Hong Kong J Radiol. 2021;24:108-15 | https://doi.org/10.12809/hkjr2117090

ORIGINAL ARTICLE

Assessment of Commercially Available In-plane Bismuth Breast Shields for Clinical Use in Patients Undergoing Thoracic Computed Tomography

V Karami[1], M Albosof[2], M Najarian[1], M Gholami[3]

[1]Student Research Committee, Dezful University of Medical Sciences, Dezful, Iran
[2]Department of Medical Engineering, Islamic Azad University, Dezful Branch, Iran
[3]Department of Medical Physics, Lorestan University of Medical Sciences, Khorramabad, Iran

ABSTRACT

Objective: *We aimed to assess qualitatively the effects of a bismuth breast shield by measuring image noise and computed tomography (CT) number changes with 0-, 1-, 2-, and 3-cm shield-to-phantom distances. We also sought to assess the dose reduction achieved by the shield and to evaluate its effect on image quality.*

Methods: *A cylindrical body phantom was scanned using an adult thoracic CT protocol with 0-, 1-, 2-, and 3-cm foam spacers placed between the shield and the phantom, measuring the noise and CT numbers (in Hounsfield units [HU]) of the image data. We also used the shield with 3-cm spacer over the left breast in 180 female patients referred for chest CT. Dose measurements were performed using thermoluminescent dosimeters. The image quality was assessed following European guidelines.*

Results: *A 0-cm shield-to-phantom distance significantly increased noise and CT numbers of the image data. The 3-cm shield-to-phantom distance effectively lowered shield-induced image noise; however, the HUs remained significantly increased over all shield-to-phantom distances ($p < 0.001$). In the patient study, the average absorbed doses to the shielded and non-shielded breasts were 13.6±3.1 mGy and 24.04±4.7 mGy, respectively; a 43.4% dose reduction.*

Conclusion: *Combining a bismuth shield with a 3-cm shield-to-breast foam spacer significantly reduced radiation exposure without qualitative or quantitative deterioration of images in terms of image noise. However, increases in the HUs of the images persisted.*

Key Words: *Bismuth; Radiation dosage; Radiation protection; Tomography, X-ray computed*

Correspondence: *Dr M Gholami, Department of Medical Physics, Lorestan University of Medical Sciences, Khorramabad, Iran*
Email: karami.ajums@yahoo.com

Submitted: 23 Feb 2019; Accepted: 27 May 2019

Contributors: VK designed the study. VK and MA acquired the data. All authors analysed the data, drafted the manuscript and critically revised the manuscript for important intellectual content. All authors had full access to the data, contributed to the study, approved the final version for publication, and take responsibility for its accuracy and integrity.

Conflicts of Interest: The authors have no conflicts of interest to disclose.

Funding/Support: This study has been funded by the student research committee of Dezful University of Medical Sciences, Dezful, Iran (Grant number: RC2.P1.1397). The funder had no role in study design, data collection, analysis or interpretation and manuscript preparation.

Ethics Approval: The study was approved by Dezful University of Medical Sciences Research Ethics Committee (Ref IR.DUMS.REC.1397.053). The patients provided written informed consent.

中文摘要

商用縱切面鉍屏蔽對胸部電腦斷層掃描臨床使用的評估

V Karami、M Albosof、M Najarian、M Gholami

目的：透過測量圖像噪聲以及水模至屏蔽距離為0、1、2和3厘米時的CT值變化來定性評估使用鉍屏蔽的效果，並評估鉍屏蔽對減少輻射劑量和圖像質量的影響。

方法：使用成人胸部CT協議掃描圓柱體模，於水模和屏蔽間放置0、1、2和3厘米的泡沫墊片，以測量圖像噪聲和其CT值。我們於180名轉診進行胸部 CT 的女性患者的左乳房上使用3厘米墊片的鉍屏蔽。使用熱釋光劑量計進行劑量測量，並根據歐洲指南評估圖像質量。

結果：水模至屏蔽距離為0厘米時，圖像噪聲和CT值顯著增加。水模至屏蔽距離為3厘米時能有效降低屏蔽引起的圖像噪聲；然而，CT值在所有水模至屏蔽距離上仍顯著增加（$p < 0.001$）。患者研究中，使用屏蔽和不使用屏蔽時乳房的平均幅射吸收劑量分別為 13.6 ± 3.1 mGy 和 24.04 ± 4.7 mGy，劑量減少43.4%。

結論：結合鉍屏蔽與3厘米屏蔽至乳房泡沫墊片可顯著減少輻射暴露，且不會因圖像噪聲而定性或定量劣化圖像。然而，圖像的CT值持續增加。

INTRODUCTION

Computed tomography (CT) is an indispensable diagnostic tool, providing cross-sectional and 3-dimensional images of anatomical structures with exquisite anatomical detail.[1] During the last few years, the number of CT examinations performed has steadily increased.[2,3] In 1980, three million CT scans were performed in the United States.[4] This figure expanded to 57 million in 2000,[5] 62 million in 2007,[4] and 85 million in 2011.[6] A United States study in 2009 found that although CT accounts for 11% of all radiological examinations, it is responsible for 75.4% of the overall population dose.[7] Concerns over exposure and overutilisation of CT have resulted in several publications on the potential risk of detrimental health effects.[8,9] These studies have linked CT with increasing the risk of radiation-induced carcinogenesis, especially when radiosensitive tissues are within the scan field.

