Journal of Medical Imaging and Radiation Sciences 54 (2023) 145–152

Journal of Medical Imaging and Radiation Sciences

Journal de l'imagerie médicale et des sciences de la radiation

www.elsevier.com/locate/jmir

Research Article

Trade-off between breast dose and image quality using composite bismuth shields in computed tomography: A phantom study

Parinaz Mehnati[a], Reza Malekzadeh[a], Hussein Ali Hussein[b], Noor H. Obaid[c], Saadat Ebrahimiyan[d], Mohammad Yousefi Sooteh[a] and Soheila Refahi[e,*]

[a] *Department of Medical Physics, School of Medicine, Tabriz University of Medical Sciences, Tabriz, Iran*
[b] *Scientific Research Center, Al-Ayen University, Thi-Qar, Iraq*
[c] *Anesthesia Techniques Department, Al-Mustaqbal University College, Babylon, Iraq*
[d] *Department of Medical Physics and Radiology, School of Medicine, Gonabad University of Medical Sciences, Gonabad, Iran*
[e] *Department of Medical Physics, School of Medicine, Ardabil University of Medical Sciences, Ardabil, Iran*

ABSTRACT

Introduction: Many researchers have suggested that bismuth composite shields (BCS) reduce breast dose remarkably; however, the level of this reduction and its impact on image quality has not been assessed. This study aimed to evaluate the efficiency of nano- and micro- BCS in reducing the dose and image quality during chest computed tomography (CT) scans.

Materials and methods: Bismuth shields composed of 15 weighting percentage (wt%) and 20 wt% bismuth oxide (Bi_2O_3) nano- and micro-particles mixed in silicon rubber polymer were constructed in 1 and 1.5 mm thicknesses. The physical properties of nanoparticles were assessed using a scanning electron microscope (SEM), X-ray diffraction (XRD), and energy-dispersive X-ray (EDX). Breast radiation doses were measured experimentally during chest CT using PMMA standard dosimetry phantom (body phantom, 76-419-4150, Fluke Biomedical) in the presence of the shields. The image quality was assessed by calculating signal and noise values in different regions.

Results: The SEM images showed that the average size of Bi_2O_3 nano- and micro-particles was about 70 nm and 150 μm, respectively. The breast doses were reduced by increasing the shield thickness/bismuth weight percentage. The maximum dose reduction was related to the 20% weight of Bi_2O_3 nano-particles and a thickness of 1.5 mm. The minimum dose reduction was related to the 15% weight of Bi_2O_3 micro-particles with a thickness of 1 mm. The mean noise was higher in nano-particle bismuth shields than in micro-particles.

Conclusion: Composite shields containing bismuth nano- and micro-particles can reduce the breast dose during chest CT examinations while negatively impacting diagnostic image quality. Several critical factors, such as bismuth concentration, particle size, and shield thickness, directly affect the efficiency.

RÉSUMÉ

Introduction: De nombreux chercheurs ont suggéré que les boucliers composites au bismuth réduisent considérablement la dose reçue par le sein, mais le niveau de cette réduction et son incidence sur la qualité de l'image n'ont pas été évalués. Cette étude avait pour but d'évaluer l'efficacité des boucliers composites de nano- et micro-particules de bismuth dans la réduction de la dose et de la qualité de l'image pendant les tomographies thoraciques.

Matériel et méthodologie: Des écrans au bismuth composés de nano- et micro-particules d'oxyde de bismuth (Bi_2O_3) à 15 et 20 % en poids

Competing interests: The authors declare that they need no conflicts of interest.
Contributors: All authors contributed to the conception or design of the work, the acquisition, analysis, or interpretation of the data. All authors were involved in drafting and commenting on the paper and have approved the final version.
Funding: This study did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.
Ethical Approval: This study was approved by Tabriz University of Medical Sciences, Tabriz, Iran (IR.TBZMED.REC.1396.973).

* Corresponding authors: Soheila Refahi: Department of Medical Physics, School of Medicine, Ardabil University of Medical Sciences, Ardabil, Iran.
E-mail address: soheila52@yahoo.com (S. Refahi).

https://doi.org/10.1016/j.jmir.2022.12.005

mélangées à une matrice à base de caoutchouc de silicone ont été construits en 1 et 1,5 mm d'épaisseur. Les propriétés physiques des nanoparticules ont été évaluées au moyen du microscope électronique à balayage (MEB), de la diffraction des rayons X (DRX) et des rayons X à dispersion énergétique (EDX). Les doses de rayonnement au niveau du sein ont été mesurées expérimentalement au cours d'une tomographie thoracique à l'aide d'un fantôme de dosimétrie standard en PMMA (body phantom, 76-419-4150, Fluke Biomedical) en présence des écrans. La qualité de l'image a été évaluée en calculant les valeurs de signal et de bruit dans différentes régions.

Résultats: Les images au microscope électronique (SEM-MAP) ont montré que la taille moyenne des nanoparticules et microparticules de Bi_2O_3 était d'environ 70 nm et 150 μm, respectivement. Les boucliers composites avec 15 % en poids et 20 % en poids d'oxyde de bismuth ont montré une réduction de dose de 12 à 33 %, respectivement, en fonction du pourcentage de remplissage, de l'épaisseur du bouclier et de la taille des particules. Les doses de poitrine ont été réduites en augmentant l'épaisseur du bouclier et le pourcentage en poids d'oxyde de bismuth. Le bruit moyen a augmenté de 8 à 29 % dans la position du sein et de 4 à 25 % à l'emplacement des artères coronaires.

