic vertebra and the proximal humerus are displayed in Figures 2B and 3B, respectively. Similar plots for all bone sites are available in the electronic Annexes A and B.

As one may infer from the plots of kerma coefficient and DRF, the RD of the AM kerma coefficient with respect to the AM DRF is low at low incident neutron energies. While theoretically the RD should be zero at low energies due to static CPE, small differences are observed due to the fact that the ICRU Report 63 data are evaluated, as explained previously. The RD increases with increasing incident neutron energy from approximately 10 eV to 600 keV for the following bone sites: clavicles, craniofacial bones, proximal femora, proximal humeri, mandible, os coxae, and scapulae. For the remaining axial bone sites, the maximum RD occurs at 20 MeV. The RD then decreases with energy and is within 10% for all axial bone sites at 100 MeV. The AM kerma coefficient always overestimates the AM DRF.

The TM kerma coefficient correlates well with the TM₅₀ DRF at low incident neutron energies. The TM kerma coefficient is within 10% of the TM₅₀ DRF until around 1 MeV, at which point the RD increases to a maximum and then decreases with increasing incident neutron energy. The maximum RD observed is 15% to 30%, and the RD is within 15% for all bone sites at 100 MeV.

At low incident neutron energies, the spongiosa kerma coefficient underestimates the AM DRF (axial skeleton) and overestimates the TM₅₀ DRF (axial and appendicular skeleton). These differences are driven solely by the differences in composition among AM, TM, and spongiosa. At intermediate incident neutron energies, the spongiosa kerma coefficient overestimates the AM DRF for the clavicles, proximal femora, proximal humeri, mandible, os coxae, and scapulae. For the remainder of the axial bone sites, the spongiosa kerma coefficient continues to underestimate the AM DRF. The maximum RD for the spongiosa

kerma coefficient as an estimator of the AM DRF ranges from 10% to 60%. For all axial and appendicular bone sites, the spongiosa kerma coefficient underestimates the TM_{50} DRF at intermediate incident neutron energies. Finally, the difference associated with approximating the AM DRF and TM_{50} DRF with the spongiosa kerma coefficient is low at energies greater than 100 MeV. The relationship between the spongiosa kerma coefficient and the AM and TM_{50} DRFs for the craniofacial bones at high incident neutron energies is not the same as the other axial bone sites. At the maximum incident neutron energy, the spongiosa kerma coefficient still underestimates the AM DRF and the TM_{50} DRF by about 20%. This difference is likely due to the large amount of trabecular bone in the craniofacial bones, particularly in the occipital bone (Hough *et al.*, 2011). The craniofacial bones are really a collection of individual, unique bones, with varying compositions and trabecular structures, and so it is not surprising that the craniofacial DRFs exhibit exotic behavior. The findings of this study indicate that further investigation of the bones comprising the cranium is warranted.

Previously, active marrow neutron DRFs were calculated by Kerr and Eckerman (1985). A homogeneous skeleton was used in this study, along with AF data generated from optically acquired path-length distributions on contact radiographs performed at the University of Leeds (Beddoe *et al.*, 1976). It was determined that the AF data for lumbar vertebra could be used as a surrogate for AF data for all other bone sites except for the craniofacial bones, where AF data from the parietal bone were used instead. Only isotropic scattering on hydrogen nuclei was considered for incident neutron energies ranging from 0.5 MeV to 20 MeV; kerma coefficients were applied for all other elements.

A comparison between the lumbar vertebra AM DRF calculated in this study and that calculated previously by Kerr and Eckerman (1985) is displayed in Figure 4. The two datasets correspond well. Note that the newly-calculated DRF curve is slightly lower than that calculated by Kerr and Eckerman; the difference is small since the contribution from proton-producing interactions from elements other than hydrogen is almost zero in this energy range. The difference appears to be increasing towards the end of the energy range, as the relative importance of non-hydrogenous constituent elements begins to increase, emphasizing the importance of including the contributions of these constituents.

