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Mass Energy Transfer Coefficients for the Calculation of Air Kerma in Tissues

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ABSTRACT: The Adult Male® phantom of ORNL was modified and subjected to photon exposure from Ir-192 source. A general-purpose Monte Carlo Transport Code, MCNPX2.7E (Monte Carlo N-Particle Transport Extended Version 2.7) was employed to estimate the energy loss due to escape radiation-bremsstrahlung for twelve radiosensitive tissues in anteroposterior geometry for thirteen photon energy bins (0.1-10.0MeV). The tissues include the lung, testes, ovaries, brain, and the soft tissues. The soft tissues are the liver, stomach wall, thyroid, kidney, pancreas, spleen, gall bladder, heart, and small intestine. Photon histories (nps) of one hundred million (10^8) was used to achieve a relative error in the simulation of less than 5% (<0.05). High error rate was initially observed for low energies(<0.1MeV), this inhibit the simulation of energy bins below 0.1MeV. Hence, certain energies within the diagnostic range were omitted to ensure reliability of the result. The g-factor was estimated from the bremsstrahlung data as a fraction of the photon energy. The mass-energy absorption coefficient values of National Institute of Standard, NIST/ICRU 44 and the estimated g-fraction values were used to calculate the mass-energy transfer coefficient for the tissues. The result obtained compare favorably among the tissues.

Keywords: Absorb Dose; Kerma; Mass Energy Absorption Coefficient; Mass Energy Transfer Coefficient; MCNPX; Phantom

Abbreviations: MCNPX, Monte Carlo N-Particle Extended.

I. INTRODUCTION

When ionizing radiation pass through a medium, it carries along with-it photons of energy. A fraction of the radiation is transmitted, passing through the medium unattenuated. Another part of the radiation is absorbed within the medium, contributing to absorb dose within the medium while the remaining radiation is scattered in diverse angles within and outside the medium. These scattered photons have the tendency to cause more ionization and also generate more energies due to further collisions, thereby increasing the radiation absorb dose within the medium. Hence, it is a fact that energy is transferred from the photons to the absorbing medium when photon travels within the medium. The energy absorption coefficient, μ_{en}[1] is a measure of the energy absorbed within the medium and $\frac{\mu_{en}}{\rho}$ is the massabsorption coefficient. These coefficients have tissue identification properties [2, 3] and they are useful in the estimation of the absorbed dose, a measure of the energy absorbed per unit mass of the medium. The energy transfer coefficient, μ_{tr} [1] is the photon energy transferred into charged particles kinetic energy per thickness of the absorbing medium, this is the coefficient used for the estimation of the kinetic energy received per unit mass, Kerma. The mass energy transfer coefficient, $\frac{\mu_{tr}}{\rho}$ is an intermediate quantity in estimating mass energy absorption coefficient, $\frac{\mu_{en}}{\rho}$[1]-[4]. When $\frac{\mu_{tr}}{\rho}$ multiply the photon energy fluence, it yields Kerma (K) the sum of the kinetic energies of charged primary particles released by uncharged particles per unit mass[1]. Also, multiplying $\frac{\mu_{en}}{\rho}$ with the photon fluence energy yields the absorb dose (D), the energy impacted on a medium per unit mass[5]. The photon energy fluence is the product of the photon energy and the photon fluence.

II. MATERIALS AND METHODS

In this study, the input file of the Adult Male® phantom of ORNL was modified, tally cards were provided for the estimation of the fluence and the energy deposition in the tissues to estimate Kerma approximates [6] using F4:P and F6:P respectively. The simulation was achieved using the MCNPX Visual Plotter version 2.7E installed on a PC with Intel(R) Core (TM) i3-6100U, 2.3GHz processor, 64-bit OS and 4.00 GB RAM. The radiation source specification is Ir-192, ρ=22.56g/cm^3, ZAID: 77193.30y, AWR: 192.96300, MCNP Library: LLLDOS, LLNL/ACTL Date: <1983 Length: 243

A. Monte Carlo Estimation

The Adult Male® phantom input file was given a density of 0.25g/cm^3 for the lung and 1.04 g/cm^3 for the soft tissues and other tissues. The F4:P and F6:P tallies for relevant tissues were included in the input file to provide for the estimates of the fluence and energy deposition respectively. Photon histories (nps) of one hundred million (10^8) was used to lower the relative error in the simulation to less than 5% (<0.05). The modified input file was then imported into MCNPX2.7E visual editor graphic interface.

The energy loss due to bremsstrahlung was obtained from the tally fluctuation chart, tfc for each simulation and photon energy bin. That is, the energy loss due to bremsstrahlung is a measure of the photon energy. The bremsstrahlung obtained from the MCNPX simulation of the modified phantom was used to estimate the g-fraction [1, 4, 7]. g is bremsstrahlung energy fraction [8] or radiative fraction [7], the average fraction of the transferred energy that is lost through radiative processes to the primary charges in the medium.

In this study, the estimated g-fraction obtained from the bremsstrahlung data was used to estimate the mass energy transfer coefficient. The bremsstrahlung is a relevant property of the material and a useful tool in other applications [9-13].

