Application of personal non-lead nano-composite shields for radiation protection in diagnostic radiology: a systematic review and meta-analysis

Parinaz Mehnati [1], Reza Malekzadeh [1, 2], Mohammad Yousefi Sooteh [1, 3]*

[1]Department of Medical Physics, School of Medicine, Tabriz University of Medical Sciences, Tabriz, Iran
[2]Medical Radiation Sciences Research Team, Tabriz University of Medical Sciences, Tabriz, Iran
[3]Student Research Committee, Tabriz University of Medical Sciences, Tabriz, Iran

ABSTRACT

Currently, the use of flexible, light-weight, and environmentally friendly, nontoxic, lead-free polymer composites with micro- and nano-metal fillers has attracted the attention of researchers for radiation shielding applications. Lead toxicity and heaviness have oriented extensive research toward the use of non-lead composite shields. The present study aimed to systematically review the efficiency of the composite shields of various micro- and nano-sized materials as composite shields have been considered in radiation protection and diagnostic radiology. In addition, a meta-analysis was performed to determine the effects of filler size, filler type, shield thickness and tube voltage on dose reduction. The relevant studies published since 2000 were identified via searching in databases such as Google Scholar, Medline, Web of Science, Scopus, and Embase. In total, 51 articles were thoroughly reviewed and analyzed. Heterogeneity was assessed using the $\chi 2$ and I-square (I2) tests, and a fixed effects model was used to estimate the pooled effect sizes. The correlations between the subgroups were determined separately using meta-regression analysis. According to the results, the bismuth shield dose reduced from 22% to 98%, while the tungsten shield dose increased from 15% to 97%. The rate also increased from 6% to 84% in the barium sulfate shields. The combination of two metals resulted in higher attenuation against radiation, with the nano-shields exhibiting higher attenuation compared to the micro-shields, especially in low energies. Moreover, the meta-analysis indicated that the fixed effects pooled estimation of dose reduction was 89% for shield thickness (95% CI: 79-100; P<0.001), 73% for tube voltage (95% CI: 63-83; P<0.001; 50-100 kV), and 59% for tube voltage (95% CI: 35-82; P<0.001; kV>100). The single-metal personal shields made of bismuth powder had better performance than tungsten and barium sulfate. In addition, the combined metals in a shield showed more significant attenuation and dose reduction compared to the single-metal shields.

Keywords: Aprons, Garments, Radiology, Non-lead shields, Patient Radiation Protection

INTRODUCTION

Ionizing radiation (especially X-ray in diagnostic medical imaging) is a critical element, which requires radiation protection principles due to the findings attesting to the effects of radiation damage on humans. The hazards of X-rays could be diminished through various methods, as well as the use of proper protective equipment. Effective shielding largely attenuates X-rays even in short distances, thereby protecting the workers and patients who are exposed to the source of the beams for longs periods [1, 2]. Protective aprons are traditionally made of lead, which has high density and atomic number and are commonly used by staff for protection against secondary and scattered X-rays or the primary rays of patients. However, lead is a toxic material with heavier radiation garb [3-6].

Depending on photon energy, some non-lead materials could be more effective in attenuation based on their K-edge. In addition, materials with variable sizes (e.g., micro- and nano-sized materials) have been reported to have adequate efficiency in the attenuation of X-rays [7-9].

Several materials are employed as shields,

while three metals have shown proper potential for radiation protection. Heavy metals such as tungsten (W), with the atomic number of 74 and high density, have recently been used for the manufacturing of non-lead protectors [10]. Moreover, barium sulfate ($BaSO_4$) has been employed in composite shields [11]. Bismuth (Bi), with the atomic number of 83, has also been currently used to manufacture non-lead shields. The use of Bi shields is considered to be a novel approach to the reduction of organ damage against X-rays [12-14].

The interaction of X-rays with materials in radiation shields is influenced by factors such as their effective atomic number (Z_{eff}) and shield thickness, which may also affect the mass or linear attenuation coefficient of the shield [15]. The protective composites that are equivalent to lead are produced by mixing metal powders (e.g., Bi, W and $BaSO_4$) with a base polymer matrix, such as silicone (Si) rubber. The amount of the material within the shield is of the adequate size to properly distribute throughout the field of the matrix volume. In addition to their remarkable effect on the reduction of X-rays, these metals have high strength and flexibility and do not break for long periods [16, 17].

In a study, Zuguchi et al. compared a non-lead shield made of W and zinc (Zn) with a routine lead shield, reporting that the efficiency of the shields was similar in the reduction of the scattering rays within the energy range of 60-120 kVp, while the non-lead shields were lighter and weighed 20% less than the lead shield [18]. Similarly, Sonsilphong et al. stated that a dual-layer shield of W and Bi with the thickness of 0.14 millimeters had the same attenuating ability as lead (0.5 mm) within the energy range of 70-90 kVp although it weighed approximately 36% less than the conventional lead shield [19]. According to the findings of McCaffrey et al. in this regard, Bi shields had the same or better attenuation compared to lead. The mentioned study was performed on a hand cream composed of Bi, indicating its higher efficacy compared to Bi gloves in the attenuation of X-rays [20].

When composite aprons are used in the layered and mixed forms in shields, their protective ability to reduce X-rays increases, which is associated with their increased attenuation capacity at higher energies. Composite aprons are lighter and non-toxic compared to lead apron, which is another

key advantage of these shields, rendering them a proper replacement for lead shields [21, 22].

Although several studies have been focused on Bi shields and W and Ba as lead substitutes, the effectiveness of their replacement by lead aprons for workers and patients against X-rays remains unclear. To date, no review studies have specifically addressed the advantages and disadvantages of using heavy metal (e.g., Bi, W, and Ba) in this regard. The present study aimed to investigate X-ray attenuation at various thicknesses and energies and evaluate the ability of radiation attenuation based on the type of materials and particle sizes, as well as their differences in reducing radiation.

MATERIALS AND METHODS
Search strategy and study selection

This systematic review was performed to identify the published articles involving the use of heavy metal composite shields for radiation protection in the radiosensitive organs of patients and staffs during diagnostic imaging procedures. The articles published within the past two decades were identified via searching in databases such as Google Scholar, PubMed, Web of Science, and Scopus using keywords such as lead-free shielding, radiation protection radiology, photon shielding, composite shield, shielding material, and bismuth shield. For each eligible study, one reviewer extracted the data, and the results were assessed by a second reviewer. Possible discrepancies were resolved through discussion and by consulting a third reviewer. After the final selection of the studies, the required data were extracted and summarized using an extraction table.

Inclusion and exclusion criteria

The inclusion criteria for the relevant studies were as follows: 1) original and quantitative research published in a peer-reviewed journals; 2) studies involving the performance of experimental and simulation procedures, such as Monte Carlo methods (e.g., Geant 4); 3) studies involving the evaluation of the effect of heavy metal personal shielding on radiation protection; 4) testing of photon shielding rather than particle shielding, and 5) studies published in English within the past two decades.

Statistical analysis

Data analysis was performed in STATA version 14.1 at the significance level of $P < 0.05$.

