Scientific Paper

A comprehensive Monte Carlo study to design a novel multi-nanoparticle loaded nanocomposites for augmentation of attenuation coefficient in the energy range of diagnostic X-rays

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Abstract

Introduction: The present study aimed to investigate the radiation protection properties of silicon-based composites doped with nano-sized Bi₂O₃, PbO, Sm₂O₃, Gd₂O₃, WO₃, and IrO₂ particles. Radiation shielding properties of Sm₂O₃ and IrO₂ nanoparticles were investigated for the first time in the current study.

Material and methods: The MCNPX (2.7.0) Monte Carlo code was utilized to calculate the linear attenuation coefficients of single and multi-nano structured composites over the X-ray energy range of 10–140 keV. Homogenous distribution of spherical nanoparticles with a diameter of 100 nm in a silicon rubber matrix was simulated. The narrow beam geometry was used to calculate the photon flux after attenuation by designed nanocomposites.

Results: Based on results obtained for single nanoparticle composites, three combinations of different nano-sized fillers Sm₂O₃+WO₃+Bi₂O₃, Gd₂O₃+WO₃+Bi₂O₃, and Sm₂O₃+WO₃+PbO were selected, and their shielding properties were estimated. In the energy range of 20–60 keV Sm₂O₃ and Gd₂O₃ nanoparticles, in 70–100 keV energy range WO₃ and for photons energy higher than 90 keV, PbO and Bi₂O₃ nanoparticles showed higher attenuation. Despite its higher density, IrO₂ had lower attenuation compared to other nanocomposites. The results showed that the nanocomposite containing Sm₂O₃, WO₃, and Bi₂O₃ nanoparticles provided better shielding among the studied samples.

Conclusions: All studied multi-nanoparticle nanocomposites provided optimum shielding properties and almost 8% higher attenuation relative to single nano-based composites over a wide range of photon energy used in diagnostic radiology. Application of these new composites is recommended in radiation protection. Further experimental studies are suggested to validate our findings.

Key words: nanocomposite; radiation; attenuation coefficient; diagnostic X- rays; MCNPX.

Introduction

Nowadays, low energy X-ray beams are widely employed in diagnostic radiology including radiography, fluoroscopy, mammography, angiography, and interventional image-guided procedures. On the other hand, due to the dangerous and harmful effects of direct or scattered radiation for personnel and patients, it is essential to optimize the radiation protection regulations and develop effective shielding materials. Therefore, protection against X-ray exposures plays a vital role in the safe usage of X-rays in a clinical environment.¹⁻³ The absorption of photons by a thickness of shielding material is simply expressed by the Lambert-Beer law: $I = I_0 e^{-\mu x}$, where I_0 and I are the incident and transmitted beam intensities, also x is the thickness of the attenuator material, and μ is the linear attenuation coefficient. The selection of the appropriate materials for shielding depends

on the radiation source's type, intensity, and energy. The probability of interactions depends on the energy of the incident photon, the atomic number, and the density of the shielding material.⁴⁻⁷

Lead aprons are commonly considered protection devices. The high atomic number of lead and its high density enhance its efficiency in the absorption of the radiation. In contrast, prolonged use of these types of protectors due to their heaviness leads to physical fatigue and back strain and may compromise the performance of radiologists and technologists. Toxicity and easily cracking are the other disadvantages of lead garments. Most recent studies focused on lightweight and strong non-lead composite materials to guarantee the safe usage of protective aprons and devices.⁸⁻¹⁰

Polymer composites are strong, lightweight, and comfortable. They have shown favorable mechanical performance, heat

resistance, and are capable of absorbing radiation more effectively. Various polymers such as polyethylene, silicon, and epoxy resin are used as a matrix bed in these composites, and various metallic elements can be used as fillers. Recently, metallic fillers in micro and nano scales have been employed in the composition of new shielding composites. Studies have revealed that nanoparticles exhibit unique physical and chemical properties in micro and macro dimensions compared to the same material. Besides, nanomaterials have a higher surface-to-volume ratio and higher photon absorption in the low energy range.¹¹⁻¹³

