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Calculations of the transmitted gamma photons through infinite slabs

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Abstract The intensity and number of transmitted multiple scattered photons are calculated for 0.123, 0.320, 0.511, 0.662, and 1.115 MeV gamma photons normally incident on slabs of carbon, aluminum, iron, copper, water, muscle, bone, and concrete with thicknesses varying from 1 to 10 mean free paths. The dependence of the transmission probability and energy distribution on the incident energy and material are examined. In general, the obtained results show good agreement with the other values calculated by the Monte Carlo method.

Keywords Monte Carlo simulation · Gamma photons · Energy distribution · Transmission probability

1 Introduction

Moment method, successive scatterings, and Monte Carlo method are widely used in investigating the penetration and diffusion of scattered gamma photons in materials [1–8]. The Monte Carlo method is the most effective one to follow the penetration of gamma photons through material. Understanding the interactions of ionizing radiation with matter is important for several fields, particularly those dealing with detection of gamma photons, radiation protection, and measurement. The main processes of interaction of gamma rays with matter are the photoeffect, both in its photoelectric and photonuclear forms, Compton scattering, and electron positron pair production. To a minor extent, photofission, Rayleigh scattering, and Thomson scattering also occur. Each of these processes emerges in different forms. Different types of scattering can occur depending on the quantum–mechanical properties of the gamma photons. Electron positron pairs can be formed in the field of a nucleus and in that of an electron [9]. The photoelectric can knock out atomic electrons, whereas the photonuclear reaction would knock out elementary particles from the nucleus [10].

In this work, simple algorithms for the simulation of the passage of gamma photons in different mediums and incident energies are proposed. The present calculations are chosen arbitrarily at 0.123 (Eu^{154}), 0.320 (Cr^{51}), 0.511 (Cu^{64}, Ga^{68}, As^{74}), 0.662 (Cs^{137}/Ba^{137m}), and 1.115 (Zn^{65}, Ni^{65}) MeV incident photon energies to achieve a range from low to medium energy range [11]. Since the upper limit of incoming photon energy is 1.115 MeV, the main physical processes associated with the transport of gamma photons through matter are incoherent Compton scattering (or inelastic scattering) and the photoelectric effect. In the energy range of about 1 MeV, incoherent scattering of photons with atom is the most dominant process in which the energy of photons is transferred to the electron. At smaller energies, the photons are also expected to interact with atom through the photoelectric absorption process. In both processes, the energy of photons is transferred to electrons within a very short distance in comparison with the mean free path of the gamma photons [12].

For the basic gamma photon scattering interactions, more detailed and precise experimental information, in particular the energy distribution of transmitted and backscattered photons, is required to establish the validity of existing theories. This work is aimed to obtain the

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energy distribution of transmitted events following the interactions of photons with materials using Monte Carlo simulation. In our previous work, only backscattering probabilities for gamma photons entering normally into materials and their backscattered energy distributions have been considered. An analog Monte Carlo program has been developed to simulate the backscattering of photons for different mediums with infinite slab geometries. The detailed description of the physical ingredients involved in this code has been reported in a previous work [13]. The code can be used in a wide range of energy for many different materials. Now, it has been modified to calculate the transmission probabilities and the energy distributions with the same physical assumptions made in a previous work. Therefore, the details of this calculation can be found in a paper by Aydın [13].

2 Theoretical methods

In this work, the photoelectric absorption and Compton scattering (incoherent) cross sections of gamma photons were taken from XCOM database developed by Berger et al. [14]. An algorithm for the transport of gamma photons in a medium for simple and relatively easy geometries, like a layer with infinite parallel faces, can be developed (i.e., photons are normally incident on a finitely thick slab of infinite extent with plane parallel faces). For simplicity, we assume that the medium consists of a single material. The simulation of the random processes is carried out by a Monte Carlo method. The quantities of q (random number) and the position coordinate (θ, $\varnothing$) are chosen as randomly generated parameters with the selection of the processes (photoelectric or Compton) when an interaction occurs. A gamma photon propagates inside the medium until either it is absorbed by the photoelectric effect or leaves the medium, that is, until the position of the next randomly generated interaction occurs outside the medium. We used the acceptance–rejection method for sampling the angular distribution in Compton scattering from the Klein–Nishina differential scattering cross section [15, 16].

