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A comprehensive study for mass attenuation coefficients of different parts of the human body through Monte Carlo methods

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Abstract The gamma-ray mass attenuation coefficients of blood, bone, lung, eye lens, adipose, tissue, muscle, brain and skin were calculated at different energies (60, 80, 150, 400, 500, 600, 1000, 1250, 1500, and 2000 keV) by various theoretical methods such as FLUKA, GEANT4 Monte Carlo (MC) methods and XCOM program in this work. Calculated coefficients were also compared with the National Institute of Standards and Technology (NIST) values. Obtained results were highly in accordance with each other and NIST values. Our results showed that FLUKA was quite convenient in comparison to GEANT4 in the calculation of the mass attenuation coefficients of the used human body samples for low-energy photons (60, 80, and 150 keV) when compared with the NIST values.

Keywords Gamma-ray mass attenuation coefficient · FLUKA · GEANT4 · XCOM

1 Introduction

When a beam of X or gamma rays pass through the matter, the removal of photons from the beam is called attenuation. Absorption and scattering of the primary photons cause to attenuation. The linear attenuation coefficient (μ) is defined as the fraction of photons removed from a monoenergetic beam of X or gamma rays per unit thickness of material. It is typically expressed in units of inverse centimeters (cm^{-1}). For a monoenergetic beam of photons, the relationship between the number of incident photons (N_0) and those that are transmitted (N) through a thickness x without interaction is exponential.

$$N = N_0 e^{-\mu x} \tag{1}$$

The numbers of atoms per volume affect the probability of interaction for a given thickness. The linear attenuation coefficient is normalized by dividing the density of the material to overcome the dependency of the material. This is called the mass attenuation coefficient. The units of the mass attenuation coefficient are cm^2/g [1].

XCOM is a program which generates mass attenuation coefficients for desired energies from 1 keV up to 100 GeV and also elements, compounds, and mixtures. It does not only generate attenuation coefficients but also generate partial cross sections for incoherent, coherent scattering, photoelectric absorption and pair production from the nucleus of atom or atomic electrons [2].

The simulation to estimate the mass attenuation coefficient can also be done with the use of well-known simulation programs such as GEANT4 and FLUKA [3–6]. These tools are based on the Monte Carlo (MC) methods to simulate the interaction of particles with their traversing medium. Their application areas vary from a wide range of topics concerning space, accelerators, medical, high energy, and particle physics [7–10].

Tomal et al. [11] experimentally determined the linear attenuation coefficient of the breast tissue. Linear attenuation coefficients of tissue were theoretically calculated by Böke [12]. Akar et al. [13] investigated mass attenuation

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coefficients of bone, muscle, fat, and water by an experimental method.

In medical imaging, such as PET, an attenuation correction for gamma photons is fulfilled to enhance the spatial resolution, i.e., image quality. This correction is performed by taking into consideration the mass attenuation coefficients of the related parts of the human body. In this regard, mass attenuation coefficients of the related biological materials have great importance in this process. For this reason, another MC method (FLUKA) was utilized for the first time to determine the coefficients for blood, bone, lung, eye lens, adipose, tissue, muscle, brain, and skin materials at different energies in this study as an alternative way and the obtained results were compared with GEANT4, XCOM, and NIST values.

2 Methods

GEANT4 is a C++-based MC simulation code. There are three mandatory classes for the geometry description (DetectorConstruction), physics (PhysicsList), and generated particles (PrimaryGeneratorAction), while there are additional user classes to get information from each step, event and run (SteppingAction.cc, EventAction.cc and RunAction.cc). FLUKA is another well-known code which is based on the FORTRAN language. Even if there are built-in scoring cards to evaluate requested quantities, it also has various routines to retrieve information from different processes. In this work, userini.f, userin.f, and mgdraw.f routines and their entries (bxdraw, endraw) were used. For both MC codes, we utilized the advantage of built-in physics lists, PENELOPE (PENetration and Energy LOss of Positrons and Electrons) physics for GEANT4 (version tag 4.10.p02) and PRECISIOn physics for FLUKA (version tag 2011.2c). It takes into account detailed photoelectric edge treatments, Compton scattering with inelastic factors and computed without fully taking into account binding and orbital electron motion, Rayleigh scattering, and fluorescence. PENELOPE is essential for low energies, and it includes Compton scattering, photoelectric effects, Rayleigh scattering, gamma conversion, bremsstrahlung, ionization, and positron annihilation [14]. More details about this physics lists can be found in the literature [15, 16]. While performing simulations for each photon energy impinging on different materials, we also took advantage of parallel job executions by using the power of PYTHON scripting language, as well as in the analysis phase of the results. The primary photons impinging on the materials are monoenergetic photons, which are defined as point-like particles without any divergence.

