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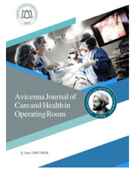

Original Article

Designing Flexible Shield From Lead With High Protection Against X-rays in Operating Room Using Monte Carlo Simulation

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Abstract

Background: The use of non-flexible lead shields in X-ray detection systems requires a high cost, and it is heavy and subject to frequent cracks and fractures. Therefore, the shield should be designed in a way that has less weight, appropriate efficiency in reducing ionizing radiation, and a more reasonable price.

Methods: In the operating room using the MCNPX (Monte Carlo N-Particle extended) code, the shield compounds were modeled to determine the optimal composition (with less weight, higher efficiency in removing ionizing radiation, and in more appropriate price), and then the amount of dose was calculated around the lead chamber with 10 cm from the walls of a detection system.

Results: Using a weight combination of 80% lead and 20% polyvinyl chloride was a suitable option in the diagnostic radiology domain which has less weight, lower cost, and good efficiency in reducing X-rays compared to lead shields.

Conclusion: The amount of dosage rate on all sides outside the chamber became less than 1 μSv/h, indicating that the combination of lead and polyvinyl chloride is suitable for the body of the chamber.

Keywords: Operating room, Simulation, Monte Carlo, Flexible shield, Lead, X-ray

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Introduction

Today, air, sea, and land transportation are important parts of the world economy. Annually, a large volume of cargo such as food, industrial components, and the like is exchanged among countries using ships, plains, railroads, or land. Hence, complete control must exist over these exchanges so that the entry or exit of unauthorized goods is prevented. One of the common and effective ways used in Customs Organization is the use of Gamma rays at entry and exit points of the countries (1-4).

Photon rays easily penetrate inside closed containers and provide a clear image of the contents inside them. Among the important advantages of such systems, we can refer to extremely high inspection accuracy, high scanning speed, and the need for very few crew for inspection. The accuracy of these systems is so high that methods of hiding drugs inside other materials, poisoning drugs to make them unidentifiable by search dogs, and the like are not effective. For these reasons, these systems are considered the best type of scanning in the world (5-9).

Despite the wide application of these rays, due to their ionizing nature and the biological damages that they incur in the body of living organisms, using suitable protection against them seems to be necessary to prevent their radiation to the body. Lead is one of the best insulators against X-rays, which is used in manufacturing most radiation shields. However, the high cost, on the one hand, and the lack of flexibility of the lead, on the other hand, will create problems regarding its widespread use in the required shields. As a result, an attempt is made to manufacture flexible lead and non-lead absorbers against medical ionizing rays. To this end, composites are one of the most appropriate and widely used materials for making shields of ionizing radiations with desired mechanical properties.

A composite material is a physical compound at a macroscopic scale that is obtained from two or more different materials. In the simplest form, a composite includes a polymer base and one or more components that function as fillers (10-20).

Lead is the most widely used material for radiation protection in diagnostic radiology because its ability to attenuate x-rays is superior to other materials due to its high atomic number, high density, and higher economic affordability. However, lead shields have serious disadvantages such as high toxicity, heavy weight, poor flexibility, and low chemical stability. These disadvantages have stimulated extensive research on the use of non-lead composite shields. Some materials and compounds were proposed as alternatives to lead in X-ray shields, and their effectiveness in removing the limitations of standard lead shields was explored (21,22).

To ensure the amount of leaked dose within the permissible limit, polymer layers of flexible lead must be placed in the body of the chamber. Therefore, the thickness of these layers must be calculated accurately so that they can reach the leaked dose within the permissible limit. In recent years, several research and commercial teams have been trying to provide lead shields with sufficient capability to reduce the radiation dose, on the one hand, and efficient production cost, on the other hand. Although some products with limited applications have been produced, research and attempts have been made in this field to produce better products with wider applications. Given these needs, this study attempted to design a flexible lead shield and investigate its photon attenuation properties using the Monte Carlo Simulation method. Thus, this study aimed to design a combination of lead and polyvinyl chloride to provide appropriate protection in the field of diagnostic radiology with less weight, lower cost, and more appropriate efficiency in reducing X-rays compared to lead shields.