Monte Carlo simulation is used to determine photon transmission probabilities and their energy distributions and examine their dependence on material thickness. In the Monte Carlo simulation, the trajectory of each photon is followed until (1) it comes back and emerges from the surface (counted as backscattered), or (2) it is transmitted and emerges from the other side of the solid target (counted as transmitted). The computer program is written to calculate the intensity and number of multiple scattered photons. The photons in the infinite slab mediums are followed until their transmission or energies are below 10 keV. The photon simulation is continued until a maximum number of one million histories have taken place. The

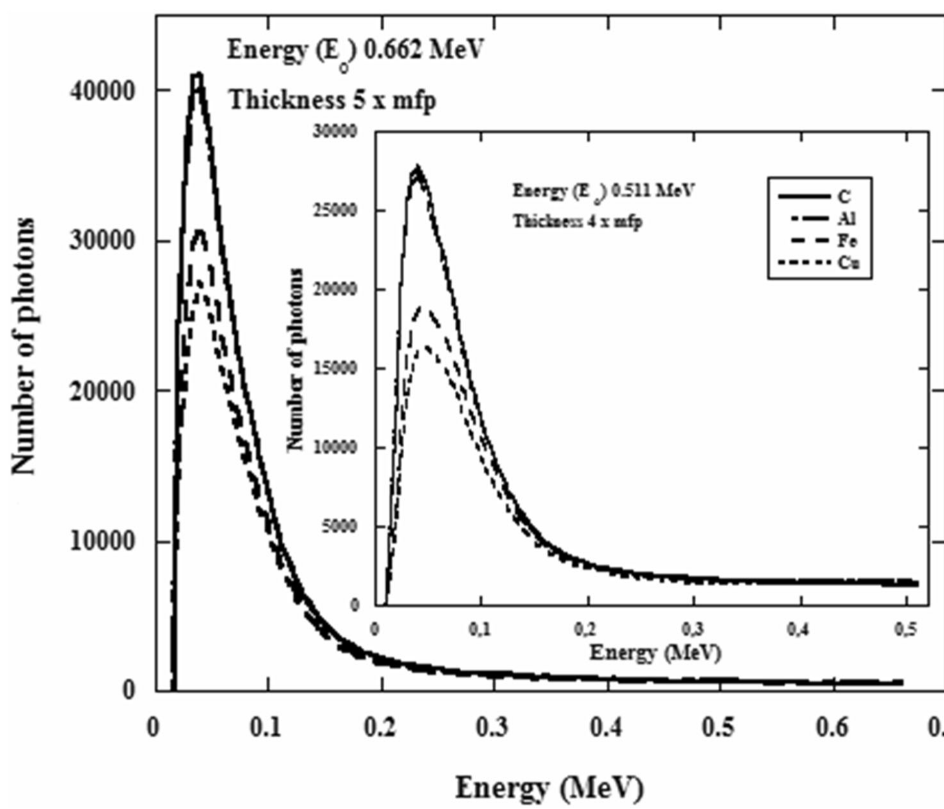

Fig. 1 The energy distributions of transmitted photons in 4 × mfp and 5 × mfp thicknesses C, Al, Fe, and Cu at 0.511 and 0.662 MeV energies, respectively

program can be used for the phenomenology of the interaction of gamma rays in matter. Namely, the dependence on the material properties and energy can be easily tested. All the calculations have been performed by a Turbo Basic compiler. The computing time for a typical run is a few s, or min, to follow one million histories on an Intel Core i5-based (2.4 GHz) PC.