Nanomed. J. 7(3): 170-182, Summer 2020

171

Table 1. Evaluation of dose reduction by considering the thickness, size, proportion by weight in the Bismuth shields

References (date)	Metal Powder	Size	Base material	Thickness	Particle weight Ratio (%)	Device	Tube voltages (kVp)	Radiation reduction (%)
Aral et al. 2016 [23]	Bi	149 µm	Silicone rubber	0.425 mm	60%	diagnostic X-ray machine	80 100 150	43% 36% 22%
Aral et al. 2017 [34]	Bi	-	Silicone rubber	0.5 mm 1mm 1.5mm 2mm	60%	medical X-ray machine	100	80% (For 1 mm)
Cho et al. 2015 [25]	Bi$_2$O$_3$	10 - 100 nm	Silicone rubber	0.4 mm 0.7 mm	80%	X-ray beam generator	50 80 100 120	A B 90.5 % 98.73% 77.81% 92.15% 70.82% 86.94% 65.31% 83.34%
Chai et al. 2016 [26]	Bi$_2$O$_3$	2 µm	methyl vinyl silicone rubber (VMQ) matrix	2mm	80%	standard X-ray machine	55 70 100 125 170 210	65% (At 100 kVp)
Heaney et al. 2006 [24]	Bi	-	synthetic rubber (neoprene)	1 mm	50 %	Toshiba Medical Systems single slice X-press SX CT Scanner	120	Eye = 48% Thyroid = 47% Breast = 23%
Maghrabi et al. 2016 [52]	Bi$_2$O$_3$	10 µm	Nylon, poly vinyl chloride resin	1.03mm 1.47mm 1.04mm 1.27mm 1.04mm 1.33mm	23.08% 23.08% 50% 50% 66.67% 66.67%	medical X-ray machine	80	X-ray transmitted (%) 67% 46% 26% 17% 17% 8%
Nambiar et al. 2013 [27]	Bi$_2$O$_3$	90 to 210 nm	PDMS	1.3 mm	28.57 % 37.73 % 44.44 %	diagnostic X-ray machine	40 to 150	C D 45% 35% 62% 48% 68% 56%
Azman NZN et al. 2013 [28]	Bi$_2$O$_3$	10 µm	Commercial FR251 epoxy resin (Bisphenol-A diglycidyl ether polymer) and FR251 hardener (Isophoronediamine)	8 mm	10% 30% 50% 70 %	diagnostic x-ray machine	40 to 127	X-ray transmission For 100 kv 50% 25% 15% 10%
Pulford et L. 2016 [29]	Bi$_2$O$_3$			1.9 cm	70 %	diagnostic x-ray machine	90	72

A: Radiation reduction for 0.4 mm Thickness, B: Radiation reduction for 0.7 mm Thickness, C: Radiation reduction for 100 kVp, D: Radiation reduction for 150 kVp, Bi2O3: Bismuth trioxide, Bi: Bismuth
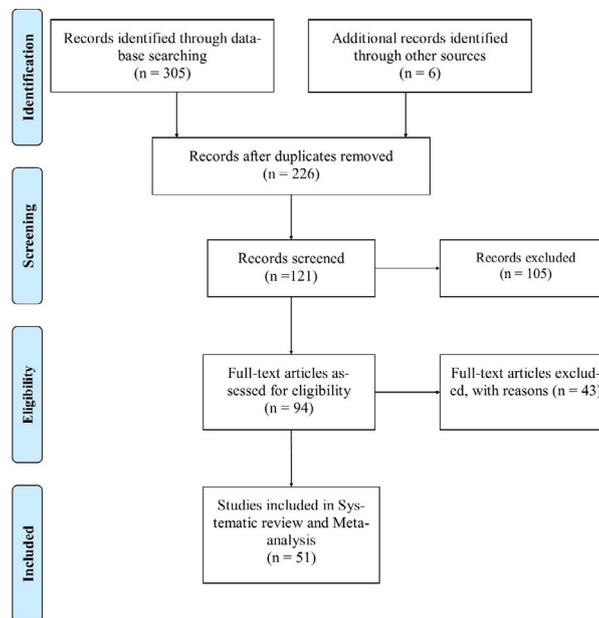
Fig. 1 Study selection flow diagram

The percentage of the reports was calculated in each study, and heterogeneity was assessed using the Cochran's Q test. In addition, the I^2 test was used to determine the percentage of heterogeneity, and the fixed effects model was applied to estimate the pooled effect sizes. The

172

Nanomed. J. 7(3): 170-182, Summer 2020

correlations between dose reduction, shield thickness, and tube voltage were evaluated separately using meta-regression analysis.

RESULTS AND DISCUSSION

In total, 94 articles were identified based on the keywords. Based on the exclusion criteria, 51 articles were reviewed with the complete data (Fig 1).

In the selected studies, the shields of Bi, W, and BaSO$_4$ in micro- and nanoparticle sizes were used for radiation protection. These materials were mixed in various matrixes, such as silicone rubber, polyvinyl chloride (PVC), FR251 epoxy resin, methyl vinyl silicone rubber (VMQ) matrix, and polyethylene resin. In the design of these shields, which were used instead of lead shields, the selected metals were initially blended for 15-60 minutes. To remove air bubbles from the matrix, the metal and matrix complex was vacuumed for 30 minutes. In some of the articles, scanning electron microscopy (SEM) was used to indicate the presence of the particles and their distribution in the shields. Moreover, the ability of the shields to reduce of the effects of X-rays was measured in radiology, mammography, dental radiography, and CT-scan. In some cases of radiology, the shields were typically placed at the distance of 100 centimeters from the X-ray tube, and the dosimeter was placed under the shield or within a short distance below.

In the reviewed studies, the size of the particles used in the construction of the shields was a significant influential factor in the ability of the composite shields to reduce radiation. Micro- and nanoparticles are employed in the design of radiation shields for several reasons, one of which is that the traditional radiation shields that are currently available to staff, patients, radioactive containers, and other requests may not be manufactured with the optimal shape and construction for various applications. In children, young women, and physicians, lead products must be of a more innovative design in order to enhance the efficacy of the shields for easy application. Bi and W powders have been applied in two different dimensions in micro- and nano-sizes (tables 1 & 2). Only seven studies used nanoparticles for the construction of radiation composite shields. Therefore, the results were classified based on the type of the shields made of various metals in micro- (2-150 μm) and nano-sizes (10-100 nm).

Protective effects of bismuth (bi) on the reduction of radiation

According to the obtained results, the dose reduction by Bi shields was within the range of 22-98%, which depended on the proportion by weight of the Bi powder used in the shield (23-80%), protector thickness (0.4 mm to 1.8 cm in different sizes), and kVp (Table 1).

According to a research, the Bi shield thickness of 0.4 millimeter and Bi proportion by weight of 60% resulted in the dose reduction of primary X-ray by 36% at 100 kVp. In the mentioned study, when the shield was used in a four-layer form, the dose reduction increased to 73% [23]. In another experiment, Heaney et al. tested a Bi shield with 50% of Bi in the matrix in CT-scan, reporting that a shield with the thickness of one millimeter could reduce the dose to 48% for the eye and 23% for the breast [24].

Another research indicated that the use of nano-Bi trioxide for the construction of a Bi shield with 80% Bi powder and 20% Si matrix caused the shield to attenuate primary X-rays by 86% with the thickness of 0.7 millimeter at 100 kVp [25]. Furthermore, Chai et al. used micro-sized Bi$_2$O$_3$ powder at the proportion by weight of 80%, and the results demonstrated that the dose reduction by the shield was 65% at 100 kVp [26]. In another research, Nambiar et al. used nano-sized Bi$_2$O$_3$ powder to develop a Bi protector, observing that with the Bi shield containing 44% Bi in the base matrix, it was possible to reduce the dose to 68% at 100 kVp [27]. In a similar study, Bi$_2$O$_3$ powder was applied to prepare and incorporate Bi protectors containing 70% Bi into the matrix, with the findings indicating that the protectors could reduce the quantity of X-rays by 90% [28]. On the other hand, a similar research with the same conditions (proportion by weight of 70% Bi and 30% base material) was performed at 90 kVp, and the obtained results showed that the Bi protector could reduce 70% of the initial X-rays [29].

