Biological polymeric shielding design for an X-ray laboratory using Monte Carlo codes

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Abstract

Photon irradiation facilities are often shielded using lead despite its toxicity and high cost. In this study, three Monte Carlo codes, EGS5, MCNPX, and Geant4, were utilized to investigate the efficiency of a relatively new polymeric base compound (C_nH_{2n}), as a radiation shielding material for photons with energies below 150 keV. The proposed compound with the densities of 6 and 8 g cm^{-3} were doped with the weight percentages of 8.0 and 15.0% gadolinium. The probabilities of photoelectric effect and Compton scattering were relatively equal at low photon energies, thus the shielding design was optimized using three Monte Carlo codes for the conformity of calculation results. Consequently, 8% Gd-doped polymer with thickness less than 2 cm and density of 6 g cm^{-3} was adequate for X-ray room shielding to attenuate more than 95% of the 150-keV incident photons. An average dose rate reduction of 88% can be achieved to ensure safety of the radiation area.

Keywords Polymeric compounds · Monte Carlo codes · Gadolinium

1 Introduction

Lead (^{82}Pb) is one of the most commonly used materials for attenuating gamma rays in high-dose rate nuclear facilities. In low-dose rate facilities such as medical X-ray generators, some recent works considered the use of non-lead shields for photons. The main reason is the toxicity of lead, in addition to its high price. Several studies have been performed, mainly to quantify the photon attenuation (gamma/X) by non-lead shielding materials [1–3].The use of non-lead polymeric compounds doped with heavy elements [4–13] will eliminate the concern of high public biological risks.

The risk from photon exposure to human health is quantified by the amount of absorbed dose. It is important to evaluate the effective photon dose reduction by the shielding of the irradiation facilities to ensure the safety of the public and radiation workers. In this study, the shielding design was based on two proposed compounds, polymer (C_nH_{2n}) doped

with weight percentages of 8 wt% and 15 wt% gadolinium (^{64}Gd).

Monte Carlo (MC) codes are widely used for designing the shielding of nuclear facilities [10–16]. In a radiation transport calculation using MC code, the interaction of radiation inside a material was followed using random numbers based on the statistical method to sample the probability distributions. It is well known that each MC code has its own restrictions, abilities, energy range, and cross-sectional data libraries. Hence, in such calculations related to radiation safety, using several MC codes increases the reliability of the final conclusion, particularly in the low-energy photon regime.

In this study, three MC codes were used: GEANT4.10.2-p02 [17, 18], MCNPX2.4.0 [19], and EGS5 [20]. The main objective of the study was to optimize, by calculations, the shielding of 150-keV photons by the Gd-doped compounds. In the first case, the mass attenuation coefficients (cm^2 g^{-1}) of Pb^{82} and Gd^{64} elements were calculated and compared with standard data from XCOM [21] to confirm the codes set up for our shielding calculations. Then the percentage of photon attenuation was calculated, and the mass attenuation coefficient was deduced for all the compounds. No direct relationship between the photon dose and mass attenuation coefficient could be established, particularly when the emission of fluorescent radiation was considered during the

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calculations. Therefore, in the second case, the photon dose reduction was calculated by multiplying the calculated photon energy fluence (MeV cm^{-2}) by the mass energy absorption coefficient (cm^2 g^{-1}).

2 Materials and methods

Table 1 lists the mass fractions of hydrogen (^{1}H), carbon (^{6}C), and gadolinium (^{64}Gd) corresponding to 8 wt% and 15 wt% of Gd in the polymer (C$_n$H$_{2n}$). The densities of each compound were 6 and 8 g cm^{-3}. Compounds with lower densities are less capable of photon attenuation of 8 and 15 wt% with the percentage amounts of Gd. Parallel 150-keV photons were incident on the slab of the compounds with the surface dimension of 10 cm × 10 cm.

2.1 Codes setup

Electron Gamma Shower version 5 (EGS5) was set to run for 10^7 events using photon cross sections of the PHOTX library [20]. Photon interactions such as photoelectric absorption, Compton scattering, and Rayleigh scattering were considered. The probable production and transport of K- and L-edge fluorescence was also included in the calculations. The photons in the compounds of various thicknesses were followed until they were transmitted or slowed down to 1 keV.

