Indian Journal of Pure & Applied Physics
Vol. 57, June 2019, pp. 433-437

Mass attenuation coefficients, water and tissue equivalence properties of some tissues by Geant4, XCOM and experimental data

Mohammed Sultan Al-Buriahi[a]*, Halil Arslan[b] & Barıs T Tonguç[a]

[a]Department of Physics, Sakarya University, Sakarya, 54187, Turkey

[b]Electrical and Electronics Engineering, Sakarya University of Applied Sciences, Sakarya, 54187, Turkey

Received 28 August 2018; accepted 01 March 2019

The mass attenuation coefficients (μ/ρ) of some tissues such as muscle (ICRU-44), adipose (ICRP) and blood (Whole) and tissue equivalents such as soft tissue model ($H_{63}C_6O_{28}N$) and water have been investigated using Geant4 simulation tool kit. Appreciable variations have been noted for μ/ρ values by changing the photon energy for the studied tissues. The simulated μ/ρ have been compared with experimental data available in the literature and theoretical XCOM results in the energy region 1 keV–100 GeV, and good agreement has been observed. Also, mass attenuation coefficients relative to water have been calculated in the entire energy region to evaluate the water equivalence of the studied tissues. It is shown that a maximum difference of 8.8 % between water and mentioned soft tissue is observed at 8 keV and soft tissue is found to be a good tissue equivalent for blood and muscle tissue.

Keywords: Mass attenuation coefficient, Tissue equivalence, Geant4 simulations, XCOM

1 Introduction

In the biological and medical context, mass attenuation coefficient is a key parameter used to characterize the radiological properties of various dosimetric materials[1–4]. Since it is defined by taking into account the weight of different partial radiation mechanisms in different energy regions, it is considered as an energy dependent parameter and it also varies with respect to the chemical composition of a given material. Knowledge on the μ/ρ in complex medium, especially in human body, is of importance because, for example, when photons degrade their energy in tissues, the radiation dose can be estimated based on mass attenuation coefficients. The term of soft tissue refers to tissues that connect, support, or surround other structures and organs of human or animal body. Thus, the soft tissue includes muscles, tendons, ligaments, fascia, nerves, fibrous tissues, adipose, blood, and synovial membranes. The Geant4 simulation can be carried out to estimate the mass attenuation coefficients for various tissues and energies in computer environment that gives flexibility and ease of use, instead of performing experiments[5]. For this reason, Monte Carlo models would be useful for further experiments which sometimes cannot be implemented; the model can be used through macro file to determine μ/ρ of different materials and mixtures over a wide range of energies. Recently, several authors have made extensive successful contributions that were based on Geant4 simulations for determination the mass attenuation coefficients in different materials[6–8].

In literature, several publications have been considered the study of soft tissue and compared with water by using various methods and different models for the soft tissue. Salehi *et al.* calculated the energy absorption coefficient, kerma relative to air for the soft tissue[2]. This theoretical study was carried out by NIST-XCOM database. Sardari *et al.* estimated the photons buildup factor in soft tissue with Monte Carlo method[3] using MCNP4C code. Aslam *et al.* assessed the soft tissue and water substitutes for multiple mega-voltage photon beams by using the simulation of the Linac's head using BEAMnrc[4]. In the present work, an investigation regarding different type of soft tissue such as muscle, adipose and blood to show the better tissue equivalents for these tissues has been achieved. For this purpose, the Geant4 simulations have been carried out to determine the mass attenuation coefficient for the samples involved. These parameters were also calculated relative to water. The results of this study have been compared with the standard XCOM database. Also, the tissue equivalence properties of the studied tissues are

*Corresponding author (E-mail: mburiahi@gstd.sci.cu.edu.eg)

discussed. The importance of such work arises from the fact that in the medical applications of radiation, the studied tissues are usually approximated by soft tissue models and/or water.

2 Materials and Methods

Chemical composition, weight fractions of the constituent elements and densities for tissue and tissue equivalents studied in the present work are given in Table 1. These values are taken from the ICRP Publication[9] 89 and ICRU Report[10] 44 which are reference data that provide needed input to prospective dosimetry calculations for radiation protection purposes.