Various studies have been done to examine the properties of protective compounds with different elements and K- absorption edge energies, such as Cu, Sn, Ba, W, Sb, Y, Pb, Gd, and Zr. The nanomaterials used in previous studies have properties such as high density and a suitable K-absorption edge for the used photon energy. Among the studied atoms, elements such as tungsten $Z = 74$ and bismuth $Z = 83$, which have lower toxicity and are inexpensive, can be considered as a replacement for toxic Pb and provide better attenuation in the energy range of 70-90 keV.¹⁴⁻¹⁶

There are enormous articles on the use of nanoparticles for radiation shielding.¹⁷ A study showed that a sheet with a thickness of 1 cm made of epoxy-Gd₂O₃ nanocomposite was able to absorb 50-70% of X-rays in the energy range of 40-100 kVp. In another experimental study, a composite shield containing Gd₂O₃ nanomaterial fillers with thicknesses of 8 to 16 mm provided all degrees of X-ray protection needed in the clinic and also improved the mechanical and fracture toughness of the epoxy resin.^{18,19} According to the results obtained by Verdipour et al. the mass attenuation coefficient of WO₃, Bi₂O₃, and PbO nanoparticles was 17% higher compared to their microparticles in silicon resin and PbO and Bi₂O₃ nanoparticles provided better absorption compared to WO₃.²⁰ Furthermore, the researchers showed that the samarium incorporated into carbon fiber improved the performance of gamma radiation and neutron shielding.²¹ In an experimental study, EPVC composites containing micro and nano-powders of bismuth (Bi₂O₃), lead (PbO), and tungsten (WO₃) were compared for photons with the tube voltages of 40-100 kVp. Composites containing bismuth nanoparticles or lead oxide microparticles showed the most efficient attenuation. It was concluded that the Bi₂O₃ nano-sized particles can be an appropriate alternative to PbO in the fabrication of shielding composites.¹⁵

The attenuation and interaction of different elements with X-ray through photoelectric effect depend strongly on the proximity of photon energy and the K-electrons' binding energy. When the energy of photons becomes slightly higher than the K-absorption edge energy of electrons, the absorption of photons increases remarkably. Indeed, the attenuation coefficient of elements rises at their K- absorption edge and exhibits an intense peak then declines exponentially with an increase in photon energy. Regarding the variation in K- absorption edge energy for individual elements, choosing a material to maintain protection

over a particular energy range can be challenging. In addition to the materials studied in previous publications, other potential elements were examined in the present study. Elements such as lead, bismuth, tungsten, and gadolinium have been used in previous studies. On the other hand, iridium and samarium have not been studied in any other investigation for X-ray shielding in the diagnostic energy range.

The authors of the current work think that if several types of nanoparticles with different K- absorption edges are applied in the composition of new composites which we will name multi-nanoparticle composites (MNC) in this article, it may provide better protection over a wide range of photon energy used in diagnostic radiology, i.e., 40-140 keV. Therefore, the current study aimed to investigate whether composites made of different elements with different K- absorption edges would be more effective than single-nanoparticle composites and would create stronger attenuation in the wide range of photon energies applied in diagnostic radiology. The linear attenuation coefficients of all samples composed of single nanoparticles were calculated by using Monte Carlo (MC) method and compared. Then, some MNC compositions were derived from results, and their shielding properties were tested and compared. Finally, several MNCs composed of different elements were examined, and the most effective composition was introduced as a novel MNC for shielding purposes in diagnostic radiology.

Materials and methods

Monte Carlo simulation model

In this study, the MCNPX MC code (version.2.7.0) was used for the simulation. MCNPX is a three-dimensional N-particle radiation transport code. It is utilized to calculate the transport, modeling, and analysis of the interaction of neutrons, protons, photons and electrons with materials. In this study, to reduce the statistical errors and MC runtime, all calculations were done in the photon mode and the importance of electrons was considered zero in all cells. The narrow beam geometry including source, collimators, and detector was modeled and are shown in **Figure 1**. The source was defined as a surface source with a radius of 5 mm, placed in a hole with a radius of 1 cm and length of 5 cm inside the first lead cylinder, and emitted parallel photons. The collimators were two lead cylinders with a radius of 20 cm and a length of 20 cm to remove the scattered beams and satisfy narrow beam geometry conditions. The detector was defined in a hole with a radius of 1 cm and a length of 5 cm in the second lead cylinder. They were defined at a distance of 40 cm from the nanocomposite shield. In other words, the shielding material placed between lead cylinders and the distance from each cylinder was 40 cm. Only the primary photons reached the detector after passing through the shield. The shielding material consisted of silicon rubber as a matrix was doped with different nanoparticles. We used the lattice (LAT) and universe (U) cards to define matrix and fillers as seen in **Figure 1**.