In terms of implementation, the format of the response function to be used is dictated by the range of incident neutron energies. For cases in which the maximum incident neutron energy is less than 150 MeV, the fluence over spongiosa should be recorded. Next, the product of the DRF and the fluence is integrated to return the absorbed dose to either active marrow or total shallow marrow. Neutron exposure situations in which this form should be used include occupational exposures at nuclear reactors (Shultis and Faw, 2000) and proton therapy for tumors at relatively shallow depths, such as eye treatments. For cases in which the maximum incident neutron energy exceeds 150 MeV, the kerma to spongiosa ratios should be considered. Here, two energy regimes must be considered separately - kerma due to neutrons of incident energies under 150 MeV and those exceeding 150 MeV. For the first regime, the product of the tabulated dose-to-kerma ratio and the recorded kerma is integrated. To return the total absorbed dose, this value must be summed with the total kerma from neutrons of the second regime. This form should be used for secondary neutrons resulting from proton

therapy for tumors at greater depths, such as prostate treatments, or for neutron exposures in space (NCRP, 2006).

In addition to providing skeletal neutron DRFs for specific bone sites, skeletal-averaged values were calculated to allow for the calculation of absorbed dose to sensitive skeletal tissues. Skeletal averaged values of the DRFs are given in Table 7, with graphical displays shown in Figure 5. These formulations may be used in the case of a uniform, whole-body irradiation by neutrons, such as in occupational exposures to neutrons at nuclear reactors or space exposures.

5. Conclusions

The results of this study indicate that large errors may be introduced by approximating dose to AM and TM₅₀ by the kerma to homogeneous spongiosa. For some bone sites, such as the thoracic vertebra, the error that occurs is small to moderate (< 20%). For other bone sites, such as the proximal humeri, the error that occurs is large, exceeding 50% at given energies. In cases of uniform neutron irradiation of the body, the skeletal average dose to AM and TM₅₀ are desired. Here, using kerma to spongiosa to estimate dose to TM₅₀ results in errors exceeding 40%, while using kerma to spongiosa to estimate dose to AM results in errors exceeding 30%.

The skeletal neutron DRFs presented in this study improve upon previously-calculated skeletal neutron DRFs in a number of ways. First, the incident neutron energy range has been extended greatly. Second, secondary proton anisotropy is explicitly considered for neutron scatter on hydrogen nuclei from energies ranging from thermal to 150 MeV. All proton-producing reactions are considered above incident neutron energy of 20 MeV. Finally, the new calculations consider bone site-specific spongiosa compositions.

Future areas for improvement include considering resultant charged particles other than recoil protons. While protons account for most of the difference between absorbed dose and kerma, assuming kerma conditions for the other charged particles introduces some error. Extending the energy range considered would be beneficial for confirming the existence of charged particle equilibrium above about 100 MeV. Explicitly accounting for neutron activation is another area of investigation not addressed in the current study, although it does contribute to absorbed dose. Finally, the appropriateness of the infinite spongiosa approximation for proton transport should be validated using Monte Carlo simulations in the UF hybrid phantoms.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.
The angular distribution of neutrons following scatter interactions with hydrogen nuclei.

Figure 2.

(A) Neutron dose-response functions and kerma coefficients for the spongiosa of the thoracic vertebrae within the ICRP 89 reference adult male. (B) Plots of percent relative difference for these quantities.

Figure 3.

(A) Neutron dose-response functions and kerma coefficients for the spongiosa of the proximal humeri within the ICRP 89 reference adult male. (B) Plots of percent relative difference for these quantities.

Figure 4.
Comparisons between current and previously published active marrow neutron dose-response functions for lumbar vertebrae within the ICRP 89 reference adult male.

Figure 5.

(A) Skeletal-averaged neutron dose-response functions and kerma coefficients for the ICRP 89 reference adult male. (B) Plots of percent relative difference for these skeletal-averaged quantities.

Table 1

Elemental composition of the skeletal tissues used in this study (ICRU, 1992).

Element	Composition by Mass (%)		
	<i>Active Marrow</i>	<i>Inactive Marrow</i>	<i>Trabecular Bone</i>
Hydrogen	10.5	11.5	3.4
Carbon	41.4	64.4	15.5
Nitrogen	3.4	0.7	4.2
Oxygen	43.9	23.1	43.5
Sodium ^a	0	0.1	0.1
Magnesium ^a	0	0	0.2
Phosphorous	0.1	0	10.3
Sulfur ^a	0.2	0.1	0.3
Chlorine ^a	0.2	0.1	0
Potassium ^a	0.2	0	0
Calcium	0	0	22.5
Iron	0.1	0	0

^aThese elements were not considered in the neutron DRF formulation.