Conclusion: Les écrans composites contenant des nanoparticules et des microparticules de bismuth peuvent réduire la dose au sein pendant les examens de tomodensitométrie thoracique tout en ayant une incidence négative sur la qualité de l'image diagnostique. Plusieurs facteurs critiques tels que la concentration de bismuth, la taille des particules et l'épaisseur du bouclier affectent directement l'efficacité.

Keywords: Nano-composite; Computed tomography; Dose reduction; Image quality; Breast imaging

Introduction

Computed tomography (CT) has become one of the main methods for medical diagnosis due to its simple applications and high clinical efficiency [1–3]; however, this modality uses ionizing radiation that develops the probabilities of radiation-induced harmful effects like cancer. Therefore, it is essential to minimize the patient's radiation exposure dose in CT examinations as low as reasonably achievable (ALARA). In chest CT, the breast tissue is exposed to primary radiation and is often not the target organ for imaging [4,5]. Furthermore, female breast tissue was recently found to be more radiosensitive than earlier [6]. Studies showed that exposure to ionizing radiation during chest radiological imaging remarkably increases breast cancer risk [5,7]. Several methods have been proposed to reduce the breast dose during chest CT, including tube current modulation (TCM) [8], organ-based TCM [8], shielding [9], decreasing the radiation field [10], and novel image reconstruction algorithms with lower exposures [11,12].

Researchers have suggested flexible and non-toxic polymer composite shields with metal particles for patient radiation protection through CT examinations [13]. In conventional lead protection, the goal is to reduce ionizing radiation to a specific area. In this situation, lead causes remarkable metal artifacts and the image quality decreases significantly. While with a polymer composite shield, the X-ray is partially blocked to reduce the dose to the underlying tissue and satisfy enough transmitted X-ray beams to make a valuable diagnostic CT image [14]. The bismuth composite shields (BCS) are commercially available now as one of the common patient dose reduction methods to protect superficial organs, such as the eyes, thyroid, and breast, during CT examinations. These shields are usually positioned over the surface of the sensitive superficial organs and attenuate the primary X-ray beams by 20-40% [15]. Tapouni et al. have shown that BCS can decrease breast radiation dose by about 37% while maintaining image quality [16]. However, the use of BCS increases image noise, changes CT numbers, and decreases image quality [17]. Einstein et al. reported that using BCS reduced the contrast to noise levels by about 21% and increased image noise significantly [18]. Kalra et al. presented similar findings, and they showed that applying BCS up to 6 cm below the radiation shield caused a significant increase in the CT number and image noise [19].

Despite all the advantages of BCS, losing the image quality and diagnostic value of the medical images are the considerable challenges in clinics. The purpose of the present study was to evaluate the impact of BCS with different concentrations and thicknesses on dose and image quality for female breasts during chest CT scans. In this regard, nano- and micro-particles of bismuth oxide (Bi_2O_3) were constructed and their properties were evaluated using a scanning electron microscope (SEM), X-ray diffraction (XRD), and energy-dispersive X-ray (EDX) examinations. The effect of shield thickness, bismuth weight percentage, and particle size was evaluated on the performance (dose reduction and image quality) of radiation composite shields.

Materials and methods

Preparation and characterization of the BCS

A newly designed BCS of bismuth nano- and micro-particles with 15 weight percentage (wt%) and 20 wt% mixed in silicon rubber polymer with 1 mm and 1.5 mm thicknesses and 20 × 20 cm^2 size was used in this study. Bi_2O_3 nano-particles were synthesized and analyzed with SEM and XRD examinations. The EDX analysis, as an analytical technique, was used to evaluate the chemical compositions of BCS. After the synthesis, Bi_2O_3 nano-particles ($\leq$100nm) and micro-particles ($\leq$150μm) were blended by a mechanical stirrer into the silicon with the relevant weight percentages. The shields were dried for two weeks in the laboratory. SEM imaging was used to evaluate the distribution of bismuth particles within the silicone [20–22].

Measurements of X-ray transmission

A conventional radiographic device (VARIAN tube type) and a DIADOS E dosimeter (T11035-0206, PTW Company,

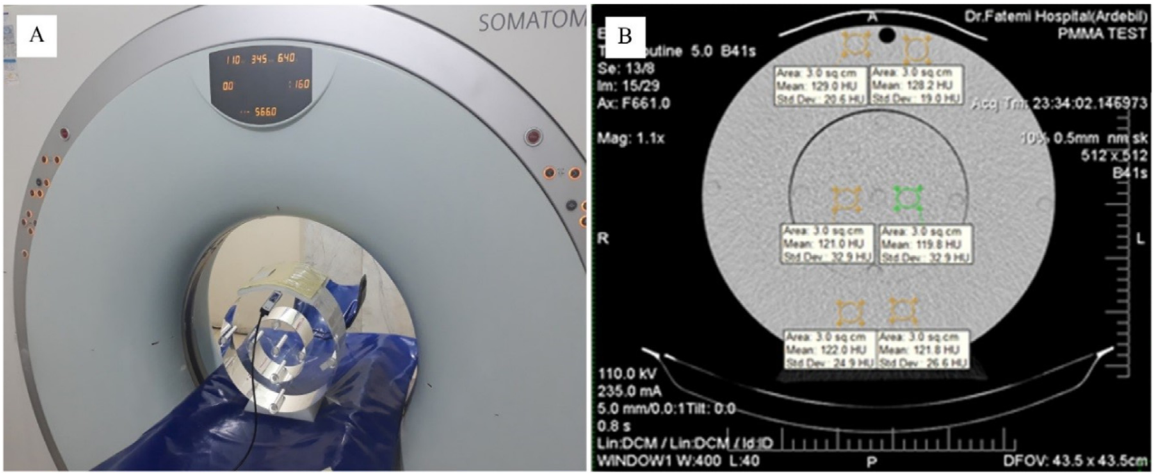

Fig. 1. Image quality assessment in regions of interest position of CT phantom with and without different nano- and micro- bismuth composite shields. A: Standard CT phantom covered by composite shield and 1 cm foam. B: The three area were selected to analysis image quality.