3 Results and discussion

Monte Carlo simulations of energy distribution of photons for elemental solids and biological and shielding materials are reported for the incident mono-energetic photon beams of 0.123, 0.320, 0.511, 0.662, and 1.115 MeV. Thicknesses varying from 1 to 10 mean free paths have been studied to examine the behavior of photons in different thickness materials. The energy distributions of transmitted photons with slab geometry for various thicknesses of carbon, aluminum, iron, copper, gold, water, bone, and concrete materials were calculated. The mechanism of interaction depends on type of particle, energy, density, and especially atomic number of the medium or, in case of compounds like concrete [17], bone [17], and muscle [17], the average atomic number.

The thicknesses of carbon, aluminum, iron, and copper slabs are chosen at about five mean free paths (5 × mfp) for 0.662 MeV energy, and the results are shown in Fig. 1. The inset of Fig. 1 shows the transmission energy distributions for the same materials with different thicknesses and incident energies. As shown in Fig. 1, the energy distributions of photons are similar.

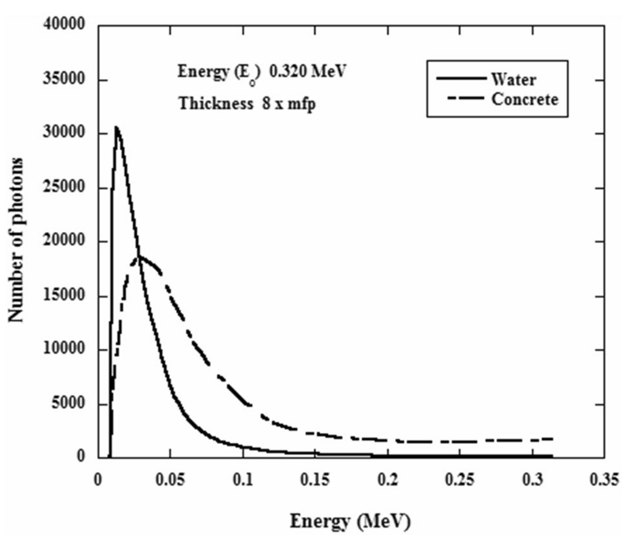

Fig. 2 The energy distributions of transmitted photons in 8 × mfp thickness water and concrete at 0.320 MeV energy

The energy distributions of the transmitted gamma photons for various thicknesses of biological and shielding materials were calculated. The results are shown in Fig. 2 for water and concrete which are selected as biological and shielding materials, respectively. The thicknesses of these materials fixed at eight mean free paths (8 × mfp) are targeted with the incident photon energy of 0.320 MeV. The energy distribution of gamma photons was compared for water and concrete materials at the same thickness and energy value. As shown in Fig. 2, the energy distribution of the transmitted photons in the water material is weaker than that of concrete.

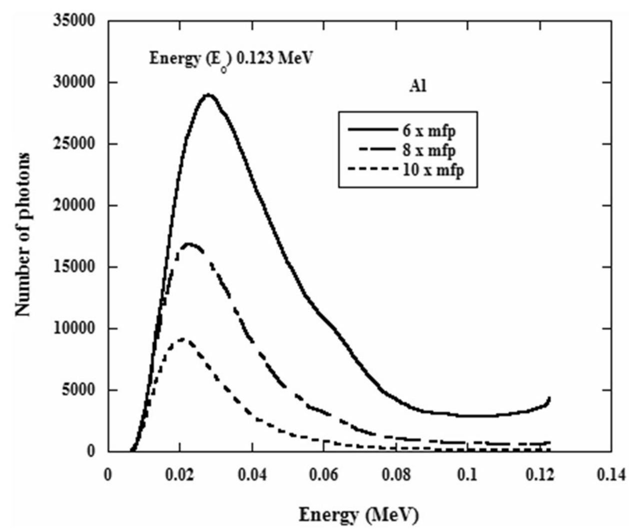

Fig. 3 The energy distributions of transmitted gamma photons for aluminum of various thicknesses at 0.123 MeV energy