Thoracic CT is a common examination that contributes to radiation exposure to the breasts.[10] During thoracic CT, the breasts receive approximately 17 to 22 mGy of radiation.[11,12] This is particularly due to their superficial position that allows the breasts to be exposed to low-energy scattered photons.[13] The breast tissue is highly radiosensitive. Delivery of as little as 10 mGy to a young woman is reported to increase the risk of radiation-induced breast cancer by 13.6%.[3] Thoracic CT is intended to evaluate the lung parenchyma and mediastinum, and often the breast is not under diagnostic evaluation.[3,10] Therefore, it is necessary that the radiation dose be kept as low as reasonably achievable.[14]

The in-plane bismuth breast shield has shown to be effective at reducing radiation exposure to the breasts during thoracic CT.[3,15,16] Dose reductions of 26% to 61% have been reported in both phantom and clinical studies using these shields.[5,10,16,17] However, some drawbacks, such as introduction of image noise, streak and beam-hardening artefacts, and changes in CT number (in Hounsfield units [HU]) of the images have been concerns.[15,18-20] It is suggested that placement of a 1-cm thickness of foam or cotton between the shield and the breast surface can reduce image noise.[21] Despite variations in the dose reduction levels, there is agreement in the literature on the potential radiation dose reduction of bismuth shields, but their effect on image quality remains controversial. Moreover, insufficient data exist regarding the influence of the shield-to-breast distance on image quality during thoracic CT.

The first aim of this study was to assess quantitatively the effects on image noise and CT number changes in image data following placement of 0-, 1-, 2-, and 3-cm shield-to-phantom spacers in a homogenous body phantom. The second aim was to assess dose reduction achieved by the shield and a qualitative assessment of image quality based on image criteria adopted from the European guidelines on quality criteria for thoracic CT.

METHODS

Phantom Study

A 32-cm cylindrical body water phantom (GE Healthcare, Milwaukee [WI], US) was positioned at the isocentre of a 16-slice GE CT scanner (BrightSpeed, GE Healthcare) and a scanogram was obtained to plan the scanning range. The phantom was scanned using a standard protocol routinely used for adult thoracic CT (120 kVp, 100 effective mAs, 6-mm section thickness, 0.5 s/gantry rotation, 27-mm table increment per rotation). A commercially available 0.06-mm lead equivalent radioprotective bismuth breast shield (F&L Medical Products Co., Vandergrift [PA], US) was placed directly upon the anterior surface of the phantom and a second scan was acquired. Subsequent scans were acquired after placing a 1-, 2-, and 3-cm polyurethane foam spacer between the shield and the anterior surface of the phantom (Figure 1). Identical scan parameters were used for all acquisitions (Figure 2).

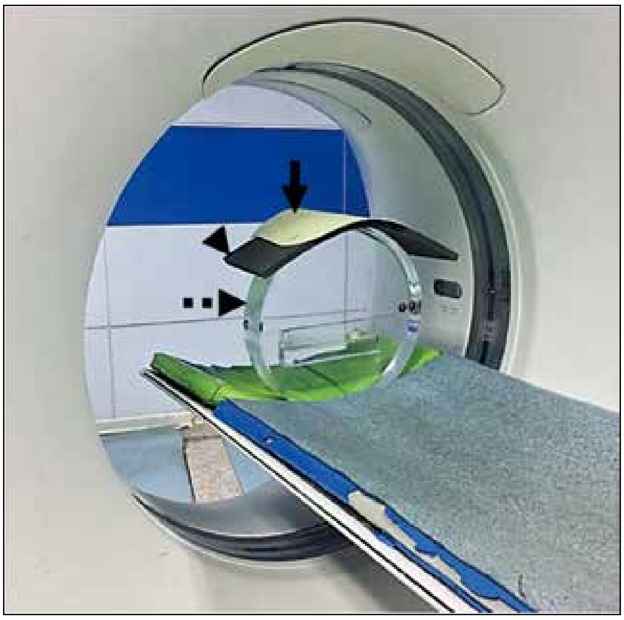

Figure 1. Bismuth breast shield (arrow) and interval spacer (arrow head) in the homogenous cylindrical body water phantom (dashed arrow).