When the photon transverses in the material, it loses its energy by well-known processes such as Compton scattering, photoelectric effects, and pair production. Blood, bone, lung, eye lens, adipose, tissue, brain, muscle, and skin materials, which they have the dimensions of 10 cm (width) × 10 cm (height) × 5 cm (thickness), as sketched in Fig. 1, were selected to investigate the photon attenuation.

All material definitions, such as stoichiometry and density were kept the same in order to compare results amongst performed simulations. The elemental concentrations (% weight) of the materials are presented in Table 1. These concentrations were determined according to the ICRP report [17]. Photons with different energies were tracked from the surface of the material in the simulation. Afterwards, we determined the number of absorbed photons by subtracting the transferred photons from the incident ones in the material to evaluate mass attenuation coefficients from the known Eq. (1).

XCOM program (ver. 3.1) was also used to calculate the gamma-ray mass attenuation coefficients of the selected materials. This program used ICRU Report 44 [18] for material concentration. In the program, material types were first defined by their elemental fractions, which are exactly the same as in FLUKA and GEANT4, and then the gamma-ray energies were specified. The coefficients of the selected materials were finally calculated by the XCOM program.

In the MC calculation process, 10^6 photons were sent to the used samples. They were tracked and the transmitted photons through the samples were determined. The linear attenuation coefficients were calculated according to Eq. (1) for each sample. Their mass attenuation coefficients were determined by dividing the obtained linear attenuation coefficients by the sample densities. This process was repeated for 10^3 cycles for each sample. The averages of the results were found, and the uncertainties were obtained by calculating their standard deviations.

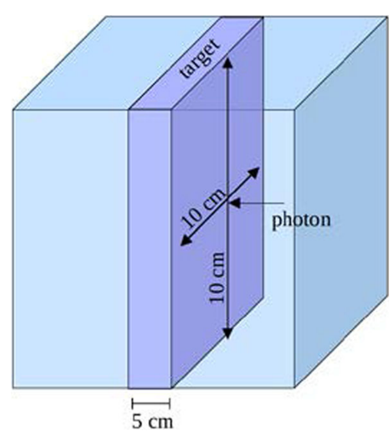

Fig. 1 Sketch of simulated geometry

Table 1 Elemental concentrations (% weight) of the materials used by all programs

Elemental concentration (% weight)	Materials								
	Adipose tissue	Blood	Eye lens	Lung	Muscle	Tissue	Bone	Brain	Skin
H	0.11947	0.10186	0.09926	0.10127	0.10063	0.10447	0.06398	0.11066	0.10058
C	0.63724	0.10002	0.19371	0.10231	0.10783	0.23219	0.27800	0.12542	0.22825
N	0.00797	0.02964	0.05327	0.02865	0.02768	0.02488	0.02700	0.01328	0.04642
O	0.23233	0.75941	0.65375	0.75707	0.75477	0.63023	0.41001	0.73772	0.61900
Na	0.00050	0.00185	–	0.00184	0.00075	0.00113	–	0.00184	0.00007
Mg	0.00002	0.00004	–	0.00073	0.00019	0.00013	0.00200	0.00015	0.00006
Si	–	0.00003	–	–	–	–	–	–	–
P	–	0.00035	–	0.00080	0.00180	0.00133	0.07000	0.00354	0.00033
S	0.00016	0.00185	–	0.00225	0.00241	0.00199	0.00200	0.00177	0.00159
Cl	0.00119	0.00278	–	0.00266	–	0.00134	–	0.00236	0.00267
K	–	0.00163	–	0.00194	–	0.00199	–	0.00310	0.00085
Ca	–	0.00006	–	0.00009	–	0.00023	0.14700	0.00009	0.00015
Fe	–	0.00045	–	0.00037	–	0.00005	–	0.00005	0.00001
Zn	–	0.00001	–	0.00001	–	0.00003	–	0.00001	0.00001