Freiburg, Germany) were used to evaluate the X-ray attenuation properties of these shields and calculate their linear attenuation coefficient (μ). All equipment had been quality controlled and calibrated regarding the recommended protocols of AAPM (American Association of Physicists in Medicine) report No. 74 and company standards [23], and they were performing within manufacturer and required national standards. The shields were placed at a distance of 1m from the X-ray tube focal point, and the dosimeter was placed under the shield. The X-ray transmission values were measured in the presence and absence of BCS at three energies (60, 80, and 100 kVp) [24]. The measurements were performed for different thicknesses of 1, 1.5, and 2.0 mm for each shield, and the linear attenuation coefficients were estimated using the Beer-Lambert formula [25].

Dosimetry condition and image quality analysis

A standard polymathic methacrylate (PMMA) CT phantom (body phantom, 76-419-4150, Fluke Biomedical) was used for dosimetry and image quality assessment. The PMMA phantom is made of solid acrylic and has five measurement holes at the center and in the 12, 3, 6, and 9 o'clock positions. The ion chamber (10 cm pencil-shaped ionization chamber, Model 205-3 CT, Monrovia, USA) was positioned in the 12 o'clock position for breast dose measurement [26] because this hole is nearest to the phantom upper surface, simulating the breast location. The phantom was scanned using a 16 multi-slice CT scan scanner (SOMATOM Emotion, model 03815300, Siemens) with a standard protocol of adult chest CT, including the tube potential of 110 kVp, tube current of 105 mAs, pithch=1, and 5-mm slice thickness. Each BCS was fixed on the phantom surface with 1 cm foam. The location of phantoms and the shield on the breasts can be seen in Fig. 1A. The image quality was assessed by measuring mean CT numbers and their standard deviations in chosen regions of interest (ROIs) of approximately 2 cm^2. The noise values were the standard deviations of CT numbers in each ROI on the CT images with and without BCS. The ROIs were defined in anterior, central, and posterior regions on five consecutive slices (Fig. 2B). The quantitative image was evaluated by the eFilm Lite image analysis software (version 3.4, Java, 2010 Merge Healthcare). The dose reduction by BCS was calculated based on Eq. 1:

$$Dosereduction(\%) = \frac{\text{Measured dose without shield} - \text{Measured dosein the presence of shield}}{\text{Measured dose without shield}} \times 100 \quad (1)$$

Results

Morphological and structural analysis

An SEM image of the Bi_2O_3 nano-particle morphologies is shown in Fig. 2. The Bi_2O_3 nano-particles obtained are almost semi-spherical with some agglomerated particles. The average size of Bi_2O_3 nano-particles varied from 50 nm to 150 nm, and the average size of Bi_2O_3 micro-particles was about 150μm.

The XRD analysis of Bi_2O_3 nano-particles is illustrated in Fig. 3A. The experimental analysis was performed at diffraction angles ranging from 20° to 70°. The location of the peaks indicated the successful synthesis of Bi_2O_3 nanoparticles, and the main curve peak near 27° indicates the existence of Bi_2O_3. The mean particle size of the Bi_2O_3 nanoparticles was calculated by applying the Scherer equation [27] to the plane diffraction peak and found to be 40–90 nm in the composite. The distribution of Bi_2O_3 nano- and micro-particles in the silicone matrix was calculated through SEM analysis, and a sample image is shown in Fig. 3B. The SEM test showed that the particles are well dispersed in 15% to 20% BCS, indicating the correct process of synthesis and fabrication of the BCS. The EDX analysis