Quantitative Assessment of Image Noise in the Phantom Study

To determine the influence of the shield and foam spacers on image noise and HU variation, in each session, we applied region of interest (ROI) methodology on three consecutive axial slices. To obtain reliable results, three sets of identical scans were obtained. Five circular ROIs with areas of 1.5 cm^2 were applied to each axial section at the 12, 3, 6, and 9 o'clock positions plus one ROI in the centre. The standard deviation of the density of ROIs was considered as a quantitative analysis of image noise. The mean HUs were recorded to determine variations caused by the shield.

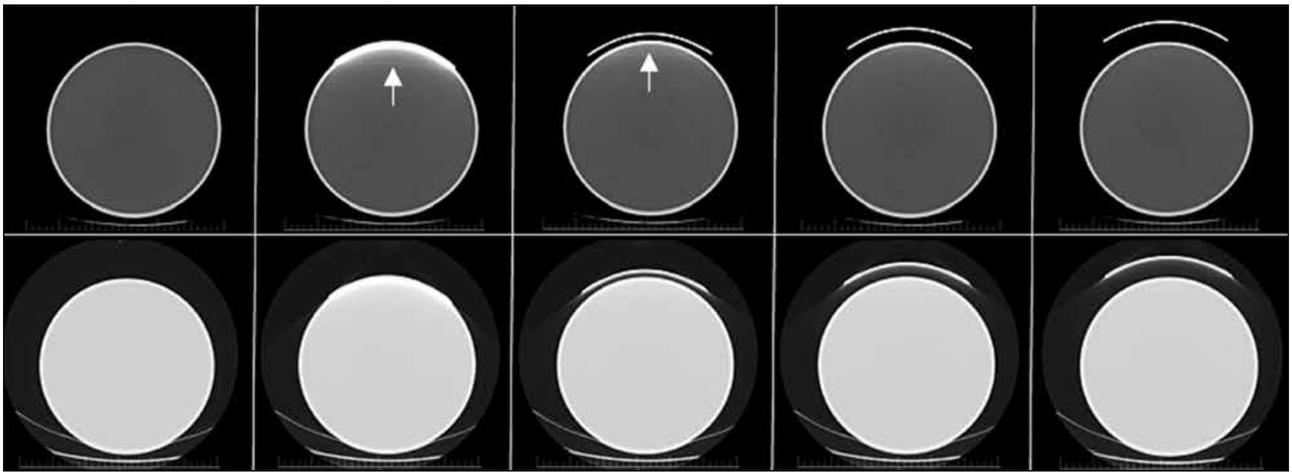

Figure 2. Axial scans of a 32-cm cylindrical body water phantom in mediastinal (top row) and lung (bottom row) windows. The use of the shield significantly increased image noise and streak artefacts, when directly positioned upon the phantom surface or when there was 1-cm shield-to-phantom distance (arrows). 3-cm shield-to-phantom distance resulted in lower image noise and artefact by shifting the artefacts outside the phantom surface.

Patient Study

Following approval from the university ethics committee (approval number: IR.DUMS.REC.1397.053), 180 female patients (≥18 years) scheduled to undergo a thoracic CT at our institution were recruited into the study. Patients were considered eligible for inclusion if they could follow the requirements of the study for standard positioning (supine and arms above the head) and had signed an informed consent form to participate in the study as assigned by the ethics board. All emergency studies and patients with unilateral or bilateral mastectomies were excluded from the study. Based upon our quantitative assessment of image noise in the phantom study, we found that by using a 3-cm shield-to-phantom distance, there was no significant increase in noise or HU of the phantom images (except the anterior part of the phantom) as compared to the case where no shielding is applied. Therefore, we followed this strategy in the patient study.

Thermoluminescent dosimeters (TLDs) [GR-200, Hangzhou Freqcontrol Electronic Technology Ltd., China] were used for dose measurements. Before the study, the TLDs were calibrated. Initially, all TLDs were simultaneously irradiated with the same dose of Cobalt-60 and then read out by a Harshaw 3500 TLD reader (Harshaw, Solon [OH], US) and their element correction coefficients were calculated. TLDs were divided into 15 batches and exposed together with a 3-cm^3 Radcal ionisation chamber (Radcal Corp., Monrovia, [CA], US) at different doses in a diagnostic X-ray unit at 120 kV tube voltage. Following this, TLDs were read out again and a calibration curve was generated to convert the TLD charge in nanocoulombs to absorbed dose in mGy. Before and after each use, TLDs were annealed with a standard annealing regime recommended by the manufacturer (245°C for 10 minutes).[22,23] To prevent the probable physical and chemical damage during the dosimetry process, each TLD batch was placed in a thin plastic bag. Throughout the study, three TLDs were used as controls to measure background radiation. Patients were positioned at the isocentre of the CT scanner in the supine position. Images were acquired from the thoracic inlet to the adrenal glands. To mark the approximate adrenal region, the shadow of the kidneys was used as a guide.[16] Following this, four fresh TLDs were carefully placed on each breast (around the nipple since it is relatively flat in supine position). A radioprotective bismuth breast shield with a 3-cm shield-to-breast foam spacer was placed over the left breast so that it covered the entirety of the breast and the TLDs. The right breast remained non-shielded. The craniocaudal scan was performed on the basis of the scanogram. The same scanner and identical scan parameters were used in both the phantom and clinical studies.