Table 2 Obtained mass attenuation coefficient values for adipose tissue ($\rho = 0.92$ g/cm^3)

μ_ρ values according to photon energies (keV)	Method			
	FLUKA	GEANT4	XCOM	NIST
60	0.19806 ± 0.00019	0.18615 ± 0.00039	0.19740	0.19740
80	0.17985 ± 0.00001	0.17707 ± 0.00002	0.18050	0.18000
150	0.15058 ± 0.00010	0.14824 ± 0.00001	0.15060	0.15000
400	0.10653 ± 0.00001	0.10641 ± 0.00008	0.10670	0.10620
500	0.09881 ± 0.00007	0.09742 ± 0.00013	0.09740	0.09696
600	0.08951 ± 0.00004	0.08951 ± 0.00001	0.09009	0.08965
1000	0.07060 ± 0.00013	0.07279 ± 0.00005	0.07113	0.07078
1250	0.06332 ± 0.00006	0.06329 ± 0.00001	0.06361	0.06330
1500	0.05778 ± 0.00008	0.05763 ± 0.00012	0.05789	0.05760
2000	0.05016 ± 0.00001	0.04979 ± 0.00014	0.04964	0.04940

All calculated coefficients from FLUKA, GEANT4 and XCOM programs were compared to NIST values [19]. The results are given in the next section.

3 Results

The calculated mass attenuation coefficients (μ_ρ) through FLUKA, GEANT4, XCOM, and NIST values (except for skin) are presented in Tables 2, 3, 4, 5, 6, 7, 8, 9, and 10. In these tables, the calculated coefficients via the FLUKA and GEANT4 programs were given with their standard deviations.

In Figs. 2, 3, 4, 5, 6, 7, 8, 9, and 10, calculated mass attenuation coefficients versus the photon energies of each absorber material are shown. The comparison of the results from the programs with the NIST values can be seen in these figures and tables.

4 Discussion and conclusion

The gamma-ray mass attenuation coefficients of blood, bone, lung, eye lens, adipose, tissue, muscle, brain, and skin were calculated at different energies from low energy to high energy (60, 80, 150, 400, 500, 600, 1000, 1250, 1500, and 2000 keV) through FLUKA, GEANT4 MC, and XCOM programs. Calculated mass attenuation coefficients were also compared with NIST values.

Table 3 Obtained mass attenuation coefficient values for blood ($\rho = 1.069$ g/cm^3)

μ_ρ values according to photon energies (keV)	Method			
	FLUKA	GEANT4	XCOM	NIST
60	0.20330 ± 0.00020	0.19302 ± 0.00013	0.20500	0.20570
80	0.18345 ± 0.00009	0.17421 ± 0.00012	0.18240	0.18270
150	0.14866 ± 0.00001	0.14603 ± 0.00020	0.14920	0.14920
400	0.10593 ± 0.00018	0.10402 ± 0.00015	0.10520	0.10520
500	0.09453 ± 0.00002	0.09592 ± 0.00006	0.09598	0.09598
600	0.08956 ± 0.00001	0.08845 ± 0.00016	0.08873	0.08874
1000	0.07088 ± 0.00006	0.07050 ± 0.00003	0.07006	0.07007
1250	0.06252 ± 0.00001	0.06226 ± 0.00003	0.06265	0.06265
1500	0.05751 ± 0.00008	0.05678 ± 0.00001	0.05701	0.05701
2000	0.04870 ± 0.00002	0.04876 ± 0.00003	0.04896	0.04896

Table 4 Obtained mass attenuation coefficient values for eye lens ($\rho = 1.1$ g/cm^3)