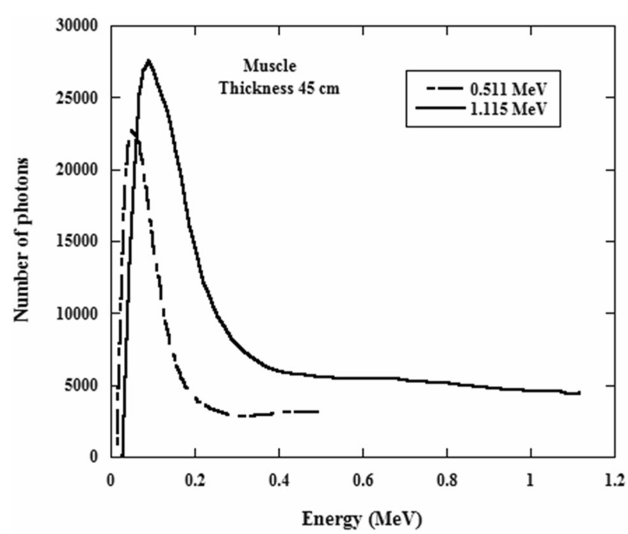

Fig. 4 Comparisons of the energy distribution of transmitted photons in muscle for 0.511 and 1.115 MeV energies at 45 cm thickness

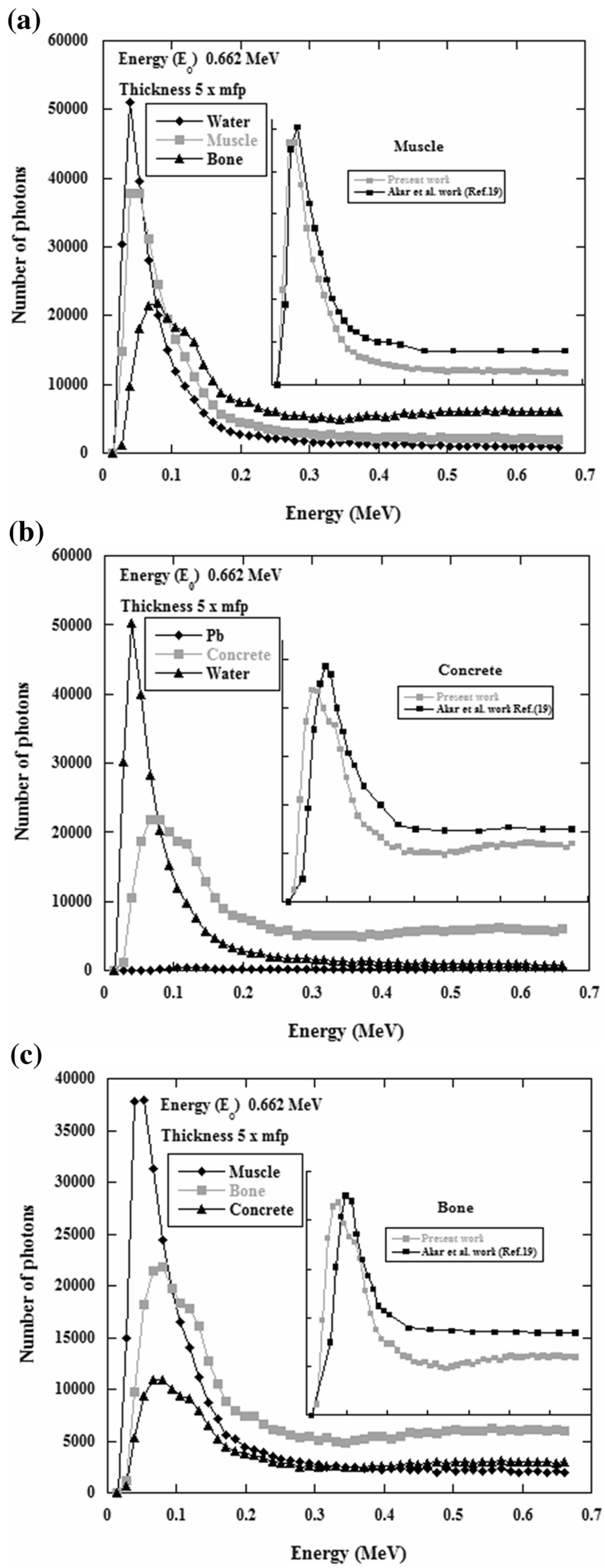

Fig. 5 The distributions of the number of transmitted photons versus energy in **a** water, muscle, and bone (muscle Akar et al.'s work), **b** lead, concrete, and water (concrete Akar et al.'s work), **c** muscle, bone, and concrete (bone Akar et al.'s work [19])