Qualitative Assessment of Image Quality in the Patient Study

Three expert radiologists with a mean experience of 6 ± 2.3 years visually assessed the quality of patient images based on image criteria adopted from the European guidelines on quality criteria for thoracic CT (Table 1).[24] Initially, the picture archiving and communication system of the hospital was retrospectively investigated to identify a reference thoracic CT (non-shielded) in which each image quality criterion was consistent with the European guidelines described in Table 1. After obtaining one thoracic image as reference, all 180 thoracic image datasets of the clinical study were divided into left (shielded) and right (non-shielded) sections in the 2-dimensional axial view as shown in Figure 3. Each image quality criterion in each section was compared by the identical criterion of the reference image and graded as follows: (1) quality much lower than reference image and diagnostically unacceptable; (2) quality lower than reference image but diagnostically acceptable; (3) quality equal to reference image, and (4) quality better than reference image.

Statistical Analysis

Data were entered into spreadsheet software (Excel, Microsoft Inc., Redmond [WA], US) and statistical

Table 1. European guidelines on quality criteria for thoracic computed tomography.

Image criteria
Visualisation of the entire:
1. thoracic wall*
2. thoracic aorta and vena cava*
3. heart*
4. lung parenchyma†
Visually sharp reproduction of the:
5. thoracic aorta*
6. anterior mediastinal structures, including thymic residue (if present)*
7. trachea and main bronchi†
8. paratracheal tissue*
9. carina and associated lymph nodes*
10. oesophagus*
11. pleuromediastinal border*
12. large and medium sized pulmonary vessels*
13. segmental bronchi†
14. lung parenchyma†
15. border between the pleura and the thoracic wall*

* Criteria that are usually evaluated in the mediastinal window.
† Criteria that are usually evaluated in the lung window.

analysis was performed using a statistical package SPSS (Windows version 20.0; IBM Corp, Armonk [NY], US). The normality of the data was assessed using the Kolmogorov–Smirnov test. To compare the HU and image noise (standard deviation of HUs) of the non-shielded phantom with 0-, 1-, 2-, and 3-cm shield-to-phantom distances in each location (12, 3, 6, and 9 o'clock, and centre), the Scheffe test (post hoc) was used with alpha level of 0.05 and a confidence interval of 95%. Student's *t* test was used to compare the radiation dose received by the breasts. A paired *t* test was used to compare each image criterion of the shielded and non-shielded sections of the thoracic images in terms of image quality. A p value <0.05 was considered statistically significant.

RESULTS

The influence of the shield and the different shield-to-phantom distances on the quantitative image noise and HU at the anterior, lateral, posterior, and central regions of the phantom images is summarised in Tables 2 and 3. The increasing noise and HU of the shielded images was progressively more pronounced at the anterior portion of the phantom compared to the lateral, posterior, and central regions. Increasing shield-to-phantom distance resulted in lower image noise and HU variation. There was no statistically significant difference between shielded and non-shielded images in terms of image noise at all phantom regions when there was a 3-cm shield-to-phantom distance (all $p > 0.05$). The shield increased HU of the phantom images at all phantom regions (except the posterior region) without a spacer and with all spacer thicknesses. Streak artefacts were noted with no spacing and with a 1-cm shield-to-phantom distance (Figure 2).

In the patient study, the patients' age ranged from 18 to 74 years (mean, 41.5 ± 15.7). The mean absorbed dose at the surface of shielded and non-shielded breasts was 13.6 ± 3.1 mGy and 24.04 ± 4.7 mGy, resulting in a 43.4% reduction in the breast dose (Figure 4). The mean image quality scores in the shielded and non-shielded sections of the thoracic images were 2.98 and 3.02 for the mediastinal windows and 2.94 and 2.98 for the lung windows, respectively (Figure 5) [$p = 0.997$]. All thoracic images were interpreted as diagnostically acceptable.

