COMPUTATIONAL METHOD FOR REALISTIC ESTIMATES OF THE DOSE TO ACTIVE MARROW*

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INTRODUCTION

Calculation of absorbed dose to active marrow from photon radiation is a complex problem because electronic equilibrium may not exist in the vicinity of soft tissue-bone mineral interfaces.[1-5] Snyder et al.[6] recognized the intractable geometry of trabecular bone in their studies of photon transport in the body and formulated marrow dose estimates in a conservative manner. Other investigators[7-10] have noted that this approach leads to overestimates by factors of 3 or more at low photon energy. In this paper the absorbed dose is formulated in terms of physical and anatomical parameters defining the energy deposition in the marrow space.

ABSORBED DOSE FORMULATION

Consider the trabeculation of a bone experiencing a fluence, $\Psi(E)$, of photons of energy E. Let m(TB) and m(RM) denote the mass of bone (trabeculae) and marrow comprising the trabeculation. If we index the type of photon interaction by i and the region in which it occurred by r, r = TB or RM, then the absorbed dose in active marrow per unit photon fluence, $D(RM)/\Psi(E)$, can be expressed as

$$\frac{D(RM)}{\Psi(E)} = \sum_r \frac{m(r)}{m(RM)} \sum_i \int_0^\infty \phi(RM \leftarrow r, T_i) \; (i/\rho)_r \; n_r(T_i) \; T_i \; dT_i \quad , \qquad (1)$$

where

$\phi(RM \leftarrow r, T_i)$ is the absorbed fraction in RM from r for electrons of energy T_i,

$(i/\rho)_r$, $i = \tau, \sigma$, and k, denotes the mass attenuation coefficients in medium r for the photoelectric, Compton, and pair-production interactions, respectively,

$n_r(T_i)dT_i$ denotes the number of electrons of energy between T_i and $T_i + dT_i$ liberated in region r per interaction i.

This formulation separates the energy transfer process from the process of energy dissipation by secondary electrons. With this approach the mathematical analogue of man,[6] with its homogeneous skeleton, can be retained in photon transport calculations and the energy dissipation can be addressed on a microscopic scale. The energy dissipation is embodied in the absorbed fraction quantity.

ENERGY DISTRIBUTION OF SECONDARY ELECTRONS

Photons transfer energy to electrons through three major interactions: the photoelectric effect, the Compton effect, and pair-production. Photon cross-section data of Hubbell[11] and elemental composition data of Kerr[12] were used in evaluating the energy transfer. Photoelectrons were assumed to be of discrete energy corresponding to the incident photon energy. The energy distribution of Compton electrons was calculated from the Klein-Nishina relationship,[13] and the positron-electron energy distribution was derived from the Bethe-Heitler theory of pair-production.[14]

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ABSORBED FRACTIONS FOR MONOENERGETIC ELECTRONS

Because the geometry of trabecular bone could not be described in simple terms, Spiers introduced a method of calculating energy deposition using the path-lengths traversed by particles.[15] These path-lengths are based on chord-length distributions for trabeculae and marrow cavities obtained by optically scanning the trabeculation.[16] Absorbed fraction data for monoenergetic electrons, as required in Eq. (1), were computed as outlined by Whitwell and Spiers.[17] Data for the parietal bone and lumbar vertebra of the skeleton of a 44 year-old male are shown in Fig. 1. Dose factor quantities for beta emitters calculated from our monoenergetic absorbed fraction data were in excellent agreement with values reported by Whitwell and Spier.[17]

RESULTS AND DISCUSSION

The complete results of our calculations for various bones of the skeleton are given in Table 1. These data can be applied to photon fluence estimates derived from Monte Carlo transport calculations in mathematical analogues of the body to estimate absorbed dose. Variations with incident photon energy in the ratio of absorbed dose in active marrow to the equilibrium dose (kerma) in soft-tissue are indicated in Fig. 2. These ratios are maximal at photon energies in the region of 50 to 60 keV and are higher for the thick trabeculae and small marrow cavities of the parietal bone than for the thinner trabeculae–larger marrow cavities of other bones. The ratios at low energy conform to the general features indicated by Spiers.[5] However the parietal bone exhibits a substantially higher enhancement of the marrow dose than other trabecular bones. This enhancement should be considered in deriving skeletal average values for the diagnostic x-ray region. Enhancement of dose in the high energy (pair production) region is also indicated in our calculations. Enhancement is small, about 5%, for most trabecular sites but approaches 20% for the parietal bone. Considering the highly stylized analogue of the skeleton used in photon transport calculations, we recommend that the skull be treated as a separate bone region and data for the parietal bone in Table 1 be applied to estimate marrow dose. The lumbar vertebra appears to be representative of other trabecular sites.