μ_ρ values according to photon energies (keV)	Methods			
	FLUKA	GEANT4	XCOM	NIST
60	0.20135 ± 0.00008	0.18781 ± 0.00003	0.20070	0.20130
80	0.18078 ± 0.00001	0.17071 ± 0.00013	0.18030	0.18030
150	0.14807 ± 0.00009	0.14558 ± 0.00021	0.14860	0.14820
400	0.10482 ± 0.00005	0.10367 ± 0.00008	0.10490	0.10460
500	0.09683 ± 0.00002	0.09603 ± 0.00006	0.09576	0.09547
600	0.08854 ± 0.00028	0.09041 ± 0.00003	0.08853	0.08827
1000	0.06961 ± 0.00006	0.07035 ± 0.00013	0.06991	0.06969
1250	0.06138 ± 0.00013	0.06274 ± 0.00001	0.06251	0.06232
1500	0.05615 ± 0.00002	0.05699 ± 0.00006	0.05688	0.05671
2000	0.04869 ± 0.00001	0.04795 ± 0.00007	0.04884	0.04869

Table 5 Obtained mass attenuation coefficient values for lung ($\rho = 1.05$ g/cm^3)

μ_ρ values according to photon energies (keV)	Methods			
	FLUKA	GEANT4	XCOM	NIST
60	0.20323 ± 0.00011	0.18919 ± 0.00006	0.20520	0.20530
80	0.18380 ± 0.00004	0.17419 ± 0.00008	0.18240	0.18260
150	0.14833 ± 0.00008	0.14702 ± 0.00003	0.14910	0.14930
400	0.10461 ± 0.00003	0.10382 ± 0.00021	0.10510	0.10530
500	0.09585 ± 0.00006	0.09596 ± 0.00008	0.09592	0.09607
600	0.08911 ± 0.00004	0.08915 ± 0.00003	0.08869	0.08882
1000	0.07071 ± 0.00015	0.07006 ± 0.00011	0.07002	0.07013
1250	0.06182 ± 0.00001	0.06199 ± 0.00015	0.06262	0.06271
1500	0.05684 ± 0.00002	0.05649 ± 0.00003	0.05698	0.05706
2000	0.04909 ± 0.00003	0.04831 ± 0.00010	0.04893	0.04900

Table 6 Obtained mass attenuation coefficient values for muscle ($\rho = 1.04$ g/cm^3)

μ_ρ values according to photon energies (keV)	Methods			
	FLUKA	GEANT4	XCOM	NIST
60	0.20207 ± 0.00007	0.19035 ± 0.00017	0.20330	0.20480
80	0.18323 ± 0.00014	0.17421 ± 0.00020	0.18160	0.18230
150	0.14823 ± 0.00009	0.14527 ± 0.00010	0.14900	0.14920
400	0.10550 ± 0.00002	0.10434 ± 0.00003	0.10510	0.10520
500	0.09622 ± 0.00011	0.09588 ± 0.00011	0.09592	0.09598
600	0.08842 ± 0.00003	0.08939 ± 0.00008	0.08868	0.08874
1000	0.07003 ± 0.00007	0.06998 ± 0.00001	0.07002	0.07007
1250	0.06351 ± 0.00002	0.06180 ± 0.00005	0.06261	0.06265
1500	0.05635 ± 0.00013	0.05668 ± 0.00003	0.05698	0.05701
2000	0.04780 ± 0.00003	0.04710 ± 0.00003	0.04893	0.04896

Table 7 Obtained mass attenuation coefficient values for tissue ($\rho = 1.00$ g/cm^3)

μ_ρ values according to photon energies (keV)	Methods			
	FLUKA	GEANT4	XCOM	NIST
60	0.20167 ± 0.00007	0.19044 ± 0.00017	0.20330	0.20480
80	0.18317 ± 0.00014	0.17369 ± 0.00020	0.18170	0.18230
150	0.14863 ± 0.00009	0.14492 ± 0.00010	0.14930	0.14920
400	0.10446 ± 0.00002	0.10591 ± 0.00003	0.10540	0.10520
500	0.09524 ± 0.00011	0.09592 ± 0.00011	0.09619	0.09598
600	0.08882 ± 0.00003	0.08923 ± 0.00008	0.08893	0.08873
1000	0.06922 ± 0.00007	0.07041 ± 0.00001	0.07022	0.07006
1250	0.06294 ± 0.00002	0.06226 ± 0.00005	0.06279	0.06265
1500	0.05801 ± 0.00013	0.05674 ± 0.00003	0.05714	0.05701
2000	0.04866 ± 0.00003	0.04915 ± 0.00003	0.04905	0.04895