Figure 1. A schematic representation of the simulated narrow beam geometry and lattice-universe arrangement for the silicon rubber matrix filled with nanoparticles.

Nanoparticles designation in MCNPX code

The nano-sized fillers selected for this study included iridium (Ir, $K = 76.11$ keV), lead (Pb, $K = 88$ keV), tungsten (W, $K = 69.5$ keV), gadolinium (Gd, $K = 50.2$ keV), bismuth (Bi, $K = 90.5$ keV) and samarium (Sm, $K = 46.83$ keV). These particles have a relatively high atomic number and density. Therefore, we tested these nanoparticles and investigated their performance as shielding nanocomposites individually and as MNC samples in the 10-140 keV energy range. The attenuation coefficient of the above-mentioned nanoparticles was calculated by using the Monte Carlo method.

The silicon rubber with the elemental composition of $\text{SiO}_2(\text{CH}_3)$ and the density of 1.05 g/cm^3 was considered as the matrix of the composite. The silicon rubber was divided into cubic cells or voxels. Each nanoparticle was situated as a sphere with a diameter of 100 nm in the center of voxels. The nano fillers consisted of WO_3 , PbO , Gd_2O_3 , Sm_2O_3 , IrO_2 , and Bi_2O_3 used in this investigation.

The linear attenuation coefficient calculations

The linear attenuation coefficient was calculated for each single nano-based composite. To make the calculations and data more accurate, at least six different thicknesses were used. For this purpose, in each MC simulation; photon transmittance was calculated for thicknesses of 0.2-1.2 mm of each sample, and then the transmittance-thickness curve was obtained for each sample. The concentration of each nano-sized filler was 30 wt% of silicon matrix. The used X-ray energy was from 10 to 140 keV in the radiology range with ten steps. For calculation of photon flux inside the detector cell, the F4 tally of MCNPX was used in terms of n/cm^2 . The fluencies of detected photons with different thicknesses of shielding materials were used to acquire transmittance-thickness semilog curves. The linear attenuation coefficient was derived from the obtained curve. The gradient of

the obtained linear descending curve was linear attenuation coefficient of each sample. The runtime of MC simulations was 1 h on a pc system. The statistical errors of MC results were less than 1% on average for all simulations. In the next step, some MNCs were designed based on the superimposition of K-absorption edge energy of individual nanoparticles in different energy of photons.

Each sample contained silicon rubber as a matrix and nano oxides as fillers. Fillers were selected based on better attenuation in each energy range obtained in the first step for single-particle composites. In other words, the logic for their selection was that in the diagnostic radiology a continuous spectrum of photons is used. Thus, to have more efficient shielding, a composite composed of multiple different nanoparticles with K-absorption edges located in the different part of photon spectrum would be more effective. The selected nano-sized fillers for MNC samples included: (1) $\text{Sm}_2\text{O}_3 + \text{WO}_3 + \text{PbO}$ (2) $\text{Sm}_2\text{O}_3 + \text{WO}_3 + \text{Bi}_2\text{O}_3$ (3) $\text{Gd}_2\text{O}_3 + \text{WO}_3 + \text{Bi}_2\text{O}_3$.

The total concentration of selected fillers in MNC composition was 30 wt% of silicon rubber. Then, the transmission of photons (n/cm^2) was calculated for all MNC samples. To evaluate the radiation protection efficiency of studied MNC samples, their attenuation rates were compared with 0.25 mm Pb in the energy range of 10-140. The thicknesses of single and multiple nanostructured composites were considered 1 mm. The MNC samples were examined also for the spectral CT energy spectra for 140 kVp and their transmission rates were compared to each other.

Results

Validation of the simulation narrow beam geometry

In the present study, the simulated narrow beam geometry was verified according to the data provided by the WinXCom software.^{22,23} For this aim, the linear attenuation coefficients of lead (density = 11.35 g/cm³), bismuth (density = 9.78 g/cm³), and the silicon rubber (density = 1.05 g/cm³) at the photon energies of 50, 100 and 150 keV were calculated by MC model then were compared with WinXCom. The results of benchmarking of the MC model are presented in **Table 1**.

