Gadolinium-doped polymeric as a shielding material for X-ray

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Abstract. A relatively new polymeric base compounds (CₙH₂ₙ) had been proposed as a shielding material for 150 keV photon for an X-ray laboratory. When doped with 8% gadolinium (Gd), a thickness of 2 cm shielding compound (6 g cm⁻³) could attenuate more than 90% of the incident photons with an average dose rate reduction of more than 88% for 150 keV incident photon. While considering the transmitted photons after the shielding, it is necessary to account for reflected photons and its dose contribution. The reflected photons and ambient dose equivalent were calculated for single-photon energy of 150 keV and an X-ray of 150 kVp. The shielding compound was successfully attenuated most of the incident photon energies particularly below 90 keV. In both cases of photon sources, two significant reflected photon peaks at ~40 and 50 keV were observed as a result of Gd characteristic X-rays. A Compton scattered photon at energy of 95 keV appeared as a result of large scattering angle within 130° - 140° for 150 keV incident photons. Thus it is necessary to add a thin inner layer at the source-facing side of the shielding compound to shield the radiation workers and patient inside the X-ray room during the X-ray procedure. An iron layer with thickness of 0.5 cm was adequate to shield almost completely the reflected photons and ambient dose for X-ray 150 kVp source.

1. Introduction

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], such as at UniSZA X-ray laboratory (150 kVp). While attenuate the photons, the lead material itself is poisonous and 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]. As an example the authors had successfully demonstrated the polymeric compounds doped with heavy element other than lead as an alternative shielding materials for 150 keV photons with an...
affordable thickness [15]. The gadolinium (Gd-64)-doped polymeric compounds had been calculated by the authors to have ~90 % photon attenuation with less than 2 cm thickness for 150 keV incident photon, which will be adequate for shielding an X-ray room.

While Gd-doped the polymeric compounds is successfully attenuated the transmitted photons significantly, the impact of reflected photons due to the polymeric compounds itself need to be evaluated to ensure the radiation safety area either outside or inside of the irradiation facility. The medical radiation workers may need to attend to the patients inside the room during an X-ray procedure such as fluoroscopy, thus the effect of reflected photons and its dose must be evaluated. As an example, the author had concluded the contribution of reflected photons and dose from the clay material is negligible for low energy photon [16].

In this study, the reflected photons and ambient dose equivalent (Sv/photon) were evaluated by Monte Carlo simulation (EGS5 code, [17]) for the previous recommended thickness of Gd (8 %) doped-polymeric compounds (6 g cm$^{-3}$). The selection photon energy of 150 keV is based on our X-ray machine at UniSZA which have maximum setting of 150 kVp. The energy used is closed to the one who used Co-57 gamma source (0.0144 keV, 0.122 keV and 0.136 keV photons). We also include the calculation for X-ray of 150 kVp. Consequently, an additional layer of light element at the inner side (source-facing side) of the polymeric compounds is important to avoid unnecessary dose due to reflected photons. This outcome enabled us to shield properly the photons that transmitted and reflected by the Gd doped-polymeric compound in our facility.

2. Calculation of transmitted and reflected photon energy spectra of 150 keV photon

It was assumed Gd element might have kind of ‘reflective effect’ to the photons. As example, Gd had been used as a reflective material coating for X-ray mirror in some applications [18]. Thus we investigated the photons energy and dose that reflected from the shielding compound. As recommended in previous study, for subsequent calculations, a thickness of 2 cm shielding Gd-doped polymer compound (10 cm x 10 cm x 2 cm) was chosen for 150 keV parallel photon beams. Surface crossing was used to calculate the reflected dose and photon spectra on the surface of 2 x 2 cm$^2$ scoring region.

Figure 1 shows the intensity of transmitted and reflected photon spectra when a parallel beam of 150 keV incident photon pass through a 2 cm thickness of gadolinium (Gd). The detector response was not considered in the calculated photon spectra. The dotted and full lines of the Figure 1 represent transmitted and reflected photons, respectively. The transmitted and reflected average energy is 145.5 keV and 73.4 keV, respectively. A very small reflected peak of 150 keV photons appeared as a result of backscattered photons as represent by the full line.