Table 2

Representative isotopes for elements addressed in ICRU Report 63.

Element	Isotope	Natural Percent Abundance
Hydrogen	¹ H	99.9885
Carbon	¹² C	98.93
Nitrogen	¹⁴ N	99.632
Oxygen	¹⁶ O	99.757
Aluminum	²⁷ Al	100
Silicon	²⁸ Si	92.2297
Phosphorous	³¹ P	100
Calcium	⁴⁰ Ca	96.941
Iron	⁵⁶ Fe	91.754
Copper	⁶³ Cu	69.17
Tungsten	¹⁸⁴ W	30.64
Lead	²⁰⁸ Pb	52.4

Table 3

TV DRF

Energy (eV)	DRF (Gy·m ²)		Energy (eV)	DRF (Gy·m ²)		Energy (eV)	DRF (Gy·m ²)	
	AM	TM ₅₀		AM	TM ₅₀		AM	TM ₅₀
1.00E-03	3.08E-17	2.35E-17	1.00E+01	1.48E-18	1.15E-18	1.00E+05	6.67E-16	6.96E-16
1.50E-03	3.10E-17	2.36E-17	1.50E+01	1.28E-18	1.02E-18	1.50E+05	8.61E-16	9.02E-16
2.00E-03	3.12E-17	2.38E-17	2.00E+01	1.19E-18	9.62E-19	2.00E+05	1.02E-15	1.07E-15
3.00E-03	3.15E-17	2.40E-17	3.00E+01	1.11E-18	9.35E-19	3.00E+05	1.27E-15	1.33E-15
4.00E-03	3.17E-17	2.41E-17	4.00E+01	1.11E-18	9.66E-19	4.00E+05	1.52E-15	1.59E-15
5.00E-03	3.19E-17	2.43E-17	5.00E+01	1.15E-18	1.02E-18	5.00E+05	1.62E-15	1.71E-15
6.00E-03	3.20E-17	2.44E-17	6.00E+01	1.20E-18	1.09E-18	6.00E+05	1.76E-15	1.86E-15
8.00E-03	3.20E-17	2.44E-17	8.00E+01	1.34E-18	1.26E-18	8.00E+05	2.02E-15	2.14E-15
1.00E-02	3.19E-17	2.43E-17	1.00E+02	1.50E-18	1.44E-18	1.00E+06	2.38E-15	2.48E-15
1.50E-02	3.09E-17	2.35E-17	1.50E+02	1.96E-18	1.93E-18	1.50E+06	2.70E-15	2.82E-15
2.00E-02	2.92E-17	2.22E-17	2.00E+02	2.45E-18	2.45E-18	2.00E+06	3.09E-15	3.15E-15
3.00E-02	2.50E-17	1.90E-17	3.00E+02	3.45E-18	3.50E-18	3.00E+06	3.77E-15	3.69E-15
4.00E-02	2.18E-17	1.66E-17	4.00E+02	4.48E-18	4.58E-18	4.00E+06	4.31E-15	4.09E-15
5.00E-02	1.94E-17	1.48E-17	5.00E+02	5.51E-18	5.65E-18	5.00E+06	4.49E-15	4.17E-15
6.00E-02	1.77E-17	1.34E-17	6.00E+02	6.55E-18	6.73E-18	6.00E+06	4.68E-15	4.35E-15
8.00E-02	1.53E-17	1.17E-17	8.00E+02	8.62E-18	8.88E-18	8.00E+06	5.24E-15	4.96E-15
1.00E-01	1.37E-17	1.04E-17	1.00E+03	1.07E-17	1.10E-17	1.00E+07	5.63E-15	5.38E-15
1.50E-01	1.12E-17	8.55E-18	1.50E+03	1.58E-17	1.63E-17	1.50E+07	6.40E-15	6.30E-15
2.00E-01	9.72E-18	7.40E-18	2.00E+03	2.09E-17	2.16E-17	2.00E+07	6.79E-15	6.81E-15
3.00E-01	7.91E-18	6.03E-18	3.00E+03	3.08E-17	3.20E-17	3.00E+07	7.25E-15	7.35E-15
4.00E-01	6.86E-18	5.23E-18	4.00E+03	4.06E-17	4.21E-17	4.00E+07	7.64E-15	7.76E-15
5.00E-01	6.14E-18	4.68E-18	5.00E+03	5.02E-17	5.22E-17	5.00E+07	7.85E-15	7.98E-15
6.00E-01	5.61E-18	4.27E-18	6.00E+03	5.98E-17	6.22E-17	6.00E+07	8.11E-15	8.24E-15
8.00E-01	4.87E-18	3.71E-18	8.00E+03	7.88E-17	8.19E-17	8.00E+07	8.76E-15	8.89E-15
1.00E+00	4.35E-18	3.31E-18	1.00E+04	9.77E-17	1.02E-16	1.00E+08	9.58E-15	9.75E-15
1.50E+00	3.56E-18	2.72E-18	1.50E+04	1.45E-16	1.50E-16	1.50E+08	1.29E-14	1.32E-14

