Evaluation of scattering effects for radiation shielding or filter materials by using Monte Carlo simulation

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Abstract. Most radiology departments utilize ordinary concrete and lead for radiation shielding as the primary radiation can be reduced through photon absorption. There are many studies done focusing on the transmitted photons that penetrate the shielding materials for radiation shielding. However, the scattering from the shielding materials would be ignored. When high-energy photons impinge on thick shields, most of the incident energy is absorbed in the shielding materials, but some of it can also be deflected sideways or in a backward direction. This is important as the backscatter radiation can contribute to unnecessary additional radiation dose to healthcare workers. Hence, this study evaluates several shielding materials namely aluminium, iron, copper, lead, ordinary concrete, and heavy concrete particularly for its attenuated and scattered photons for radiation shielding. The shielding materials were evaluated using the Monte Carlo simulation, specifically PHITS code. In the simulation, all shielding materials were modelled as a fixed 30 x 30 cm rectangular shape with a fixed thickness of 10 cm. Mono-energy and pencil beam photon energies ranging from 100 keV until 1 MeV were directed to the shielding materials. As a result, at 100 keV, lead shielding showed the least amount of transmitted dose compared to other shielding materials. However, lead shielding also showed the highest reflected dose at the same incident photon energy. As copper showed the least amount of reflected dose at this incident energy, hence applying a thin layer of this material to lead shielding can tolerate the compromise between low transmitted dose and high reflected dose. Therefore, this can improve the radiation shielding at various irradiation facilities. In conclusion, the reflected dose for all materials studied will increase or higher when the incident photon energy increase, except for lead as well as for low-Z element materials rather than high-Z element materials.

1. Introduction

Ordinary concrete and lead are commonly used as shielding materials in the radiology department to reduce the primary radiation by photon absorption or transmission. Although primary radiation can be reduced, the photons might also be scattered either by transmission or reflection from the shielding materials themselves. Many studies were done focusing on the efficacy of the shielding materials in...
attenuating photons for radiation shielding, specifically for the transmitted photons that passed through the shielding materials. The scattering effects from the shielding materials were often ignored, such as backscattered radiation. Backscattered radiation can be a source of unnecessary additional radiation dose to the workers that may stay inside the irradiation room. Therefore, this study not only focuses on the photon attenuation but also the scattered radiation by evaluating shielding materials that would produce the least scattered radiation by using the PHITS code to improve the radiation shielding.

Lead (Pb-82) material in the order of millimeters thickness had been widely used since 1970 to attenuate the photons either to shield the emission of photons from radioactive source or used in a large scale to shield the room [1,2]. While attenuate the photons, the lead material itself is poisonous and expensive [3, 4,5]. Many scientists had proposed other materials to replace the lead element as a gamma or X-ray shielding such as clay [6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. As an example, the authors had successfully demonstrated the polymeric compounds doped with heavy element other than lead as an alternative shielding material for 150 keV photons with an affordable thickness [16, 17].

In this study, the reflected photons and ambient dose equivalent (Sv/photon) were evaluated by Monte Carlo simulation (PHITS code [18]) for several commonly used shielding or filtering materials. This outcome enabled us to shield properly the photons that transmitted and reflected by the material in our facility.

2. Calculated Transmitted Photons of the Elements
For verification of our Monte Carlo code with theory and literature data, we calculated the percentage of transmitted photon after the elements such as Gd-64 and Pb-82 for single-photon energy of 150 keV photons. Figure 1 shows the materials geometry was modelled as rectangular shape with a pencil beam of mono-energy photons was incident to the center of element. The distance was set at 20 cm from the surface of material. All the main photon’s interaction, such as photoelectric absorption, Compton scattering (including Rayleigh scattering), and pair productions were considered in our calculation. The scattered photons that penetrate the material were ignored for comparison with the attenuation coefficients generated by XCOM [19].

![Figure 1](image-url)  
**Figure 1.** Simulation geometry modeled in simulation for estimating the effect of elements on the transmitted and scattered photons.
Figure 2 shows the calculation of transmitted photons as a function of material thickness for a pencil beam of 150 keV photon. From this graph, it can be seen that the percentage of calculated transmitted photon decreased exponentially with increasing thickness of material. Then, the data were fitted with an exponential equation to obtain the value of the linear attenuation coefficient ($\mu; \text{cm}^{-1}$). Overall, the calculated $\mu$ value has a good agreement, within 1% with the XCOM as in Table 1. This indicates that the $\mu$ value calculated by the simulation was reliable and verified to be used for the study of photon interactions between radiations and energy within the material.

![Graph showing the calculation of transmitted photons](image)

**Figure 2.** The calculated transmitted photons of Pb-82 and Gd-64 for photon of 150 keV. Calculated $\mu$ values are 22.93 cm$^{-1}$ and 8.694 cm$^{-1}$ for Pb-82 and Gd-64, respectively.