MCNPX.2.4.0 was tallied by F1 as surface current scorer and the MCPLIB04 was used for the photon interaction cross-sectional library. Coherent scattering and Doppler broadening were turned on in these simulations. The code results were obtained after 10^7 number of events with error less than 0.1%.

GEANT4.10.2 simulations used EMLOW6.48 for photon cross sections and each run was also set for 10^7 number of events for good statistics.

2.2 Calculation validation

The compatibility or negligible discrepancy between the calculated results and the standard data shows the validity

Table 1 Mass fractions of elements in the proposed compounds

Element	Elements mass fraction in the compounds (wt%)	
	C$_n$H$_{2n}$(Gd: 8 wt%)	C$_n$H$_{2n}$(Gd: 15 wt%)
C	78.844	72.845
H	13.156	12.155
Gd	8.0	15.0

of the three codes set up, thus confirming the reliability of photon attenuation and dose results of the proposed shielding compounds. The transmitted photons intensity (I) from the shield can be expressed as [22]

$$I = BI_{o}e^{-\mu x}, \qquad (1)$$

where I_{o} is the intensity of the incident photons and μ(cm^{-1}) is the linear attenuation coefficient of the material related to its thickness x. In this expression, the buildup factor B (energy dependent) has been included to correct the effect of the scattered photons.

To determine the mass attenuation coefficient by simulation and to eliminate the buildup factor B, only the transmitted photons were scored by the codes; hence, Compton scattered photons are not considered. This set up is necessary for the simulations for comparison with the attenuation coefficients generated by XCOM. Figure 1 shows a small discrepancy between MCNPX and NIST for the mass attenuation coefficient of lead. Table 2 summarizes the comparison, between the calculated and the corresponding standard data (NIST) of mass attenuation coefficients for 150 keV photons, for lead and gadolinium. The negligible difference between the codes and reference data comes from the statistical errors, hence validating the performed calculations.
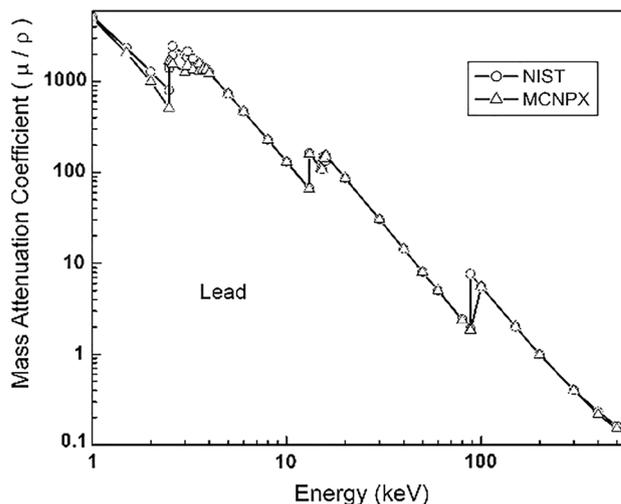

Fig. 1 Comparison of mass attenuation coefficients of lead element between MCNPX and NIST data [21]

Table 2 Comparison of calculated mass attenuation coefficients (cm^2 g^{-1}) for 150 keV photons

Element	EGS5	MCNPX	GEANT4	NIST [21]
Gd	1.102	1.093	1.073	1.100
Pb	2.029	2.008	2.004	2.014

3 Results and discussion

3.1 Photon attenuation calculations of the polymer

The percentage of photon attenuation for 150 keV photons incident on the polymer base compound was calculated for the two following cases:

1. 8% of Gd-doped polymer with densities of 6 and 8 g cm^{-3},
2. 15% of Gd-doped polymer with densities of 6 and 8 g cm^{-3}.

The aforementioned percentages and densities were selected as the most desirable values for attenuating the X-ray photons. Lower densities would demand higher percentages of gadolinium, consequently leading to an increase in the cost. The results of the calculated photon attenuation are presented in Figs. 2, 3, 4 and 5.