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Energy (eV)	DRF (Gy·m ²)		Energy (eV)	DRF (Gy·m ²)		Energy (eV)	DRF (Gy·m ²)		Energy (eV)	DRF (Gy·m ²)	
	AM	TM ₅₀		AM	TM ₅₀		AM	TM ₅₀		AM	TM ₅₀
2.00E+00	3.09E-18	2.36E-18	2.00E+04	1.88E-16	1.95E-16						
3.00E+00	2.53E-18	1.94E-18	3.00E+04	2.67E-16	2.77E-16						
4.00E+00	2.21E-18	1.70E-18	4.00E+04	3.39E-16	3.52E-16						
5.00E+00	1.99E-18	1.53E-18	5.00E+04	4.04E-16	4.20E-16						
6.00E+00	1.83E-18	1.41E-18	6.00E+04	4.65E-16	4.84E-16						
8.00E+00	1.62E-18	1.26E-18	8.00E+04	5.72E-16	5.97E-16						

Table 4

Proximal humeri DRF

Energy (eV)	DRF (Gy·m ²)		Energy (eV)	DRF (Gy·m ²)		Energy (eV)	DRF (Gy·m ²)	
	AM	TM ₅₀		AM	TM ₅₀		AM	TM ₅₀
1.00E-03	3.08E-17	1.25E-17	1.00E+01	1.45E-18	6.62E-19	1.00E+05	4.17E-16	7.16E-16
1.50E-03	3.10E-17	1.25E-17	1.50E+01	1.24E-18	6.17E-19	1.50E+05	5.35E-16	9.23E-16
2.00E-03	3.12E-17	1.26E-17	2.00E+01	1.13E-18	6.10E-19	2.00E+05	6.30E-16	1.10E-15
3.00E-03	3.15E-17	1.27E-17	3.00E+01	1.03E-18	6.46E-19	3.00E+05	7.90E-16	1.38E-15
4.00E-03	3.17E-17	1.28E-17	4.00E+01	1.01E-18	7.13E-19	4.00E+05	9.72E-16	1.64E-15
5.00E-03	3.19E-17	1.29E-17	5.00E+01	1.01E-18	7.92E-19	5.00E+05	1.02E-15	1.79E-15
6.00E-03	3.20E-17	1.29E-17	6.00E+01	1.04E-18	8.80E-19	6.00E+05	1.11E-15	1.95E-15
8.00E-03	3.20E-17	1.29E-17	8.00E+01	1.13E-18	1.07E-18	8.00E+05	1.32E-15	2.23E-15
1.00E-02	3.19E-17	1.29E-17	1.00E+02	1.23E-18	1.26E-18	1.00E+06	1.67E-15	2.58E-15
1.50E-02	3.09E-17	1.25E-17	1.50E+02	1.55E-18	1.78E-18	1.50E+06	2.04E-15	2.96E-15
2.00E-02	2.92E-17	1.18E-17	2.00E+02	1.91E-18	2.30E-18	2.00E+06	2.52E-15	3.31E-15
3.00E-02	2.50E-17	1.01E-17	3.00E+02	2.64E-18	3.36E-18	3.00E+06	3.32E-15	3.88E-15
