Volume 21, No 4 | International Journal of Radiation Research, October 2023

Evaluation of the radiation protection capability of a low density and non-Lead composite shield using Monte Carlo model

H. Khosravi[1*], K. Ghazikhanlu sani[1*], S. Jafari[1], S. Nikzad[2]

[1]*Department of Radiology, School of Allied Medical Sciences, Hamadan University of Medical Sciences, Hamadan, Iran*

[2]*Department of Medical Physics, School of Medicine, Hamadan University of Medical Sciences, Hamadan, Iran*

► ***Short report***

***Corresponding author:**
Hossein Khosravi, Ph.D. & Karim Ghazikhanlu sani, Ph.D.,
E-mail:
hkhosravi55@gmail.com, ghazi1356@gmail.com

Received: February 2023
Final revised: February 2023
Accepted: March 2023

Int. J. Radiat. Res., October 2023; 21(4): 833-836

DOI: 10.52547/ijrr.21.4.32

Keywords: *Radiation protection, shielding, X-ray, simulation.*

ABSTRACT

Background*:** This study aimed to evaluate the capability of a novel non-Lead composite shield with a lower density compared to commercial Lead shield to protect against 10-100 keV X-ray. ***Materials and Methods: In the present study, Monte Carlo calculations were performed to study the attenuation properties of a composite designed shield. For this reason, the attenuation rate of 8-material alloy including Tungsten, Bismuth, Barium, Gadolinium, Cesium, Cerium, Tin, and Antimony elements was compared to the 8-layers combination of these elements. Tungsten, Gadolinium, Cerium, and Bismuth were selected to simulate 4-layer and an alloy shields. The resulting X-ray fluence spectra attenuated by the designed shields were calculated. ***Results:*** Preliminary results showed that at the energy of 68 keV, the attenuation value by the 8-layer composition was 2.6 times higher than the value achievable by the alloy. It should be noted that the attenuation of 4-layer shield combined from Tungsten, Gadolinium, Cerium and Bismuth in the energy range of 72-100 keV, was 3.5 times higher than that of the alloy shield built from these elements. ***Conclusions:*** According to the results, a combination of Tungsten, Gadolinium, Cerium, and Bismuth materials can be effectively used to create non-Lead shields. The four-layer shield with higher density offers better attenuation compared to the alloy shield.

INTRODUCTION

Lead poisoning is a global issue. Lead is mainly absorbed by the body through digestion and respiration. According to available information, Lead is stored in the blood, bones, soft tissues, hair, nails, pancreatic secretions, bile, stomach, and testiness [1-3]. Lead is harmful to young people, children, and infants, as well as poses many risk to the mental development and nervous system. The permissible exposure level for Lead is 50 µm/cm^3 of air within 8-hours. The World Health Organization (WHO) has set an allowable threshold for adult blood Lead levels of 20 to 30 micrograms per deciliter [3-5]. Values greater than this range lead to biological effects, including effects on the formation cycle and inhibition of the activity of relevant enzymes, as well as the mitochondria of bone marrow cells [3-7].

In diagnostic radiology, Lead shields are used to protect personnel and patients from ionizing radiations. There has been evidence that the heavyweight of Lead caps puts a strain on radiation workers and causes long-term back and neck pain [1-7].

Lead is an excellent absorbent for X-rays in the energy range used in diagnostic tests, due to its high atomic number [8-13]. However, this material is known as a toxic substance that pollutes the environment [14]. In recent years, many studies have been conducted to find better materials with suitable radiation protection capability as an alternative to Lead. In this regard, various materials such as Tungsten, Bismuth, Lead, and Iron have been used. Among them, Bismuth and Tungsten have been introduced as good alternatives to lead in the low and high energy ranges. These two substances are not environmentally hazardous [5]. In McCaffrey *et al.*, study on the comparison of Lead shields with Lead-free shields showed that metals with high atomic numbers and low densities provided the highest possible shielding attenuation [6]. In addition, shields containing Sn and Ba weigh less than lead with proper shielding attenuation (equivalent to 0.5mm Lead) at 60 keV to 100 keV [6]. A comparison of Pb and W shields showed that shields containing pure W had better photon attenuation compared to the pure Lead shields at energies between 100 keV and 120 keV [6].