The variation of multiple scattered events under transmitted energy peak as a function of target thickness of the aluminum medium is shown in Fig. 3 for 0.123 MeV energy. The first distribution increases more rapidly compared to the second and third ones. In other words, as the thickness of aluminum increases, the number of transmitted photons decreases and the position of peak is shifting toward the left.

The energy distributions of the transmitted gamma photons in muscle medium at fixed thickness for two different energies are shown in Fig. 4. The peak positions of the transmitted number of photons are slightly shifted to higher energies, and the intensity of the peak increases as the incident photons energy increases.

Although there are many experimental studies on energy and intensity distributions of multiple scattering photons in the literature [18–23], there is only one work [19] reported with the same geometry as investigated in this work. Gamma photons with 0.662 MeV incident energy were followed in shielding materials and biological samples with the thickness of 5 $\times$ mfp by the Monte Carlo method [19]. The energy distributions of the transmitted photons were calculated for the same mediums, thickness, and energy. The obtained results are shown in Fig. 5a–c. The comparison of Akar et al.'s work [19] results was made to avoid confusion for separate muscle, concrete, and bone mediums. As shown in Fig. 5, the obtained energy distributions show small difference with Akar et al.

The transmission probability (transmitted total photon number/total photon number) is calculated for the transmitted gamma photons from different materials with various energies and thicknesses. Figure 6 and the inset of Fig. 6 show the transmission probabilities for the incident photon energy of 0.511 MeV for various mediums as a function of thicknesses.

In addition, the energy transferred to electrons in various mediums with infinite slab geometry is also calculated. The energy is deposited in the medium at a certain distance from the point where the photon interacts. The quantity of absorbed energy is of interest in radiotherapy and radiobiology. Our simulation program, unlike Akar et al.'s work, determines the energy transferred to electrons (deposited energy) at the target thickness. Akar et al.'s simulation work [19] determines the energy that is deposited at any interaction depth of the target media. Figure 7 shows the ratios of the deposited energy to the total incident photon energy (as percentage) as a function of thickness. In our work, the deposited energy of 0.662 MeV impinging on various targets was found to be different from Akar et al.'s work. As shown in Fig. 7, the percentage of deposited energy by the photons decreases with increasing the mediums thickness.