4.00E-02	2.18E-17	8.79E-18	4.00E+02	3.39E-18	4.44E-18	4.00E+06	3.93E-15	4.24E-15
5.00E-02	1.94E-17	7.85E-18	5.00E+02	4.14E-18	5.51E-18	5.00E+06	4.15E-15	4.26E-15
6.00E-02	1.77E-17	7.13E-18	6.00E+02	4.90E-18	6.58E-18	6.00E+06	4.38E-15	4.48E-15
8.00E-02	1.53E-17	6.19E-18	8.00E+02	6.40E-18	8.73E-18	8.00E+06	5.00E-15	5.08E-15
1.00E-01	1.37E-17	5.53E-18	1.00E+03	7.89E-18	1.09E-17	1.00E+07	5.43E-15	5.46E-15
1.50E-01	1.12E-17	4.53E-18	1.50E+03	1.15E-17	1.62E-17	1.50E+07	6.26E-15	6.44E-15
2.00E-01	9.72E-18	3.93E-18	2.00E+03	1.50E-17	2.16E-17	2.00E+07	6.62E-15	7.02E-15
3.00E-01	7.91E-18	3.20E-18	3.00E+03	2.18E-17	3.22E-17	3.00E+07	7.09E-15	7.57E-15
4.00E-01	6.86E-18	2.78E-18	4.00E+03	2.81E-17	4.28E-17	4.00E+07	7.52E-15	7.94E-15
5.00E-01	6.14E-18	2.48E-18	5.00E+03	3.43E-17	5.33E-17	5.00E+07	7.76E-15	8.15E-15
6.00E-01	5.61E-18	2.27E-18	6.00E+03	4.04E-17	6.36E-17	6.00E+07	8.02E-15	8.38E-15
8.00E-01	4.87E-18	1.97E-18	8.00E+03	5.24E-17	8.40E-17	8.00E+07	8.68E-15	9.05E-15
1.00E+00	4.34E-18	1.76E-18	1.00E+04	6.44E-17	1.04E-16	1.00E+08	9.40E-15	9.91E-15
1.50E+00	3.56E-18	1.45E-18	1.50E+04	9.41E-17	1.54E-16	1.50E+08	1.26E-14	1.35E-14

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Energy (eV)	DRF (Gy·m ²)		Energy (eV)	DRF (Gy·m ²)		Energy (eV)	DRF (Gy·m ²)		Energy (eV)	DRF (Gy·m ²)	
	AM	TM ₅₀		AM	TM ₅₀		AM	TM ₅₀		AM	TM ₅₀
2.00E+00	3.08E-18	1.26E-18	2.00E+04	1.21E-16	2.00E-16	3.00E+00	2.53E-18	1.04E-18	3.00E+04	1.71E-16	2.85E-16
4.00E+00	2.20E-18	9.21E-19	4.00E+04	2.16E-16	3.63E-16	5.00E+00	1.98E-18	8.38E-19	5.00E+04	2.57E-16	4.35E-16
6.00E+00	1.82E-18	7.80E-19	6.00E+04	2.95E-16	5.01E-16	8.00E+00	1.60E-18	7.07E-19	8.00E+04	3.60E-16	6.17E-16