Protective effects of tungsten (w) on the reduction of radiation

According to the findings of the review, dose reduction by W shields was within the range of 15-97% due to factors such as the proportion by weight of the W powder used in the shield (5-80% W powder in the base matrix), shield thickness (0.4-3 mm in different sizes), and variable tube potential (Table 2).

Nanomed. J. 7(3): 170-182, Summer 2020

173

Table 2. Evaluation of dose reduction by considering the thickness, size, proportion by weight in the Tungsten shields

References (date)	Metal Powder	Size	Base material	Thickness (mm)	Particle weight Ratio (%)	Device	Tube voltage (kV)	Radiation reduction (%)
Aral et al. 2016 [31]	W	12 μm	Silicone rubber	0.41	60 %	general x-ray machine	80 / 100 / 150	36% / 31% / 15%
Aral et al. 2016 [23]	W	12 μm	Silicone rubber	0.41	60%	general x-ray machine	80 / 100 / 150	36% / 31% / 15%
Azman NN et al. 2013 [32]	WO₃	20 μm <100 nm	FR251 epoxy resin	7	5% 10% 20% 30% 35%	Mammography, general diagnostic x-ray machine	25–49 40–120	For 35% transmission Micro Nano Log 0/5 log 0/3 Log 0/2 log0/1
Aghaz et al. 2016 [33]	WO₃	less than 20 μm / 20 to 100 nm	poly vinyl chloride (PVC)	1	20% 50% 60%	Shimadzu diagnostic digital radiography machine	40 50 70 80 100	in 100 Kv, Nanostructured shields reduce the dose 2.98% for 60% against micro shields
Aral et al. 2017 [34]	W	-	Silicone rubber	0.5 1 1.5 2	60% 70% 80%	medical X-ray machine	100	For 1 mm 70% 88% 97%
Chai et al. 2016 [26]	W	6 μm	methyl vinyl silicone rubber (VMQ) matrix	2	80%	standard X-ray machine	55 70 100 125 170 210	At 100 KVp 92%
Kim S et al. 2014 [30]	W	-	Silicone polymers	1 2 3	200 g Tungsten + 100 g Silicone	CT scan 64-channel SOMATOM Sensation (Simens)	120	For eye 1mm= 34.8% 2mm= 46.61% 3mm= 87.05%

W: Tungsten, WO₃: Tungsten oxide.

In this regard, Kim et al. examined W shields to measure the scatter dose in the eye and thyroid in abdominal CT-scan. The protector contained 200 grams of the W powder and 100 grams of Si base in the thickness of 1-3 millimeters. According to the obtained results, the rate of dose reduction in the eye was 34.8% with the thickness of one millimeter, while in the thickness of three millimeters, the rate of was estimated at 87%. Moreover, the rate of dose reduction in the thyroid was reported to be 29% with the thickness of one millimeter of the protector, while it was 85% in the thickness of three millimeters [30]. In another study, a composite shield was made of W microparticles with the thickness of 0.4 millimeter. The proportion by weight of the Si base material was 40%, and the added W powder was 60%. In the mentioned research, the rate of dose reduction by this shield was estimated at 31% in radiology at 100 kVp. The shields were also tested in multilayers, and the results demonstrated that using a five-layer W shield caused the dose reduction to reach 76% [31]. Similarly, Azman et al. developed shields using the microparticles and nanoparticles of WO₃ in various proportions by weights (5-35%). According to the findings, at the low voltages of approximately 30 kVp, the X-ray transmission ratio from the shield containing the WO₃ microparticles was 1.2-3 times higher than the shields containing the WO₃ nanoparticles. On the other hand, at high voltages (e.g., 100

kVp), the X-ray transmission ratio in the shield containing the nanoparticles was slightly lower compared to the shield with the microparticles, whereas the nanocomposite shield attenuation was slightly higher [32]. In another research, Aghaz et al. prepared shields using WO₃ microparticles and nanoparticles, reporting that at low kV, the shield with the proportion by weight of 60% containing the WO₃ nanoparticles had 34% better attenuation compared to the WO₃ microparticles, while at higher energies (100 kVp), their efficiency diminished, causing the X-rays to become closer, so that the difference was estimated at 3% [33]. In another study, Aral et al. assessed W shields with variable thickness (0.5-2 mm), observing that the composite shield containing 80% W and 20% Si base material could reduce the primary X-rays by approximately 97% at the shield thickness of one millimeter at 100 kVp [34].

Protective effects of barium sulfate (baso₄) on the reduction of radiation

According to the reviewed studies, dose reduction by $BaSO_4$ shields was within the range of 6-84%. In a study conducted at 30 kVp, dose reduction was reported to be 100%. Several factors affected the dose reduction, such as the proportion by weight of the $BaSO_4$ powder used in the shield (10-70% in the base matrix), protective thickness (in sizes of 0.2 mm to 1.9 cm), and variable kV (Table 3).

174

Nanomed. J. 7(3): 170-182, Summer 2020

Table 3. Evaluation of dose reduction by considering the thickness, size and proportion by weight sulfate in the Barium Sulfate shields. All references used Barium Sulfate (BaSO4)

References (date)	Size	Base material	Thickness	Particle weight Ratio (%)	Device	Tube voltages (kVp)	Radiation reduction (%)
Aral et al. 2016 [31]	less than 5 µm	Silicone rubber	0.405 mm	60%	general x-ray machine	80 100 150	22% 18% 6%
Aral et al. 2016 [23]	5 µm	Silicone rubber, Cotton	0.405 mm	60%	general x-ray machine	80 100 150	22% 18% 6%
Kusuktham et al. 2016 [35]	1.60-2.00 µm	Polyacrylate substance, acrylic emulsion, Cotton fabric	0.227 mm 0.294 mm	10% 20% 30% 40% 50%	general x-ray machine (X-ray Toshiba Model).	50 70 80 100	For 50% 22% 18% 15% 12%
Maghrabi et al. 2016 [36]	1 µm	PVC	1.46mm 1.46mm	16.7% 33.3%	Medical X-ray machine (SHIMADZU X-ray system)	80	Transmission rate % 84.5 % 70.5%
Kim S-C et al. 2012 [37]	0.03 – 0.05 µm	liquid Silicone resin (LSR)	1mm	100g lsr with A=350g B=450 g C=500g Baso4	X-ray generator (DK-525, Toshiba E7239X)	30 60 100 150	A B C 96% 100% 100% 87% 95% 98% 82% 85% 92% 76% 78% 87%
Kim S et al. 2014 [30]	-	Silicone polymers	1 mm 2 mm 3 mm	250 g barium sulfate + 100 g silicone	CT scan 64-channel SOMATOM Sensation (Simens)	120	For eye 1mm= 34.74% 2mm= 48.51% 3mm= 84.52%
Pulford et al. 2016 [29]	-	-	1.9 cm	70 %	Medical X-ray machine	90	21%

Table 4. Evaluation of dose reduction by considering the thickness, size and proportion by weight of Bismuth-Tungsten and Bismuth-Barium Sulfate combined in the shields