DISCUSSION

The bismuth shield is reported to be an effective tool for reducing radiation exposure of the breast during thoracic CT.[16] However, some drawbacks such as increasing noise level and HU of the images, especially in the anterior thoracic region, have been reported.[15,18-20]

In our quantitative assessment of image noise, we demonstrated that a bismuth shield with no spacer significantly increased noise and HU of the images

Table 2. Effect of the shield-to-phantom distance on image noise (standard deviation) at the anterior (12 o'clock), lateral (3 and 9 o'clock), posterior (6 o'clock), and central regions of a 32-cm homogenous body phantom.*

Clock location	No shield	Shield with 0-cm spacer	Shield with 1-cm spacer	Shield with 2-cm spacer	Shield with 3-cm spacer
12	4.12 ± 0.32	23.63 ± 5.08	8.04 ± 0.44	7.17 ± 0.64	5.69 ± 0.32
3	4.61 ± 0.26	4.81 ± 0.28	4.72 ± 0.20	4.86 ± 0.18	4.64 ± 0.27
6	5.16 ± 0.32	5.21 ± 0.27	5.49 ± 0.30	5.55 ± 0.45	5.26 ± 0.23
9	4.42 ± 0.30	4.81 ± 0.27	5.02 ± 0.20	5.56 ± 0.30	4.45 ± 0.26
Centre	7.13 ± 0.37	7.93 ± 0.34	7.78 ± 0.46	8.39 ± 0.42	7.17 ± 0.39

* Data are shown as mean ± standard deviation.

Table 3. Effect of the shield-to-phantom distance on Hounsfield Units at the anterior (12 o'clock), lateral (3 and 9 o'clock), posterior (6 o'clock), and central regions of a 32-cm homogeneous body phantom.*

Clock location	No shield	Shield with 0-cm spacer	Shield with 1-cm spacer	Shield with 2-cm spacer	Shield with 3-cm spacer
12	1.22 ± 0.53	92 ± 6.73	47.11 ± 2.90	25.89 ± 2	16.33 ± 1.25
3	0.83 ± 0.60	6 ± 0.82	2.94 ± 0.40	3.94 ± 1.72	2.83 ± 0.74
6	-1.44 ± 0.50	-0.22 ± 1.13	-0.61 ± 1.16	-0.78 ± 0.53	-0.67 ± 0.47
9	1.50 ± 0.50	5.28 ± 0.56	4.50 ± 0.50	3.61 ± 0.59	3.17 ± 0.37
Centre	-4.11 ± 0.66	-0.72 ± 0.56	-0.61 ± 1.01	-2.89 ± 1.59	-2.39 ± 0.68

* Data are shown as mean ± standard deviation.

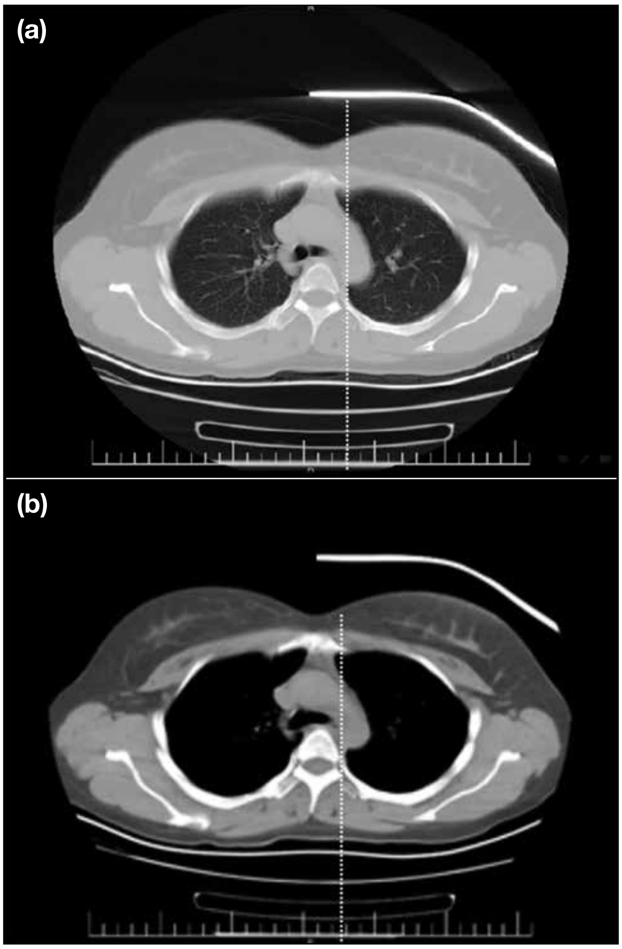

Figure 3. Thoracic computed tomography of a 31-year-old female patient in (a) lung and (b) mediastinal windows. The left breast was shielded using 3-cm shield-to-breast distance. The scan quality is fully diagnostic in both the shielded and non-shielded sections.