Table 5

TV dose-to-kerma ratios

Energy (eV)	Dose-to-Kerma Ratio		Energy (eV)	Dose-to-Kerma Ratio		Energy (eV)	Dose-to-Kerma Ratio	
	AM	TM50		AM	TM50		AM	TM50
1.00E-03	1.161	0.884	1.00E+01	1.124	0.878	1.00E+05	1.072	1.119
1.50E-03	1.161	0.884	1.50E+01	1.115	0.888	1.50E+05	1.068	1.119
2.00E-03	1.161	0.884	2.00E+01	1.108	0.899	2.00E+05	1.065	1.117
3.00E-03	1.161	0.884	3.00E+01	1.098	0.923	3.00E+05	1.060	1.114
4.00E-03	1.161	0.885	4.00E+01	1.092	0.947	4.00E+05	1.062	1.111
5.00E-03	1.161	0.885	5.00E+01	1.088	0.967	5.00E+05	1.053	1.113
6.00E-03	1.161	0.885	6.00E+01	1.085	0.985	6.00E+05	1.048	1.109
8.00E-03	1.161	0.885	8.00E+01	1.083	1.014	8.00E+05	1.043	1.103
1.00E-02	1.161	0.885	1.00E+02	1.083	1.036	1.00E+06	1.046	1.092
1.50E-02	1.161	0.885	1.50E+02	1.083	1.067	1.50E+06	1.037	1.081
2.00E-02	1.161	0.885	2.00E+02	1.082	1.083	2.00E+06	1.043	1.063
3.00E-02	1.161	0.884	3.00E+02	1.083	1.099	3.00E+06	1.045	1.022
4.00E-02	1.161	0.884	4.00E+02	1.083	1.106	4.00E+06	1.041	0.987
5.00E-02	1.160	0.884	5.00E+02	1.082	1.110	5.00E+06	1.037	0.963
6.00E-02	1.160	0.884	6.00E+02	1.081	1.111	6.00E+06	1.030	0.958
8.00E-02	1.160	0.883	8.00E+02	1.080	1.113	8.00E+06	1.021	0.966
1.00E-01	1.159	0.883	1.00E+03	1.078	1.113	1.00E+07	1.015	0.969
1.50E-01	1.158	0.882	1.50E+03	1.075	1.112	1.50E+07	1.008	0.991
2.00E-01	1.158	0.882	2.00E+03	1.072	1.110	2.00E+07	0.999	1.002
3.00E-01	1.156	0.881	3.00E+03	1.064	1.104	3.00E+07	0.995	1.010
4.00E-01	1.155	0.880	4.00E+03	1.059	1.100	4.00E+07	0.995	1.010
5.00E-01	1.155	0.880	5.00E+03	1.055	1.097	5.00E+07	0.993	1.009
6.00E-01	1.154	0.879	6.00E+03	1.053	1.096	6.00E+07	0.992	1.007
8.00E-01	1.152	0.878	8.00E+03	1.056	1.099	8.00E+07	0.988	1.003
1.00E+00	1.151	0.878	1.00E+04	1.063	1.105	1.00E+08	0.997	1.015
1.50E+00	1.148	0.876	1.50E+04	1.079	1.121	1.50E+08	0.992	1.018

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Energy (eV)	Dose-to-Kerma Ratio		Energy (eV)		Dose-to-Kerma Ratio		Energy (eV)		Dose-to-Kerma Ratio	
	AM	TM50								
2.00E+00	1.146	0.875	2.00E+04	1.079	1.121					
3.00E+00	1.141	0.873	3.00E+04	1.077	1.120					
4.00E+00	1.139	0.873	4.00E+04	1.079	1.122					
5.00E+00	1.136	0.873	5.00E+04	1.082	1.125					
6.00E+00	1.133	0.874	6.00E+04	1.081	1.125					
8.00E+00	1.128	0.876	8.00E+04	1.073	1.118					

