Calculation of Attenuation Parameter for Ir-192 Gamma Source in Shielding Materials

Adila Hanim Aminordin Sabri, M. Z. Abdul Aziz, S. F. Olukotun, S. M. Tajudin

School of Medical Imaging, Faculty of Health Sciences, Universiti Sultan Zainal Abidin, Terengganu, 1Oncological and Radiological Science Cluster, Advanced Medical and Dental Institute, Universiti Sains Malaysia, Penang, Malaysia, 2Department of Physics and Engineering Physics, Obafemi Awolowo University, Ille-ife, Nigeria

Abstract

Purpose: Calculation of photon attenuation is necessary for the selection of shielding materials for an irradiation facility. Methods and Materials: In this work, a Monte Carlo simulation was utilized to assess the effectiveness of clay-polyethylene mixture and clay as the radiation shielding materials for high-energy gamma sources (Ir-192). Ordinary concrete was also studied as the benchmark. Results: The calculated linear attenuation values for ordinary concrete are within 0.44% of the standard XCOM value for 380 keV photon. In the case of a multienergy Ir-192 gamma source, the calculated linear attenuation coefficient (µ) for ordinary concrete is 15.5% and 7.25% higher than clay and fabricated clay-polyethylene, respectively. Meanwhile, the µ value for fabricated clay-polyethylene is 8.3% higher than that of clay. Conclusion: In conclusion, a 10 cm thickness of clay and clay-polyethylene mixture is sufficient to attenuate 87% and 89% of photons from Ir-192 source. The calculated linear attenuation coefficients for the three shielding materials are also consistently higher, about 7.5%, than that of the XCOM value for 380 keV photon.

Keywords: Clay, fabricated clay-polyethylene, Ir-192, linear attenuation coefficient, Monte Carlo, ordinary concrete

INTRODUCTION

Many studies conducted since 1970 have proved that lead (Pb-82) is effective in photon attenuation either to shield the emission of photons from radioactive sources or as a shielding material for the wall of an irradiation facility room[1-13] such as for diagnostic and radiotherapy room. However, the disadvantages of lead, along with its advantages, are the lead material itself is toxic and expensive.[14-16] Due to these reasons, many studies have been conducted to replace the lead element with other materials as a shielding material.[7-14] As an example, the authors had successfully revealed that the gadolinium compound doped with the polymer could be used as an alternative shielding material other than lead for 150 keV with a minimum thickness of 2 cm.[15] The authors calculated when gadolinium-doped polymeric compounds had been applied, more than 90% photon attenuation with 2 cm thickness for 150 keV incident photon will be adequate for shielding an X-ray laboratory. Recent studies led by Kaura et al.[16] and Agar et al.[17] proposed the utilization of metallic alloy as a potential gamma-shielding material by doping with a high atomic number (Z) element.

To compare with the XCOM values, the primary concern most of the time in many cases of photon shielding studies was about the transmitted photons that penetrate the shielding materials, both scattered and unscattered photons. Typically the transmitted photons count after where typically the amount of interest is measured or calculated from the attenuating material. For instance, Sayyed et al. had read attenuation properties for the chose germanate glasses-based shielding compound through hypothetical calculations.[18] Other investigations of radiation attenuation had been conducted by hypothetical calculation for different concretes[19] and by trial work for glass-based shielding compound.[20,21] As well as attenuation coefficient (µ) and its related parameters, it is likewise important to assess the transmitted or reflected intensities because of the shielding material, especially for a recently evolved shielding material and photon energy (keV).

Address for correspondence: Dr. Adila Hanim Aminordin Sabri, Faculty of Health Sciences, Universiti Sultan Zainal Abidin, Terengganu, Malaysia. E-mail: adilahanim@unisza.edu.my
As we need to guarantee the radiation dose rate is pretty much as low as possible according to background radiation, such assessment is significant when planning a radiation shielding facility or for source storage. It is upon this motivation that we conducted the study of our relatively newly developed clay\cite{14} and clay-polyethylene,\cite{22} benchmarked against ordinary concrete,\cite{23} as radiation shielding materials for high-energy gamma sources (Ir-192).