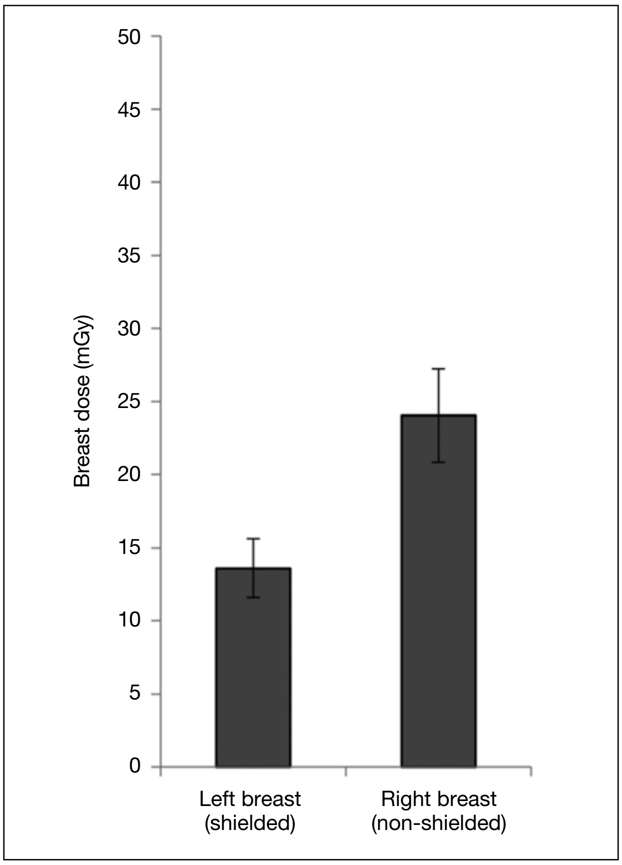

Figure 4. Radiation dose received by the left breast (shielded) and right breast (non-shielded). Standard deviations are shown as error bars.

at the anterior portion of the phantom. This result is commensurate with the previous literature.[15,25,26] Our result, however, is in contrast with that of Fricke et al,[12] who reported no quantitative change in image noise between shielded and non-shielded regions of the lung for ≤18-year-old patients. This discordance may be due to the fact that their study was performed on paediatric patients that are typically scanned at low radiation doses and therefore higher image noise was introduced, whereas, in our study, the phantom was scanned with a standard adult CT protocol that is associated with higher radiation dose and lower image noise.[15] Consistent with previous studies,[15,27,28] our study demonstrated that increasing shield-to-phantom distance lowered noise in the phantom images. When there was a 3-cm shield-to-phantom distance, there was no statistically significant difference between shielded and non-shielded images at all phantom regions in terms of image noise (all $p > 0.05$); however, except in the posterior region, the increase in HU was statistically significant in all other phantom regions ($p < 0.001$). In a similar study, Kalra et al[15] reported a significant HU increase at the anterior and central portions of the images, with 0-, 1-, 2- and 6-cm shield-to-phantom distances. Kim et al[27] reported a 19% to 40% image noise increase in the anterior lung with a 1-cm shield-to-patient distance. Similarly, Vollmar and Kalender[26] reported that bismuth shielding with no spacer increased image noise up to 40%. The commercially available bismuth breast shields have 1 cm of foam or cotton as a spacer between the shield and the patient's breast. We found that a 3-cm shield-to-breast distance lowered image noise. However, the increase in HU remains a concern.

According to our results, the mean radiation dose delivered to the shielded breast was 13.6 mGy, which represents a 43.4% reduction in the patients' breast

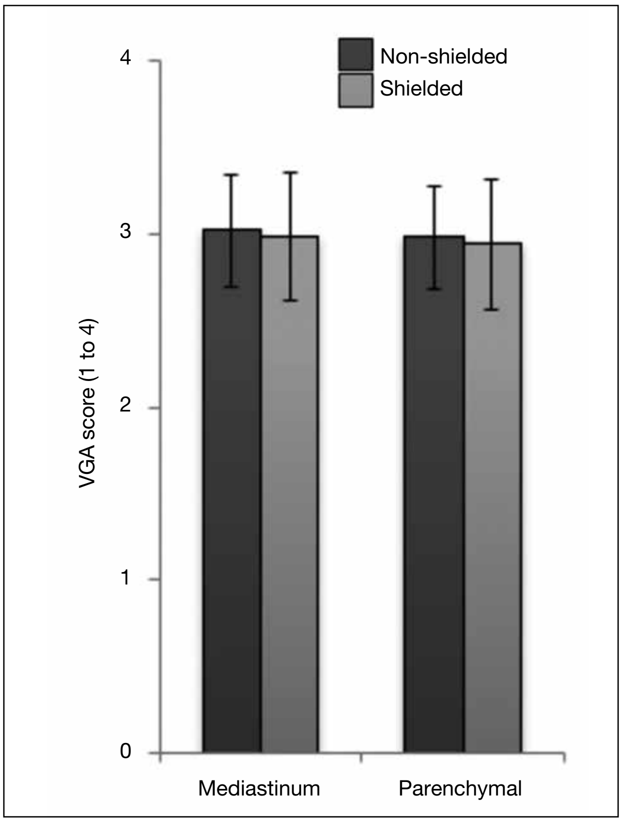

Figure 5. Vermont Golf Association (VGA) scores of the shielded and non-shielded sections of the thoracic images in both the mediastinum and parenchymal windows. Standard deviations are shown as error bars.

dose (24.04 mGy vs 13.6 mGy; $p < 0.001$). This result is consistent with that of Yilmaz et al,[16] who reported a 40.5% reduction.