As it can be seen, a maximum difference of 0.6% was found between MC and WinXCom values. Hence, the MC model was validated. The difference was calculated according to the following equation:

$$\text{Difference}(\%) = \frac{\mu_{MC} - \mu_{Winx}}{\mu_{Winx}} \times 100 \quad \text{Eq. 1}$$

Effect of nanomaterial concentration on nanocomposite attenuation

All nanomaterials were loaded inside the silicon rubber matrix in concentrations of 5, 15, and 30%. The linear attenuation coefficients were calculated for the aforementioned nanocomposites to investigate the effect of nanomaterials concentration. The obtained results are illustrated in **Figure 2** (next page). It can be deduced from **Figure 2**, the increase in the concentration of nanoparticles leads to a greater attenuation coefficient for all studied nanocomposites.

Results of MCNPX code for linear attenuation coefficient for each nano-based composite are given in **Figure 3** (next page). As it can be seen, the silicon rubber sample without nanomaterial fillers had the minimum attenuation. Also, 100 wt% nanoparticle samples showed maximum attenuation. In the middle part, the linear attenuation coefficients of nanocomposites composed of 70 wt% silicon rubber and 30 wt% fillers including Bi₂O₃, PbO, IrO₂, WO₃, Gd₂O₃, and Sm₂O₃ in terms of photon energy (keV)

are shown. The attenuation coefficient of each nanocomposite and pure silicon rubber in the energy range of 10-40 keV showed no significant difference. However, after 40 keV, nano-based composites provided superior attenuation relative to pure silicon rubber.

Effect of different K- absorption edge energy on linear attenuation coefficients

The calculated attenuation coefficients for 30% concentration by MC model for all samples were compared and presented in **Figure 4**.

Figure 4 indicates that in the energy range of 10 to 20 keV, the behaviours of all samples were almost the same. In the range of 20-30 keV, nanofillers of Sm₂O₃ and Gd₂O₃ had a higher attenuation coefficient. In the range of 30-50 keV, WO₃ was higher than other nanoparticles. In the energy range of 50-60 keV, Sm₂O₃, and, 60-70 keV, nano Gd₂O₃ particles, and in the energy range of 70-100 keV, tungsten nanofillers had higher attenuation. PbO had a peak at 90 keV. For photons higher than 100 keV, Bi₂O₃ and PbO had better attenuation. On the other hand, the attenuation provided by IrO₂ nanocomposite, despite its higher density, was lower than other nanostructured composites.

Table 1. Comparison of the linear attenuation coefficients of Pb, Bi, and Silicon rubber calculated by the MC model with WinXcom.

Energy(keV)	Samples	MCNPX	WinXCom	Difference %
50	Pb	90.69	91.18	0.54
	Bi	81.68	81.94	0.32
	Silicon	0.35	0.31	0.11
100	Pb	62.79	62.92	0.2
	Bi	55.8	56.12	0.58
	Silicon	0.1788	0.17955	0.00417
150	Pb	22.731	22.83	0.47
	Bi	20.251	20.36	0.54
	Silicon	0.1478	0.1512	0.0238

Figure 4. The comparison of linear attenuation coefficients for nanocomposites of Bi₂O₃, WO₃, Gd₂O₃, Sm₂O₃, IrO₂, and PbO.

Figure 2. The comparison of linear attenuation coefficients for the studied nanocomposites at the concentrations of 5, 15, 30% a) Bi_2O_3 , b) PbO , c) Sm_2O_3 , d) IrO_2 e) WO_3 , f) Gd_2O_3

Figure 3. The comparison of the linear attenuation coefficients of pure silicon rubber with different nanocomposites: a) 30% Bi_2O_3 +70% Silicon and 100% Bi_2O_3 b) 30% Gd_2O_3 +70% Silicon and 100% Gd_2O_3 c) 30% Sm_2O_3 +70% Silicon and 100% Sm_2O_3 d) 30% PbO +70% Silicon and 100% PbO , e) 30% IrO_2 +70% Silicon and 100% IrO_2 , f) 30% WO_3 +70% Silicon and 100% WO_3