[DOI: 10.61186/ijrr.21.4.833]

In another study, Compared Lead aprons with Sn-containing and vapors containing 80% Sb and 20% Bi. In this study, three categories of beams with a voltage of 60, 75, and 120 keVwere used. Comparisons between the three types of robes showed that Sn-plated caps had less attenuation than the other two types, and Sn-plated and Bi coatings slightly increased the surface dose [15].

In Radiology clinics, it is needed to expose only a part of the patient's body while other parts are protected against hazardous radiation need to be protected against radiation in a radiological facility. Flexible non-Lead adsorbents are developed to protect against ionizing medical radiation. Among these, composites are more widely used for the protection of ionizing radiation with the desired mechanical properties. A composite material is a physical compound on a macroscopic scale obtained from two or more elements [16-19].

Multilayer attenuators have been used for "hardening" X-ray beams for many years. For example, Thoraeus filters employ an initial layer of tin combined with a second layer of copper and a third layer of aluminum. In these filters, the layers are placed in the beam in descending order of atomic number (Z), so that the subsequent layers can remove X-fluorescence beams originating from the higher Z layer upstream [1-10].

The present study aimed evaluate attenuation effects of various combinations of materials by Monte Carlo N-Particle (MCNP) simulations to design a Non -Lead composite shield, and indicate the effectiveness of multilayers in maximizing the radiation attenuation properties and minimizing the weight.

MATERIAL AND METHODS

In the present study, the MCNPX MC code (Version.2.6.0) was applied for modeling. MCNPX as a three-dimensional N-particle radiation transport code is generally used to estimate the transport, modeling, and analysis of the interaction of photons and electrons with materials. For this reason, nine commercial and pre-commercial materials, including Pb, W, Bi, Ba, Gd, Cs, Ce, Sn, and Sb were investigated in this study. Due to the time consuming attenuation measurement, extensive preliminary MC calculations were done. Due to the advances of the selected materials and alloy such as being cost-effective, nontoxicity, and photoelectric absorption edges (in the range 25–85 keV), they were selected. In order to optimize the arrangement in the proposed shield, MC calculations were used.

Simulation was performed for a point source with a maximum energy of 100 kVp. The output information was determined by the F5 (photon flux) and * F8 (energized energy) pulses. Cutoff energies for the transport of electrons and photons were set to be 1 keV in the both cases. For each simulation, about one billion photons in the range of 10-100 keV were simulated. The distance between the source and the target was considered to be 100 cm in all simulations. A statistical error of less than 0.5% for 10^8 the particle history was obtained in all simulations.

An aluminum plate with a thickness of 1 mm was applied in the geometry as a target for validating the output results in the mentioned geometry. Moreover, mass attenuation coefficient of the aluminum plate was estimated through the code at 100 keV photon energy. Finally, the obtained values were compared with standard tables [21]. It is noteworthy that the relative error reported after each run was not more than 0.04% in any of the cases.

At first, the attenuation rate of the 8-material alloy (W, Bi, Ba, Gd, Cs, Ce, Sn and Sb) were compared with the combination of 8-layers of the same elements. Finally, four materials of W, Bi, Gd, and Ce were selected. All materials were provided as sheets with dimensions of 10 ×10 ×0.1 cm^3. The arrangement of these layers (from the radiation source) was in the order of W, Gd, Ce, and Bi.

RESULTS

MCNP output for six commercial materials is shown in figure 1. The calculated flounce spectra for 8-layer material and alloy composed of non-Lead materials (W, Bi, Ba, Gd,Cs, Ce, Sn, and Sb) are shown in figure 2. As shown here, the attenuation rate in the multi-layersshield was more than that in the alloying shield for the energy range of 50 to 100 kVp. The largest difference in the flux of passing photons through alloys and 8-layers materials was at the energy level of 68 kV. The flux of photons that pass through the alloy material was about 2.6 times more than that of the 8-layer.