Materials and Methods

In the operating room, the MCNPX (Monte Carlo N-Particle extended) code was used to simulate the designed shield, and the Monte Carlo method was used to check the transmitted dose (leak). This simulation was performed for a spring with a maximum energy of 100 keV. First, a chamber with dimensions of 100 × 100 × 100 cubic centimeters was simulated. The location of the outer walls of the lead chambers in three directions of X, Y, and Z was -50 50 -50 50 -50 50, respectively. The thickness of the walls is one millimeter, which was made of pure lead. Furthermore, the combinations of lead-polyethylene, lead- polypropylene, and lead-polyvinyl chloride were considered (Table 1). Next, a point source with a radiation field of 10 × 10 square centimeters was placed in a chamber with dimensions of 1 cubic meter. The coordinates of the desired spring were 0, 10, and 49.80, and the direction of the ray radiation was downwards (vec 0 0-1), as depicted in Figure 1.

To simulate the dosimeters required for calculating the outgoing dose in each direction, it is necessary to place the collimators and metals in the direction of the movement of photons toward the inside of the chamber to prevent the scattering of the photons and also absorb some of the energy of the photons. By passing through the filters that are placed in the conductor, photos release some dose inside and outside the chamber.

Detectors are considered at different distances of the lead chamber (top, bottom, left, and right). Detectors No. 3 and 4 are respectively located in the coordinates 0 -60 0 and 0 70 0, detectors No. 5, 6, and 7, in coordinates 60 -10 0, 60, 0 0, -60 -10 0, and detector No. 8 is located in coordinates 60 0 0. It should be noted that all the distances mentioned above were measured in centimeters.

Table 1. Composition and Weight Fraction of Lead and Lead Flexible Materials Used as Shield

Materials	Composition	Density (g/cm³)	Absorption Edge (keV)
Pb	100% Pb	11.34	88
Pb-PVC	80% Pb, 20% PVC	4.74	68

Note. Pb: Lead; PVC: Polyvinyl chloride.

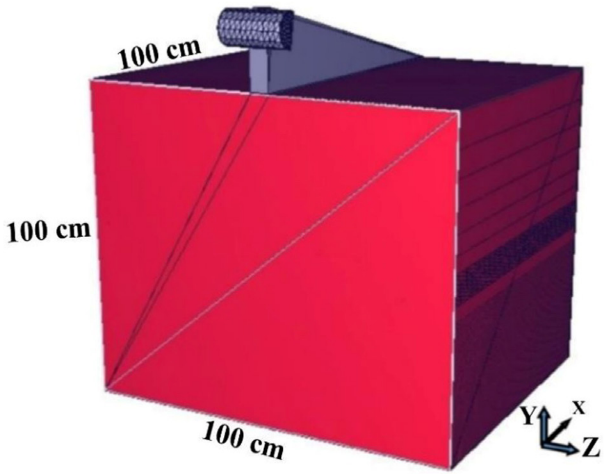

Figure 1. A Schematic View of the Lead Chamber with a Point Spring Inside

Assuming that the number of photons emitted from the anode in one second is 0.001 per electron collision, if the flow of electrons from the cathode to the anode is 1.5mA, we will have

$$1.5\ mA = 1.5\times10^{-3}\frac{c}{s\times\frac{1e}{1.6\times10^{-19}c}} = 9.4\times10^{15}e/s \tag{1}$$

Therefore, the number of photons that are emitted from the surface of the anode in one second is obtained from the following equation.

$$Np = 1\times\frac{10^{-3}}{e}p\times9.4\times\frac{10^{15}}{s}e = 9.4\times10^{12}\,p/s \tag{2}$$

The output information was determined by F5 (photon flux) and * F8 (delivered energy). To carry out each program, about one million photons with different energy levels were checked and assessed using the MCNPX code so that the resulting error is as small as possible. In the end, the energy spectrum of photons passing through different shields was drawn using MATLAB software.