B. Relevant Kerma Equations

From [1, 7, 8, 14]

$$Absorb\ Dose, D = \varphi E\left(\frac{\mu_{en}}{\rho}\right) \text{ (MeVg}^{-1}\text{)} \quad (1)$$

$$Kerma, K = \varphi E\left(\frac{\mu_{tr}}{\rho}\right) \text{ (MeVg}^{-1}\text{)} \quad (2)$$

$\varphi = Photon\ Fluence, m^{-2}$ or cm^{-2}

$E = Photon\ Energy,$ J or MeV

$\frac{\mu_{tr}}{\rho} = Mass\ Energy\ Transfer\ Coef.,$ m^2Kg^{-1} or cm^2g^{-1}

$\frac{\mu_{en}}{\rho} = Mass\ Energy\ Absorption\ Coef.,$ m^2Kg^{-1} or cm^2g^{-1}

$$\therefore \varphi E = \Psi[1] \quad (3)$$

Ψ = Photon Fluence Energy, MeV cm^{-2}

For photon energy spectrum [7, 15]

$$\Psi_E = \int E\varphi_E \quad (4)$$

$$\text{Dose, D} = \int_{E=0}^{E_{max}} \varphi E\left(\frac{\mu_{en}}{\rho}\right) dE \quad (5)$$

$$\text{Kerma, K} = \int_{E=0}^{E_{max}} \varphi E\left(\frac{\mu_{tr}}{\rho}\right) dE \quad (6)$$

From [1, 4, 7] $\quad \mu_{en} = \mu_{tr}(1-g) \quad (7)$

For emphasis [7] $\quad K = K_c + K_r \quad (8)$

$\mathrm{K_c}$ and $\mathrm{K_r}$ = Collisional and radiative Kerma

where $\quad K_c = K(1-g) \quad (9)$

$\quad K_r = Kg \quad (10)$

According to [1], g includes bremsstrahlung, positron annihilation, fluorescence emission, energy-loss straggling and knock-on electron production as the secondary particles slow down. In actual MCNP result, bremsstrahlung and fluorescence account for energy loss at energies ≤ 1.0MeV, positron-annihilation however contributes at higher energies. Investigating mass energy transfer coefficient with molecular procedure was reported by [16] but [17] assert that simulation provide reliable estimate of g and subsequently accurate mass energy transfer coefficient.

C. Calculation Method

The calculation of the energy transfer coefficient, $\frac{\mu_{tr}}{\rho}$ was achieved by substituting the estimated g-fraction and the mass absorption coefficient, $\frac{\mu_{en}}{\rho}$ data from [1] in equation 12. New values of $\frac{\mu_{en}}{\rho}$ were reported in ICRU 90 but reference[18] confirmed that it has negligible deviations from the values of mass absorption coefficient in [1]. From equation 7, mass energy absorption coefficient:

$$\frac{\mu_{en}}{\rho} = \frac{\mu_{tr}}{\rho}(1-g) \quad (11)$$

$$\text{Then: } \frac{\mu_{tr}}{\rho} = \frac{\left(\frac{\mu_{en}}{\rho}\right)}{1-g} \quad (12)$$

Comparing equation 9, 10 and 11, it is obvious that

$$K_c \equiv \frac{\mu_{en}}{\rho} \quad (13)$$

$$K \equiv \frac{\mu_{tr}}{\rho} \quad (14)$$

and $\quad K_r \equiv \frac{\mu_{tr}}{\rho} \times g \quad (15)$

With known photon energy fluence, estimates for absorb dose, D and Kerma, K are achievable using the appropriate equations.

III. RESULTS AND DISCUSSION

A. The Mass Energy Transfer Coefficient

The energy bins considered in this study range from 0.1MeV to 10.0MeV. The relative error observed for energies below 0.1MeV was very high, making the simulation results unreliable. Most of the organs recorded zero flux despite increased in nps and/or the computer run time.

The mass energy transfer coefficients, $\frac{\mu_{tr}}{\rho}$ of the tissues are presented in Table 1 and Fig. 1 is a combined representation of the behavior of the mass energy transfer coefficient for all the tissues.The corresponding mass energy transfer coefficient increases from 0.1MeV photon energy for all the tissues. It attain highest point between photon energy 0.5-0.6MeV for the tissues and the coefficient decreases afterwards until it flattens. However, the actual behavior after 10.0MeV is not investigated in this study.

B. The Radiative and Collisional Kerma

There are different approaches to estimating the radiative and collisional Kerma [19, 20] but the sum of the radiative and the collisional Kerma yield the total Kerma. Hence, the g-fraction is an important component andneccesary multiplier to ascertain the estimates of the two variables [17]. The dose to kerma ratio has also proven to be a very reliable property in radiation studies [21].