References (date)	Metal Powder	Size	Base Material	Thickness	particle weight Ratio (%)	Device	Tube voltages (kVp)	Radiation reduction (%)
Maghrabi et al. 2016 [36]	BaSO$_4$ and Bi$_2$O$_3$ were obtained from Sigma Aldrich	BaSO$_4$ was ~1 µm Bi$_2$O$_3$ was 10 µm	PVC	1.46mm	33.3% (20% BaSO$_4$ and 13.7% Bi)	Medical X-ray machine (SHIMADZU X-ray system).	80	Transmission 55.6 %
Çetin et al. 2017 [39]	Tin, Antimony, Bismuth and Tungsten	20–50 µm	polymer	1mm	50% 70% 80% 85%	medical X-ray machine	50–125	In 125 kVp 40% 89% 89% 87.5%
Kim C-G 2016 [38]	Barium Sulfate(BaSO$_4$) and Bismuth trioxide (Bi$_2$O$_3$)	µm	Silicone polymer and tourmaline	0.12 mm, 0.25 mm, 0.5 mm	-	Dental panoramic test device, GENORAY GDP-1	68	0.12 mm = 84% 0.25 mm = 92% 0.5 mm = 96%
Chai et al. 2016 [26]	Bi$_2$O$_3$ powder and W powder	2 µm and 6 µm	methyl vinyl silicone rubber (VMQ) matrix	2mm	80% 1: 70% Bi$_2$O$_3$ and 10% w 2: 10% Bi$_2$O$_3$ and 70% w	standard X-ray machine (MG-325, Germany)	55 70 100 125 170 210	At 100 kVp 1= 72% 2= 90%
Kim SC et al. 2016 [48]	Barium Sulfate (BaSO$_4$) and Bismuth trioxide (Bi$_2$O$_3$)	-	polyethylene resin	0.15 mm 0.21 mm 0.29 mm	-	Radiography system (Shimadzu company)	100	23.9 % 49.2 % 75.9 %
Pulford et al. 2016 [29]	Barium Sulfate (BaSO$_4$) and Bismuth trioxide (Bi$_2$O$_3$)	-	-	1.9 cm	70 %	Medical X-ray machine	90	72%

According to the study by Kusuktham et al., the BaSO$_4$ shield containing 50% BaSO$_4$ caused 22% dose reduction at 50 kVp, while in the kilo voltage of 100 kVp, the rate decreased to 12%. When the shields were placed in 10 layers, the attenuation was approximately 70% at 100 kVp [35]. In another study, BaSO$_4$ protectors were used with the thickness of 0.4 millimeter, consisting of 40% Si base material and 60% BaSO$_4$. In addition, the protectors could attenuate X-rays by 18% at 100 kVp, while the five-layer shield increased the attenuation to 60% [31].

Nanomed. J. 7(3): 170-182, Summer 2020

175

Another research in this regard was carried out by Maghrabi et al., and the obtained results showed that $BaSO_4$ protectors with the thickness of 1.4 millimeters, along with $BaSo_4$ consisting of 33% of the total weight, could attenuate 30% of X-ray at 80 kVp [36].

On the same note, Kim et al. developed a $BaSO_4$ composite shield with the thickness of one millimeter by adding 500 grams of $BaSO_4$ to 100 grams of Si base, and the attenuation was measured at 100 kVp. According to the findings, the protector made with the materials could attenuate 92% of the X-ray beams, and the reduction value was equivalent to lead protectors [37]. On the other hand, Pulford et al. assessed a $BaSO_4$ protector with 70% $BaSO_4$ and 30% base material, and the results showed that the protector could reduce 21% of the dose at 90 kVp [29].

Combination shields containing Bi, W, and $BaSO_4$

According to our findings, dose reduction by Bi-W and Bi-$BaSO_4$ protectors was within the range of 24-96%, which depended on factors such as the proportion by weight of various materials used in the protective matrix, thickness of the protector in various sizes (0.12 mm to 1.9 cm), and variable tube potential (Table 4).

In a study, Maghrabi et al. evaluated a shield with 20% Bi and 13% Ba in the matrix, reporting that the combination of these materials in a protector with the thickness of 1.46 millimeters could reduce the intensity of the X-rays in radiography by 55% [36]. In another research, Kim et al stated that during the dental panoramic test at 68 kVp, the thyroid dose decreased by approximately 96% with the application of the thyroid Bi-$BaSO_4$ shield [38]. In a research in this regard, Chai et al. compared the effects of various proportions by weight of Bi and W powder, observing that the shield made of 70% Bi and 10% W could reduce radiation by about 70%. On the other hand, the shield made of 70% W powder and 10% Bi decreased 90% of the dose [26]. Similarly, another study demonstrated that Bi and W, two other metals (e.g., tin and antimony), which were used in a shield with the thickness of one millimeter could diminish the beams by 90% at 125 kVp energy [39].

Attenuation coefficients of single-metal and Bi shields against X-rays

Materials with various atomic numbers exhibit

different abilities in attenuating radiation (Tables 1-3). Considering the input and output beams of I_0 and I), the linear attenuation coefficient (μ) could be calculated from $I=I_0e^{-\mu x}$, which describes the attenuation ratio of the shield [40]. Materials such as Si rubber, which had a low atomic number, have no significant effect on the reduction of X-rays; when X-rays pass through a shield that is purely made of this type of material, the initial X-rays reduce to a very small rate. In fact, these materials cannot be an essential factor to X-ray attenuation. However, the matrix structure and proper flexibility of these materials have rendered them suitable for the manufacturing of protectors. Attenuation and absorption in shields could be mainly attributed to Bi, W, and $BaSO_4$ metals, which are mixed in the base matrix. In addition, an influential factor in X-ray absorption by matter is the atomic number of the substance. Bi has an atomic number of 83, which is very close to lead (atomic number: 82) and could be a proper alternative for lead aprons.

The comparison of three types of shields with the same thickness and similar proportions by weight of the metal has indicated that the shield containing Bi particles could absorb and reduce X-rays more than the W and $BaSO_4$ shields. On the other hand, $BaSO_4$ shield has been reported to cause the slightest reduction dose compared to the other two shields.

Linear attenuation coefficient (μ) decreases with increased kV, thereby reducing the density of materials [41]. The μ of W is higher than Bi in diagnostic energy (30-150 kVp) and the pure powder form, which is associated with higher ability to absorb X- rays. The μ of $BaSO_4$ is lowest in two other materials, while the equivalent proportion by weight of Bi or W is used to manufacture shields, and Bi shields demonstrate higher attenuation; this is due to the different densities of these materials. In fact, the lower density of Bi (8.9 g/cm³) compared to W (19.3 g/cm³) has led to the lower volume ratio of Bi in the same proportion by weight of the two substances, so that the number of the Bi particles in a specific volume of a protector is lower than W. According to Aral et al., the Bi protectors consisting of 60% Bi exhibited higher attenuation compared to the W shield and $BaSO_4$ with the same properties, as well as the same thickness and energy (100 kVp) [23].