In each of the four figures, the maximum discrepancy among the three codes occurs at 1-cm compound thickness, while they have a good agreement at all the other thicknesses. The percentage of difference is within 5% and 2% between Figs. 2 and 3, and 3 and 4 at 1 cm thickness, respectively. For the 8% Gd-doped polymer, ~ 85% and 92% photons were successfully attenuated at 2 cm thickness for the compounds with densities 6 and 8 g cm^{-3}, respectively. The photon attenuation was 95% and 98% for the two densities of 6 and 8 g cm^{-3}, respectively. On the contrary, 90% photon attenuation was achieved at 1.5 cm and 1.7 cm thickness of the 15% Gd-doped polymer for 6 and 8 g cm^{-3} densities, respectively.
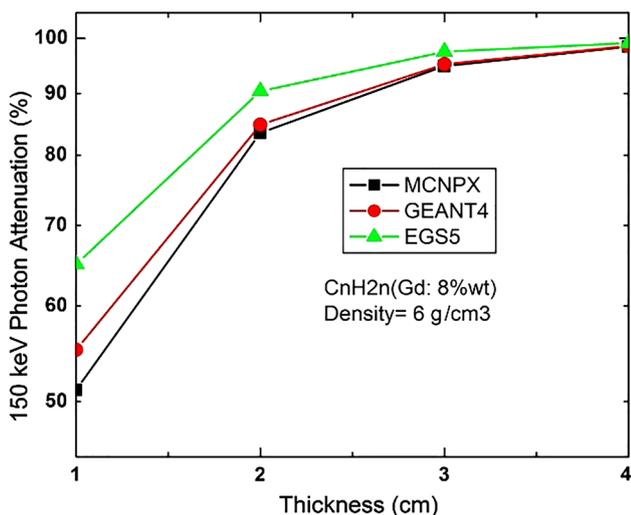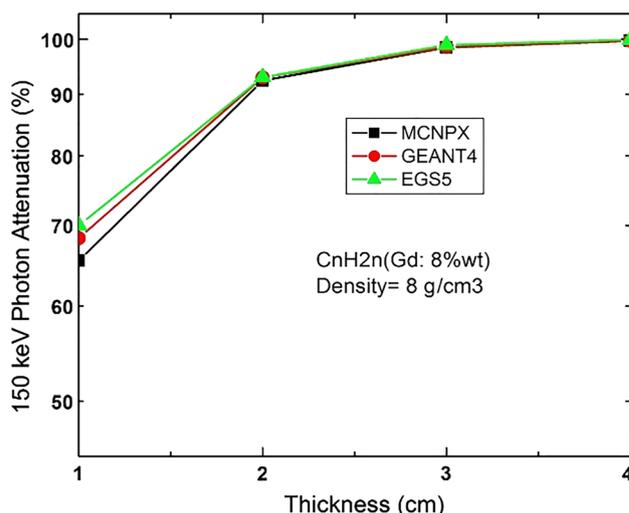

Fig. 3 Attenuation for Gd: 8% and 8 g cm^{-3} compound density

Table 3 summarizes the calculated mass attenuation coefficients for 8% and 15% Gd-doped polymers with density 6 g cm^{-3}. In comparison with Table 2, the attenuation of the proposed polymer for 150-keV photons is one order of magnitude less than that of lead, implying that a larger thickness is required for decreasing the photon dose rate. Table 4 lists the calculated half-value layers of the polymer compounds. The HVL values indicate the capability of photon to penetrate a compound at a particular energy. The HVL was evaluated from the calculated linear attenuation coefficient values obtained using the equation:
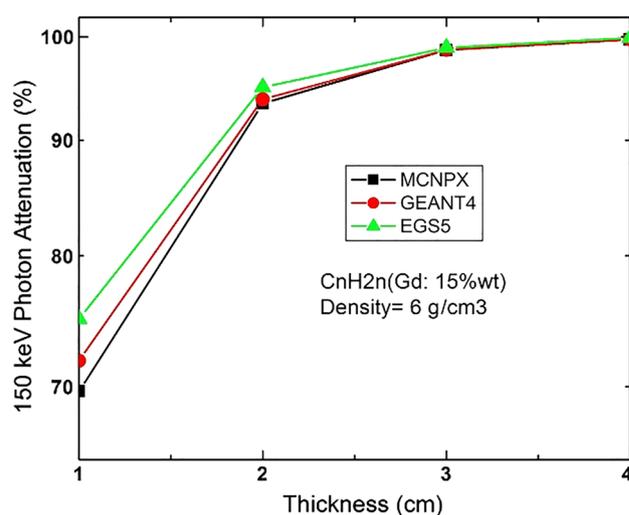
$$\text{HVL} = \frac{0.693}{\mu}. \tag{2}$$