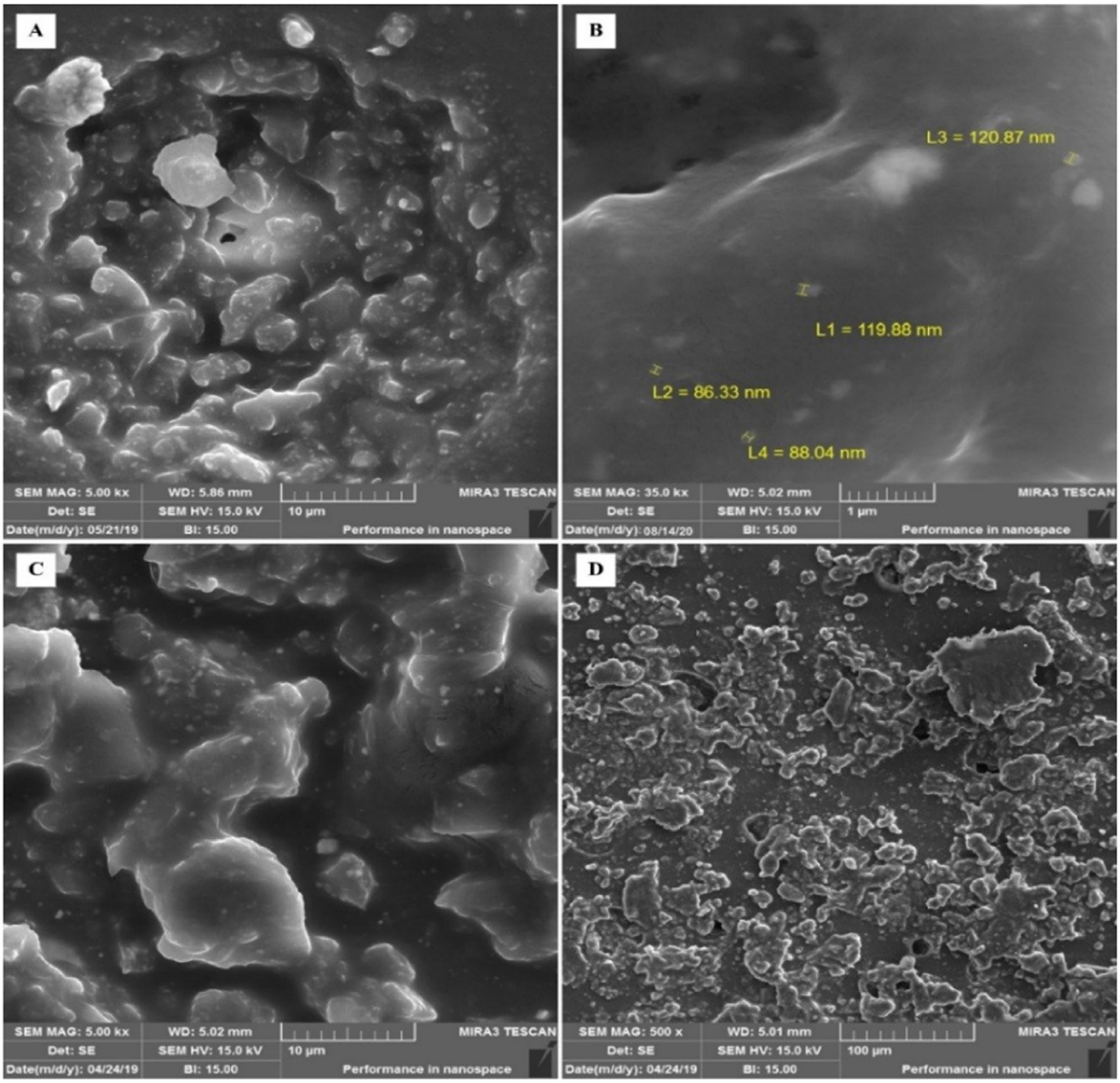

Fig. 2. SEM images of Bi2O3 particles in the silicon rubber matrix. A and B: With less magnification and more magnification of 15% composites. C and D: With less magnification and more magnification of 20% composites.

confirmed that the shield contained silicone, carbon, oxygen, and bismuth. These results were similar to the values obtained from SEM and XRD examinations. The Bi_2O_3 particles had a good uniform distribution inside the polymer. This property prevented radiation from passing through the empty spaces in composite shields.

Radiation protection properties

Figs. 4 and 5 present the linear attenuation coefficient values of nano- and micro-BCS with different percentages and thicknesses at three energies of 60, 80, and 100 kVp. According to Fig. 4, the μ values at 100 kVp for the 100% silicon shield was equal to 1.12 cm^{-1}. The linear attenuation coefficients for the 15% and 20% of nano-BCS with a thickness of 1 mm were 5.66 cm^{-1} and 7.36 cm^{-1}, respectively. Also, for 15% and 20% of nano-BCS with a thickness of 1.5 mm, the μ values were 4.78 cm^{-1} and 6.34 cm^{-1}, respectively. Details of the μ values at 80 and 60 kVp energies are presented in Fig. 4. In addition, the μ values for micro-BCS are shown in Fig. 5. They were 4.98 cm^{-1} and 6.67 cm^{-1} for the 15% and 20% bismuth with 1 mm thickness, respectively. Furthermore, for a thickness of 1.5 mm, these values were 4.23 cm^{-1} and 5.77 cm^{-1}, respectively. The μ values at 80 and 60 kVp energies are presented in Fig. 5.

Breast radiation doses

The breast average dose with and without the use of BCS with different percentages, particle sizes, and thicknesses are presented in Fig. 6. The breast dose was 8.65 mGy before applying shields through a chest CT scan. The maximum dose reduction was related to the bismuth shield with 20% weight of Bi_2O_3 nano-particles and a thickness of 1.5 mm. The minimum dose reduction was related to the bismuth shield with 15% weight of Bi_2O_3 micro-particles with a thickness of 1 mm.