Table 8 Obtained mass attenuation coefficient values for bone ($\rho = 1.85$ g/cm^3)

μ_ρ values according to photon energies (keV)	Methods			
	FLUKA	GEANT4	XCOM	NIST
60	0.27581 ± 0.00005	0.25330 ± 0.00002	0.27520	0.31480
80	0.20855 ± 0.00004	0.19483 ± 0.00001	0.20870	0.22290
150	0.14942 ± 0.00002	0.14325 ± 0.00001	0.14910	0.14800
400	0.10136 ± 0.00004	0.09948 ± 0.00004	0.10180	0.09910
500	0.09263 ± 0.00010	0.09333 ± 0.00003	0.09275	0.09022
600	0.08547 ± 0.00002	0.08548 ± 0.00011	0.0856	0.08332
1000	0.06738 ± 0.00002	0.06759 ± 0.00004	0.06758	0.06566
1250	0.06061 ± 0.00003	0.06013 ± 0.00007	0.06043	0.05871
1500	0.05478 ± 0.00013	0.05556 ± 0.00003	0.05501	0.05346
2000	0.04710 ± 0.00004	0.04737 ± 0.00006	0.04733	0.04607

Table 9 Obtained mass attenuation coefficient values for brain ($\rho = 1.039$ g/cm^3)

μ_p values according to photon energies (keV)	Methods			
	FLUKA	GEANT4	XCOM	NIST
60	0.20274 ± 0.00005	0.19398 ± 0.00007	0.20650	0.20580
80	0.18351 ± 0.00002	0.17661 ± 0.00033	0.18380	0.18310
150	0.14752 ± 0.00003	0.14690 ± 0.00023	0.15030	0.14980
400	0.10443 ± 0.00002	0.10563 ± 0.00009	0.10600	0.10560
500	0.09456 ± 0.00003	0.09716 ± 0.00009	0.09672	0.09640
600	0.08729 ± 0.00001	0.09047 ± 0.00001	0.08942	0.08913
1000	0.06932 ± 0.00005	0.07082 ± 0.00004	0.07061	0.07037
1250	0.06163 ± 0.00007	0.06321 ± 0.00008	0.06314	0.06293
1500	0.05671 ± 0.00001	0.05790 ± 0.00004	0.05745	0.05726
2000	0.04799 ± 0.00010	0.04893 ± 0.00005	0.04933	0.04917

Table 10 Obtained mass attenuation coefficient values for skin ($\rho = 1.1$ g/cm^3)

μ_ρ values according to photon energies (keV)	Methods			
	FLUKA	GEANT4	XCOM	NIST
60	0.20108 ± 0.00003	0.18962 ± 0.00011	0.20190	–
80	0.18023 ± 0.00012	0.17506 ± 0.00002	0.18090	–
150	0.14921 ± 0.00017	0.14590 ± 0.00019	0.14880	–
400	0.10489 ± 0.00003	0.10445 ± 0.00023	0.10500	–
500	0.09693 ± 0.00010	0.09548 ± 0.00002	0.09586	–
600	0.08669 ± 0.00007	0.08815 ± 0.00004	0.08863	–
1000	0.07069 ± 0.00005	0.06908 ± 0.00001	0.06998	–
1250	0.06252 ± 0.00004	0.06361 ± 0.00007	0.06257	–
1500	0.05720 ± 0.00001	0.05682 ± 0.00002	0.05694	–
2000	0.04868 ± 0.00007	0.04870 ± 0.00005	0.04888	–