Figure 5. The comparison of transmitted intensity from the thickness of 1 mm of nanocomposites composed of a single nanoparticle and 70% Silicon rubber with multi-nanoparticle composites

Based on obtained results, samarium, gadolinium, tungsten, bismuth, and lead nano-oxides were selected for designation of new MNCs. Three compositions that produced higher attenuation in the whole range of photon energy were selected including, (1) $\text{Sm}_2\text{O}_3 + \text{WO}_3 + \text{PbO}$ (2) $\text{Sm}_2\text{O}_3 + \text{WO}_3 + \text{Bi}_2\text{O}_3$ (3) $\text{Gd}_2\text{O}_3 + \text{WO}_3 + \text{Bi}_2\text{O}_3$. The results are depicted in **Figure 5**.

In **Figure 5a** the results show that the transmitted intensity of MNC in the energy range of 10 to 50 keV was overall 3.5% lower than PbO and Sm_2O_3 nano- based composites. In the energy range of 50 to 70 keV, the MNC sample provided 5% higher attenuation than WO_3 and PbO composites. In the 70 to 80 keV energy range, the MNC absorbed photons 4% more than lead nanocomposite. For 90 keV, the sample had the minimum transmission in comparison with other nanostructured composites. The maximum percentage difference was 7% for 90 keV between Sm_2O_3 and the MNC sample. After 100 keV, the MNC sample attenuated the X-ray beams more than WO_3 and Sm_2O_3 nano-based composites. In other energy ranges, the obtained superiority was lower than 4%. This figure also indicates that single-nanoparticle nanocomposites had their best performance only in their K-absorption edge energy, while the MNC nanocomposite supplied more effective attenuation properties over the entire radiology energy range.

In **Figure 5b**, the transmitted intensity of the MNC in the energy range of 10 to 50 keV was almost 3% lower than Bi_2O_3 and Gd_2O_3 nanostructured composites. In the energy range of 50 to 70 keV, the attenuation capability of the MNC sample was 7% more than WO_3 and Bi_2O_3 composites. In the 70 to 100 keV energy range, the MNC absorbed photons almost 5% better than nano-bismuth composite. The maximum difference was overall 7% in 60 keV between WO_3 and MNC. After 100 keV the MNC sample provided superior attenuation of the X-ray beams compared to WO_3 and Gd_2O_3 single nanocomposites. In other energy ranges, the obtained discrepancies were lower than 3%.

In **Figure 5c** The transmitted intensity of MNC in the energy range of 10 to 50 keV was overall 4% lower than the composites doped with nano- Bi_2O_3 and nano- Sm_2O_3 . In the energy range of 50 to 70 keV the MNC sample shielded photons 8% more than WO_3 and Bi_2O_3 composites. In the 70 to 100 keV energy range, the MNC absorbed photons almost 6% more than Bi_2O_3 . The maximum overall percentage difference was 8% in 70 keV between Bi_2O_3 and MNC. After 100 keV, the MNC sample shielded the X-ray beams more efficiently than WO_3 and Sm_2O_3 nano-based composites. In other energy ranges, the obtained discrepancies were lower than 5%.

a) 30% Sm_2O_3 , 30% WO_3 , 30 % PbO and multiple nanocomposite of $\text{Sm}_2\text{O}_3 + \text{WO}_3 + \text{PbO}$

b) 30% Gd_2O_3 , 30% WO_3 , 30% Bi_2O_3 and multiple nanocomposite of $\text{Sm}_2\text{O}_3 + \text{WO}_3 + \text{Bi}_2\text{O}_3$

c) 30% Sm_2O_3 , 30% WO_3 , 30%, Bi_2O_3 and multiple nanocomposite of $\text{Gd}_2\text{O}_3 + \text{WO}_3 + \text{Bi}_2\text{O}_3$