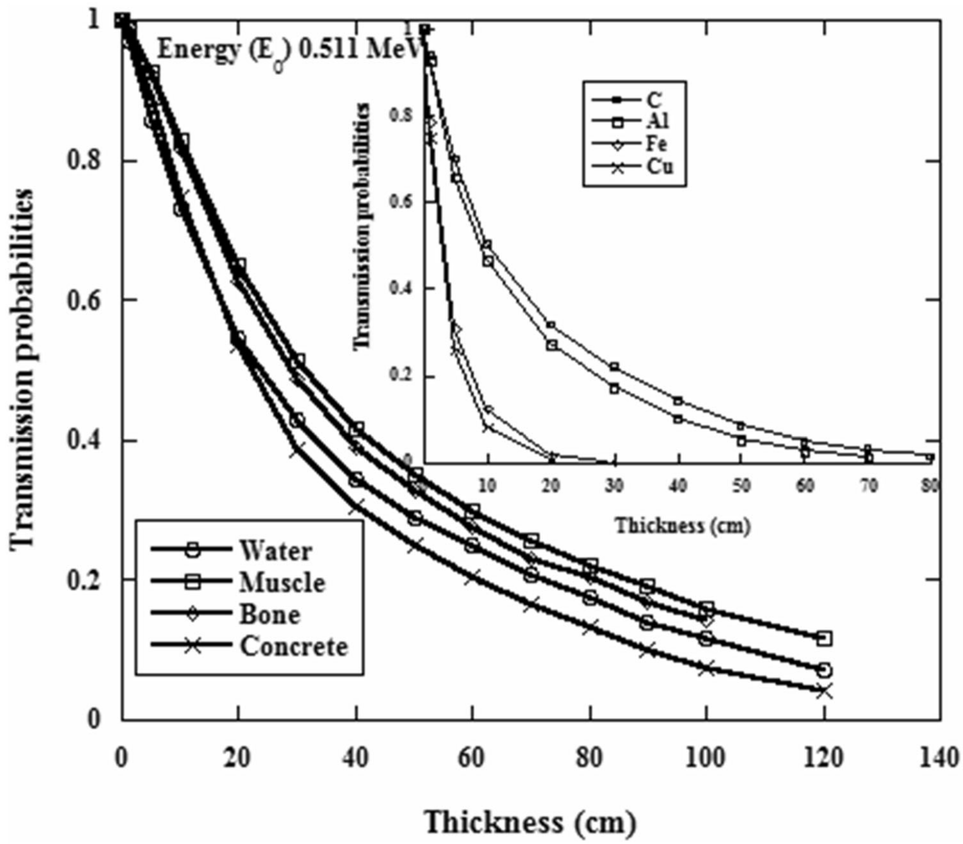

Fig. 6 Transmission probabilities versus the thicknesses for various materials at 0.511 MeV photon energy

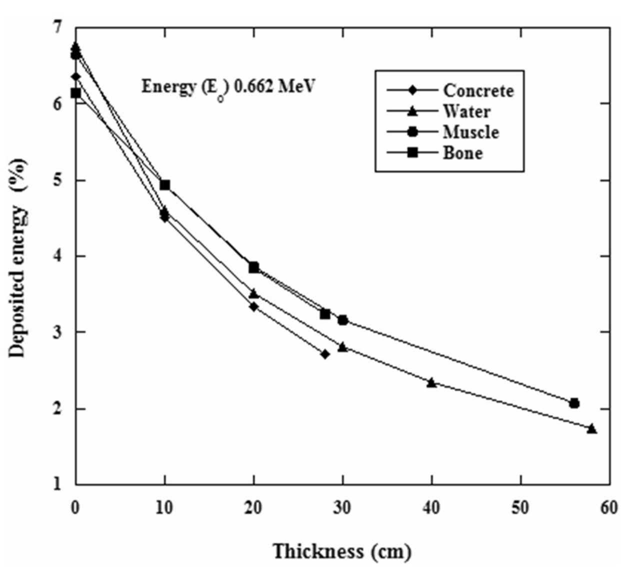

Fig. 7 Distribution of the deposited energy percentage versus the thickness for concrete, water, muscle, and bone

Furthermore, the ratios of the transmitted total energy to the incident photon energy (E/E_o) are calculated for the materials with different thicknesses and shown in Fig. 8a.

Figure 8b shows the dependence of transmitted energy ratios on atomic numbers for 0.320 and 1.115 MeV photon energies. The changes in transmitted energy rates are seen to depend on the incident photon energies and materials. The transmitted energy ratios decrease due to the Compton scattering cross sections decreasing with increasing atom number of the medium.