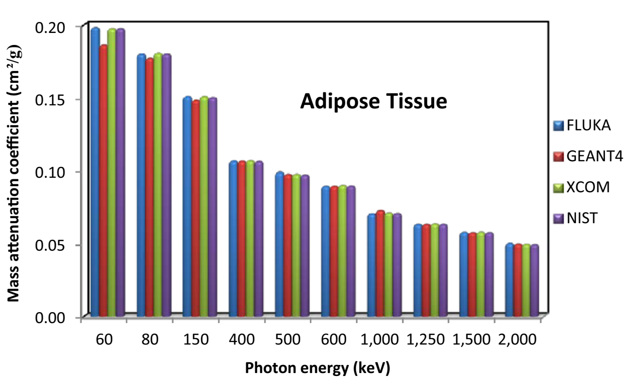

Fig. 2 Obtained mass attenuation coefficients versus different photon energies for adipose tissue ($\rho = 0.92$ g/cm^3)

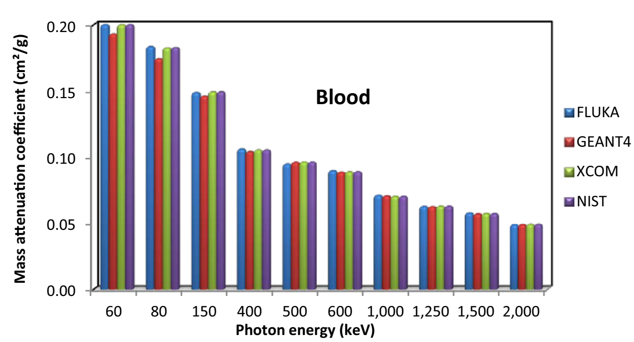

Fig. 3 Obtained mass attenuation coefficients versus different photon energies for blood ($\rho = 1.069$ g/cm^3)

In the low-energy region, the calculated mass attenuation coefficients via GEANT4 were less than those of FLUKA when they were compared to NIST values, as seen in Figs. 2, 3, 4, 5, 6, 7, 8, 9, and 10 and Tables 2, 3, 4, 5, 6, 7, 8, 9, and 10. The results show that the FLUKA and GEANT4 values have differences at low energies up to

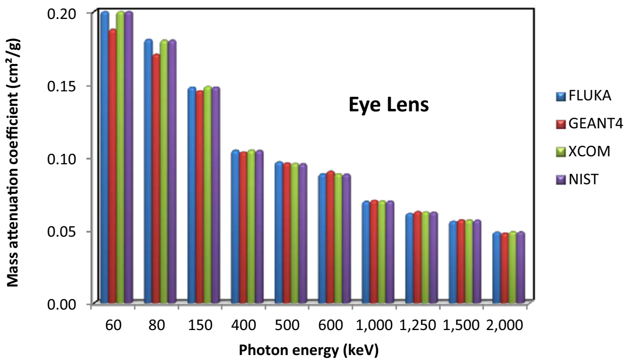

Fig. 4 Obtained mass attenuation coefficients versus different photon energies for eye lens ($\rho = 1.1$ g/cm^3)

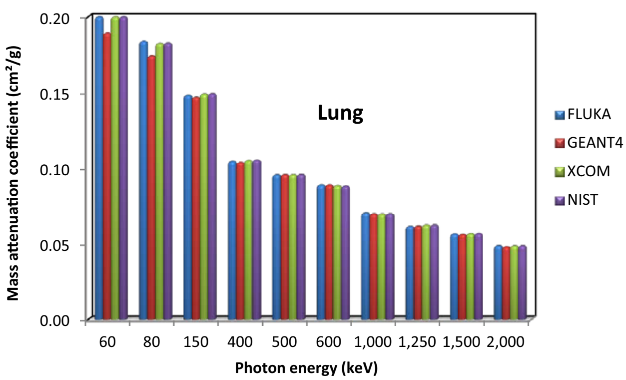

Fig. 5 Obtained mass attenuation coefficients versus different photon energies for lung ($\rho = 1.05$ g/cm^3)