The K-absorption edge for Bi is 90/5 keV, while it is 69/5 keV for W and 37/4 keV for Ba; this factor has been reported to enhance the

176

Nanomed. J. 7(3): 170-182, Summer 2020
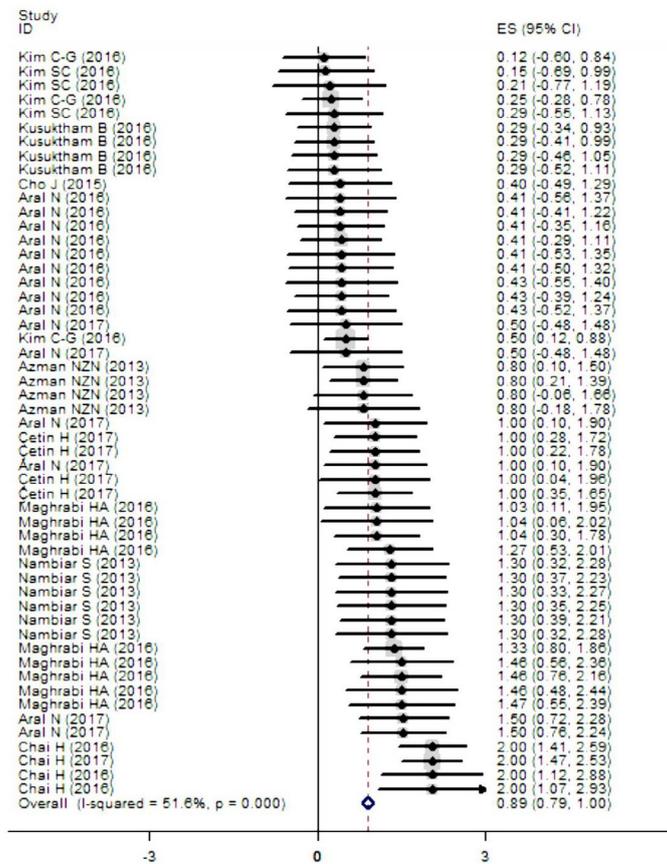
Fig 2. Pooled estimation of thickness (mm) among studies

ability of materials to absorb X-rays [42]. Using the combination of these materials with different K-edge in the construction of a shield is associated with the increased shield ability for dose reduction. In Bi and $BaSO_4$ shields, the beams with higher energy are absorbed by the Bi metal, while the low-energy beams are absorbed by $BaSO_4$. As a result, the lower thickness of the shield with the same dose reduction is possible. In this regard, the findings of Pulford et al. demonstrated that Bi and $BaSO_4$ shields could reduce 86% of primary X-rays, while the attenuation in a separate Bi shield and $BaSO_4$ shield was 72% and 21%, respectively [29].

The literature review indicated that the increased thickness of shields reduces their flexibility, and the possibility of fractures increases as well. A fracture in the shield eliminates its effectiveness in dose reduction, which in turn restricts the thickness of the shields, so that they could not be freely set in the making of protective equipment; therefore, thickness cannot increase as desired.

The thickness of shields in studies has

been reported to be within the range of 0.12-3 millimeters, while it was estimated at 1.9 centimeters in one study. Based on the data of the reviewed studies and considering the constant thickness of the shield, Bi composite shields offer better radiation protection properties.

Influential factors in dose reduction by single-metal and bimetal shields
Effect of particle size on the shield dose reduction

Bi and W nanoparticles increase the number of these particles in the shield. The surface-to-volume ratio of Bi and W nanoparticles is higher than microparticles, which increases the level of collision with the beams. The distribution and uniformity of these nanoparticles are also better than the microparticles, which reduce the empty space in the matrix and response, so that fewer beams would pass through the shield. Therefore, the attenuation ability of X-rays by the shields containing Bi or W nanoparticle is higher than the microparticles of these metals at equal kVp energy. In fact, using nanoparticles rather than

Nanomed. J. 7(3): 170-182, Summer 2020

177

microparticles in the construction of shields could provide higher quality and lower weight in the shields, thereby enhancing their efficacy in X-ray dose reduction.

According to Noor Azman et al., changing the size of Bi particles from micro-Bi to nano-Bi caused the linear attenuation coefficient (μ) to change significantly [43]. Furthermore, in the tube potential of less than 40 kVp, the transmission ratio of Bi_2O_3 microparticles was reported to be 1.2-2.4 times higher than the Bi_2O_3 nanoparticle shield. At the energy up to 100 kVp and higher, the micro- and nano-shields showed the same or close attitude to the reduction of X-rays [44]. This attitude of the shields has been reported to be absorbed by Botelho et al. as well [45]. In low energies in mammography, the shields containing W nanoparticles also demonstrated higher attenuation compared to the shield containing micro-W [32].

In a study regarding the microparticles and nanoparticles of WO_3 at various energies, Aghaz et al. observed that nano-WO_3 had higher attenuation by 34% than the micro-W oxide in the shield at 40 kVp, while at 100 kVp, the nanoparticle shield had only 3% difference in dose reduction compared to the microparticle shield [33]. Similarly, Rashidi et al. prepared an ointment containing 70% Bi nanoparticles, reporting that the protection ability of the ointment was 56% [46].

The similarity of the micro- and nano-shield findings may be attributed to the Compton Effect at higher energies. When the Compton Effect increases, the attenuation of shields decreases, and the response of the shields became similar with the nanoparticle and microparticle of W and Bi [47].

Meta-analysis of dose reduction

This was the first meta-analysis review based on meta-regression analysis to examine the correlations between thicknesses, voltage, and dose reduction. In the current review, the dependency of various factors and dose reduction was also assesed.

Fig 2 shows the forest plot of the 12 studies (60 reported data), including the percentage of dose reduction between the studies as well as the 95% confidence intervals (CIs). Among the other data are the thickness (mm) and 95% CIs. The overall fixed effect of the pooled estimation of the reported thickness among studies was 0.89

millimeter (95% CI: 79-100; P<0.001), suggesting that in order to achieve 70% attenuation, 0.89 millimeter of thickness is required.

Fig 3 shows the correlation of dose reduction with thicknesses based on meta-regression analysis. Although a positive association was observed between dose reduction and thicknesses, it was not considered statistically significant (0.16; 95% CI: -0.03-0.35; P=0.096).
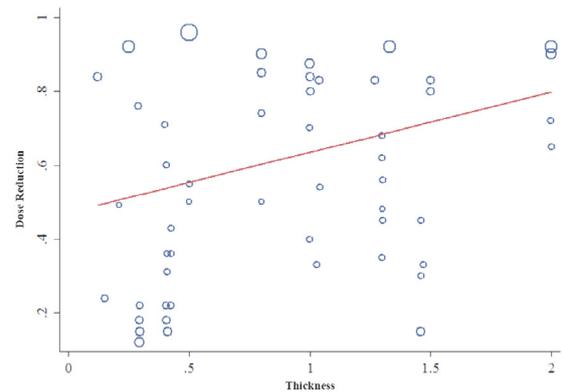
Fig 3. Relation between dose reduction and thickness of composite shields was calculated using meta-regression analysis

Fig 4 and 5 show the forest plot of the 12 studies (60 reported data), including the tube voltage value (kVp) between the studies and 95% CIs. The overall fixed effect of the pooled estimation of the reported tube voltage (kVp) among the studies was 87.2 kVp (95% CI: 87.1-87.3; P<0.001).

Fig 6 depicts the correlation between the tube voltage and dose reduction based on meta-regression analysis. A significant, negative correlation was observed between the tube voltage and dose reduction (-0.0043; 95% CI: -0.0076-0.0009; P=0.012). Therefore, the increased tube voltage was associated with the decreased X-ray attenuation. Several other findings in this regard could also be extracted by the meta-analysis.