In **Figure 6**, the attenuations of the selected MNCs were compared to 0.25 mm of pure Pb. For the pure Pb, an abrupt fall-off is evident in the energy of about 88 keV due to its k-edge binding energy. In other words, at the k-edge binding energy, the probability of photoelectric interaction of photons with k-electrons increases significantly and leads to lower transmission of photons from the shielding layer. According to our calculations, for the energy range of 40-140 keV, 5 mm of our MNCs were equivalent to 0.25 mm Pb. Furthermore, among all the MNC samples, the nanocomposite containing Sm_2O_3 , WO_3 and PbO in the energy range of 80 to 100 was the most efficient sample. In the energy range of 40 to 80 keV and 100 to 140 keV, the sample containing Sm_2O_3 , WO_3 and Bi_2O_3 had the maximum attenuation. In addition to the mono-energetic mode, the MNC samples were also examined against the photon spectrum of a CT machine with the peak tube voltage of 140 kVp. The output is tabulated in **Table 2**. As it can be deduced from **Table 2**, there was no significant difference between all the MNC samples in attenuation of the photon energy spectrum of X-ray CT. However, the Sample with Bi_2O_3 nanoparticles attenuated the X-ray beam slightly higher than others.

Figure 6. A comparison of transmitted intensity (n/cm^2) for multi-nanoparticle nanocomposites with thickness of 1 mm and 0.25 mm of Pb.

Table 2. The X-ray transmission intensity of photons for the selected multi-nanoparticle composites in an x-ray CT energy spectrum.

Nanocomposites	Transmitted intensity (n/cm^2) per initial photon
$\text{Gd}_2\text{O}_3+\text{WO}_3+\text{Bi}_2\text{O}_3$	2.75E-01
$\text{Sm}_2\text{O}_3+\text{WO}_3+\text{Bi}_2\text{O}_3$	2.74E-01
$\text{Sm}_2\text{O}_3+\text{WO}_3+\text{PbO}$	2.76E-01

Discussion

Most recent investigations have shown that the incorporation of nanomaterials within polymer-based composites can absorb and attenuate radiation more efficiently. In this study we investigated shielding properties of single and MNCs by MC simulation. In order to verify the narrow beam geometry of the MC model and show the reliability of obtained results, the differences between MC and WinXCom results must be as low as 1%. The maximum percentage differences obtained at a photon energy of 50 keV was 0.54% for lead and at a photon energy of 100 keV was 0.58% error for bismuth. At photon energy of 50, 100, and 150 keV percentage differences were less than 0.6% for lead, bismuth, and silicon rubber. Due to the interactions of low energy photons with high atomic number materials such as our used nanoparticles, the photoelectric effect becomes the predominant phenomenon, so with the increase in the concentration of fillers, attenuation increases proportionately. In other words, the number of high atomic atoms in the pathway of photons increases directly with an increase in the concentration of the filler. In addition to the nanoparticles used in the previous studies, we also examined the effect of Sm_2O_3 and IrO_2 . An evident increase was observed in attenuation coefficients of all nanoparticles in the vicinity of their K- absorption edges. Sm_2O_3 had good performance in 40-70 keV. In 70-90 keV and up to 100 keV, WO_3 and Bi_2O_3 had better shielding efficiency. The MNC sample containing Sm_2O_3 , WO_3 and Bi_2O_3 provided higher protection compared to other MNCs.

On the other hand, due to economic reasons and availability of Gd to Sm, the MNC sample include Gd_2O_3 , WO_3 and Bi_2O_3 can be introduced as a cost-effective composite than other multiple samples. The MNC samples were investigated in spectral CT energy too. The composite samples containing $\text{Sm}_2\text{O}_3+\text{WO}_3+\text{Bi}_2\text{O}_3$ and $\text{Gd}_2\text{O}_3+\text{WO}_3+\text{Bi}_2\text{O}_3$ nano-sized particles had higher attenuation. Using appropriate composite materials with different K- absorption edges provides dominance of photoelectric effect to Compton scattering in beams absorption and leads to a reduction in weight with equivalent protection. Indeed, X-rays would be absorbed several times by multiple K- absorption edges.

