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Original paper

Targeted radiation energy modulation using Saba shielding reduces breast dose without degrading image quality during thoracic CT examinations

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ABSTRACT

Objective: Breasts dose during thoracic computed tomography examinations is a serious challenge and practical dose reduction strategies is needed. The bismuth shielding is an available method for dose reduction; however, its use is on debate due to degrading effects on image quality. The aim of this study is to explore and evaluate the efficiency of a new composition of the X-ray absorbing material to achieve a shield with a lower impact on image quality.
Materials and Methods: Different shields were manufactured with combinations of various weight percentage of copper and bismuth. Dose reduction ratio and image quality were evaluated in phantom studies. A controlled trial with 20 female participants was conducted for image quality assessment. The shield with a lower impact on image quality, named Saba shielding, was used in the clinical trial.
Results: Shielding by one (1 T) and three thickness (3 T) of the constructed shields reduced the mean entrance skin dose of breasts about 52% and 73%, respectively. The shield with a composition of 90% Cu and 10% Bi (Saba shielding) had the lowest while the shield with 100% bismuth had the highest degrading effect on image quality. The Saba shielding could provide 21% higher dose reduction than the Bi shielding at the equivalent image quality. The 1 T Saba shielding did not cause artifacts in the reconstructed images.
Conclusion: The Saba shielding is flexible, cheap and user-friendly for shielding breasts in thoracic CT examinations while do not have the degrading effect of the Bi shielding on image quality.

1. Introduction

The use of computed tomography (CT) as diagnostic imaging technology has increased significantly over the last two decades. CT examinations have higher radiation doses in comparison to other imaging modalities that use ionizing radiation, making it be responsible for more than 70% of the overall doses from medical applications [1,2].

Multidetector computed tomography (MDCT) is an advanced technology that can obtain images faster than old generations of CT scanner, but at the cost of a higher dose to the patients [3]. Because of its excellent role in the diagnosis of a wide variety of thoracic diseases, CT has become the most accurate technique for lung examinations [3,4]. In thoracic CT examinations, radiosensitive breast tissue is subjected to increased radiation dose because of its superficial location [5]. It should be noted that the radiation dose is maximum on the surface of the patient and decreasing as it passes through the patient [6]. A chest CT typically gives 0.02–0.035 Gy to the breast tissue, which is equivalent to 10 mammograms or 100 chest radiographs [7,8].

Because of high radiosensitivity of the breast with the related tissue-weighting factor of 0.12 and its exposure to large doses of radiation during thoracic CT examinations, reduction of radiation dose to the breast is a very important issue [9–13]. This is more critical in children because they are as much as ten times more susceptible to radiation damages than adults [14].

The use of bismuth shielding during chest CT procedures is an effective method to reduce the absorbed dose to the breast [8,9]. Bismuth shielding reduces dose to superficial organs by absorbing low energy photons [15]. Many studies have shown dose saving from 26% to 57% in the case of Bi shielding [6–8,16–23]. Hopper reported between about 40–60% dose saving for the breast, thyroid, and eye using 1 T, 2 T, or 3 T of bismuth-coated latex in both patient and phantom studies [6,8]. In another study by Alonso et al. a dose reduction amount of approximately 50% was achieved for the breasts using bismuth shielding [3]. Tappouni and Mathers showed that bismuth shielding reduced radiation dose to the breast by 38% [7]. Einstein et al. recorded 46%-57% organ dose saving using a commercial breast bismuth shield during

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coronary CT angiography [22]. Lambert and Gould showed that a breast bismuth shield reduced skin dose by 38% [23].

In spite of dose reduction benefits, several studies have indicated degrading effects of bismuth shielding on image quality such as increasing in image noise, causing streak artifacts, and changing in CT numbers [8,10,13,22,24–26]. Wang et al. showed that bismuth shielding increased image noise in the heart and lung [27]. Einstein et al. indicated that the use of bismuth shielding in coronary computed tomographic angiography (CCTA) significantly increased image noise in the location of the coronary artery [22]. In a phantom study, Tappouni and Mathers reported that a commercial breast bismuth shield with padding between shield and skin increased CT numbers by 20 HU and increased noise by 1.86 HU in the anterior region compared to the posterior region [7]. Hohl et al. showed that a commercial breast bismuth shield with 1 cm spacer between phantom and shield increased noise by 8.5 HU [20].