In this study, the transmitted photons of ordinary concrete, clay, and fabricated clay-polyethylene materials were assessed by Monte Carlo simulation (EGS5 code).\cite{24,25} Transmitted photons using clay and fabricated clay-polyethylene materials were calculated for gamma-ray of multi-energy source of Ir-192. While concrete as a standard shielding material that usually utilized, we come out with another sort of shielding material, for example, clay and clay-polyethylene. Clay materials are used for construction and building purpose in many developed and developing nations. Clay products such as burnt bricks, ceramic woods, and tiles that commonly used for floor and material, are less expensive and tougher structure materials than concrete, particularly under tropical condition.\cite{26}

**Calculated Transmitted Photon for Monoenergy Photon**

Monte Carlo code for electron and photon transport Electron Gamma Shower (EGS5 code)\cite{24,25} was used to calculate the transmitted primary photons. EGS5 code has been developed at the High Energy Accelerator Research Organization, Japan.\cite{24} EGS code is a general-purpose package for the Monte Carlo simulation to transport electrons and photons in an arbitrary geometry with energies above a few keV up to several hundred GeV.\cite{24} Simulation results obtained from this code were reported in many publications. As an example, simulations of the longitudinal and radial distributions of energy deposition of electrons of various energies made using EGS5 were compared with experimental results in the literature.\cite{27} This example research confirms that the results from EGS5 simulation can be used for approximating the various energy depositions of electrons. Tajudin \textit{et al.}\cite{28} stated that they were successfully demonstrated two-energy calibrations (~200 keV and 662 keV) to be used for survey meter calibration from a monoenergetic radioactive source (Cs-137) and believed that their method would be very effective for accurate calibration of dosimeters which in turn essential for any instrument. Weber \textit{et al.}\cite{29} also agreed that simulations indicate an excellent polarimeter quality of such detector systems when used as Compton polarimeters. Moreover, good agreement is found between simulations and recently obtained experimental data. The photons interaction such as photoelectric absorption, Compton scattering, and pair productions were considered. The branching ratio of the gamma sources were sampled as the JRIA data book.\cite{30} The photons were emitted in the parallel beam to the material and the Rayleigh scattering option was requested for the material. The materials data for concrete and clays and their density for the calculations correspond to the literature data.\cite{31}

Several studies have been conducted to compare the values of simulated linear attenuation coefficients from Monte Carlo calculation with the values from XCOM\cite{32,33} to get the value of discrepancies. The radiation attenuation is an inherent property of materials, which can be clarified by the exponential decay equation as:

$$\frac{I}{I_o} = e^{-\mu x} \quad (1)$$

where \(I_o\) is the initial attenuated intensity of photons while \(I\) is the attenuated intensity of photons. The quantity \(x\) represents the thickness of the material, and \(\mu\) is the linear attenuation coefficient. Commonly, the unit for linear attenuation coefficient is cm\(^{-1}\). However, it is usually identified as the mass attenuation coefficient \(\mu/\rho\) in a unit of cm\(^2\) g\(^{-1}\). The radiation attenuation in materials is determined by the interaction of photons with particles, electrons, or atoms in matter, including pair production, Compton scattering, coherent scattering, and the photoelectric effect.

The calculation of transmitted photons as a function of ordinary concrete thickness has been shown in Figure 1 for a pencil beam of 380 keV incident photon. It has to be noted that photons of Compton scattering that penetrate the clay-shielding material were disregarded in our calculation for comparison with the attenuation coefficients generated by XCOM.\cite{34} The full square points were suited with an exponential function to get linear attenuation coefficient (\(\mu\)) values of 0.228/cm. Good agreement was achieved between the calculated \(\mu\) value and theory value, which is within 0.44% to legitimize the resulting calculations for multi-energy gamma sources. The error of 0.13% appeared in the Figure 1 for the calculated \(\mu\) value comes from exponential fitting error.