Fig. 2 Photon attenuation for Gd: 8% and 6 g cm^{-3} compound density

Fig. 4 Attenuation for Gd: 15% and 6 g cm^{-3} compound density
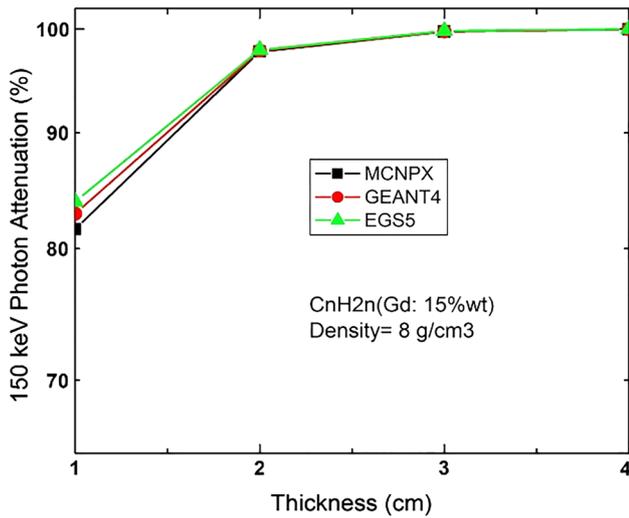
Fig. 5 Attenuation for Gd: 15% and 8 g cm^{-3} compound density

Table 3 Calculated mass attenuation coefficients of polymer compounds

Compound (6 g cm^{-3})	$\frac{\mu}{\rho}$ (cm^2 g^{-1})		
	EGS5	MCNPX	GEANT4
C$_n$H$_{2n}$(Gd: 8 wt%)	0.2315	0.2288	0.2370
C$_n$H$_{2n}$(Gd: 15 wt%)	0.2988	0.2849	0.2989

Table 4 Calculated half-value layer (HVL) of the polymer compounds

Density (6 g cm^{-3})	EGS5	MCNPX	GEANT4
C$_n$H$_{2n}$(Gd: 8 wt%)	0.4989	0.5048	0.4873
C$_n$H$_{2n}$(Gd: 15 wt%)	0.3865	0.4054	0.3864

From Table 4, it can be seen that the HVL value of 8% Gd-doped polymer is higher compared to that of 15% Gd. The average percentage of difference in the HVL values between 8% and 15% Gd-doped polymer is less than 23%. The calculation method and results for photon dose rate (Sv s^{-1}) are presented in the next subsection.

3.2 Dose rate calculation methods

In this study, the photon dose was calculated via the following two approaches. In the first approach, the dose rate was defined as the ratio of the absorbed energy per unit mass ($\frac{J}{kg\ h} = \frac{Gy}{h}$), and the rate of energy deposited in the medium was calculated using the codes in air and soft tissue (near the shield surface). To calculate the absorbed dose rates $\dot{D}$ ($\frac{Gy}{h}$ or
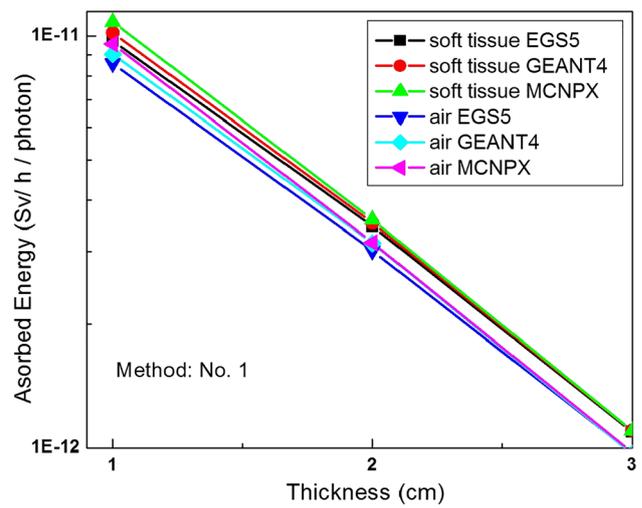