These corrupting effects of bismuth shielding on image quality have caused major concerns about the diagnostic accuracy of the images and have made its usage challenging in clinical examinations [9]. The AAPM has recently released a statement recommending against bismuth shielding application due to its degrading effect on image quality [28].

There are several other techniques to reduce breast dose during thoracic CT examinations [9,19,23,27,29]. The organ-based tube current modulation technique is a method that can give dose reduction equivalent to Bi shielding without degrading effect on image quality. In the organ-based tube current modulation (OBTCM) technique, tube current is decreased from the reference scan current within a given angular range over the anterior surface of the patient. During the remaining angular arc of scanning range, tube current is increased [27,29]. This technique is efficient in the case of dose reduction and reduces the amount of dose as Bi shielding [27]. Several studies have indicated that its impact on image quality is not considerable [23]. However, Ulla Nikupaavo reported an increase in image noise as much as 30% in the posterior and central parts of the brain [30]. This technique has several major limitations; most importantly, it increases the radiation dose to the more posteriorly located organs such as lungs [23]. Research by Hoang et al. reported dose increases of 29% to the upper lungs and 15–20% to the spinal bone marrow [31]. This limitation challenges the applicability of this technique for thoracic CT, because of equality of weighting factors for the lung and breast tissue, based on ICRP 103.

In this study, we have designed and constructed a new physical shield that is a fully applicable and efficient method for protecting breast organs during thoracic CT examinations while all the drawbacks and disadvantages of the conventional bismuth shield have been resolved and fixed in it. The efficiency of this new shield has been evaluated using various phantom and clinical studies. The methods and materials, as well as the results, are presented in the following sections.

2. Materials and methods

2.1. Phantoms and dosimetry

A tissue-equivalent Alderson Rando female anthropomorphic phantom was used to measure surface dose at the location of the breast organ. These measurements were obtained using LiF: Mg, Cu, P (GR-200A) thermoluminescence dosimeters (TLD). Two TLDs were placed on the left and right breast surfaces to obtain reliable results and the measurements were repeated twice with fresh TLDs [20,32]. Before irradiation, TLDs were annealed for 1 h at 400 °C followed by 20 h at 80 °C. Readout of the TLDs was done by Harshaw 5500 automatic chip reader. For reducing dose measurements uncertainties, the TLDs were irradiated with 5 mGy air kerma by a Cs-137 beam and the element correction coefficients (ECC) were determined for each TLD. The calibration procedure was repeated three times and the TLDs were omitted which were out of the range of reading so that the standard deviation of the calibration factors was < 2%. In order to convert the reading of TLDs to the delivered dose, the selected TLDs were irradiated by various doses of the Cs-137 source (0.5, 2, 5, 10, 20, 50, and 100 mGy) and three TLDs were considered as a control to record the background dose. A linear dose-response equation was obtained with a regression coefficient of 0.9999. For energy correction, a conventional X-ray tube, producing a beam with quality similar to that of the CT scanner was used (120 KVp, 7.5 mm total Al filtration). A calibrated ionization chamber (with uncertainty less than 1%) and TLD were irradiated simultaneously and then the energy correction factor was obtained and used in dose calculations.

Acrylic CTDI phantom was used to measure the image noise and the CT number changes. The effect of distance from the shield on image noise was also measured by the CTDI phantom to find the optimized distance. The effect of the shields on image quality was furthermore studied using the female anthropomorphic phantom.