![Calculated \(\mu\) of concrete for single-photon energy in comparison with the theoretical value. The calculated \(\mu\) value is 0.228/cm for 380 keV incident photon to have a decent concurrence with the theory value within 0.44%](image)

Figure 1: Calculated \(\mu\) of concrete for single-photon energy in comparison with the theoretical value. The calculated \(\mu\) value is 0.228/cm for 380 keV incident photon to have a decent concurrence with the theory value within 0.44%
Clay had been effectively demonstrated to diminish transmitted photon compared with ordinary concrete for low-incident photon energy in our previous study due to predominant photoelectric absorption.\cite{35} Photon’s pencil beam was incident to the focal point of cylinder clay. In this study, we considered the photon’s interaction, for example, photoelectric absorption, Compton scattering (including Rayleigh scattering), and pair productions. µ value was calculated for multi-energy gamma source of Ir-192, and according to the JRIA data book,\cite{30} the branching ratio of the gamma source adopted in the calculation was sampled as in Table 1.\cite{30}

Figure 2a-c shows the calculation of transmitted photons as a capacity of the material thickness (ordinary concrete, clay, and fabricated clay, respectively) for a pencil beam of Ir-192 gamma source. The full square points were fitted with an exponential function in Figure 2 to get linear attenuation coefficient (µ) values for each shielding material, as shown in Table 2 (0.243/cm). While the calculated values by EGS5 are for Ir-192, the XCOM values were obtained for a single-photon energy of 380 keV. According to Rijnders, 380 keV photon could be used as the average energy of Ir-192 gamma source.\cite{36} As an example, from Figure 2a-c, a thickness of 10 cm is satisfactory to lessen up to 91% of the photons from Ir-192 source for ordinary concrete, 87% and 89% for our clay and fabricated clay, respectively. Among the three materials, ordinary concrete is the highest value of attenuation because of its higher density compared to clay and fabricated clay, which is 2.302 g/cm$^3$. The attenuation value decreases as density decreases, where the density of fabricated clay is 2.03 g/cm$^3$ with attenuation of 89%, while the density of the clay is 1.99 g/cm$^3$ with attenuation of 87%.

From Table 2, the calculated values of linear attenuation coefficient for the three shielding materials are consistently higher, about 7.5% than the XCOM value for 380 keV photon. The higher calculated value by EGS5 was expected as the Ir-192 gamma source also consisted of a few percent low photon energies, as shown in Table 1, which are not considered in the theoretical value. The XCOM values are outputted from single-photon energy of 380 keV. Therefore, one who has no facility to do experiments or perform Monte Carlo simulation could simply use the XCOM database to estimate the shielding attenuation parameter with a few percent difference on account of multi-energy gamma sources. As the XCOM database is only for single-photon energy, the use for gamma sources needs to be verified either by experiment or simulation as the particular gamma source might have lower and higher energy photons that need to be considered.

### Table 1: List of gamma energies with its own branching ratio

| Source   | Energy (MeV) | Branching ratio (%) |
|----------|--------------|---------------------|
| Ir-192   | 0.296        | 28.7                |
|          | 0.308        | 29.7                |
|          | 0.317        | 82.7                |
|          | 0.468        | 47.8                |
|          | 0.589        | 4.5                 |
|          | 0.604        | 8.2                 |
|          | 0.612        | 5.3                 |
|          | 0.0664       | 7.3                 |
|          | 0.0764       | 1.9                 |
|          | 0.0104       | 4.1                 |
|          | 0.206        | 3.3                 |
|          | 0.485        | 3.2                 |
|          | 0.0626       | 3.4                 |

### Table 2: Calculated linear attenuation coefficient ($\mu$) cm$^{-1}$ for Ir-192 gamma source

| Materials                  | XCOM (380 keV) | EGS5 (Ir-192) | Percentage increase (%) of calculated value |
|----------------------------|----------------|---------------|---------------------------------------------|
| Ordinary concrete          | 0.227          | 0.243         | 7.04                                        |
| Clay\cite{14}              | 0.193          | 0.208         | 7.77                                        |
| Fabricated clay-polyethylene\cite{22} | 0.210          | 0.226         | 7.62                                        |
location. The source activity when the experiment was carried out was 10.3 Curie. The dose rate was measured by an ionization chamber survey meter of 1000 cm$^3$ effective volume (Victoreen 451P-RYR). The agreement of calculated with theory and measured value with the average difference of 1.37% ambient dose rate in air are adequate to justify or validated our next simulations for photon dosimetry with concrete and our fabricated clay materials for Ir-192.