Fig. 6 Calculated dose rate in terms of the thickness for 6 g cm^{-3} C$_n$H$_{2n}$(Gd: 8 wt%) according to the energy deposition rate in air and soft tissue unit of mass

$\frac{Sv}{h}$) in air and soft tissue (analytically), the related expression was used as the second method [22]:

$$\dot{D} = \frac{\varphi\left(\frac{photon}{cm^2\ s}\right) \times E\left(\frac{MeV}{photon}\right) \times 1 \cdot 6 \times 10^{-13}\left(\frac{J}{MeV}\right)}{1\left(\frac{J}{Gy}\right)} \times \mu_{med.}\left(\frac{cm^2}{kg}\right),$$

(3)

where φ, E, and $\mu_{med.}$ are the photon flux (obtained by the code), photon energy (0.15 MeV) and mass energy absorption coefficient in the medium ($\mu_{(air)} = 25.1\ \frac{cm^2}{kg}$ and $\mu_{(tissue)} = 27.3\ \frac{cm^2}{kg}$ [22]), respectively.

Figure 6 shows the plot of the dose rate ($\frac{Gy}{h}$) against the thickness obtained by calculating the deposited energy in air and soft tissue for C$_n$H$_{2n}$(Gd: 8 wt%) with density 6 g cm^{-3}. Here, one should be concerned that the results have maximum variations less than 10%. For example, at 1 cm thickness, the absorbed energies per photon in soft tissue are 9.7×10^{-12} ($\frac{Sv}{h \cdot photon}$), 1×10^{-11} ($\frac{Sv}{h \cdot photon}$), and 1.08×10^{-11} ($\frac{Sv}{h \cdot photon}$) by EGS5, GEANT4, and MCNPX, respectively (6% variation). For 1 cm thickness, the absorbed energies per photon in air are 9.5×10^{-12} ($\frac{Sv}{h \cdot photon}$), 9×10^{-12} ($\frac{Sv}{h \cdot photon}$), and 8.78×10^{-12} ($\frac{Sv}{h \cdot photon}$) by EGS5, GEANT4 and, MCNPX, respectively (9% variation). The dose rate per photon near the surface for 2 cm thickness may be predicted to be almost 3.5×10^{-12} ($\frac{Sv}{h \cdot photon}$) and 3×10^{-12} ($\frac{Sv}{h \cdot photon}$) for soft tissue and air, respectively.