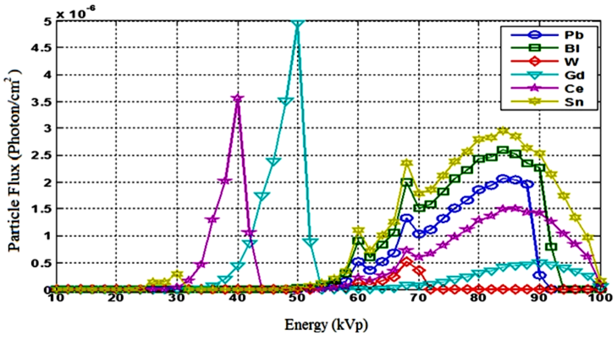

Figure 1. 100 kVp X-ray fluence spectra passing through the equivalent thicknesses of Pb, W, Bi, Gd, Ce, and Sn.

[DOI: 10.61186/ijrr.21.4.833]

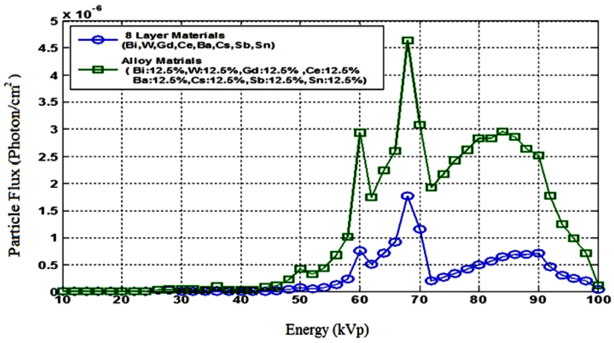

Figure 2. MC Calculations of the photons flux for 8- layers and alloy composed of non-Lead materials. The output of the MC code for 4-layerand alloy shield of non-Lead materials (W, Bi, Gd, and Ce,) is shown in Figure 3. As can be seen here, the attenuation in the four-layershield was more than that of the alloying shield with energy range from 70 to 100 kVp. The largest difference in the flux of passing photons for the alloy and 4-layershield was at 86 kV photons. The flux of photons passing through the alloy shield was about 3.5 times more than that of the 4-layers.

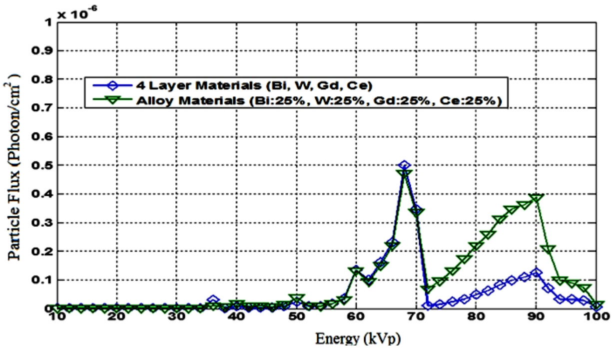

Figure 3. MC Calculations of the photons flux for 4- layers and alloy composed of non-Lead materials. The output of the Monte Carlo code for a multi-layer shield with different combinations is shown in Figure 4.

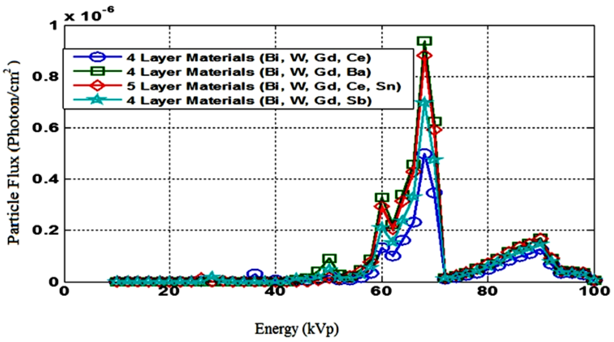

Figure 4. Calculated photons flux passing through different combinations of the multi-layershield. The output of the Monte Carlo simulation for a four-layer shield is shown in Figure 5. Four materials of W, Bi, Gd, and Ce were used in different combinations, and then, the two compounds (Figure 5) provided the greatest attenuation for X-ray photons. It should be noted that attenuation of the 4-layers shield with the arrangement of W, Gd, Ce, and Bi was better than the other combinations for low-energy (up to 30 to 40 kV).