Results

Figure 2 shows the photo flux diagram of the lead shield in terms of energy. As can be seen in this figure, the reduction of the photons is quite noticeable at low energy levels, but the reduction of passing photons is low at high energy levels (above 70 keV). Figure 3 presents the photon flux diagram of different lead-based composites such as polyethylene, polypropylene, and polyvinyl chloride in terms of the energy of the radiation ray.

For the 100 keV rays, the results obtained from this study showed that the greatest decrease in the intensity of the rays is related to the weight compound of 80% lead and 20% polyvinyl chloride, which significantly reduced the flux of passing photons at energy levels above 80 keV (Figure 3).

In the MCNP code output, any value of the result that was calculated by the MCNP code must be multiplied by the value of 9.4×10^{12} to obtain the actual dose or dose rate.

The amount of assigned energy (Tally *F8) was calculated at 10 cm from the body compartment (chamber) using MCNPX. To this purpose, cells as the detectors were considered around the chamber (four sides of the chamber), and the amount of dose rate passing the lead chamber was calculated in each cell. Figure 1 demonstrates the simulated geometry of the cells (detectors) around the chamber.

Given the energy and the current of electrons emitted towards the anode, which are 100 keV and 1.5 mA for this system, respectively, some photons are emitted outward from the surface of the anode. As explained above, collimators and metals must be placed in the direction of the movement of the photons toward the inside of the chamber to prevent the scattering of the photons and absorb a small percentage of the energy of the photons. Photons release or emit some dose inside and outside the chamber while passing through the filters. Table 2 shows the values of the corresponding dose rates using equation 2 for pure lead shields and the combination of lead with polyvinyl chloride.

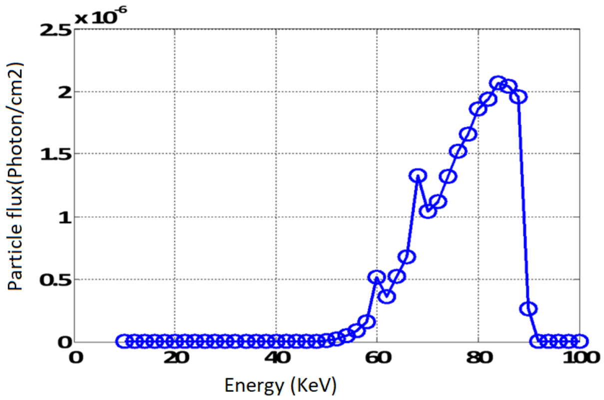

Figure 2. Photon Beam Flux Diagram Passing through the Lead Shield in Terms of Energy Using Tally F5 in MCNPX Code

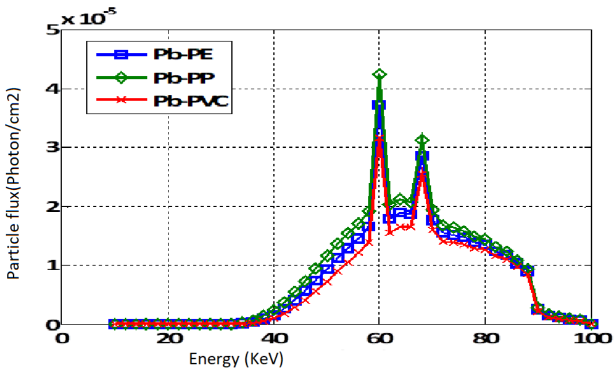

Figure 3. Photon Beam Flux Diagram Passing through Lead Shields with Polymer Base in Terms of Energy Using Tally F5 in MCNPX Code. *Note.* Pb: Lead; PE: Polyethylene; PP: Polypropylene; PVC: Polyvinyl chloride

Discussion

The simulation (modeling) results indicated that the rate of the dose (leak) is maximum exactly in the direction of the radiation beam which is the location of detector No. 3. At the same time, the amount of dose (leakage) in other parts (top, left, and right) of the chamber declined. In addition, the results of the simulation revealed that the dose is less than the permissible limit in all areas around the chamber. As Table 1 demonstrated, the amount of dose outside the chamber made of lead and polyvinyl chloride on all sides is much less than 1 µSv/h (except detector No. 3 which is located in the direction of the radiation beam).