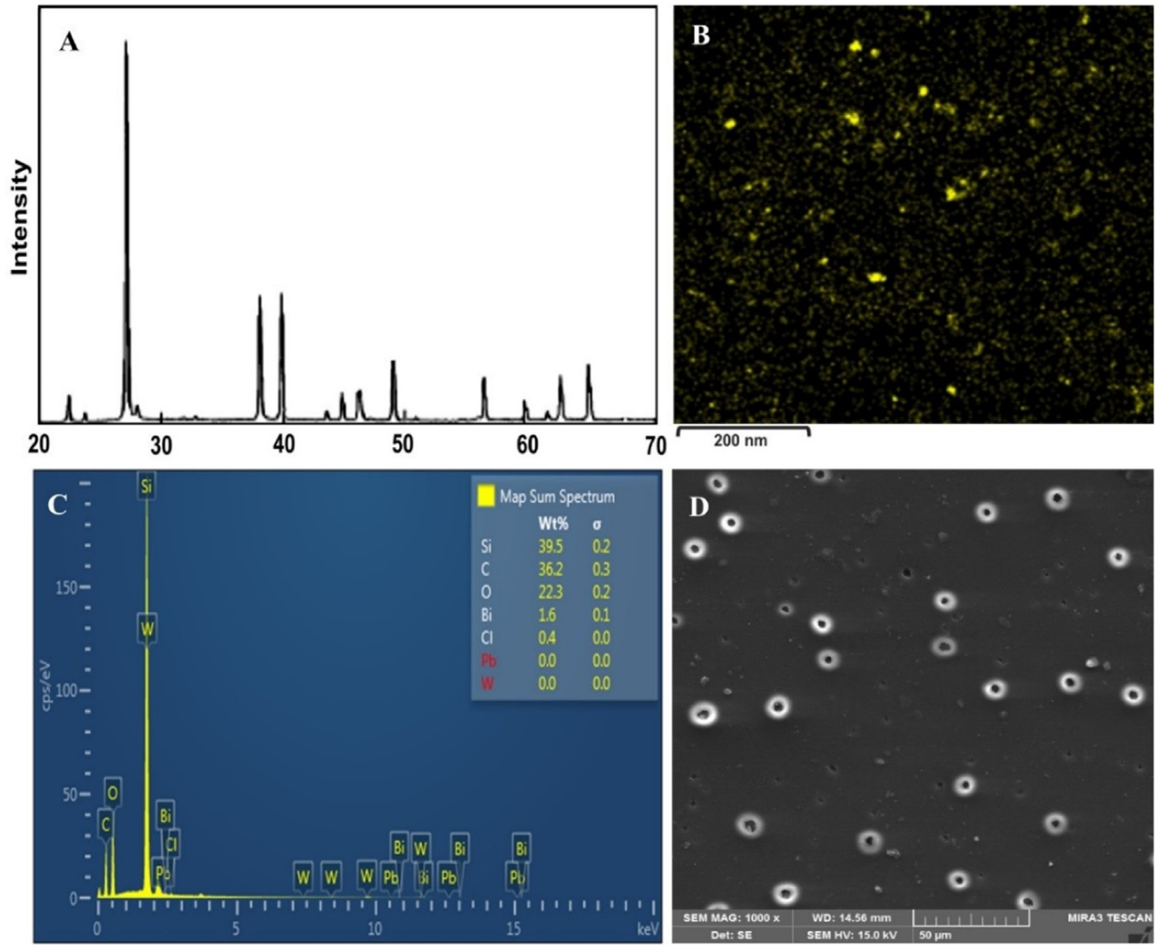

Fig. 3. The XRD (A), EDX (C) and SEM (B and D) results of Bi2O3 particles in silicon rubber matrix.

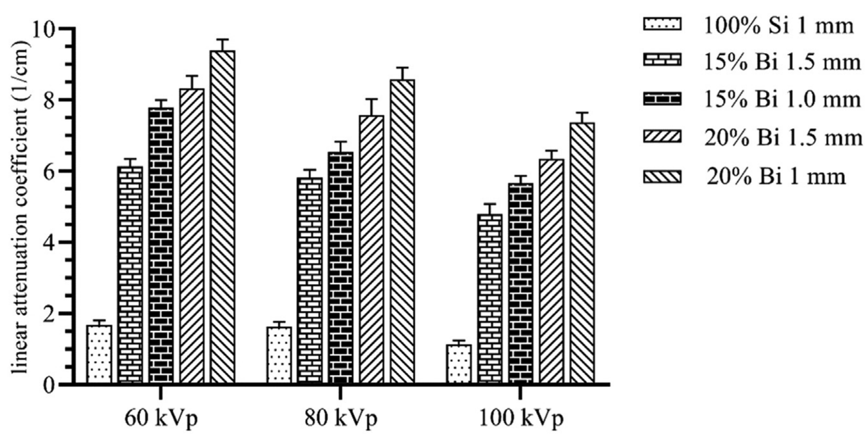

Fig. 4. Linear attenuation coefficients of different composite shields with bismuth nano-particles at different energies.

Fig. 7 shows the percentage of breast dose reduction using nano- and micro-BCS with two different Bi_2O_3 concentrations and thicknesses. The use of BCS with 15% weighted bismuth nano-particles and thicknesses of 1 mm and 1.5 mm reduced the breast dose by 16.55% and 20.82%, respectively. Furthermore, BCS with 20% weighted bismuth nano-particles and thicknesses of 1 mm and 1.5 mm reduced the breast dose by 27.76% and 33.54, respectively.

Image quality assessment

Table 1 represents the average of mean values and the highest value of standard deviations in the three ROI regions (posterior, center, anterior) contoured on CT images. According to this table, the noise was higher in nano-particle bismuth shields than that of micro-particles. The signal values were lower in nano-particle shields.

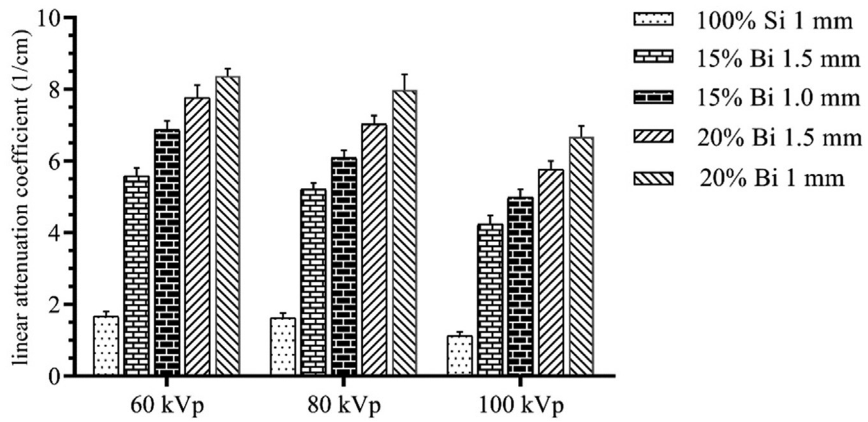

Fig. 5. Linear attenuation coefficients of different composite shields with bismuth micro-particles and at different energies.