According to our results and Dong et al. findings, the attenuation coefficient of the composites doped with nano- WO_3 had an increase in the energy range of 69.5 keV, which is due to the specific absorption at the K- absorption edge energy of WO_3 and increases the protective properties of the shield.²⁴ Our obtained results demonstrate that adding Bi_2O_3 and WO_3 to nano-based composites leads to better attenuation, in agreement with previous studies. For instance, Nambiar et al., in an experimental study, investigated the X-ray absorption by polymer nanocomposites for protection in IVR and diagnostic categories. PDMS nano-polymers with different concentrations of bismuth oxide as fillers were considered. To achieve the amount of absorption that occurs in lead aprons, a more

thickness of nanostructured composites was required, so that the thickness of 0.25 mm of pure lead was equivalent to 3.73 mm of bismuth oxide (44.44 wt %).²⁵

Our results were in close agreement with an experimental study that designed a nanocomposite shield containing tungsten and bismuth oxide. The prepared samples of 18.75 wt% Bi₂O₃ and 18.75 wt% W had the lowest HVL and better shielding performance. Moreover, the multiple shields had an acceptable attenuation over a wide energy range because of the several absorption edges. However, single nanoparticle composites had higher absorption in a limited energy range.²⁶

In previously published studies, the linear attenuation coefficient was calculated for Bi₂O₃ and PbO and their mixtures. The multiple nanocomposites were the most effective sample that was similar to our obtained results. Ozdemir and et al. designed a plastic-based protective material with a flexible nature that protects patients and staff in radiant environments, using EPDM as a matrix for lead oxide nanoparticles as filler. Lead nanoparticles with concentrations of 1, 5, 10, 15, and 20% were considered and irradiated. Also, nanocomposites containing a mixture of bismuth 20,30,40 wt% and 20 wt% lead nanofillers were irradiated too. The sample with 20% lead oxide and 40% bismuth oxide in a thickness of 6 mm had a 99.4% attenuation coefficient and maximum Pb equivalent thickness (0.65 mm).²⁷ Moreover, our results were consistent with previously published results of Sonsilphong et al., who exhibited lower transmission in 70-90 keV for double layer W/Bi sheet, which is blind absorption zone for lead. 0.4 mm of this sheet with an equal thickness ratio of W and Bi in 70-90 keV showed the same attenuation of 0.5 mm Pb. The designed double-layer shield was 36% lighter than the standard 0.5 mm Pb sheet.²⁸ In another study, seven shielding materials were investigated, including Pb, Pb-rubber, Reg. lead, Hx-lead, W-rubber, green Lite, and Sn-Ba in the diagnostic imaging energy range. The samples with lower atomic numbers (Green Lite, Hx-Pb, Sn-Ba) in most cases exhibited better attenuation than that of pure Pb protectors. W-rubber material had effective attenuation similar to Pb containing materials for 100 and 120 keV.²⁹ Also, a previously published study measured the attenuation effectiveness of some metal powders incorporated into polymer sheets such as BaSO₄, Gd₂O₃, and Bi₂O₃ to introduce new

radiation protection materials. Gd+Bi and Ba+Bi were prepared as bilayer shields in which the low atomic number layer was close to the source, and the attenuation effect of samples was examined. The minimum transmission was for Gd₂O₃+Bi₂O₃ sample and performed better than commercial Pb shielding.³⁰

The obtained results in this study show that MNCs have better attenuation in comparison with single nanoparticle ones. They have better performance for widespread energy range. Our studied MNCs containing less toxic particles are suitable alternatives for toxic, uncomfortable and heavy traditional Pb garments. Also, due to MNCs' good mechanical properties, strength, lower weight, and flexibility, they can be manufactured in various shapes and sizes for different organs in IVR energy range and experimental evaluation of our findings is strongly recommended for their actual applications in medicine and industry.

Conclusion

In the current study, we designed and evaluated six nanoparticle-loaded shielding materials using a silicon matrix. The attenuation efficiencies of all nano-based composites with different concentrations of 5, 15 and 30% and photon range of 10-140 keV were calculated using MCNPX MC code. Also, a novel idea of applying the MNCs capable of enhancing the attenuation of shielding material in a wide range of photon beams was tested. The results indicated that MNCs have better performance compared to single-nanoparticle composites. In order to enhance the efficiency of nanostructured composites we examined three MNC samples. The sample containing Sm₂O₃, WO₃, and Bi₂O₃ exhibited greater shielding effectiveness in the photon energy range of 10-140 keV. Considering the potentials of multi-nanoparticle loaded composites, utilization of other polymers bases for special applications are suggested.

Acknowledgments

This project was performed as a part of MSc thesis of medical physics and funded by Medical Radiation Sciences Research Team of Tabriz University Of Medical Sciences.

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