From Figure 3, the calculated dose rate for fabricated clay is always higher than an ordinary concrete with a percentage of difference <4% for the thickness <8 cm. However, the dose rate for clay is higher than concrete up to 15% at a thickness of 20 cm, as the effect of concrete has a higher density than developed clay. In previous, we have successfully described the fabricated clay for neutron shielding purposes.$^{[31]}$ Nevertheless, as an example, at a thickness of 20 cm, both samples successfully decreased the dose rate to 92%. All the calculated dose rates have an error of <1%.

The average energy ($\langle E \rangle$) of a photon spectrum was calculated by the equation:

$$\langle E \rangle = \frac{\int E \cdot f(E) \, dE}{\int f(E) \, dE}$$

(2)

where $f(E)$ is the number of photons with energy $E$, each photon was multiplied by its corresponding energy and all the product was integrated over the whole spectrum. The integral of all the products were divided by the total number of photons to yield the mean energy.

From Figure 4, the average photon energy of Ir-192 at 0.83 cm distance in the air without a sample is 349.5 keV. With 8 cm of concrete and clay, the transmitted average photon energies are 272.2 keV and 282.9 keV, respectively. Furthermore, the photon peaks of 468 keV and above from the source were attenuated within a factor of 5, while the photon peaks of less 400 keV, including the 317 keV with 82.7% branching ratio, were significantly reduced by almost a factor of 7.

As the gamma source energy used is considerably high, there is a possibility for backscatter radiation which is the radiation scattered with a large angle after undergoing Compton scattering interaction inside the material. Figure 5 shows an example of reflected photon scored from an 8 cm thickness of concrete and fabricated clay due to Ir-192 source incident photon emitted in the 4$\pi$ direction. The average reflected photon energy is 130.5 keV. The impact of reflected photon energy and its dose rate will be further investigated.

In another example, Tajudin et al.$^{[14]}$ had shown how to diminish reflected photon spectra from the clay material for Am$^{241}$ gamma source by utilizing an iron (Fe-26) element. At whatever point vital, if the added reflected dose is sufficiently high to legitimize attempting to lessen it, at that point, it turns into a matter of cost and comfort in choosing what approach may be ideal for diminishing reflection.

**Conclusion**

In this study, the linear attenuation coefficient of ordinary concrete and both newly-developed clay and the clay-polyethylene mixture were calculated using the Monte Carlo method for multi-energy gamma source Ir-192. It was found that a 10 cm thickness of ordinary concrete could allow 9% transmitted photon, while it was 13% and 11% for the same thickness of clay and clay-polyethylene, respectively.

| Table 3: Measured, theory, and calculated dose rate for Ir-192 source (10.3 Curie) at a distance of 83 cm |
|-------------------------------------------------------------|
| **Measured** | 75.504 mSv/h (±0.98%) |
| **Theory$^{[37]}$** | 76.894 mSv/h |
| **Calculated (EGS5)** | 75.327 mSv/h (±1.11%) |

**Figure 3:** Calculated ambient dose rate (mSv/h) of fabricated clay-polyethylene for single-photon energy compared to ordinary concrete and theoretical value

**Figure 4:** Average photon energy (keV) of fabricated clay-polyethylene (blue dotted line), concrete (black dotted line), and without a sample (full red line). With 8 cm of concrete and clay, the transmitted average photon energies are 272.2 and 282.9 keV, respectively.
In terms of attenuation coefficients $\mu$, the value for ordinary concrete was higher by 15.5% and 7.25% compared to clay and clay-polyethylene, respectively, due to its higher density. However, clay offers a much lighter mass than ordinary concrete for a similar photon attenuation value. For calculated ambient dose equivalent, the agreement of calculated with theory and measured value with the average difference of 1.37% ambient dose rate in the air is adequate to satisfactory to legitimize or approved our next simulations for photon dosimetry with concrete and our fabricated clay material for Ir-192. From the simulation, all the calculated ambient dose rates have an error of $<1\%$, and the average reflected photon energy is 130.5 keV. The impact of reflected photon energy and its dose rate from both types of clays will be further investigated.