Table 6

Proximal humeri dose-to-kerma ratios

Energy (eV)	Dose-to-Kerma Ratio		Energy (eV)	Dose-to-Kerma Ratio		Energy (eV)	Dose-to-Kerma Ratio	
	AM	TM50		AM	TM50		AM	TM50
1.00E-03	1.767	0.714	1.00E+01	1.586	0.724	1.00E+05	0.648	1.112
1.50E-03	1.767	0.714	1.50E+01	1.506	0.748	1.50E+05	0.641	1.107
2.00E-03	1.767	0.714	2.00E+01	1.431	0.772	2.00E+05	0.638	1.109
3.00E-03	1.767	0.714	3.00E+01	1.305	0.818	3.00E+05	0.639	1.113
4.00E-03	1.767	0.714	4.00E+01	1.209	0.856	4.00E+05	0.663	1.115
5.00E-03	1.767	0.714	5.00E+01	1.135	0.887	5.00E+05	0.638	1.121
6.00E-03	1.767	0.714	6.00E+01	1.079	0.912	6.00E+05	0.638	1.120
8.00E-03	1.768	0.714	8.00E+01	1.002	0.950	8.00E+05	0.659	1.113
1.00E-02	1.768	0.714	1.00E+02	0.953	0.976	1.00E+06	0.716	1.108
1.50E-02	1.768	0.714	1.50E+02	0.885	1.011	1.50E+06	0.755	1.099
2.00E-02	1.768	0.714	2.00E+02	0.851	1.028	2.00E+06	0.822	1.078
3.00E-02	1.767	0.714	3.00E+02	0.820	1.046	3.00E+06	0.885	1.034
4.00E-02	1.766	0.714	4.00E+02	0.805	1.054	4.00E+06	0.918	0.989
5.00E-02	1.765	0.713	5.00E+02	0.796	1.058	5.00E+06	0.936	0.960
6.00E-02	1.765	0.713	6.00E+02	0.790	1.061	6.00E+06	0.934	0.956
8.00E-02	1.763	0.713	8.00E+02	0.781	1.064	8.00E+06	0.946	0.960
1.00E-01	1.762	0.712	1.00E+03	0.774	1.066	1.00E+07	0.958	0.963
1.50E-01	1.760	0.711	1.50E+03	0.760	1.070	1.50E+07	0.957	0.986
2.00E-01	1.759	0.711	2.00E+03	0.749	1.073	2.00E+07	0.946	1.002
3.00E-01	1.755	0.710	3.00E+03	0.728	1.076	3.00E+07	0.944	1.008
4.00E-01	1.753	0.709	4.00E+03	0.710	1.080	4.00E+07	0.953	1.007
5.00E-01	1.750	0.708	5.00E+03	0.697	1.082	5.00E+07	0.958	1.007
6.00E-01	1.748	0.708	6.00E+03	0.688	1.084	6.00E+07	0.962	1.005
8.00E-01	1.744	0.707	8.00E+03	0.680	1.090	8.00E+07	0.962	1.002
1.00E+00	1.740	0.706	1.00E+04	0.677	1.097	1.00E+08	0.964	1.016
1.50E+00	1.730	0.705	1.50E+04	0.679	1.112	1.50E+08	0.949	1.021

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Energy (eV)	Dose-to-Kerma Ratio		Energy (eV)		Dose-to-Kerma Ratio		Energy (eV)		Dose-to-Kerma Ratio	
	AM	TMS0			AM	TMS0			AM	TMS0
2.00E+00	1.721	0.704	2.00E+04	2.00E+04	0.674	1.113				
3.00E+00	1.703	0.704	3.00E+04	3.00E+04	0.668	1.113				
4.00E+00	1.688	0.705	4.00E+04	4.00E+04	0.666	1.118				
5.00E+00	1.670	0.707	5.00E+04	5.00E+04	0.665	1.124				
6.00E+00	1.653	0.710	6.00E+04	6.00E+04	0.662	1.125				
8.00E+00	1.620	0.717	8.00E+04	8.00E+04	0.653	1.116				