**Table 1.** The percentage difference of linear attenuation coefficient for Gd-64 and Pb-82 at 150 keV.

| 150 keV | Linear Attenuation Coefficient ($\mu; \text{cm}^{-1}$) | PHITS | XCOM | % of Difference |
|---------|-----------------------------------------------------|-------|------|----------------|
| Gd-64   |                                                     | 8.694 | 8.690| 0.05           |
| Pb-82   |                                                     | 22.931| 22.839| 0.40           |

3. **The Transmitted and Reflected Photon Dose of Several Materials**

It is necessary to understand the source and mechanism through which the radiation is attenuated. This is important when determining the best shielding material for that particular radiation as several factors will influence the effectiveness of shielding such as the energy of the radiation and the atomic number of the shielding element. Figure 3 shows a graph of the transmitted dose as a function of incident photon energy from 100 keV to 1 MeV. Based on the graph, it can be seen that as the incident photon energy increased, the transmitted dose also increased for all shielding materials. This means that the higher the energy of the incident photon, the lower the amount of photon that can be trapped or absorbed by the shielding materials.

At 600 keV, the transmitted dose from Al-13 is higher within 13% compared to ordinary concrete. Heavy concrete is significantly effective to attenuate photons compared to ordinary concrete particularly...
at low energy region. At 400 keV, the transmitted dose from heavy concrete is lower about 77% compared to ordinary concrete while at 1 MeV, the transmitted dose from heavy concrete is 42% lower than ordinary concrete. In the case of an element, Fe-26 and Cu-29 show almost similar ability in photon attenuation as their Z number are close each other. At 500 keV, the transmitted dose for Cu-29 is 100% lower than Fe-26 while at 1 MeV, the transmitted dose for Cu-29 is 36% lower than Fe-26. Lead has the least amount of transmitted dose among other materials as it has the highest atomic number. As photoelectric effects is more dominant in materials with higher atomic number, lead can trap more photons than other materials. Hence reducing the number of transmitted photons.

Figure 3. The calculated transmitted dose (Sv/inc./cm²/s) as a function of incident photon energy for several elements.

Reflected photons are scored as a result of Compton scattering photons with a large angle within the materials. The probability occurs the scattered photons depends on the incident photon energy and the atomic number of the materials. As the reflected scattered photons can be a source of unnecessary additional radiation dose to the patients and workers that may stay inside the irradiation room, or close to the shielding material, therefore it is important to evaluate the reflected photons in terms of their dose and energy. Figure 4 shows a graph of reflected dose as a function of incident photon energy for shielding materials Al-13, Fe-26, Cu-29, Pb-82, ordinary concrete, and heavy concrete. Based on the graph in Figure 4, it can be seen that the reflected dose from all studied materials increased when the incident photon energy increased, except for Pb-82.
Figure 4. The calculated reflected dose (Sv/inc./cm²/s) as a function of incident photon energy for several elements.

In general, the reflected dose from all studied materials will increase as the incident photon energy increase, except for Pb-82. Although Pb-82 has the least transmitted dose, but at 100 keV, Pb-82 show the highest amount of reflected dose among the materials, which almost similar to Al-13 and ordinary concrete. This is because, low energy photon is unable to penetrate far within the lead material, which means most of photon interactions will occur only at the surface of lead. Therefore, the Compton scattered photons could easily exit the lead material as reflected photons. It was expected that the reflected dose from lead material will be higher for lower incident photon energy. Low Z element such as Al-13 and ordinary concrete, which commonly used as a shielding material show higher reflected dose among other material, in wide energy range. As the thickness of material does not affect the intensity of reflected dose, hence a thin layer of suitable material is enough to reduce the backscatter.

4. Conclusion
In conclusion, the intensity of scattered and backscattered radiation is affected by both the atomic number of shielding materials and the energy of the incident photon. An approach of photon calculations either outside or inside of an X-ray room must be considered when designing a radiation shielding to ensure radiation safety area. When photons impinge on shielding materials, most of the incident photon energy is absorbed within the material. But some photons at certain intensity and energy value could be scattered or back-scattered after undergoing Compton scattering interaction inside the material. The shielding materials must be studied both for its transmitted and reflected photons particularly if the shielding compound has a higher Z element or the source is higher energy photons.

For all shielding materials studied, lead has shown the best ability at attenuating photons at every incident photon energy compared to other materials. Furthermore, the reflected dose will increase or higher when the incident photon energy increases, except for lead (Pb-82). In addition, the reflected dose will also be higher for low-Z element materials rather than high-Z materials. Lead element has shown a high reflected dose in comparison to other material at 100 keV. Ordinary concrete that is commonly used as shielding material for an irradiation room shows the highest reflected dose in a wide photon energy range. From a radiation protection point of view, the reflected photon component is important to be evaluated. This is because the concrete walls closest to the radiation source could likely be the most significant contributors to the scattered radiation at the patient location. The unnecessary radiation dose given to the patient, especially workers that may stay near the shielding material may
cause radiation-induced skin injuries, cataracts development, cardiovascular diseases, and radiation-induced necrosis.

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