The absorbed dose rate per photon calculated using Eq. (2) versus the shield thickness in tissue and air has been plotted in Fig. 7. The dose rates per photon in soft
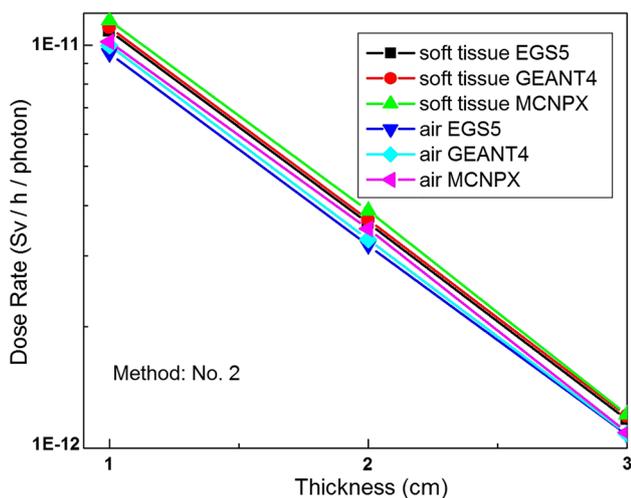
Fig. 7 Calculated dose rate in terms of the thickness for g cm^{-3} C_nH_{2n}(Gd: 8 wt%) using Eq. 2
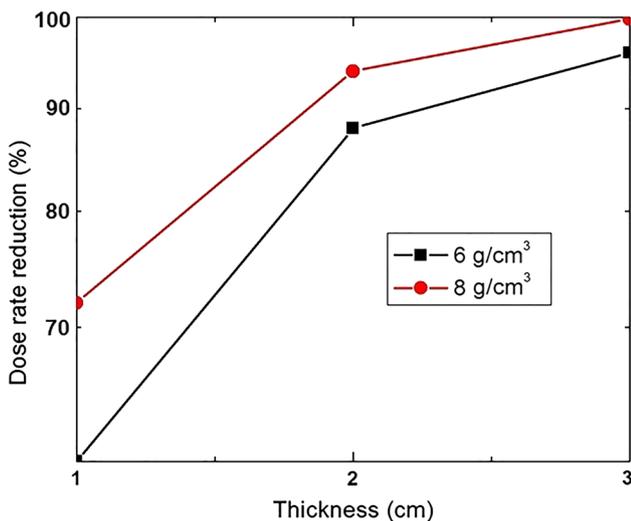

Fig. 8 Ratio of the reduced dose rate to the primary dose rate in terms of thickness

tissue and air (near the shield surface) corresponding to 2 cm thickness are 3.6×10^{-12} ($\frac{Sv}{h \cdot photon}$) and 3.1×10^{-12} ($\frac{Sv}{h \cdot photon}$), respectively, with acceptable conformity with the results obtained from the first method.

The dose rate before the shielding was calculated to be around 2.3×10^{-11} ($\frac{Sv}{h \cdot photon}$). The ratio of the reduced dose rate to the primary dose rate without shielding has been illustrated in Fig. 8. Accordingly, 2 cm thickness of the proposed polymeric compound, C_nH_{2n}(Gd: 8 wt%) reduced the dose rate up to 88% and 98% corresponding to 6 and 8 g cm^{-3} density, respectively. The real dose rate is

dependent on the primary photon intensity or the electron beam current of the X-ray machine.

In both the methods, the calculation results for the polymer of density 6 g cm^{-3} for 8% Gd doping are in good agreement for all the thicknesses. Once again, there was a small variation in results between the three codes at 1 cm thickness. Note that the graph was plotted in the log scale for the y-axis. A strong dose rate reduction (~75% reduction) is evident as the thickness increases in steps of 1 cm for the calculated compounds of 8% Gd-doped polymer with density 6 g cm^{-3}. Hence, the dose rate reduction is more significant, being ~84% for the same weight percentage of Gd for the compound with density 8 g cm^{-3} and ~90% for the 15% Gd-doped compound with density 8 g cm^{-3}. Consequently, a thickness of less than 2 cm in the case of X-ray room shielding was sufficient to reduce the dose rate values significantly. For most photon energies used in diagnostic radiology, the average energy is usually between 25% and 30% of the maximum energy. Thus, the polymeric compound containing higher weight percentages and densities of Gd are not necessary.

4 Conclusions

The attenuation of 150 keV photons for UniSZA X-ray laboratory was successfully obtained using the proposed new polymeric compounds doped with gadolinium as a lead-free shielding material. The MC codes of EGS5, GEANT4, and MCNPX were used in our shielding design to obtain reliable results of necessary compound thicknesses, doping percentages and densities. The calculated values of mass attenuation coefficient of the Pb and Gd elements agree with theoretical data. The minimum polymer density and weight percentages of Gd in our calculation, 6 g cm^{-3} and 8%, respectively, are sufficient to obtain photon attenuation of more than ~90% for 150 keV photons with less than 2 cm thickness. A 75% reduction of the calculated photon dose rate was evident for 1 cm thickness of the polymer to achieve the radiation safety goals at our premises. New materials and compounds are under development to reduce the risk of lead toxicity. Hence, the studies performed in this work could be beneficial towards the utilization of such materials in radiation facilities.

Compliance with ethical standards

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