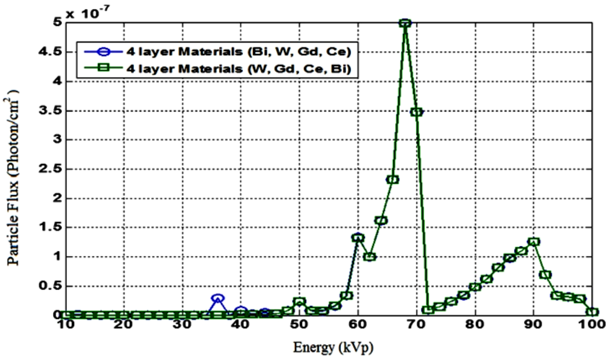

Figure 5. MC Calculations of the photons flux passing through two combinations of the 4-layers shields.

DISCUSSION

This study reported the attenuation performance of multi-layer and alloy shields for diagnostic energy range. At 68 keV, the attenuation value for the 8-layer composition was 2.6 times higher than for the alloy. A combination of elements with high and low atomic numbers that were used with equal percentages of each in the above compounds [20]. Then in order to achieve a higher damping value, the elements with medium to high atomic numbers were used. After performing various simulations, a combination of elements consisted of W, Gd, Ce, and Bi was selected. This combination caused a higher attenuation compared to the other compounds. It should be noted that the mentioned combination in the energy range of 72-100 kV, provided a more attenuation compared to the alloy composition of the elements.

According to the previous studies, tungsten and bismuth metals showed better protection compared to other materials. Also, due to the non-toxicity of these metals, they overcame the limitations of lead shields [15-20].

McCaffrey *et al.*, [6] used simulation and experimental methods to study the characteristics of composite shields and reported that the mass attenuation of some shields, such as W, Ba, and Gd, was greater or similar to that of lead. They also concluded that the simulation method could be used to design, build and optimize shields.

Generally, multi-layer shields can reduce the weight of Pb-based materials up to 65% with the same protection efficiency [15-17]. Therefore, they can be used as personal protectors to prevent unnecessary radiation [17-20].

CONCLUSION

According to the results of this study, a multilayer combination of W (25%), Gd (25%), Ce (25%), and Bi (25%) can be effectively used to provide a non-Lead composite shield, which offers lead-equivalent attenuation with less weight.

[DOI: 10.61186/ijrr.21.4.833]

ACKNOWLEDGEMENTS

Authors would like to thank the Vice-Chancellor for Research and Technology of the Hamadan University of Medical Sciences for financial support of this research.

***Funding*:** This study was supported and funded by the vice-Chancellor for Research and Technology of Hamadan University of Medical Sciences, Hamadan, Iran (Project No. 9710115919).

***Conflicts of Interests*:** The authors have declared no conflict of interest regarding this research.

***Ethical consideration*:** The study was approved by the Hamadan University of Medical Sciences, Hamadan, Iran (Ethics committee code: IR.UMSHA.REC.1397.547). We confirm that all methods were carried out in accordance with relevant guidelines and regulations.

***Authors' contributions*:** H.Kh: participation in the whole work; perception and design; generating K.Gh: plans; drafting of the article; data analysis; final approval of the version to be published. S.J: re-generating drafting the manuscript. S.N: drafting and final approval of the version to be published.