2.1 Geant4 simulation

Determination of the mass attenuation coefficient for soft tissues and tissue substitute materials given in Table 1 by Geant4 simulation code, was done by writing C++ classes depending on object oriented programming concept. The model was written using three mandatory classes; the geometry of the model that was defined in detector construction and the physics process which were coded in physics list. Finally, the class of primary generator action which used to control the generation of primaries photons and describe the initial state of the primary event. The physics of the simulation based on narrow beam geometry with the various photon energies according to Lambert–Beer's law ($I/ I_0 = exp\ [- \mu_m x]$) where I_0 and I are the incident and attenuated photon intensity, respectively. μ_m (cm2 g−1) is the mass attenuation coefficient and x is the thickness of the phantom in g/cm^2 as mentioned elsewhere[11,12]. The thickness of the phantom is optimized according to the energy of the incident beam, to avoid that all the photons are absorbed or traverse without interacting (for example, the thicknesses of the phantom were increased as photon energy increases). The energy of incident photons varied between 1 keV and 100 GeV. The mass attenuation coefficients are determined by simulating all relevant physical processes (photoelectric effect, Compton scattering, pair production, Rayleigh scattering, and electrons interactions). Geant4 electromagnetic physics processes have been compared with National Institute of Standards and Technologies (NIST) reference data successfully[13]. This statistical analysis estimated quantitatively the compatibility of Geant4 electromagnetic models with NIST-XCOM results and highlighted the respective strengths of the Geant4 simulation with uncertainties about 3%.

Table 1 – Chemical compositions of the tissues and tissue equivalent

Tissue/ Tissue equivalents	Chemical formula or weight fraction (%)	Density (g/cm3)
Muscle	H(0.102), C(0.123), N(0.035), O(0.729), Na(0.0008), Mg(0.0002), P(0.002), S(0.005), K(0.003).	1.04
Adipose	H(0.114), C(0.598), N(0.007), O(0.278), Na(0.001), S(0.001), Cl(0.001).	0.95
Blood	H(0.102), C(0.110), N(0.033), O(0.745), Na(0.001), S(0.002), Cl(0.003), K(0.002), Fe(0.001).	1.06
Soft tissue	$H_{63}C_6O_{28}N$	1.02
Water	H_2O	1

2.2 XCOM program

The mass attenuation coefficient values of tissues and tissue equivalent materials have been calculated by using XCOM program. The atomic number and atomic mass of the tissue constituent elements were taken from recent IUPAC report[14]. The database of XCOM program is for incoherent and coherent scattering[15-16], on for photoelectric absorption[17] and for pair production process[18]. The authors state that the uncertainties in the values of mass attenuation coefficient provided are rather difficult to estimate, depending on the energy range of the photons; they range from 1% to 5%, with the lowest and highest energy regions associated with larger uncertainties[19]. The difficulties for measuring these uncertainties come from that since photoelectric effect is the dominant interaction at low photon energies, where the uncertainties are the largest, these very approximate percent uncertainties can be taken as a rough guide to the uncertainties of the mass attenuation coefficient. In the region 5 MeV to 30 MeV where the photonuclear giant dipole resonance occurs in the photonuclear cross section σ_n, neglect of this cross section can make errors in μ_m in excess of 5%, at the peak of this resonance. This σ_n peak energy varies with both Z and the particular isotope of that element[20,21].

2.3 Experimental data

Experimental data for μ/ρ of the materials are available for limited photon energies of 59.5, 81.0, 356.5, 661.6, 1173.2 and 1332.5 keV that emitted by ^{241}Am (2.78 Gbq), 133Ba (2.92 GBq), 137Cs (3.14 GBq), and 60Co (3.7 Gbq) radioactive point source. The results of present work have been compared with experimental data available in the literatures[22,23]. The first experiment was performed by using gamma ray spectrometry system consisting of HPGe detector (Canberra model) coupled with analog digital converter (ADC), high voltage 5000 V with negative polarity and relative efficiency of 70%. Genie 2000 software (Canberra Industries, Meriden, USA) with analyzer cart was used to record the intensity of the incident and the transmitted gamma rays. Automatic pulse shaping and pole-zero correction settings were used and the energy scale was calibrated using point radioactive sources. Te measuring time is ranged from 5 to 10 min depending upon the photon energy and background noise. Te background was counted in the same manner of measuring intensity of attenuated photons in the samples. The second one was implemented by using energy dispersive X-ray system (EDXS) with two detection systems: a Cadmium telluride (CdTe) detector and a silicon drift detector (SDD). Acquisition times almost 1000 s were utilized to achieve adequate counting statistics, with uncertainties in the photon count smaller than 3% in both transmitted and scattered spectra.