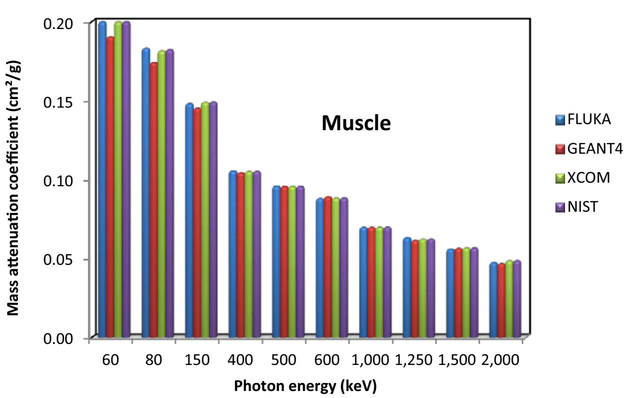

Fig. 6 Obtained mass attenuation coefficients versus different photon energies for muscle ($\rho = 1.04$ g/cm^3)

8 % under the same conditions. But the difference decreases about 1 %, which is reasonable for the higher energies. The difference at low energies comes from the variety of physics models used in each MC codes. Fundamentally, both MC codes use the EPDL (Evaluated Photon Data Library) library, which is mostly related to the NIST standard reference data products [20]. FLUKA uses

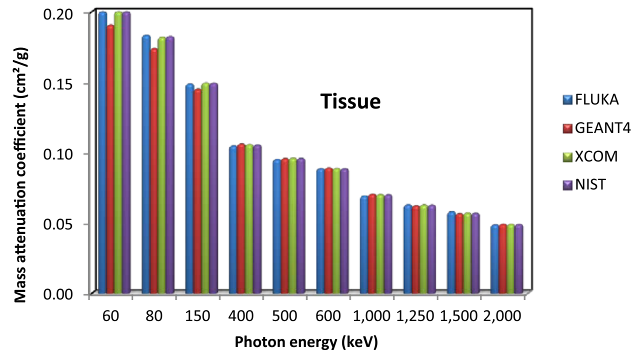

Fig. 7 Obtained mass attenuation coefficients versus different photon energies for tissue ($\rho = 1.00$ g/cm^3)

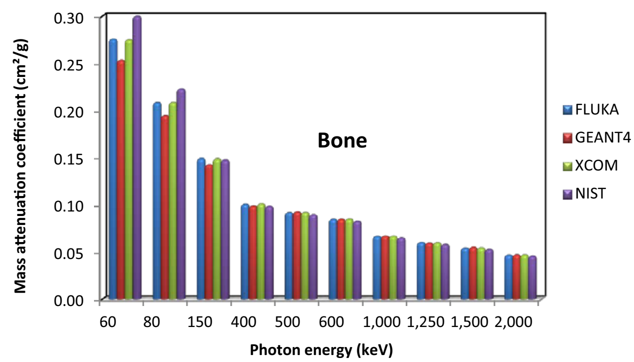

Fig. 8 Obtained mass attenuation coefficients versus different photon energies for bone ($\rho = 1.85$ g/cm^3)

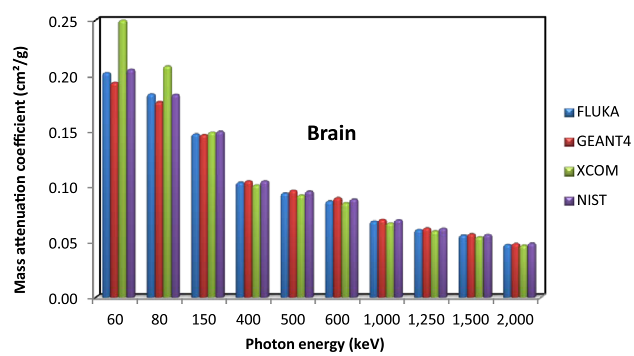

Fig. 9 Obtained mass attenuation coefficients versus different photon energies for brain ($\rho = 1.039$ g/cm^3)

the EPDL97 library for photon cross-section values, with the exception of Compton scattering, without fully considering binding and orbital electron motion [21], and performs detailed photoelectric edge treatments. GEANT4 also uses EPDL97 libraries for photon cross sections for various processes like the photoelectric effect, Compton scattering, the Rayleigh effect, and Bremsstrahlung; sub-shell integrated cross sections for the photoelectric effect and ionization; energy spectra of the secondary particles