Acknowledgment
We would like to express our gratitude to Universiti Sultan Zainal Abidin (UniSZA) for supporting and funding this research under Dana Penyelidikan Universiti (DPU) Research Grant (UniSZA/2020/DPU2.0/07).

Financial support and sponsorship
Nil.

Conflicts of interest
There are no conflicts of interest.

REFERENCES
1. George LS, Charles FB, Ruben WP. The use of lead as a shielding material. Nucl Eng Des 1970;13:3-145.
2. Hyun SJ, Kim KJ, Jahnig TA, Kim HJ. Efficiency of lead aprons in blocking radiation – How protective are they? Heliyon 2016;2:e00117.
3. Abdul Aziz MZ, Yani S, Haryanto F, Ya Ali NK, Tajudin SM, Iwase H, et al. Monte Carlo simulation of X-ray room shielding in diagnostic radiology using PHTS code. J Radiat Res Appl Sci 2020;13:704-13. [doi: 10.1080/16878507.2020.1828020].
4. Wani AL, Ara A, Usmani JA. Lead toxicity: A review. Interdiscip Toxicol 2015;8:55-64.
5. Billen P, Leccisi E, Dastidar S, Li S, Lobaton L, Spatari S, et al. Comparative evaluation of lead emissions and toxicity potential in the life cycle of lead halide perovskite photovoltaics. Energy 2019;166:1089-96.
6. Flora G, Gupta D, Tiwari A. Toxicity of lead: A review with recent updates. Interdiscip Toxicol 2012;5:47-58.
7. McCaffrey JP, Mainegra-Hing E, Shen H. Optimizing non-Pb radiation shielding materials using bilayers. Med Phys 2009;36:5586-94.
8. Yue K, Luo W, Dong X, Wang C, Wu G, Jiang M, et al. A new lead-free radiation shielding material for radiotherapy. Radiat Prot Dosimetry 2009;133:256-60.
9. Soylu HM, Lambrecht FY. Gamma radiation shielding efficiency of a new lead-free composite material. J Radioanal Nucl Chem 2015;305:529.
10. Singh AK, Singh RK, Sharma B, Tyagi AK. Characterization and biocompatibility studies of lead free X-ray shielding polymer composite for healthcare application. Radiat Phys Chem 2017;138:9-15.
11. Chang L, Zhang Y, Liu Y, Fang J, Luan W, Yang X, et al. Preparation and characterization of tungsten/epoxy composites for γ-rays radiation shielding. Nucl Instrum Methods Phys Res Sect B Beam Interact Mater Atoms 2015;89-93:356-7.
12. Tajudin SM, Tabbakh F. Biological polymeric shielding design for an X-ray laboratory using Monte Carlo codes. Radiol Phys Technol 2019;12:299-304.
13. Olukotun SF, Gbenu ST, Ibitoye I, Oladejo OF, Shittu HO, Fasasi MK, et al. Investigation of gamma radiation shielding capability of two clay materials. Nucl Eng Tech 2018;50:957-62.
14. Tajudin SM, Aminordin Sabri AH, Abdul Aziz MZ, Olukotun SF, Ojo BM, Fasasi MK. Feasibility of clay-shielding material for low-energy photons (Gamma/X). Nucl Eng Tech 2019;51:1633-7.
15. Tajudin SM, Aminordin Sabri AH, Abdul Aziz MZ, Tabbakh F. Gadolinium-doped polymeric as a shielding material for X-ray. IOP Conf Ser Mater Sci Eng 2021;1106:1-6.
16. Kaura T, Sharmah J, Singha T. Review on scope of metallic alloys in gamma rays shield designing. Prog Nucl Energy 2019;113:95-113.
17. Agar O, Sayyed MI, Akman F, Tekin HO, Kaçal MR. An extensive investigation on gamma ray shielding features of Pd/Ag-based alloys. Nucl Eng Tech 2018;51:853-9.
18. Sayyed MI, Kaky KM, Sakar E, Akbaba U, Taki MM, Agar O. Gamma radiation shielding investigations for selected Germanate glasses. J Non Cryst Solids 2019;512:33-40.
19. Bashter II. Calculation of radiation attenuation coefficients for shielding concretes. Ann Nucl Energy 1997;24:1389-401.
20. Kurudirek M, Chakrathapuram N, Laopaiboon R, Yenchai C, Bootjomchai C. Effect of Bi203 on gamma ray shielding and structural properties of borosilicate glasses recycled from high pressure sodium lamp glass. J Alloy Comp 2018;745:355-64.
21. Ersundu AE, Büyükyıldız M, Çelikbilek Ersundu M, Sakar E, Kurudirek M. The heavy metal oxide glasses within the WO3-MoO3-TeO2 system to investigate the shielding properties of radiation applications. Prog Nucl Energy 2018;104:280-7.
22. Olukotun SF, Gbenu ST, Oladejo OF, Sayyed MI, Tajudin SM, Amosun AA, et al. Investigation of gamma ray shielding capability of fabricated clay-polyethylene composites using EGS5, XCOM and Phy-X/PSD. Radiat Phys Chem 2020;177. doi: 10.1016/j. radphyschem.2020.109079.
23. Available from: https://physics.nist.gov/cgi-bin/Star/compos.pl. [Last accessed on 2021 Apr 18].
24. Hirayama H, Namito Y, Bielajew AF, Wilderman SJ, Nelson WR. EGS5 code system. SLAC Report SLAC-R-730 and KEK Rep. 2005. Vol 8; 2010.
25. Tajudin SM, Aminordin Sabri AH. SIMU-RAD programme: A learning tool for radiation (photons and charged particles) interaction. J Pol Soc Radiophyschem.2020.109079.
26. Nnuka EE, Enejor C. Characterization and properties of borosilicate glasses recycled from high pressure sodium lamp glass. J Alloy Comp 2018;745:355-64.
27. Nelson WR, Field C. Comparison of EGS5 simulations with experiment. Nucl Eng Technol 2018;50:957-62.
28. Tajudin SM, Tabbakh F. Biological polymeric shielding design for an X-ray laboratory using Monte Carlo codes. Radiol Phys Technol 2019;12:299-304.
29. Weber G, Bräuning H, Martin R, Spillmann U, Stöhlin TK, Monte...
Carlo simulations for the characterization of position-sensitive x-ray detectors dedicated to Compton polarimetry. Phys Scr 2011;2011:3. doi: 101088/0031-8949/2011/T144/014034.