2.2. Patient study

For image quality assessment, a multi-center, single-blinded for outcome assessment, controlled trial with a parallel group design was also conducted (IRCT registration number: IRCT20180730040642N1). All the procedures were in accordance with the ethical standards of the institutional research committee (IR.AJAUMS.REC.1397.027) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. 20 female patients with age of 20–75 were recruited in the study and divided into two equal groups of intervention and control. In the radiology department, after filling informed consent forms, the optimized shield was placed over the breast organ in the intervention group. A foam of 3 cm width was used as a spacer for noise reduction. In the control group, patients underwent routine CT imaging of thorax without any further action. For blinding, before assessing CT images, the picture of the shield was removed from the images. The region between the shield and breasts was appeared foggy in the lung window, particularly in the close distances to the shield, due to the increased noise; to make the removal of the shield imperceptible in the images, a 'Include free hand/ 3D' tool was used by which the target area was selected and clipped so that all the foggy area and shield fell outside of the selected area; then, the selected area was saved for further evaluations. The images of the control group were clipped and saved in the same method as the intervention group.

2.3. CT scanning

All studies were performed using a 16 slice CT scanner (Philips, Brilliance) that was operated in axial mode, at a tube voltage of 120 kVp, a tube current of 162 effective mAs and a slice thickness of 0.5 cm. The IR technique was used for the reconstruction of images as routinely performed. The automatic exposure control (AEC) set to on during imaging according to the routine daily clinical practice. The AEC system adjusts the scanner output dose based on the patient anatomy and attenuation to deliver a high-quality image with the lowest possible exposure. To do so, the scanner takes a radiograph from the patient before starting the tomographic scanning process. Placing the shield before the radiograph will lead to the tube current increase that will counter the dose reduction by the shield. In this study, first, the radiograph was taken, then the shield was placed on the patient breast to have the dose reduction benefits of both methods.

2.4. Shield construction

2.4.1. Selecting composition material

Photons energy in X-ray tubes of computed tomography scanners spans between about 10 KeV up to 120 KeV. Low energy photons could not pass through the patient's body and hence contribute mostly on patient's dose rather than the signal to noise ratio (SNR). In contrast, high energy photons could easily pass through the patient's body and play an important role in the SNR value. In order to reduce the patient dose without considerable loss in the SNR, the energy of the photons should be modulated in a targeted way so that the low energy photons be removed from the spectrum while preserving the high energy photons. Physical shielding may be used for this aim; however, the materials used in the shield composition will have a critical role in the success of this method. To find appropriate material for this aim, we carefully searched among many materials and analyzed their mass attenuation coefficient in diagnostic radiology energies. We finally found that the copper fits with the required features and hence, it was selected as the main X-ray absorbing material in the shield composition. Bismuth is another material that has been frequently used as a shielding material in the past while it does not have the above-mentioned properties and it was not a suitable choice for this purpose. The copper has high mass attenuation coefficient in low energies while it's mass attenuation coefficient decreases rapidly in higher energies, i.e. a single thickness of the copper attenuates 99.99% of 10 KeV photons and 18% of 100 KeV photons. The bismuth mass attenuation coefficient is higher than the copper in low energies; however, it has high mass attenuation coefficients in higher energies either and more importantly, it has a K-edge in 90.52 KeV, i.e. a single thickness of the bismuth attenuates 99.99% of 10 KeV photons and 68% of 100 Kev photons.

2.4.2. Construction method

Our theoretical analysis indicates that the bismuth does not have the required properties and the copper is a good candidate to be used in the physical shield construction. To examine the accuracy and efficiency of this theory, different breast shields were manufactured with a combination of different weight percentage of the bismuth and copper (Table 1). A mold made of Plexiglass with the shape of the breast was used to form shields. RTV Silicone (Room-Temperature-Vulcanizing silicone) as elastomeric medium and the bismuth and copper powders as the X-ray absorbing materials were mixed well with a mechanical stirrer. RTV silicone is a type of silicone rubber in which silicone rubber serves as a base and is mixed with a curating agent. It should be noted that the shields were manufactured based on the thicknesses of the single thickness (1 T, 0.06 mm lead equivalent attenuation) and triple thicknesses (3 T) of absorbing material that reduces primary radiation by 63% and 95% at 120 kVp, respectively. For preliminary evaluation of the new composition, the shields were made in a form of rectangular with 16 cm length and 10 cm width. The effects of these shields were evaluated on image noise and CT numbers shift using a CTDI phantom. In the next step, breast shields were made in a rectangular form with the length of 42 cm and width of 16 cm considering the anatomical shape of breasts so that the upper middle notch was designed to match to the sternal notch; Also, lower middle notch was in accordance with the separation of right and left breasts, and its edges were curved to prevent any artifact into the diagnostic image (Fig. 1A). A 3 cm spacer was used between the breasts and the shield to minimize both the image noise and the CT number shifts near the shield.