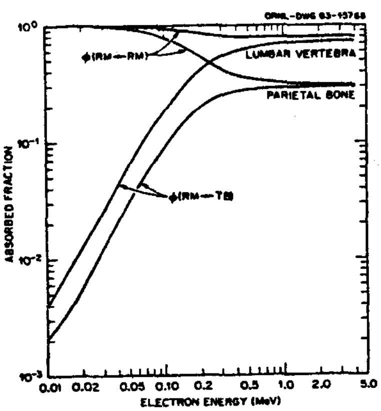

Figure 1.

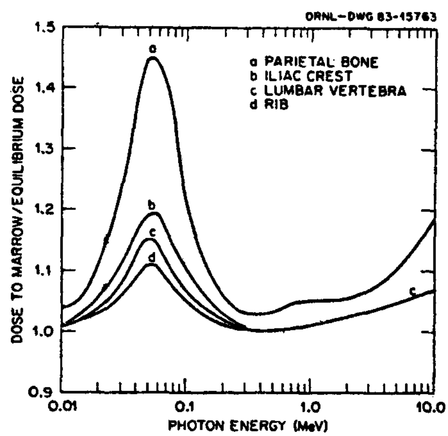

Figure 2.

Table 1. Absorbed dose in active marrow, D(RM), per unit fluence, Ψ(E), of monoenergetic photons in trabecular bones of the skeleton of a 44-year-old male.

Photon energy (MeV)	D(RM)/Ψ(E), Gy per photon/m²						
	Parietal bone	Cervical vertebra	Lumbar vertebra	Rib	Iliac crest	Head of femur	Neck of femur
0.010	6.30e-16	6.15e-16	6.14e-16	6.12e-16	6.16e-16	6.12e-16	6.12e-16
0.015	2.71e-16	2.62e-16	2.61e-16	2.59e-16	2.63e-16	2.60e-16	2.59e-16
0.020	1.53e-16	1.45e-16	1.43e-16	1.41e-16	1.45e-16	1.42e-16	1.41e-16
0.030	7.49e-17	6.60e-17	6.44e-17	6.29e-17	6.61e-17	6.39e-17	6.31e-17
0.040	5.04e-17	4.27e-17	4.11e-17	3.99e-17	4.28e-17	4.08e-17	3.99e-17
0.050	4.18e-17	3.45e-17	3.31e-17	3.20e-17	3.45e-17	3.27e-17	3.21e-17
0.060	3.93e-17	3.26e-17	3.11e-17	3.01e-17	3.24e-17	3.08e-17	3.01e-17
0.080	4.15e-17	3.58e-17	3.45e-17	3.36e-17	3.57e-17	3.44e-17	3.37e-17
0.10	4.79e-17	4.33e-17	4.22e-17	4.14e-17	4.33e-17	4.21e-17	4.15e-17
0.15	7.16e-17	6.83e-17	6.74e-17	6.68e-17	6.83e-17	6.72e-17	6.70e-17
0.20	9.88e-17	9.63e-17	9.57e-17	9.52e-17	9.64e-17	9.53e-17	9.53e-17
0.30	1.57e-16	1.54e-16	1.54e-16	1.53e-16	1.54e-16	1.52e-16	1.53e-16
0.40	2.15e-16	2.12e-16	2.10e-16	2.10e-16	2.12e-16	2.07e-16	2.10e-16
0.50	2.72e-16	2.67e-16	2.66e-16	2.65e-16	2.68e-16	2.60e-16	2.65e-16
0.60	3.28e-16	3.20e-16	3.19e-16	3.17e-16	3.20e-16	3.10e-16	3.18e-16
0.80	4.28e-16	4.17e-16	4.15e-16	4.14e-16	4.17e-16	4.04e-16	4.14e-16
1.0	5.19e-16	5.06e-16	5.03e-16	5.01e-16	5.06e-16	4.88e-16	5.02e-16
1.5	7.12e-16	6.95e-16	6.90e-16	6.88e-16	6.94e-16	6.69e-16	6.90e-16
2.0	8.77e-16	8.52e-16	8.45e-16	8.43e-16	8.50e-16	8.19e-16	8.45e-16
3.0	1.16e-15	1.11e-15	1.10e-15	1.09e-15	1.11e-15	1.06e-15	1.10e-15
4.0	1.41e-15	1.33e-15	1.31e-15	1.29e-15	1.32e-15	1.26e-15	1.30e-15
5.0	1.64e-15	1.52e-15	1.49e-15	1.46e-15	1.51e-15	1.43e-15	1.48e-15
6.0	1.87e-15	1.69e-15	1.65e-15	1.62e-15	1.68e-15	1.58e-15	1.64e-15
8.0	2.33e-15	2.02e-15	1.94e-15	1.89e-15	1.99e-15	1.86e-15	1.93e-15
10.0	2.79e-15	2.32e-15	2.21e-15	2.14e-15	2.29e-15	2.10e-15	2.19e-15

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