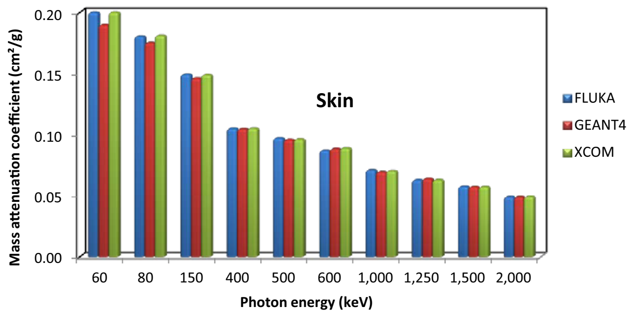

Fig. 10 Obtained mass attenuation coefficients versus different photon energies for skin ($\rho = 1.1$ g/cm^3)

for electron processes; scattering functions for the Compton effect; and form factors for the Rayleigh effect [22]. One reason for the difference between the FLUKA and GEANT4 MC codes at low energies comes from the treatment in this energy regime at which FLUKA handles a detailed photoelectric edge evaluation. On the other hand, the comparison of the MC results with the NIST values shows that calculated mass attenuation coefficients through FLUKA are closer to the NIST values than GEANT4 in the low-energy region. It can be concluded that both MC codes are generally good candidates within small relative errors for medical applications.

Our results showed that FLUKA was somewhat successful in comparison with GEANT4 in the calculation of the mass attenuation coefficients of the human body samples used here for low-energy photons (60, 80, and 150 keV) when compared to the NIST values. Additionally, Robert et al. [23] expressed that GEANT4 was originally developed for high energy physics applications, whereas FLUKA was developed and successfully applied in both the high- and the low-energy ranges. Our results have supported this expression in terms of gamma photon attenuations in the human body samples.

Medhat [24] has calculated mass attenuation coefficients of three biological samples (blood, bone, and muscle) by GEANT4. When we compared our GEANT4 results with his results, it was seen that our results were in agreement with them, even if the used energies and material concentrations were different from each other. Furthermore, comparison showed that Medhat's coefficient for muscle at 81 keV increased (0.220 cm^{2}g^{-1}) unexpectedly, while the coefficient was 0.200 cm^{2}g^{-1} for 59.5 keV gamma energy. However, our coefficient for muscle at 80 keV has normally decreased as the energy was increased. This showed that our result for muscle at 80 keV was more acceptable than his result. As the incident photon energy increases, because, a decrease in the attenuation coefficient of a material is expected.

It is suggested from our results that similar calculations for different human body or biological samples should be repeated and the obtained results should be supported by experimental data for an accurate and satisfactory conclusion. Our analysis serves as a starting point for better understanding the discrepancies between the mass attenuation coefficient results of the GEANT4 and FLUKA programs for the human body samples, especially at low energies.

The XCOM method was also used to calculate the gamma-ray mass attenuation coefficients of the materials. The mass attenuation coefficients of brain from XCOM were found to be higher than those of other programs, especially at low energies (Table 9, Fig. 9), although its elemental concentration (% weight) was the same as FLUKA and GEANT4. Since the NIST value and an experimental result were not available for the brain, it was impossible to compare our results with reference data. But this conclusion needs to be checked and repeated with further studies.

Different theoretical methods, such as Monte Carlo N-Particle Transport Code (MCNP), GEANT4, and XCOM, have been used to calculate the gamma-ray mass attenuation coefficients of various elements and compounds at various energies [25–27]. The FLUKA program was additionally used to determine the coefficients here, unlike these studies, as a novelty. The calculations through FLUKA, GEANT4, and XCOM, in this work, were performed for more materials and energy values than these studies also.

Consequently, the study was carried out to determine individual absorption radiation dose and interpret the criteria for radiation damage of the body in the future studies. It has been noticed that FLUKA results agreed better in the selected energy range of gammas with NIST values than the others. It can be proposed from this conclusion that FLUKA MC program can be efficiently used in the determination of gamma-ray mass attenuation coefficients of the samples of the human body, as well as GEANT4 and XCOM. In addition, it is believed that the FLUKA MC program can be a useful alternative tool for medical physics applications.

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