Table 7

Skeletal average DRF

Energy (eV)	DRF (Gy·m ²)		Energy (eV)	DRF (Gy·m ²)		Energy (eV)	DRF (Gy·m ²)	
	AM	TM50		AM	TM50		AM	TM50
1.00E-03	3.08E-17	1.49E-17	1.00E+01	1.47E-18	7.76E-19	1.00E+05	6.21E-16	7.11E-16
1.50E-03	3.10E-17	1.50E-17	1.50E+01	1.28E-18	7.13E-19	1.50E+05	7.98E-16	9.21E-16
2.00E-03	3.12E-17	1.51E-17	2.00E+01	1.18E-18	6.96E-19	2.00E+05	9.40E-16	1.09E-15
3.00E-03	3.15E-17	1.53E-17	3.00E+01	1.10E-18	7.21E-19	3.00E+05	1.17E-15	1.36E-15
4.00E-03	3.17E-17	1.54E-17	4.00E+01	1.10E-18	7.83E-19	4.00E+05	1.40E-15	1.62E-15
5.00E-03	3.19E-17	1.55E-17	5.00E+01	1.13E-18	8.60E-19	5.00E+05	1.48E-15	1.76E-15
6.00E-03	3.20E-17	1.55E-17	6.00E+01	1.18E-18	9.47E-19	6.00E+05	1.61E-15	1.92E-15
8.00E-03	3.20E-17	1.55E-17	8.00E+01	1.32E-18	1.14E-18	8.00E+05	1.85E-15	2.20E-15
1.00E-02	3.19E-17	1.55E-17	1.00E+02	1.47E-18	1.33E-18	1.00E+06	2.20E-15	2.53E-15
1.50E-02	3.09E-17	1.50E-17	1.50E+02	1.91E-18	1.86E-18	1.50E+06	2.53E-15	2.91E-15
2.00E-02	2.92E-17	1.42E-17	2.00E+02	2.38E-18	2.40E-18	2.00E+06	2.93E-15	3.26E-15
3.00E-02	2.50E-17	1.21E-17	3.00E+02	3.36E-18	3.48E-18	3.00E+06	3.63E-15	3.83E-15
4.00E-02	2.18E-17	1.06E-17	4.00E+02	4.35E-18	4.58E-18	4.00E+06	4.17E-15	4.21E-15
5.00E-02	1.94E-17	9.42E-18	5.00E+02	5.35E-18	5.68E-18	5.00E+06	4.35E-15	4.23E-15
6.00E-02	1.77E-17	8.57E-18	6.00E+02	6.35E-18	6.78E-18	6.00E+06	4.54E-15	4.41E-15
8.00E-02	1.53E-17	7.43E-18	8.00E+02	8.35E-18	8.96E-18	8.00E+06	5.09E-15	4.98E-15
1.00E-01	1.37E-17	6.64E-18	1.00E+03	1.03E-17	1.11E-17	1.00E+07	5.48E-15	5.34E-15
1.50E-01	1.12E-17	5.44E-18	1.50E+03	1.53E-17	1.65E-17	1.50E+07	6.24E-15	6.27E-15
2.00E-01	9.72E-18	4.71E-18	2.00E+03	2.01E-17	2.18E-17	2.00E+07	6.63E-15	6.81E-15
3.00E-01	7.91E-18	3.84E-18	3.00E+03	2.96E-17	3.23E-17	3.00E+07	7.10E-15	7.38E-15
4.00E-01	6.86E-18	3.33E-18	4.00E+03	3.88E-17	4.25E-17	4.00E+07	7.50E-15	7.79E-15
5.00E-01	6.14E-18	2.98E-18	5.00E+03	4.79E-17	5.26E-17	5.00E+07	7.72E-15	8.02E-15
6.00E-01	5.61E-18	2.72E-18	6.00E+03	5.69E-17	6.27E-17	6.00E+07	7.98E-15	8.27E-15
8.00E-01	4.87E-18	2.37E-18	8.00E+03	7.48E-17	8.28E-17	8.00E+07	8.64E-15	8.95E-15
1.00E+00	4.35E-18	2.11E-18	1.00E+04	9.26E-17	1.03E-16	1.00E+08	9.46E-15	9.83E-15
1.50E+00	3.56E-18	1.74E-18	1.50E+04	1.36E-16	1.53E-16	1.50E+08	1.28E-14	1.35E-14

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Energy (eV)	DRF (Gy·m ²)		Energy (eV)	DRF (Gy·m ²)		Energy (eV)	DRF (Gy·m ²)	
	AM	TMS0		AM	TMS0		AM	TMS0
2.00E+00	3.09E-18	1.51E-18	2.00E+04	1.77E-16	1.99E-16			
3.00E+00	2.53E-18	1.25E-18	3.00E+04	2.51E-16	2.83E-16			
4.00E+00	2.21E-18	1.10E-18	4.00E+04	3.17E-16	3.60E-16			
5.00E+00	1.99E-18	9.97E-19	5.00E+04	3.78E-16	4.30E-16			
6.00E+00	1.83E-18	9.25E-19	6.00E+04	4.35E-16	4.95E-16			
8.00E+00	1.62E-18	8.34E-19	8.00E+04	5.34E-16	6.10E-16			