Effects of the thickness and proportion by weight of the protective materials on x-ray absorption

The recorded values for the Bi powder ratios were within the range of 10-80% in the Bi protectors, and the ratio of the W powder was within the range of 5-80% in the W shields. The proportion by weight of the $BaSO_4$ was within the range of 10-70% in the protectors, and the thickness of various shields was reported to be 1.2-3 millimeters, while it was 1.9 centimeters in

178

Nanomed. J. 7(3): 170-182, Summer 2020

Study ID	ES (95% CI)
50	
Kusuktham B	0.22 (-0.59, 1.03)
Cho J	0.90 (0.33, 1.48)
Cho J	0.99 (0.77, 1.21)
Subtotal (I-squared = 37.6%, p = 0.201)	0.93 (0.73, 1.13)
68	
Kim C-G	0.96 (0.58, 1.34)
Kim C-G	0.92 (0.39, 1.45)
Kim C-G	0.84 (0.12, 1.56)
Subtotal (I-squared = 0.0%, p = 0.958)	0.93 (0.64, 1.22)
70	
Kusuktham B	0.18 (-0.57, 0.93)
Subtotal (I-squared = .%, p = .)	0.18 (-0.57, 0.93)
80	
Maghrabi HA	0.92 (0.39, 1.45)
Kusuktham B	0.15 (-0.55, 0.85)
Maghrabi HA	0.33 (-0.59, 1.25)
Maghrabi HA	0.33 (-0.59, 1.25)
Aral N	0.36 (-0.58, 1.30)
Aral N	0.22 (-0.59, 1.03)
Maghrabi HA	0.30 (-0.60, 1.20)
Maghrabi HA	0.83 (0.09, 1.57)
Aral N	0.43 (-0.54, 1.40)
Maghrabi HA	0.54 (-0.44, 1.52)
Cho J	0.78 (-0.04, 1.59)
Cho J	0.92 (0.39, 1.45)
Maghrabi HA	0.83 (0.09, 1.57)
Maghrabi HA	0.15 (-0.55, 0.85)
Maghrabi HA	0.45 (-0.53, 1.43)
Subtotal (I-squared = 0.0%, p = 0.814)	0.57 (0.38, 0.77)
100	
Aral N	0.70 (-0.20, 1.60)
Aral N	0.50 (-0.48, 1.48)
Chai H	0.72 (-0.16, 1.60)
Azman NZN	0.90 (0.31, 1.49)
Azman NZN	0.85 (0.15, 1.55)
Chai H	0.92 (0.39, 1.45)
Cho J	0.71 (-0.18, 1.60)
Kusuktham B	0.12 (-0.52, 0.76)
Aral N	0.83 (0.09, 1.57)
Nambiar S	0.62 (-0.33, 1.57)
Aral N	0.55 (-0.43, 1.53)
Aral N	0.31 (-0.60, 1.22)
Cho J	0.87 (0.21, 1.53)
Aral N	0.70 (-0.20, 1.60)
Azman NZN	0.50 (-0.48, 1.48)
Aral N	0.36 (-0.58, 1.30)
Aral N	0.18 (-0.57, 0.93)
Kim SC	0.76 (-0.08, 1.60)
Aral N	0.80 (0.02, 1.58)
Nambiar S	0.68 (-0.23, 1.59)
Chai H	0.65 (-0.28, 1.58)
Kim SC	0.49 (-0.49, 1.47)
Azman NZN	0.74 (-0.12, 1.60)
Nambiar S	0.45 (-0.53, 1.43)
Chai H	0.90 (0.31, 1.49)
Subtotal (I-squared = 0.0%, p = 0.997)	0.67 (0.51, 0.83)
Heterogeneity between group: p = 0.021	
Overall (I-squared = 0.0%, p = 0.932)	0.73 (0.63, 0.83)

Fig 4. Data analyzes of included studies for tube voltage (50-100 kV)

one study (Tables 1-3).

According to the literature, the increased shield thickness is associated with the higher ability of its dose reduction owing to the increased distance the radiation travels in the shield. In addition, the chance of collision probability of Bi, W or $BaSO_4$ particles with X-rays will be higher although when the particle ratio increases, the flexibility of the shields declines.

Fig 2 shows the details of the meta-analysis of the studies in terms of the thickness variable. As is shown in Fig 4, there was a direct correlation between increased thickness and dose reduction, But it was not statistically significant (P>0.096) (Table 5).

Table 5. Relationship of thickness, tube-voltage and dose reduction

	Coef.	Std. Err.	T	P>|t|	[95% Conf. Interval]	
Thickness	0.1636	0.0964	1.70	0.096	-0.0300	0.3573
Tube voltage	-0.0043	0.0016	-2.59	0.012	-0.0076	-0.0009

In the study by Kim et al., radiation protection was reported to increase from 24% to 76% with a change in the shield thickness of the Bi powder and $BaSO_4$, from 0.15 to 0.29 millimeters [48]. Some studies have also indicated that the increased weight percentage of Bi, W or $BaSO_4$ in the matrix could bring about the desired attenuation with lower thickness. The increased number of the particles per unit of the shield volume causes the

Nanomed. J. 7(3): 170-182, Summer 2020

179
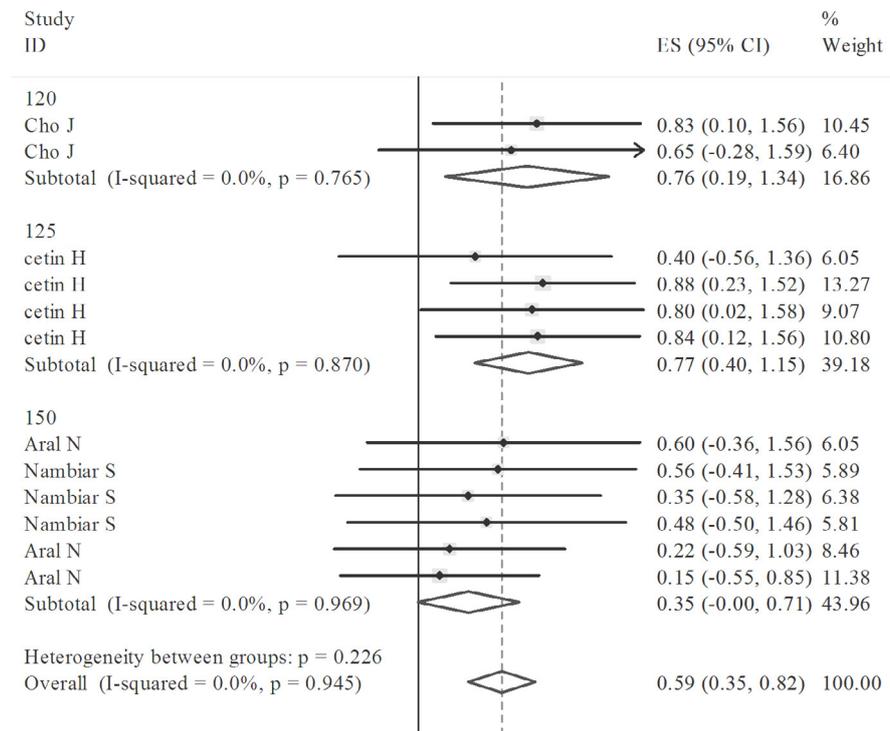
Fig 5. Data analyzes of included studies for tube voltage (100> kV)

possibility of the beam incident with the particles to increase, while the reduction of the beam energy changes dramatically. The problem of increasing the material percentage in shields such as Bi is the reduction of elasticity and higher possibility of cracking. In this regard, Thongpool et al. reported that by increasing the proportion by weight to the volume of the $BaSO_4$ in the protector from 0.2% to 0.8%, the linear attenuation coefficient also increased from 0.085 to 1.189 [49]. With the same thickness (0.4 mm), dose reduction was estimated at 43%, 36%, 22%, while with the thickness of one millimeter, the rate was 80%, 70%, and 30% in Bi, W, and Ba, respectively.