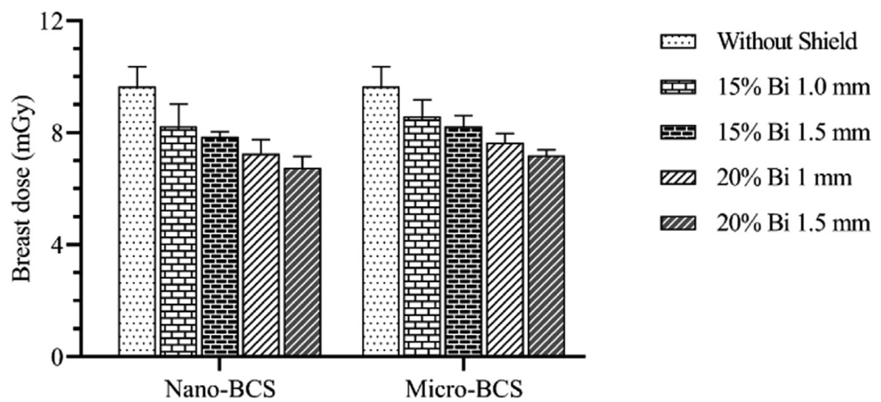

Fig. 6. The recorded dose of the breast in chest CT exams with and without using different nano- and micro- bismuth composite shields.

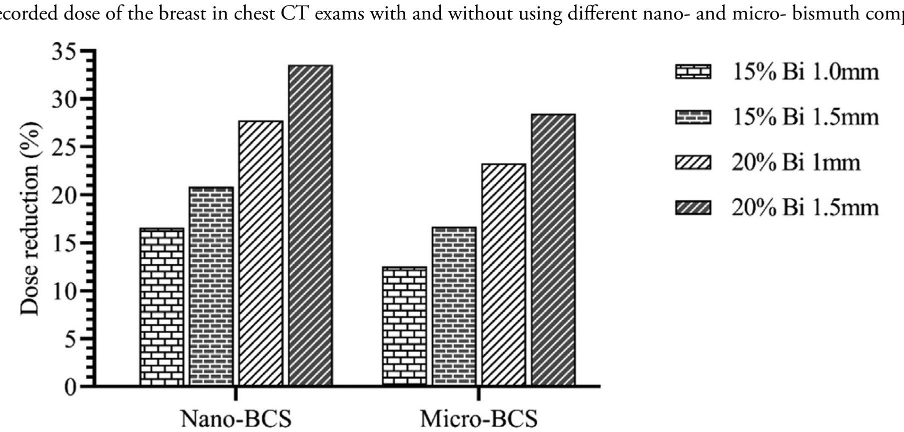

Fig. 7. Dose reduction of the breast in chest CT exams with and without using different nano- and micro- bismuth composite shields.

Table 1
Mean CT number and noise (standard deviation, SD) values measured in images obtained from chest CT scans performed with and without nano- and micro- bismuth composite shields.

Shields	Nano-BCS		Micro-BCS	
	CT Number	Noise	CT Number	Noise
Reference	-59.8±2.1	20.2	-59.8±2.1	20.2
15% Bi-1 mm	-54.5±2.8	24	-58.1±3.0	22.6
15% Bi-1.5 mm	-53.9±3.1	25.1	-56.9±2.7	23
20% Bi-1 mm	-53.1±3.5	27.4	-54.6±3.7	25.4
20% Bi-1.5 mm	-51.5±3.6	29.7	-53.4±4.1	27.1

Discussion

In the current work, the application of Bi_2O_3 nano- and micro-particles for radiation protection of the breast during chest CT examinations was assessed experimentally using a PMMA phantom.

The linear attenuation coefficient values of nano- and micro-BCS with different percentages and thicknesses were obtained. As seen in figures (4 and 5), the μ values increased with the increase in bismuth concentration. In contrast, all BCS's linear attenuation coefficient values declined when photon energy increased from 60 to 100 kVp. This may be attributed to the dominant photoelectric interaction mechanism in lower energies [28]. The effective atomic number (Z_{eff}) is very substantial in radiation shielding studies, where the Z_{eff} can be represented by a number providing many characteristics of a material. With increasing the bismuth concentration, the Z_{eff} values increase in the shields. For this reason, the linear attenuation coefficient values of the BCS with 20% bismuth weight were higher than that of 15% weight. Our findings demonstrated that μ values of the composites bismuth were lower for bismuth micro-particles. The effect of the particle size could be explained based on the probability of the photon interaction, which largely depended on the surface-to-volume ratio of the particles. The surface-to-volume ratio is considerably higher in the nano-particles compared to the micro-particles [29].

The results have shown that particle size (micro and nano-particles of bismuth) impacts radiation shielding performance. In a way that bismuth nano-particles with the same weight percentage performs better dose reduction than micro-particles. Previous studies also stated the similar behaviors of different nano-particles types in shielding materials [30]. The reason can be attributed to better distribution, the higher surface-to-volume ratio, and higher X-ray interaction probability, which increases the chance of X-rays absorption [29,31]. However, shields with bismuth nano-particles showed higher noises and lower signal-to-noise ratios due to higher dose reduction than micro-particles.