30. Japan Radioisotope Association. Radioisotope Pocket Data Book. 11th ed. Tokyo: Maruzen; 2011. p. 22-100.

31. Olukotun SF, Gibenu ST, Oladejo MF, Balogun FO, Sayyed MI, Tajudin SM, et al. The effect of incorporated recycled low density polyethylene (LDPE) on the fast neutron shielding behaviour (FNSB) of clay matrix using MCNP and PHITS Monte Carlo codes. Radiat Phys Chem 2021;182. Available from: https://doi.org/10.1016/j.radphyschem.2021.109351. [Last accessed on 2021 May 25].

32. Gerward L, Guilbert N, Jensen KB, Leving H. WinXComda Program for calculating X-ray attenuation coefficients. Radiat Phys Chem 2004;71;653-4.

33. Aminordin Sabri AH, Tajudin SM. Simulation of photon attenuation through aluminium using E-radiation simulator (EGS5 Code). J Fundam Appl Sci 2019;1:173-83.

34. Available form: https://icru.org/. [Last accessed on 2021 Apr 18].

35. Aminordin Sabri AH, Abdul Aziz MZ, Olukotun SF, Tabbakh F, Tajudin SM. Study on the shielding materials for low-energy gamma sources. IOP Conf Ser Mater Sci Eng 2020;785:1-7.

36. Rijnders A. Photon sources for brachytherapy. In: Lemoigne Y, Caner A, editors. Radiotherapy and Brachytherapy. NATO Science for Peace and Security Series B: Physics and Biophysics. Brussels, Belgium: Springer; 2009. p. 185-93.

37. Babasaheb A. Measurement of mass and linear attenuation coefficients of gamma-rays of AL for 514, 662 and 1280 keV photons. J Chem Pharm Res 2011;3:899-903.