Effect of kvp on x-ray attenuation

In the reviewed studies, the tube potential of 25-150 kVp was used. The obtained data showed that increased kilo voltage was associated with the reduced rate of radiation attenuation. Figures 4 and 5 show the meta-analysis of the studies in terms of tube voltage. As is depicted in Figure 6, there was a significant correlation between the increased tube voltage and decreased dose reduction (P<0.05) (Table 5).

A study in this regard was carried out on W

protectors with the thickness of 0.3 millimeter and 80% weight percentage of W. At 60, 80, 100, and 120 kVp, attenuation was equal to 65%, 53%, 48%, and 46%, respectively. Moreover, the obtained results showed that by increasing the kV from 60 to 120, attenuation decreased from 65% to 46% [50]. In another research, three types of Bi, W, and $BaSO_4$ protectors with the thickness of 0.4 millimeter and 60% proportion by weight of the materials were used. According to the findings, the attenuation of the Bi protector at 80, 100, and 150 kVp was approximately 43%, 32%, and 22%, respectively. As for the W shields, the values were calculated to be 36%, 31%, and 15%, while they were 22%, 18%, and 6% in $BaSO_4$, respectively. The common point regarding all the applied shield materials is the reduced radiation dose attenuation due to the increased kilo voltage [23].

According to another study focused on Ba compounds, the linear attenuation coefficients of the compounds were calculated at various energies, and the results showed that under the same conditions, changing the kilo voltage from 32 to 74 kV caused the linear attenuation coefficient (μ) of the $BaSO_4$ protector to decrease from 24.1 to 8.9 cm^{-1} [51]. As is shown in Fig 5 for the tube

180

Nanomed. J. 7(3): 170-182, Summer 2020

voltage of 100 kVp, the dose reduction was 36%, 31%, and 18% in Bi, W, and Ba.
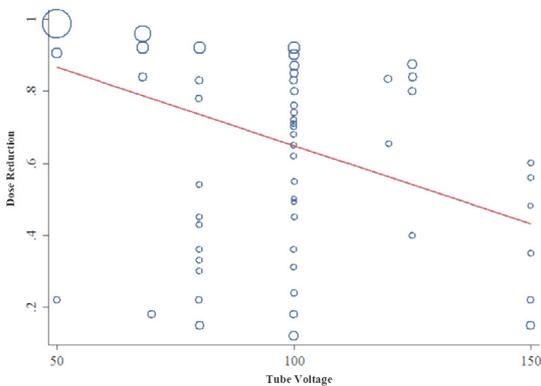
Fig. 6 Relation between dose reduction and tube voltage was calculated using meta-regression analysis

CONCLUSION

Lead aprons are typically used for protection against radiation and absorption of more than 90% of the rays emitted toward sensitive organs. Due to lead toxicity and the heaviness of these shields, several studies have been focused on the application of non-lead protective materials. Powders of material such as bismuth, tungsten, and barium sulfate in a polymer matrix with a high atomic number and better flexibility have exhibited efficient properties as alternatives for non-lead aprons. Furthermore, these materials are non-toxic, causing no damage to the body.

According to the review, the use of single-metal shields made of bismuth powder resulted in better performance than tungsten or barium sulfate shields in terms of X-ray attenuation. Additionally, the use of two metals together in a shield was associated with higher attenuation and dose reduction compared to the single-metal shields.

Several factors affect the ability of shields in reducing the X-ray dose, such as the particle size, ratio of the used metal in the shield, and tube potential (kV). Therefore, it is predicted that nanoparticle size, lower tube potential (kV), and higher metal ratio in the construction of shields could increase X-ray attenuation. Among the studied shields, bismuth-tungsten shields were reported to have better potential for radiation protection.

ACKNOWLEDGMENTS

REFERENCES

1. Hashemi SA, Mousavi SM, Faghihi R, Arjmand M, Sina S, Amani AM. Lead oxide-decorated graphene oxide/epoxy composite towards X-Ray radiation shielding. Radiat Phys Chem. 2018; 146: 77-85.
2. Farhood B, Raei B, Malekzadeh R, Shirvani M, Najafi M, Mortezazadeh T. A review of incidence and mortality of colorectal, lung, liver, thyroid, and bladder cancers in Iran and compared to other countries. Contemp Oncol. 2019; 23(1): 7-15.
3. Finnerty M, Brennan P. Protective aprons in imaging departments: manufacturer stated lead equivalence values require validation. Eur radiol. 2005; 15(7): 1477-1484.
4. Burns KM, Shoag JM, Kahlon SS, Parsons PJ, Bijur PE, Taragin BH, Markowitz M. Lead aprons are a lead exposure hazard. J Am Coll Radiol. 2017; 14(5): 641-647.
5. Mehnati P, Malekzadeh R, Sooteh MY. Use of bismuth shield for protection of superficial radiosensitive organs in patients undergoing computed tomography: a literature review and meta-analysis. Radiol Phys Technol. 2019; 12(1): 6-25
6. Ambika M, Nagaiah N, Harish V, Lokanath N, Sridhar M, Renukappa N, Suman SK. Preparation and characterisation of Isophthalic-Bi2O3 polymer composite gamma radiation shields. Radiat Phys Chem. 2017; 130: 351-358.
7. Mehnati P, Sooteh MY, Malekzadeh R, Divband B, Refahi S. Breast Conservation From Radiation Damage By Using Nano Bismuth Shields In Chest CT Scan. Crescent J Med Biol Sci. 2018; 6(1): 46-50.
8. Mehnati P, Sooteh MY, Malekzadeh R, Divband B. Synthesis and characterization of nano Bi2O3 for radiology shield. Nanomed J. 2018; 5(4): 222-226.
9. Mehnati P, Malekzadeh R, Sooteh MY, Refahi S. Assessment of the efficiency of new bismuth composite shields in radiation dose decline to breast during chest CT. Egypt j radiol nucl med. 2018; 49(4):1187-1189.
10. Yue K, Luo W, Dong X, Wang C, Wu G, Jiang M, Zha Y. A new lead-free radiation shielding material for radiotherapy. Radiat prot dosim. 2009; 133(4):256-260.
11. Nambiar S, Yeow JT. Polymer-composite materials for radiation protection. ACS Appl Mater Interfaces. 2012; 4(11):5717-5726.
12. Mukundan JS, Wang PI, Frush DP, Yoshizumi T, Marcus J, Kloeblen E, Moore M. MOSFET dosimetry for radiation dose assessment of bismuth shielding of the eye in children. Am J Roentgenol. 2007; 188(6): 1648-1650.
13. Malekzadeh R, Mehnati P, Yousefi Sooteh M, Mesbahi A. Influence of size of nano and micro-particles and photon energy on mass attenuation coefficients of bismuth-silicon shields in diagnostic radiology. Radiol Phys Technol. 2019; 12(3):325-334.
14. Mehnati P, Malekzadeh R, Yousefi Sooteh M. New Bismuth composite shield for radiation protection of breast during coronary CT angiography. Iran J Radiol. 2019; 16(3).
15. Dong M, Elbashir B, Sayyed M. Enhancement of gamma ray shielding properties by PbO partial replacement of WO3 in ternary 60TeO2–(40-x) WO3–xPbO glass system. Chalcogenide Lett. 2017; 14(3):113-118.
16. Harish V, Nagaiah N, Prabhu TN, Varughese K. Preparation and characterization of lead monoxide filled unsaturated polyester based polymer composites for gamma radiation shielding applications. J Appl Polym Sci. 2009; 112(3):1503-

Nanomed. J. 7(3): 170-182, Summer 2020

181

1508.