4 Conclusion

In summary, a Monte Carlo simulation based on Compton scattering is used for gamma photons impinging on elemental, shielding, and biological targets in order to investigate the photon transmission probability and energy distribution. A comparatively simple model for the description of scattering events of gamma photons in various materials for about 1 MeV energy region is presented. The photon trajectories are modeled as random walks keeping the ingredients simple for the calculation of the energy distributions and probabilities in infinite slab materials. The calculation provides the energy distributions of transmitted photons before they hit the detectors. The results are compared with other theoretical data for the

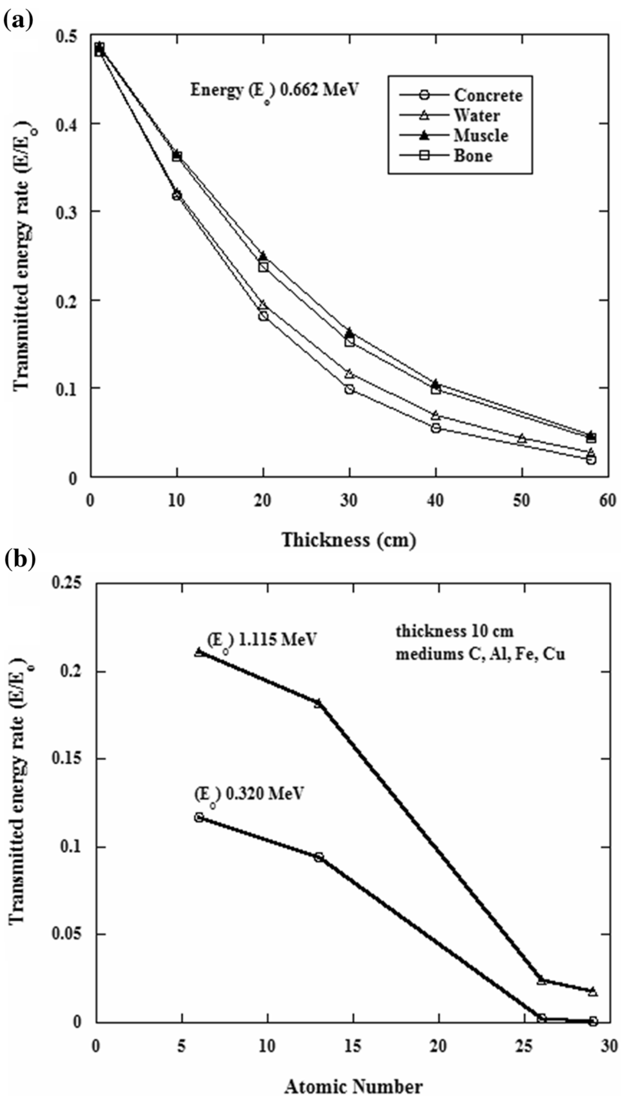

Fig. 8 **a** Transmitted energy rates versus the thicknesses, **b** transmitted energy rates dependence on the incident energy as a function of atomic numbers

different photon energies and demonstrated that this simple Monte Carlo code can easily be applied to the theoretical description of transmitted gamma photons. The energy distributions indicate almost the same behavior for working incident energies and elements. These results concerning the theoretical energy distributions of transmitted gamma photons for materials of various thicknesses are useful for radiation protection and measurement radiation studies. In the future, studies can be performed with different energies, elements, and compounds of some biomedically important elements and geometries.