The assessment of image quality in the patient study revealed no significant statistical difference between images in the shielded and non-shielded sections of the thoracic images in both the mediastinal and lung windows ($p = 0.362$). We found no image criterion reduced to the level of a diagnostically unacceptable (score 1). All images were interpreted as diagnostically acceptable. This result is commensurate with previous clinical studies.[16,29] 3-cm shield-to-breast distance effectively shifts the artefacts arising from the shield to the outside of the patient's body. Previous studies used phantoms and/or two separated groups of shielded and non-shielded patients to assess image quality and radiation dose reduction by the shield. We assumed that our methodology may be more reliable than those studies due to the fact that each measurement in patients had its own control (the opposite breast).

There are also opinions siding against the use of bismuth shielding during chest CT examinations. The American Association of Physicists in Medicine has challenged bismuth shielding, citing compromised image quality and unpredictable and undesirable results when combining with automatic exposure control (AEC).[30] Similarly, the Society of Cardiovascular Computed Tomography has avoided bismuth shielding due to its ability to influence the accuracy of coronary calcification measurements by increasing HU of the images.[31] Moreover, it has been argued that the combination of the bismuth shield with AEC would result in overestimating the patients' attenuation and, consequently, offsetting bismuth shield efficiency. Hence, if the shield is used in conjunction with AEC, the shield should be placed after acquiring the scanogram. In this situation, the desired image quality may be slightly compromised but it does not influence patient care. Moreover, it has been argued that there are other dose reduction technologies such as organ-based tube current modulation, global tube current reduction, and iterative reconstruction techniques that do not have the aforementioned drawbacks associated with bismuth shielding but offer similar or even higher dose reduction levels.[30]

According to this study, combining a bismuth shield with a 3-cm shield-to-breast distance could effectively reduce radiation exposure to the breast without quantitative and/or qualitative deterioration of image quality in terms of increasing noise and streak artefacts. However, increasing the HU at the anterior, lateral and central regions of the thorax remains a valid concern. According to Kalra et al,[15] increasing the shield-to-phantom distance up to 6 cm has also failed to eliminate this drawback. The accuracy of HU is crucial for diagnosis of some specific pathologies such as coronary artery disease, which depends upon exact calcium density measurement. Therefore, if the absolute accuracy of the HU is necessary, the use of shielding should be discouraged.

CONCLUSION

Combining a bismuth breast shield with a 3-cm spacer significantly reduced radiation exposure to the breast without qualitative or quantitative deterioration of the image quality in terms of image noise and streak artefacts. The bismuth shield was associated with increasing HU of the images, not only in the anterior thorax but also in the lateral and central regions. Therefore, when the absolute accuracy of HU is crucial, the use of bismuth breast shields should be discouraged.