Pure lead was simulated as a reference just for comparison with other composites but not discussed in this part because it is not used in apron shields in pure form. The composition of protective layers in the lead and non-lead aprons is mostly confidential for commercial products. The proposed material analysis methods can approximately determine the elements and their weight ratios (15-22). The results of this simulation revealed that the reduction of photons at low energy levels is quite noticeable, but the rate of reduction of passing photons decreased at high energy levels (above 70 keV). This phenomenon occurs due to the K absorption edge effect of the lead, the value of which is 88 keV.

For 100 keV X-rays, the results obtained from this study showed that the greatest decrease in the intensity of the rays is related to the weight compound of 80% lead and 20% polyvinyl chloride, which significantly reduces the flux of passing photons at energy levels above 80 keV. These findings illustrated that the efficiency of the composite-type shields is more dependent on the photon

Table 2. Dose Rate Values for Detectors around Enclosures with Two Different Materials

Detector Number	Coordinates (x,y,z)	Dose Rate for Lead Protection (Sv/h)	Dose Rate for Protection from Lead-polyvinyl Chloride (Sv/h)
3	0 -60 0	5.41×10^{-10}	2.76×10^{-9}
4	0 70 0	5.61×10^{-10}	3.09×10^{-9}
5 (along the beam)	0 10 -60	1.64×10^{-1}	1.76
6	0 0 60	1.37×10^{-8}	2.47×10^{-8}
7	0 -10 -60	1.06×10^{-9}	7.85×10^{-9}
8	0 0 6	2.64×10^{-10}	2.13×10^{-9}

beam energy than on lead-only type shields, as shown in previous research (11-15).

Conclusion

Considering the value of 2 μSv/h, the amount of radiation permitted in the controlled area (according to the international standards) and the area after this distance can be considered the controlled area. In this way, the imaging personnel should not approach at least less than two meters to the detector while imaging. All results obtained from the simulation in this study were obtained according to the statistical error of less than 2%. The combination of 80% lead and 20% polyvinyl chloride as an optimal shield for X-ray detection systems can reduce ionizing radiation, which is light, cost-effective, and efficient. However, the accurate choice of elements for a certain range of energy can significantly improve shielding per unit weight over conventional lead-content shields. The present study was conducted in an operating room based on the MCNP study. Therefore, further experimental study can support our findings.

Authors' Contribution

Conceptualization: Hossein Khosravi.
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Formal analysis: Hossein Khosravi, Karim Ghazikhanlu sani.
Funding acquisition: Hossein Khosravi, Karim Ghazikhanlu Sani, Safora Nikzad.
Investigation: Hossein Khosravi, Karim Ghazikhanlu Sani, Safora Nikzad, Salman Jafari.
Methodology: Hossein Khosravi, Karim Ghazikhanlu sani.
Project administration: Hossein Khosravi, Safora Nikzad, Salman Jafari.
Software: Hossein Khosravi.
Supervision: Hossein Khosravi, Karim Ghazikhanlu Sani, Safora Nikzad, Salman Jafari.
Validation: Hossein Khosravi, Karim Ghazikhanlu Sani.
Visualization: Hossein Khosravi, Karim Ghazikhanlu Sani, Safora Nikzad, Salman Jafari.
Writing–original draft: Hossein Khosravi, Karim Ghazikhanlu Sani.
Writing–review & editing: Hossein Khosravi, Karim Ghazikhanlu Sani.

Competing Interests

None.

Ethical Approval

The present study was reviewed at Hamadan University of Medical Sciences and was approved with the ethics ID of IR.UMSHA.REC.1397.547.

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