References

1. I. Umeda, Calculation of the transmission of singly scattered gamma-rays through finite thin slabs. J. Nucl. Sci. Techol. **1**(2), 37–40 (1964). https://doi.org/10.1080/18811248.1964.9732076
2. A. Shimizu, H. Mizuta, Application of invariant imbedding to the reflection and transmission problems of gamma rays (II). J. Nucl. Sci. Technol. **3**(10), 441–447 (1966). https://doi.org/10.1080/18811248.1966.9732359
3. Y. Harima, Y. Nishiwaki, Analysis of transmitted gamma-rays by multiple scattering method, (I) gamma-rays transmitted through slabs of one material. J. Nucl. Sci. Technol. **7**(8), 407–417 (1970). https://doi.org/10.1080/18811248.1970.9734710
4. G. Singh, M. Singh, B.S. Sandhu et al., Experimental investigations of multiple scattering of 662 keV gamma photons in elements and binary alloys. Appl. Radiat. Isot. **66**, 1151–1159 (2008). https://doi.org/10.1016/j.apradiso.2008.01.007
5. U. Akar Tarim, E.N. Ozmutlu, O. Gurler et al., Monte Carlo modeling of single and multiple Compton scattering profiles in a concrete material. Radiat. Phys. Chem. **85**, 12–17 (2013). https://doi.org/10.1016/j.radphyschem.2012.10.018
6. D.S. Vlachos, T.E. Simos, PDSW: a program for the calculation of photon energy distribution resulting from radioactive elements in seawater. Comput. Phys. Commun. **174**, 391–395 (2006). https://doi.org/10.1016/j.cpc.2005.10.010
7. T. Pitkanen, D. Laundy, R.S. Holt et al., The multiple scattering profile in gamma ray compton studies. Nucl. Instrum. Methods Phys. Res. A **251**, 536–544 (1986)
8. F. Arqueros, G.D. Montesinos, A simple algorithm for the transport of gamma rays in a medium. Am. J. Phys. **71**(1), 38–45 (2003). https://doi.org/10.1119/1.1509416
9. J.H. Hubbell, Electron–positron pair production by photons: a historical overview. Radiat. Phys. Chem. **75**, 614–623 (2006). https://doi.org/10.1016/j.radphyschem.2005.10.008
10. M. Ragheb, Gamma rays interaction with matter (2017). www.mragheb.com. Accessed 18 Feb 2017
11. Gamma Energy (KeV). https://www.cpp.edu/~pbsiegel/bio431/genergies.html
12. J.H. Hubbell, Review and history of photon cross section calculations. Phys. Med. Biol. **51**, R245–R262 (2006). https://doi.org/10.1088/0031-9155/51/13/R15
13. A. Aydın, Energy distributions of multiple backscattered photons in materials. Nucl. Sci. Technol. **29**, 23 (2017)
14. M.J. Berger, J.H. Hubbell, S.M. Seltzer et al., XCOM: photons cross sections database (online) (2010). http://www.nist.gov/pml/data/xcom/index.cfm/. Accessed 5 Jan 2017
15. O. Klein, Y.Z. Nishina, Über die Streuung von Strahlung durch freie Elektronen nach der neuen relativistischen Quantendynamik von Dira. Z. Phys. **52**(11–12), 853–869 (1929)
16. E.N. Ozmutlu, Sampling of angular distribution in compton scattering. Appl. Radiat. Isot. **43**(6), 713–715 (1992)
17. International Commission on Radiation Units and Measurements; ICRU Report 44; ICRU: Bethesda (1989)
18. M. Singh, G. Singh, B.S. Sandhu et al., Energy and Intensity distributions of multiple Compton scattering of 0.279, 0.662 and 1.12 MeV gamma rays. Phys. Rev. A **74**, 1–9 (2006). https://doi.org/10.1103/PhysRevA.74.042714
19. U. Akar Tarım, O. Gurler, E.N. Ozmutlu et al., Monte Carlo calculations of the energy deposited in biological samples and shielding materials. Radiat. Eff. Def. Solids **169**(3), 232–238 (2014). https://doi.org/10.1080/10420150.2013.841161

20. M. Singh, G. Singh, B.S. Sandhu et al., Angular distribution of 0.662 MeV multiply-Compton scattered gamma rays in copper. Radiat. Meas. **42**, 420–427 (2007). https://doi.org/10.1016/j.radmeas.2007.01.037
21. A.D. Sabharwal, B.S. Sandhu, B. Singh, Compton backscattering from broad beam of gamma rays in aluminium and zinc. Asain J. Chem. **18**, 3390–3394 (2006)
22. M. Singh, G. Singh, B. Singh et al., Energy and intensity distributions of 0.279 MeV multiply Compton-scattered photons in soldering material. Nucl. Instrum. Methods Phys. Res. A **580**, 54–57 (2007). https://doi.org/10.1016/j.nima.2007.05.016
23. P.P. Kane, Inelastic scattering of X-rays and gamma rays. Radiat. Phys. Chem. **75**, 2195–2205 (2006). https://doi.org/10.1016/j.radphyschem.2006.08.001