REFERENCES

1. Kubo T, Ohno Y, Kauczor HU, Hatabu H. Radiation dose reduction in chest CT — review of available options. Eur J Radiol. 2014;83:1953-61.
2. Lai NK, Liao YL, Chen TR, Tyan YS, Tsai HY. Real-time estimation of dose reduction for pediatric CT using bismuth shielding. Radiat Meas. 2011;46:2039-43.
3. 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. ISRN Radiol. 2012;2013:457396.
4. Power SP, Moloney F, Twomey M, James K, O'Connor OJ, Maher MM. Computed tomography and patient risk: facts, perceptions and uncertainties. World J Radiol. 2016;8:902-15.
5. Coursey C, Frush DP, Yoshizumi T, Toncheva G, Nguyen G, Greenberg SB. Pediatric chest MDCT using tube current modulation: effect on radiation dose with breast shielding. AJR Am J Roentgenol. 2008;190:54-61.
6. Miglioretti DL, Johnson E, Williams A, Greenlee RT, Weinmann S, Solberg LI, et al. The use of computed tomography in pediatrics and the associated radiation exposure and estimated cancer risk. JAMA Pediatr. 2013;167:700-7.
7. Fazel R, Krumholz HM, Wang Y, Ross JS, Chen J, Ting HH, et al. Exposure to low-dose ionizing radiation from medical imaging procedures. N Eng J Med. 2009;361:849-57.
8. Lee CI, Forman HP. The hidden costs of CT bioeffects. J Am Coll Radiol. 2008;5:78-9.
9. de González AB, Mahesh M, Kim KP, Bhargavan M, Lewis R, Mettler F, et al. Projected cancer risks from computed tomographic scans performed in the United States in 2007. Arch Intern Med. 2009;169:2071-7.
10. Parker MS, Kelleher NM, Hoots JA, Chung JK, Fatouros PP, Benedict SH. Absorbed radiation dose of the female breast during diagnostic multidetector chest CT and dose reduction with a tungsten — antimony composite breast shield: preliminary results. Clin Radiol. 2008;63:278-88.
11. Hopper KD, King SH, Lobell M, TenHave TR, Weaver JS. The breast: in-plane x-ray protection during diagnostic thoracic CT — shielding with bismuth radioprotective garments. Radiology. 1997;205:853-8.
12. Fricke BL, Donnelly LF, Frush DP, Yoshizumi T, Varchena V, Poe SA, et al. In-plane bismuth breast shields for pediatric CT: effects on radiation dose and image quality using experimental and clinical data. AJR Am J Roentgenol. 2003;180:407-11.
13. Curtis JR. Computed tomography shielding methods: a literature review. Radiol Technol. 2010;81:428-36.
14. World Health Organization. Communicating radiation risks in paediatric imaging: information to support health care discussions about benefit and risk. 2016. Available from: https://www.who.int/ionizing_radiation/pub_meet/radiation-risks-paediatric-imaging/en/. Accessed 7 Dec 2018.
15. Kalra MK, Dang P, Singh S, Saini S, Shepard JA. In-plane shielding for CT: effect of off-centering, automatic exposure control and shield-to-surface distance. Korean J Radiol. 2009;10:156-63.
16. Yilmaz MH, Albayram S, Yaşar D, Ozer H, Adaletli I, Selçuk D, et al. Female breast radiation exposure during thorax multidetector computed tomography and the effectiveness of bismuth breast shield to reduce breast radiation dose. J Comput Assist Tomogr. 2007;31:138-42.
17. Geleijns J, Artells MS, Veldkamp W, Tortosa ML, Cantera AC. Quantitative assessment of selective in-plane shielding of tissues in computed tomography through evaluation of absorbed dose and image quality. Eur Radiol. 2006;16:2334-40.
18. Servaes S, Zhu X. The effects of bismuth breast shields in conjunction with automatic tube current modulation in CT imaging. Pediatr Radiol. 2013;43:1287-94.
19. 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;19:100-8.
20. McCollough CH, Wang J, Gould RG, Orton CG. Point/counterpoint. The use of bismuth breast shields for CT should be discouraged. Med Phys. 2012;39:2321-4.
21. Hohl C, Wildberger JE, Süss C, Thomas C, Mühlenbruch G, Schmidt T, et al. Radiation dose reduction to breast and thyroid during MDCT: effectiveness of an in-plane bismuth shield. Acta Radiol. 2006;47:562-7.
22. Hassanpour N, Panahi F, Naserpour F, Karami V, Asl JF, Gholami M. A study on radiation dose received by patients during extracorporeal shock wave lithotripsy. Arch Iran Med. 2018;21:585-8.
23. Behroozi H, Davoodi M, Aghasi S. Radiation dose to the thyroid and gonads in patients undergoing cardiac CT angiography. Iran J Radiol. 2015;12:e20619.
24. Jessen K, Panzer W, Shrimpton P, Bongartzm G, Geleijns J, Golding S, et al. EUR 16262: European Guidelines on Quality Criteria for Computed Tomography. Luxembourg: Office for Official Publications of the European Communities. 2000.
25. Wang J, Duan X, Christner JA, Leng S, Yu L, McCollough CH. Radiation dose reduction to the breast in thoracic CT: comparison of bismuth shielding, organ-based tube current modulation, and use of a globally decreased tube current. Med Phys. 2011;38:6084-92.
26. 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;18:1674-82.
27. Kim YK, Sung YM, Choi JH, Kim EY, Kim HS. Reduced radiation exposure of the female breast during low-dose chest CT using organ-based tube current modulation and a bismuth shield: comparison of image quality and radiation dose. AJR Am J Roentgenol. 2013;200:537-44.
28. Lai CW, Cheung HY, Chan TP, Wong TH. Reducing the radiation dose to the eye lens region during CT brain examination: the potential beneficial effect of the combined use of bolus and a bismuth shield. Radioprotection. 2015;50:195-201.
29. McLaughlin D, Mooney R. Dose reduction to radiosensitive tissues in CT. Do commercially available shields meet the users' needs? Clin Radiol. 2004;59:446-50.
30. AAPM Position Statement on the Use of Bismuth Shielding for the Purpose of Dose Reduction in CT scanning. Available from: https://www.aapm.org/publicgeneral/bismuthshielding.pdf. Accessed 7 Dec 2018.
31. Halliburton SS, Abbara S, Chen MY, Gentry R, Mahesh M, Raff GL, et al. SCCT guidelines on radiation dose and dose-optimization strategies in cardiovascular CT. J Cardiovasc Comput Tomogr. 2011;5:198-224.