3 Results and Discussion

The mass attenuation coefficient of the selected tissues is shown in Figs 1 – 3. The μ/ρ values using Geant4 toolkit and experimental data at photon energies 59.5, 81.0, 356.5, 661.6, 1173.2 and 1332.5 keV were plotted in the same graphs along with theoretical XCOM results for comparison. It is clear that the Geant4 toolkit simulation results are in very good agreement with the experimental data and theoretical XCOM program. However, the experimental values tend to be lower than both theoretical and simulation values. Discrepancy of these results could be due to deviations from narrow beam geometry in the source-detector arrangements. This may attribute to lower counting rates and the error in designating the scattering and a statistical error because the errors of μ/ρ measurements mainly stem from counting statistics, impurity of the samples, non-uniformity of the absorber and the scattered photons reaching the detector[24]. Furthermore, almost in all energies the Geant4 values are lower than the corresponding values of XCOM of each tissue. The high values of XCOM database return to the effect of

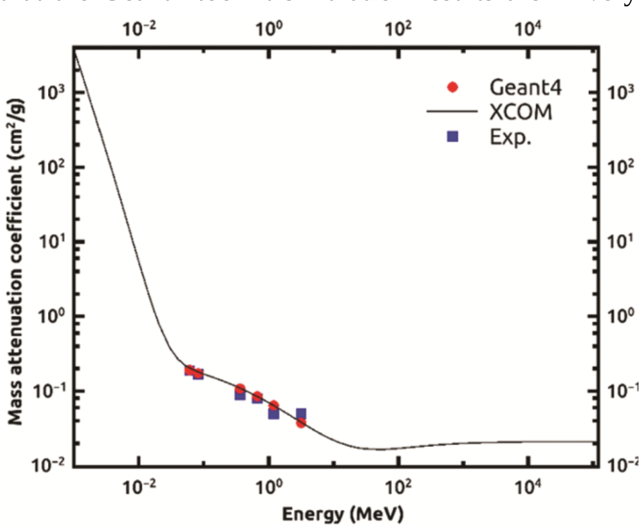

Fig. 1 – The mass attenuation coefficients (μ/ρ) as a function of photon energy for muscle tissue by using Geant4 simulations, XCOM database and experimental data.

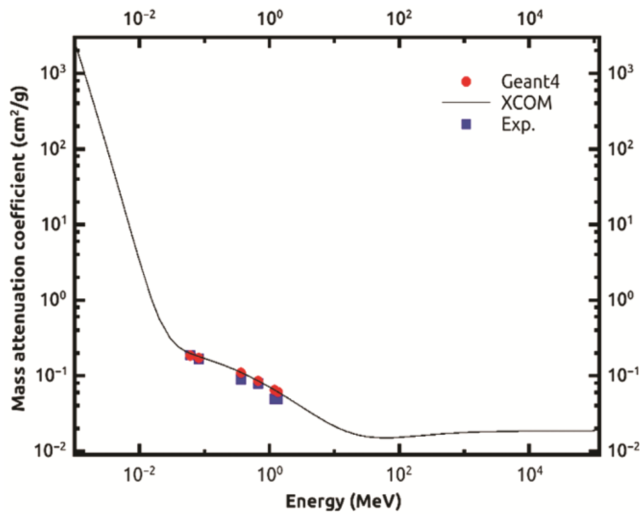

Fig. 2 – The mass attenuation coefficients (μ/ρ) as a function of photon energy for adipose tissue by using Geant4 simulations, XCOM database and experimental data.

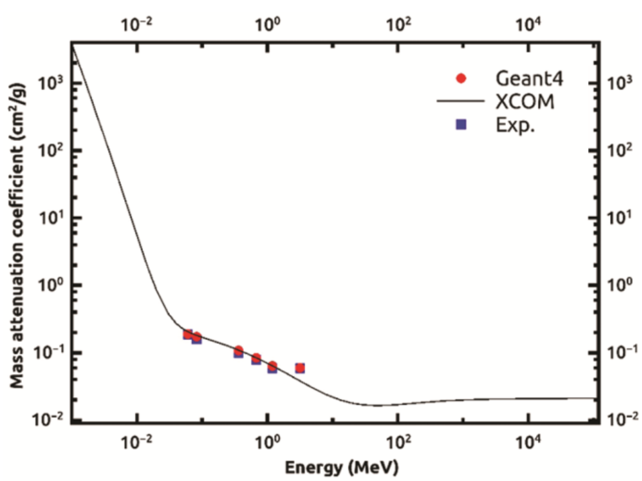

Fig. 3 – The mass attenuation coefficients (μ/ρ) as a function of photon energy for blood tissue by using Geant4 simulations, XCOM database and experimental data.

chemical composition of tissues and mixture rule without neglecting the effects of the atomic wave function of molecular bonding which can reduce the mass attenuation coefficients[11,14]. The Geant4 simula- tions findings according to XCOM results and experi- mental data are similar to the results of [7, 8, 25] which have reported the same study of μ/ρ for steel alloys, scintillation detectors and biomolecules respectively.