17. Azman NZN, Siddiqui SA, Hart R, Low IM. Microstructural design of lead oxide–epoxy composites for radiation shielding purposes. J App Polym Sci. 2013; 128(5):3213-3219.

18. Zuguchi M, Chida K, Taura M, Inaba Y, Ebata A, Yamada S. Usefulness of non-lead aprons in radiation protection for physicians performing interventional procedures. Radiat prot dosim. 2008; 131(4): 531-534.

19. Sonsilphong A, Wongkasem N. Light-weight radiation protection by non-lead materials in X-ray regimes. ICEAA. 2014; 656-658

20. McCaffrey J, Tessier F, Shen H. Radiation shielding materials and radiation scatter effects for interventional radiology (IR) physicians. Med phys. 2012; 39(7):4537-4546.

21. McCaffrey J, Mainegra-Hing E, Shen H. Optimizing non-Pb radiation shielding materials using bilayers. Med phys. 2009; 36(12): 5586-5594.

22. Nambiar S, Osei EK, Yeow JT. Effects of particle size on X-ray transmission characteristics of PDMS/Ag nano-and microcomposites. IEEE-NANO. 2015; 1358-1361.

23. Aral N, Banu NF, Candan C. An alternative X-ray shielding material based on coated textiles. Text Res J. 2016; 86(8): 803-811.

24. Heaney D, Norvill C. A comparison of reduction in CT dose through the use of gantry angulations or bismuth shields. Australas Phys Eng Sci Med. 2006; 29(2): 172-178.

25. Cho J, Kim M, Rhim J. Comparison of radiation shielding ratios of nano-sized bismuth trioxide and molybdenum. Radiat Eff Defect S. 2015; 170(7-8): 651-658.

26. Chai H, Tang X, Ni M, Chen F, Zhang Y, Chen D, Qiu Y. Preparation and properties of novel, flexible, lead-free X-ray-shielding materials containing tungsten and bismuth (III) oxide. J Appl Polym Sci. 2016; 133(10).

27. Nambiar S, Osei EK, Yeow JT. Polymer nanocomposite-based shielding against diagnostic X-rays. J Appl Polym Sci. 2013; 127(6): 4939-4946.

28. Azman NZN, Siddiqui SA, Low IM. Synthesis and characterization of epoxy composites filled with Pb, Bi or W compound for shielding of diagnostic x-rays. Appl Phys A. 2013; 110(1): 137-144.

29. Pulford S, Fergusson M. A textile platform for non-lead radiation shielding apparel. J Text I. 2016; 107(12): 1610-1616.

30. Kim S, Lee H, Cho J. Analysis of low-dose radiation shield effectiveness of multi-gate polymeric sheets. Radiat Eff Defect S. 2014; 169(7):584-591.

31. Aral N, Nergis FB, Candan C. Investigation of x-ray attenuation and the flex resistance properties of fabrics coated with tungsten and barium sulphate additives. Tekst konfeksiyon. 2016; 26(2).

32. Azman NN, Siddiqui S, Hart R, Low IM. Effect of particle size, filler loadings and x-ray tube voltage on the transmitted x-ray transmission in tungsten oxide-epoxy composites. Appl Radiat Isot. 2013; 71(1): 62-67.

33. Aghaz A, Faghihi R, Mortazavi S, Haghparast A, Mehdizadeh S, Sina S. Radiation attenuation properties of shields containing micro and Nano WO3 in diagnostic X-ray energy range. Int J Radiat Res. 2016; 14(2): 127.

34. Aral N, Nergis FB, Candan C. The X-ray attenuation and the flexural properties of lead-free coated fabrics. J Indust Text. 2017; 47(2): 252-268.

35. Kusuktham B, Wichayasiri C, Udon S. X-Ray attenuation of cotton fabrics coated with barium sulphate. JMMM. 2016;

26(1).

36. Maghrabi HA, Vijayan A, Mohaddes F, Deb P, Wang L. Evaluation of X-ray radiation shielding performance of barium sulphate-coated fabrics. Fiber Polym. 2016; 17(12): 2047-2054.

37. Kim SC, Dong KR, Chung WK. Performance evaluation of a medical radiation shielding sheet with barium as an environment-friendly material. J Korean Phys Soc. 2012; 60(1):165-170.

38. Kim CG. The development of bismuth shielding to protect the thyroid gland in radiations environment. Indian J Sci Technol. 2016; 9(5): 77-85.

39. Çetin H, Yurt A, Yüksel SH. The absorption properties of lead-free garments for use in radiation protection. Radiat prot dosim. 2017; 173(4): 345-350.

40. Sambhudevan S, Shankar B, Saritha A, Joseph K, Philip J, Saravanan T. Development of X-ray protective garments from rare earth-modified natural rubber composites. J Elastom Plast. 2017; 49(6):527-544.

41. Al-Maamori MH, Al-Bodairy OH, Saleh NA. Effect oF PbO with rubber composite on transmission of (X-ray). Acad Res Int. 2012; 3(3): 113-119.

42. Mehnati P, Malekzadeh R, Divband B, Yousefi Sooteh M. Assessment of the effect of nano-composite shield on radiation risk prevention to Breast during computed tomography. Iran J Radiol. 2020; 17(1).

43. Azman NN, Siddiqui SA, Haroosh HJ, Albetran HM, Johannessen B, Dong Y, Low IM. Characteristics of X-ray attenuation in electrospun bismuth oxide/polylactic acid nanofibre mats. J synchrotron radiat. 2013; 20(5): 741-748.

44. Azman NN, Musa NF, Ab Razak NNN, Ramli RM, Mustafa IS, Rahman AA, Yahaya NZ. Effect of Bi2O3 particle sizes and addition of starch into Bi2O3–PVA composites for X-ray shielding. Appl Phys A. 2016; 122(9): 818.

45. Botelho M, Künzel R, Okuno E, Levenhagen RS, Basegio T, Bergmann CP. X-ray transmission through nanostructured and microstructured CuO materials. Appl Radiat Isot. 2011; 69(2):527-530.

46. Rashidi M, Saffari M, Shirkhanloo H, Avadi MR. Evaluating X-ray absorption of nano-bismuth oxide ointment for decreasing risks associated with X-ray exposure among operating room personnel and radiology experts. J health Saf Work. 2015; 5(4):13-22.

47. Akkurt I, Akyildirim H, Mavi B, Kilincarslan S, Basyigit C. Gamma-ray shielding properties of concrete including barite at different energies. Prog Nucl Energ. 2010; 52(7):620-623.

48. Kim SC, Choi JR, Jeon BK. Physical analysis of the shielding capacity for a lightweight apron designed for shielding low intensity scattering X-rays. Sci Rep. 2016; 6(1): 1-7.

49. Thongpool V, Phunpueok A, Barnthip N, Jaiyen S. BaSO4/polyvinyl alcohol composites for radiation shielding. Appl Mech Mater. 2015; 804: 3-6.

50. Monzen H, Kanno I, Fujimoto T, Hiraoka M. Estimation of the shielding ability of a tungsten functional paper for diagnostic x-rays and gamma rays. J Appl Clin Med Phys. 2017; 18(5): 325-329.

51. Seenappa L, Manjunatha H, Chandrika B, Chikka H. A Study of Shielding Properties of X-ray and Gamma in Barium Compounds. J Radiat Prot Res. 2017; 42(1): 26-32.

52. Maghrabi HA, Vijayan A, Deb P, Wang L. Bismuth oxide-coated fabrics for X-ray shielding. Text Res J. 2016; 86(6): 649-658.

182

Nanomed. J. 7(3): 170-182, Summer 2020