From Table 1 and by way of percentage, for 0.1MeVphoton energy; 0.67% of K is accounted for by the radiative Kerma, K_r and the collisional Kerma, K_c account for 99.33% of K. For photon energy 0.2MeV, 1.22% of K is accounted for by the radiative Kerma, K_r and 98.78% of K is accounted for by the collissional Kerma, K_c. For photon energy 0.3MeV, 1.78% of K is accounted for by the radiative Kerma, K_r and 98.22% of K is accounted for by the collissional Kerma, K_c. At 0.4MeV, K_r is 2.13% of K and K_c is 97.87% of K. For 0.5MeV, K_r is 2.30% of K while K_c is 97.70% of K. At energy point 0.6MeV, K_r is 2.38% of K and K_c is 97.62% of K. For 0.8MeV, K_r is 2.44% of K and K_c is 97.56% of K. At 1.0MeV, K_r is 2.50% of K; K_c is 97.50% of K. At 2.0MeV, K_r is 3.02% of K; K_c is 96.98%. At 4.0MeV, K_r is 4.88% of K and K_c is 95.12%. At 6.0MeV, K_r is 7.16% of K; K_c is 92.84%. For 8.0MeV, K_r is 9.55% of K and K_c is 90.45% of K. And for 10.0MeV, K_r is 11.92% of K and K_c is 88.08%.

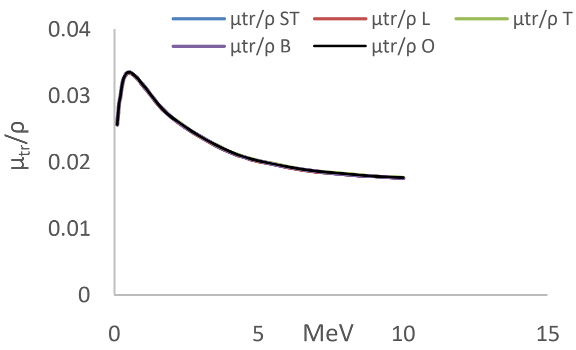

Fig. 1. μ_{tr}/ρ vs Energy for all the Tissues.

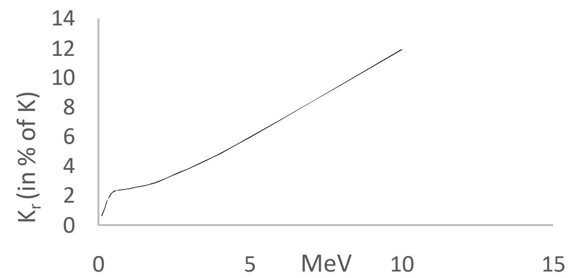

Fig. 2. Radiative Kerma, K_r against Energy**.**

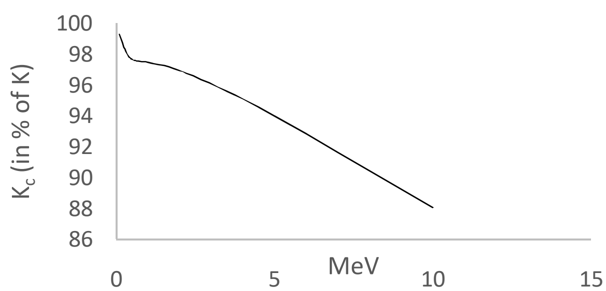

Fig. 3. Collisional Kerma, K_c against Energy.

Table 1: Mass Energy Transfer Coefficient, μ_{tr}/ρ for Soft Tissue, ST; Lung, L; Testes, T; Brain, B and the Ovaries, O.

MeV	g-fraction	μ_{tr}/ρ ST	μ_{tr}/ρ L	μ_{tr}/ρ T	μ_{tr}/ρ B	μ_{tr}/ρ O
0.1	0.006694	0.025622	0.025672	0.025642	0.025752	0.025652
0.2	0.012173	0.029783	0.029813	0.029884	0.029914	0.029864
0.3	0.017756	0.032212	0.032242	0.032324	0.032354	0.032293
0.4	0.021251	0.033195	0.033226	0.033318	0.033338	0.033287
0.5	0.022994	0.033459	0.03349	0.033582	0.033603	0.033551
0.6	0.023772	0.033332	0.033363	0.033455	0.033476	0.033425
0.8	0.02444	0.032556	0.032586	0.032679	0.032709	0.032648
1.0	0.025021	0.031529	0.03156	0.031652	0.031672	0.031621
2.0	0.030214	0.026635	0.026666	0.026738	0.026758	0.026717
4.0	0.048788	0.021499	0.02153	0.021583	0.021583	0.021572
6.0	0.071578	0.019237	0.019269	0.019312	0.019312	0.019302
8.0	0.095479	0.01812	0.018164	0.018197	0.018186	0.018197
10.0	0.11923	0.017564	0.01761	0.017644	0.017621	0.017644

IV. CONCLUSION

The mass energy transfer coefficient obtained in this study is specific to the tissue and the photon energy. The values are useful in estimating Kerma, K when the photon energy fluence is known. It is also relevant in estimating the radiative and the collisional Kerma.

V. FUTURE SCOPE

The result from this study is useful for the estimation of the Kerma for tissues at the specified photon energies.

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