From Figs 1– 3, it can be easily seen that three energy ranges related to dominant photon interactions (photoelectric absorption, Compton scattering and pair production) are the dominating attenuation processes. The energy dependence of μ/ρ values is strong below 50 keV, weak between 0.05-200 MeV and almost constant above 200 MeV. These variations are interpreted as being due to photoelectric absorption is the dominating at low energies and it is directly proportional to Z^n, where n is approximately 4 for high Z materials and closer to 4.8 for low Z materials [26,27], and inversely to E^3. At medium photon energies, Compton scattering becomes the dominating process and it varies with Z and E^{-1}. Upon increasing the photon energy, the attenuation is mainly due to pair production which varies with Z^2 and log E.

The μ/ρ relative to water has been also calculated for the tissues and soft tissue model (STM) under consideration and the tissues that show better water equivalence in the entire energy region have been determined (Fig. 4). A maximum difference of 8 % is observed at 2 keV for muscle tissue, 39.5 % at 6 keV for adipose tissue and 7 % at 2 keV for blood. These differences are found to decrease when the energy increases up to approximately 100 keV. Above 100 keV, the tissues show quite good water equivalence properties except for adipose tissue that experiences drastic change above 10 MeV.

Figure 5 shows the difference (%) in μ/ρ between tissues (including water) and STM. It should be noted that the differences (%) in μ/ρ of tissues relative to STM are close to those of relative to water. Consequently, it is worth mentioning that the values of μ/ρ related to water are greater than the values of μ/ρ related to STM, by more than 9 % in low energy regions (< 100 keV). Due to (i) photoelectric absorption is the dominating process at low energies and (ii) the constituent elements of STM which play a role in increasing the possibility of interaction and reduce μ/ρ values. Finally, the STM shows the better tissue equivalent properties for the blood (dif. up to 12 %) and muscle tissue (dif. up to 10 %). On the other hand, STM cannot be considered as tissue equivalent for adipose tissue except in very limited energy region between 100 keV and 10 MeV.

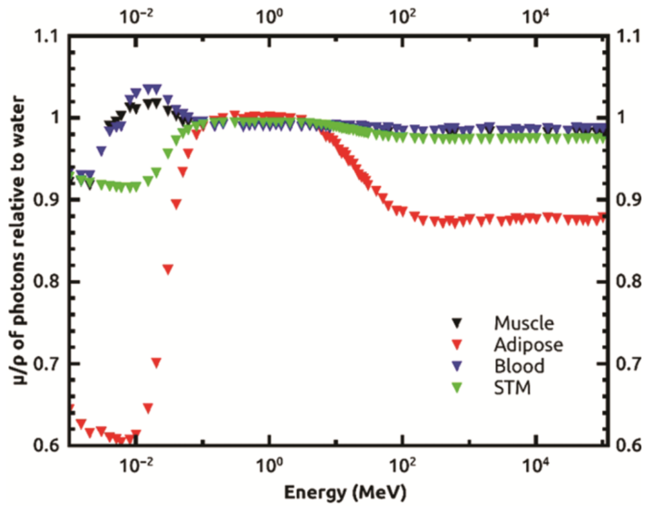

Fig. 4 – Variation of mass attenuation coefficients (μ/ρ) relative to water as a function of energy.

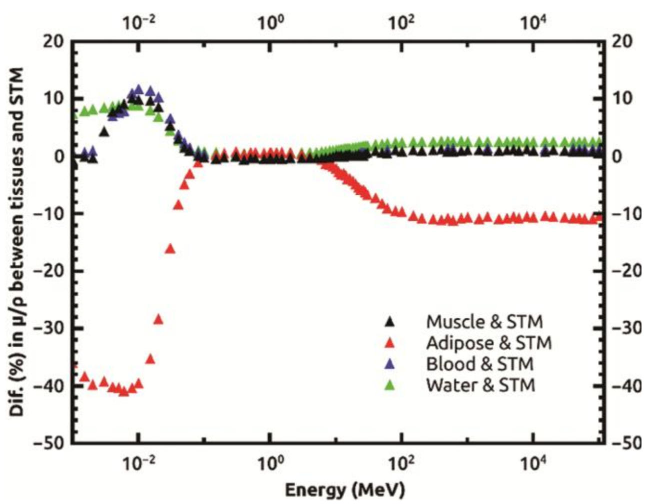

Fig. 5 – Differences (%) in mass attenuation coefficients (μ/ρ) between tissues and STM.