In both cases, two peaks at 40 and 50 keV photons are evidence due to the emission of K-L X-rays and K-edge X-rays of Gd element doped in the polymer. The tendency of characteristic X-rays to be reflected after undergoing Compton scattering interactions in the polymer is higher than the transmitted photons by a factor of 10. It should be noted that the y- axis of the graph was plotted in log scale. The dominant of reflected photon energies for 40 keV, 50 keV and 95 keV values could be easily absorbed by the human body and contribute to an additional whole body dose particularly for the radiation workers who are working inside the shielding environment. Thus, it is necessary to have an additional layer of low Z element at the inside surface of the polymer (on the face side of photons beam) to attenuated such effect.
Figure 1. The transmitted and reflected photon spectra for a Gd-doped polymer. A very small peak for backscattered photon of 150 keV photon was observed. A dominant reflected photon peaks were observed at ~95 keV as a result of Compton scattered with large angle (130 – 140°). The peak at ~ 40 and 50 keV due to the K characteristic X-rays of Gd doped in the polymer.

3. The transmitted and reflected photon energy spectra of 150 kVp X-ray
Report 78 Spectrum Processor of IPEM 1997 software [19] was used to obtain the unfiltered X-ray spectra as a source input for EGS5 code as shown in Figure 2. Figure 3 (a) and (b) shows the intensity of transmitted and reflected photon spectra of X-ray 150 kVp. In Figure (a), 2 cm of Gd-doped polymer significantly attenuated the photons below 90 keV of an X-ray spectra. The reflected photon spectra show a significant contribution of the K characteristic X-rays in comparison to the transmitted one as previous spectra. The second peak of Compton scattered photon at ~95 keV not evidence as the average energy X-ray of 150 kVp is ~ 50 keV. The reflected peak at ~95 keV (as a result of 120-130° scattering angle) from the Compton scattered photons will be appear, as an example when utilized a monoenergetic source such as Co-57. The energy of Compton scattered photon at the similar scattering angle will be higher up to ~ 200 keV when a higher energy gamma sources used such as Cs-137 and Co-60 as per Compton scattering equation.

Figure 2. X-ray photon spectra of 150 kVp as a source input in the calculation. The average energy is 49.8 keV. The X-ray spectra was adopted from Report No. 78 [19].
4. Designing an inner layer of the Gd-doped shielding compound

Having confirmed through simulation that the Gd-doped polymer compound has significant reflected photons at lower energies photons due to K characteristic X-rays and Compton scattered photons at large scattering angle, the next step is to configure the material as inner layer and apply it to the current shielding problem. The layer should be applied at the inner side of the wall shielding (Gd-doped polymer compound) of an X-ray facility. As example, a thin layer of Fe-26 with thickness of 0.5 cm was sufficient to attenuate the reflected photons at 40 and 50 keV as shown in Figure 4. The reflected peak of K-L X-rays at 40 keV photon almost completely disappeared while the reflected K-edge peak of 50 keV photon was reduced almost by a factor of 10. The reflected peak at 7 keV is due to the emission of Fe-26 K-edge and will be attenuated easily as a function of distance in air.

Our finding supported McCaffrey’s study [20] when the author had suggested a bilayer non-Pb shielding in the order of low Z and followed by high Z element to have a good gamma attenuation while not mention the reflected one.

Figure 4. Figure show the reflected photon spectra with (dotted line) and without (full line) the inner layer added to the Gd-doped shielding compound. Both reflected photons at ~40 and 50 keV photons were successfully attenuated with 0.5 cm iron (Fe-26).
5. Conclusion

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. 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. The Gd-doped polymeric compound has a significant reflected K characteristic X-rays at ~40 and 50 keV photons. If the source is a monoenergetic source such as Co-57 with the energy more than 120 keV, another significant Compton scattered peak will be reflected to have an energy ~ 95 keV due to large scattering angle within 130 – 140°. Thus an additional layer is necessary for the inner side of the attenuating materials. The shielding compound density and thickness have no effect on the intensity and energy of reflected photons. A thin layer of iron with 0.5 cm thickness is adequate to attenuate such effect significantly.

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