The use of bismuth nano-particle reduced the breast dose by 16.55% to 33.45% in different thicknesses and bismuth concentrations. A previous study reported similar value ranges for dose reduction by using bismuth shields in chest CT for the breast [32]. Bismuth shields with higher bismuth concentration (20% weight vs. 15% weight) and higher thicknesses (1.5mm vs. 1mm) showed higher dose reduction; however, the image noise was also higher in the shields with more increased thickness and bismuth concentration. Nowadays, the main concern focuses on the effect of BCS on image quality, especially CT number changes, increasing noise, and beam hardening artifacts, which may compromise diagnostic accuracy. Colombo et al. studied image quality decline in areas under a breast shield but not in areas of diagnostic interest for chest CT scans [33]. They reported that image noise increased only in the anterior portions of the lung during chest CT examination. This noise was prohibited in our study by using 1 cm foam under the shield, between the surface and the bismuth shield, reducing the amount of scatter radiation reaching the phantom. Banaei et al. also used 4 cm foam under the bismuth eye shields to reduce the image noise produced by the shields in brain CT scans [34]. They reported that a bismuth shield with a thickness of 0.02 cm above 4cm foam could decrease the lens dose to acceptable levels while providing a better image quality than the contact shield setup. Our study confirmed that the breast shield does not compromise the image quality of the phantom regarding the slight variation in CT number and noise, as reported in previous phantom studies [33]

The present study found that BCS changes the CT numbers of the structures near the surface (like breasts), which would be problematic for quantitative evaluations based on CT numbers. For example, radiation hardening may decrease the image contrast between tumors and peripheral tissue, as reported in a previous study [35]. Therefore, it is more appropriate for a visual image assessment by radiologists because most radiological diagnostic procedures are qualitative and visually assessed without considering the HU values.

Our study had agreement as well as disagreement with several studies like Vollmar et al. [36] and Geleijns et al. [37]. In a way that, they reported considerable dose reduction values during the use of breast bismuth shields, similar to our results. On the other hand, they found around 40% noise and impaired image quality in lungs and heart regions due to breast bismuth shields. Their bismuth shield was simple, and they did not use the bismuth nano- or micro-particles. Using bismuth in the form of small particles resulted in minor metal artifacts around the particles, which cannot be detected in the CT images and add noise to the structure located at small distances from the shield. Notably, we used foams between the phantom surface and shields to decrease the scattered radiation that reached the phantom and reduce the metal artifact in the superficial structures under the shield.

There are several limitations to our study. We used a phantom instead of human samples according to ethical principles and did not consider different anatomical structures. For future research, it will be appropriate to use human samples to evaluate the bismuth nano- or micro-particles composite shields' performance in chest CT examinations and show the results as clinically useful (or not).

Conclusion

The attenuation coefficients of silicon rubber-based composites containing 15% and 20% of $Bi2O3$ nano- and micro-structured with two different thicknesses (1mm and 1.5mm) were obtained experimentally. The results demonstrated that higher concentration and thickness shields provided higher dose reduction; however, these shields had higher noise and lower signal-to-noise ratio. Additionally, composite shields with bismuth nano-particles showed higher dose reduction and lower image quality than micro-particles. It was found that newly prepared BCS can play an essential role in breast dose reduction during chest CT exams with an acceptable level of image quality

Acknowledgements

The authors would like to thank the staff of the CT scan department of Imam Khomeini Hospital and Fatemi Hospital, Ardabil, Iran, for their cooperation in imaging experiments.

References

[1] Awulachew E, Diriba K, Anja A, Getu E, Belayneh F. Computed tomography (CT) imaging features of patients with COVID-19: systematic review and meta-analysis. *Radiol Res Pract*. 2020.

[2] Khoramian D, Sistani S, Firouzjah RA. Assessment and comparison of radiation dose and image quality in multi-detector CT scanners in non–contrast head and neck examinations. *Pol J Radiol*. 2019;84:e61.

[3] Davoudi M, Khoramian D, Abedi-Firouzjah R, Ataei G. Strategy of computed tomography image optimisation in cervical vertebrae and neck soft tissue in emergency patients. *Radiat Prot Dosimetry*. 2019;187(1):98–102.

[4] Ubeda C, Salazar L, Retana V, Gutierrez R, Nocetti D, Reyes C. Organ doses in paediatric interventional cardiology. First values for patients in Costa Rica. *Radiat Phys Chem*. 2019;162:48–53.

[5] Chowdhury AS, Tamanna S. Radiation-induced side effects in breast cancer patients and factors affecting them. *Asian J Med Biol Res*. 2020;6(2):138–148.

[6] Ketelsen D, Buchgeister M, Fenchel M, Schmidt B, Flohr TG, Syha R, et al. Automated computed tomography dose-saving algorithm to protect radiosensitive tissues: estimation of radiation exposure and image quality considerations. *Invest Radiol*. 2012;47(2):148–152.

[7] Hosseini SM, Banaei A, Motlagh ZH, Abedi-Firouzjah R, Falahati F, Zamani H, et al. Estimating the cancer risk and mortalities induced by routine digital radiography examinations on patient of different ages in Mazandaran province. *Int J Radiat Res*. 2020;18(4):875–884.

[8] Kalra MK, Maher MM, Toth TL, Schmidt B, Westerman BL, Morgan HT, et al. Techniques and applications of automatic tube current modulation for CT. *Radiology*. 2004;233(3):649–657.

[9] Kubo T, Ohno Y, Kauczor HU, Hatabu H. Radiation dose reduction in chest CT—review of available options. *Eur J Radiol*. 2014;83(10):1953–1961.

[10] Chityala RN, Hoffmann KR, Bednarek DR, Rudin S. Region of interest (ROI) computed tomography. In: Medical Imaging. *Physics of Medical Imaging. International Society for Optics and Photonics; 2004*. 2004:534–541.

[11] Silva AC, Lawder HJ, Hara A, Kujak J, Pavlicek W. Innovations in CT dose reduction strategy: application of the adaptive statistical iterative reconstruction algorithm. *Am J Roentgenol*. 2010;194(1):191–199.

[12] McCollough CH, Bruesewitz MR, Kofler Jr JM. CT dose reduction and dose management tools: overview of available options. *Radiographics*. 2006;26(2):503–512.