REFERENCES

1. Malone J and Zölzer F (2016) Pragmatic ethical basis for radiation protection in diagnostic radiology. *The British Journal of Radiology*, ***89****(1059): 20150713*.
2. Martin CJ and Sutton DG (Eds.) (2015) Practical radiation protection in healthcare. Oxford University Press, USA.
3. Seeram E and Brennan PC (2016) Radiation protection in diagnostic X-ray imaging. Jones & Bartlett Publishers.
4. Ngaile JE, Uiso CBS, Msaki P, Kazema R (2008) Use of lead shields for radiation protection of superficial organs in patients undergoing head CT examinations. *Radiation protection dosimetry*, ***130****(4): 490-498*.
5. Cournoyer M (2001) Lead substitution and elimination study. *Journal of Radioanalytical and Nuclear Chemistry*, ***249****(2): 397-402*.
6. McCaffrey JP, Shen H, Downton B, Mainegra-Hing E (2007) Radiation attenuation by lead and nonlead materials used in radiation shielding garments. *Medical Physics*, ***34****(2): 530-537*.
7. Botelho MZ, Künzel R, Okuno E, *et al.* (2011) X-ray transmission through nanostructured and microstructured CuO materials. *Applied Radiation and Isotopes*, ***69****(2): 527-530*.
8. Tekin HO, Altunsoy EE, Kavaz E, *et al.* (2019) Photon and neutron shielding performance of boron phosphate glasses for diagnostic radiology facilities. *Results in Physics*, ***12***: *1457-1464*. Please verify this ref.
9. Kaewjaeng S, Kothan S, Chaiphaksa W, *et al.* (2019). High transparency La2O3-CaO-B2O3-SiO2 glass for diagnosis X-rays shielding material application. *Radiation Physics and Chemistry*, ***160***: *41-47*.
10. Naji AT, Jaafar MS, Ali EA, *et al.* (2016) X-ray attenuation and reduction of backscattered radiation. *Applied Physics Research*, ***8****(4): 92-102*.
11. Mahltig B, Günther K, Askani A, *et al.* (2017) X-ray-protective organic/inorganic fiber–along the textile chain from fiber production to clothing application. *The Journal of the Textile Institute*, ***108****(11), 1975-1984*.
12. Baird DA, Hink TP, Leone DA (2020) *U.S. Patent No. 10,736,587*. Washington, DC: U.S. Patent and Trademark Office.
13. Low IM and Azman NZN (2020) *Polymer composites and nanocomposites for X-rays shielding*. Springer, Singapore.
14. Rahman Z and Singh VP (2019) The relative impact of toxic heavy metals (THMs)(arsenic (As), cadmium (Cd), chromium (Cr)(VI), mercury (Hg), and lead (Pb)) on the total environment: an overview. *Environmental Monitoring and Assessment*, ***191****: 1-21*.
15. Schlattl H, Zankl M, Eder H, Hoeschen C (2007) Shielding properties of lead-free protective clothing and their impact on radiation doses. *Medical Physics*, ***34****(11), 4270-4280*.
16. Zohdiaghdam R, Mahmoudian M, Salimi S (2020) Evaluation of synergistic effects of the single walled carbon nanotube and CeO2-hybrid based-nanocomposite against X-ray radiation in diagnostic radiology. *Radiation Physics and Chemistry,* ***168****: 108562*.
17. Apell P and Gellerstedt F (2019) U.S. Patent No. 10,364,513. Washington, DC: U.S. Patent and Trademark Office.
18. Jayakumar S, Saravanan T, Vadivel M, Philip J (2019) Synergistic effect of β-Bi 2 O 3 and graphene/MWCNT in silicone-based polymeric matrices on diagnostic X-ray attenuation. *Applied Nanoscience*, *9: 1891-1913*.
19. AbuAlRoos NJ, Amin NAB, Zainon R (2019) Conventional and new lead-free radiation shielding materials for radiation protection in nuclear medicine: A review. *Radiation Physics and Chemistry*, ***165****: 108439*.
20. McCaffrey JP, Mainegra-Hing E, Shen H (2009). Optimizing non-Pb radiation shielding materials using bilayers. *Medical Physics*, ***36*** *(12): 5586-5594*.
21. Hubbell JH and Seltzer SM (1995) *Tables of X-ray mass attenuation coefficients and mass energy-absorption coefficients 1 keV to 20 MeV for elements Z= 1 to 92 and 48 additional substances of dosimetric interest* (No. PB-95-220539/XAB; NISTIR-5632). National Inst. of Standards and Technology-PL, Gaithersburg, MD (United States). Ionizing Radiation Div.