4 Conclusions

In the present work, water and tissue equivalence properties of some tissues such as muscle (ICRU-44), adipose (ICRP) and blood (Whole) have been investigated over wide ranges of photon energies from 1 keV to 1 GeV. The Geant4 simulations have been carried out to determine the mass attenuation coefficient for the samples involved. The applicability of this method is mainly dependent on the accuracy of geometry model, composition and density distribution of the sample. The simulated values of the mass attenuation coefficients are close to experimental values better than obtained by XCOM database. The obtained results indicate that Geant4 Monte Carlo simulation is suitable to compare experiment for this kind of studies and it can be applied to estimate mass attenuation coefficients for various attenuators and energies. Also, μ/ρ relative to water has been calculated in the entire energy region for the tissues. STM, blood and muscle show quite very good water equivalent properties. The difference between STM and water mass attenuation coefficient is usually more than 8.8 %. Furthermore, muscle tissue and blood can be substituted by STM in radiological laboratories and clinical applications when measurements are made under radiation conditions where the photon attenuation is difficult to assess.

References

1 Medhat M E & Singh V P, *Indian J Pure Appl Phys*, 54 (2016) 137.
2 Salehi D, Sardari D & Jozani M S, *J Radiat Res Appl Sci*, 8 (2015) 439.
3 Sardari D, Abbaspour A, Baradaran S & Babapour F, *Appl Radiat Isot*, 67 (2009) 1438.
4 Aslam A, Kakakhel M B, Shahid S A, Younas L & Zareen S, *J Appl Clin Med Phys*, 17 (2016) 408.
5 Agostinelli S, Allison J, Amako K A, Apostolakis J, Araujo H, Arce P & Behner F, *Nucl Instrum Methods Phys Res A*, 506 (2003) 250.
6 Ermis E, Pilicer F B, Pilicer E & Celiktas C, *Nucl Sci Technol*, 27 (2016) 54.
7 Singh V P, Medhat M E & Shirmardi S P, *Radiat Phys Chem*, *106 (2015)* 255.
8 Medhat M E & Wang Y, *Ann Nucl Energy*, 62 (2013) 316.
9 Valentin J, *Ann ICRP*, 32 (2002) 1-277.
10 White D R, Booz J, Griffith R V, Spokas J J & Wilson I J, *ICRU*, 23 (1989).
11 Podgoršak E B, *Radiation physics for medical physicists,* Berlin: Springer, (2006) 285.
12 Arslan H, *Nucl Sci Tech,* in press.
13 Amako K, Guatelli S, Ivanchenko V N, Maire M, Mascialino B, Murakami K & Piergentili M, *IEEE Trans Nucl Sci*, 52 (2005) 910.
14 Wieser M E, *Pure Appl Chem*, *85* (2013) 1047.
15 Hubbell J H, *Int J Appl Radiat Isot*, 33 (1982) 1269.
16 Hubbell J H, Veigele W J, Briggs E A, Brown R T, Cromer D T & Howerton D R, *J Phys Chem Ref Data*, 4 (1975) 471.
17 Hubbell J H & Overbo I, *J Phys Chem Ref Data*, 8 (1979) 69.
18 Leroux J & Thinh T P, *Corporation Scientifique Classique Quebec*, (1977).
19 Cullen D E, Chen M H, Hubbell J H, Perkins S T, Plechaty E F, Rathkopf J A & Scofield J H, *Lawrence Livermore National Lab*, CA (USA), (1989).
20 Hubbell J H, *Phys Med Biol*, 44 (1999).
21 Andreo P, Burns D T & Salvat F, *Phys Med Biol*, 57 (2012).
22 Medhat M E, Shirmardi S P & Singh V P, *J Appl Comput Math*, 3 (2014).
23 Geraldelli W, Tomal A & Poletti M E, *IEEE Trans Nucl Sci*, 60 (2013) 566.
24 Medhat M E, *J Radioanal Nucl Chem*, 293 (2012) 555.
25 Baris T, Arslan H & Al-Buriahi M S, *Radiat Phys Chem*, (2018).
26 Kurudirek M, *Radiat Phys Chem*, 102 (2014) 139.
27 Singh V P & Badiger N M, *Radioprotection*, 48 (2013) 63.