[13] Malekzadeh R, Sadeghi Zali V, Jahanbakhsh O, Okutan M, Mesbahi A. The preparation and characterization of silicon-based composites doped with BaSO4, WO3, and PbO nanoparticles for shielding applications in PET and nuclear medicine facilities. *Nanomedicine J*. 2020;7(4):324–334.

[14] Mehnati P, Malekzadeh R, Sooteh MY. Application of personal non-lead nano-composite shields for radiation protection in diagnostic radiology: a systematic review and meta-analysis. *Nanomedicine J*. 2020;7(3):170–182.

[15] 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.

[16] Tappouni R, Mathers B. Scan quality and entrance skin dose in thoracic CT: a comparison between bismuth breast shield and posteriorly centered partial CT scans. *Int Sch Res Not*. 2013 2013.

[17] Hulten E, Devine P, Welch T, Feuerstein I, Taylor A, Petrillo S, et al. Comparison of coronary CT angiography image quality with and without breast shields. *Am J Roentgenol*. 2013;200(3):529–536.

[18] Einstein AJ, Elliston CD, Groves DW, Cheng B, Wolff SD, Pearson GD, et al. Effect of bismuth breast shielding on radiation dose and image quality in coronary CT angiography. *J Nucl Cardiol*. 2012;19(1):100–108.

[19] Kalra MK, Dang P, Singh S, Saini S, Shepard JAO. In-plane shielding for CT: effect of off-centering, automatic exposure control and shield-to-surface distance. *Korean J Radiol*. 2009;10(2):156–163.

[20] Mehnati P, Yousefi Sooteh M, Malekzadeh R, Divband B. Synthesis and characterization of nano Bi2O3 for radiology shield. *Nanomedicine J*. 2018;5(4):222–226.

[21] Fazio C, Benamati G, Martini C, Palombarini G. Compatibility tests on steels in molten lead and lead–bismuth. *J Nucl Mater*. 2001;296(1–3):243–248.

[22] Grazziotin-Soares R, Nekoofar MH, Davies TE, Bafail A, Alhaddar E, Hübler R, et al. Effect of bismuth oxide on white mineral trioxide aggregate: chemical characterization and physical properties. *Int Endod J*. 2014;47(6):520–533.

[23] *Quality Control of Diagnostic Radiology*. 74American Association of Medical Physicists. New York: AAPM; 2002 AAMP Report No.

[24] McCaffrey JP, Tessier F, Shen H. Radiation shielding materials and radiation scatter effects for interventional radiology (IR) physicians. *Med Phys*. 2012;39(7Part1):4537–4546.

[25] Malekzadeh R, Mehnati P, Sooteh MY, Mesbahi A. Influence of the size of nano-and microparticles and photon energy on mass attenuation coefficients of bismuth–silicon shields in diagnostic radiology. *Radiol Phys Technol*. 2019;12(3):325–334.

[26] 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):e96002.

[27] Monshi A, Foroughi MR, Monshi MR. Modified Scherrer equation to estimate more accurately nano-crystallite size using XRD. *World J Nano Sci Eng*. 2012;160 2012 2 154.

[28] Akkurt I, Mavi B, Akkurt A, Basyigit C, Kilincarslan S, Yalim HA. Study on Z dependence of partial and total mass attenuation coefficients. *J Quant Spectrosc Radiat Transf*. 2005;94(3–4):379–385.

[29] Yu L, Pereira AL, Tran DN, Santos AM, Losic D. Bismuth Oxide Films for X-ray shielding: Effects of particle size and structural morphology. *Mater Chem Phys*. 2021;260:124084.

[30] Mansouri E, Mesbahi A, Malekzadeh R, Mansouri A. Shielding characteristics of nanocomposites for protection against X-and gamma rays in medical applications: effect of particle size, photon energy and nano-particle concentration. *Radiat Environ Biophys*. 2020;59(4):583–600.

[31] Hosseini MA, Malekie S, Kazemi F. Experimental evaluation of gamma radiation shielding characteristics of polyvinyl alcohol/tungsten oxide composite: A comparison study of micro and nano sizes of the fillers. *Nucl Instrum Methods Phys Res Sect Accel Spectrometers Detect Assoc Equip*. 2022;1026:166214.

[32] Mehnati P, Malekzadeh R, Sooteh MY. New Bismuth composite shield for radiation protection of breast during coronary CT angiography. *Iran J of Radiol*. 2019;16(3):31.

[33] Colombo P, Pedroli G, Nicoloso M, Re S, Valvassori L, Vanzulli A. Evaluation of the efficacy of a bismuth shield during CT examinations. *Radiol Med (Torino)*. 2004;108(5–6):560–568.

[34] Banaei A, Dadashi A, Zakariaee SS, Saba V . Assessing the image quality and eye lens dose reduction using bismuth shielding in computed tomography of brain. *J Kerman Univ Med Sci*. 2018;25(6):471–482.

[35] He T, Qian X, Zhai R, Yang Z. Computed tomography number measurement consistency under different beam hardening conditions: comparison between dual-energy spectral computed tomography and conventional computed tomography imaging in phantom experiment. *J Comput Assist Tomogr*. 2015;39(6):981.

[36] Vollmar SV, Kalender WA. Reduction of dose to the female breast in thoracic CT: a comparison of standard-protocol, bismuth-shielded, partial and tube-current-modulated CT examinations. *Eur Radiol*. 2008;18(8):1674–1682.

[37] Geleijns J, Wang J, McCollough C. The use of breast shielding for dose reduction in pediatric CT: arguments against the proposition. *Pediatr Radiol*. 2010;40(11):1744–1747.