2.5. Image quality assessment

Image quality was quantitatively evaluated in a uniform and an anthropomorphic phantom by measuring the image noise and CT numbers shift in different regions of interests (ROI). The image noise was measured using the standard deviation of attenuation values (in Hounsfield units) in a homogenous region [33]. In the uniform phantom, seven 2 cm^2 ROIs were considered in the center of the phantom in the distances of 1, 2, 3, 4, 5, 9, and 12 cm from the shield (Fig. 1C). The ROIs in the distance of 2 and 4 cm from the shield were not shown in the Fig. 1C due to the overlap with the adjacent ROIs. In the case of the anthropomorphic phantom, five 2 cm^2 ROIs were defined at the anterior chest, posterior chest (paravertebral soft tissues), mediastinum, and anterior and posterior lung (Fig. 1B). The CT number and standard deviation within each ROIs were calculated for ten successive axial images and then averaged to obtain an accurate value for them.

The image artifacts were evaluated using patient data. A questionnaire was filled by two radiologists about the quality of images. Different levels of artifacts were scored by the radiologists. CT images of each patient were evaluated with the following score criteria [14]: 0-No artifact, 1-Minimal artifact, 2-Artifact limited to the anterior chest wall or anterior lung, 3-Streaks extended into the mediastinum or posterior lung, 4-Sever artifact hindering interpretation.

Table 1
Different combinations and widths of the constructed shields.

Name	Bi(%W)	Cu(%W)	Width
10%Bi-90%Cu	10	90	1 T, 3 T
50%Bi-50%Cu	50	50	1 T, 3 T
90%Bi-10%Cu	90	10	1 T, 3 T
100%Bi	100	0	1 T, 3 T

2.6. Statistical analysis

Differences between different groups were analyzed statistically by a paired student *t*-test (Excel, Microsoft) and statistical significance was set at a P value of less than 0.05. The Kolmogorov-Smirnov test was used for assessing the normality of data. In the case of the clinical trial, the statistical difference between two groups in term of image quality was assessed using the non-parametric Mann-Whitney test.

3. Results

3.1. Surface dose using an anthropomorphic phantom

Mean values and standard deviations of the measured entrance skin dose (ESD) for different manufactured shields with the thickness of 1 T and 3 T are displayed in Table 2. The mean ESD of the breast during thoracic CT scan was 22.02 ± 1.12 mSv without shielding. Using 10% Bi-90%Cu, 50%Bi-50%Cu, 90%Bi-10%Cu and 100%Bi shields with the thickness of 1 T reduced the ESD by 52.1%, 54.1%, 50.8%, and 52.8%, respectively. For shields with the thickness of 3 T, 10%Bi-90%Cu, 50% Bi-50%Cu, 90%Bi-10%Cu and 100%Bi shields reduced the ESD by 73.6%, 73.4%, 73.1%, and 72.1%, respectively.

For all manufactured shields, the dose reductions were statistically significant ($P < 0.05$). By increasing the thickness of the shields from 1 T to 3 T, a more surface dose reduction of about 20% was achieved.

3.2. Image quality analysis using a CTDI phantom

The shields were placed in a contact position over the uniform phantom during CT scanning for image quality assessments. Seven ROIs were considered in the center of the phantom with different distances from the shield. The CT numbers and noise were measured and averaged in 10 successive slices for each ROI; then the CT numbers shift and noise increase from the reference dose mode (the measured dose without shield) was calculated. As can be seen from Fig. 2, increasing the weight percentage of the Cu in the shield composition reduces the noise and CT numbers shift in the images. The shield with 10% Bi and 90% Cu had the lowest degrading effect on the image quality considering the image noise and drift in CT numbers. This shield is named Saba shield and used for further evaluations in a clinical trial.

The effect of offsetting the shield from the patient body is also shown in Fig. 2. The CT numbers shift and image noise decreases rapidly by increasing the distance between the shield and ROI.

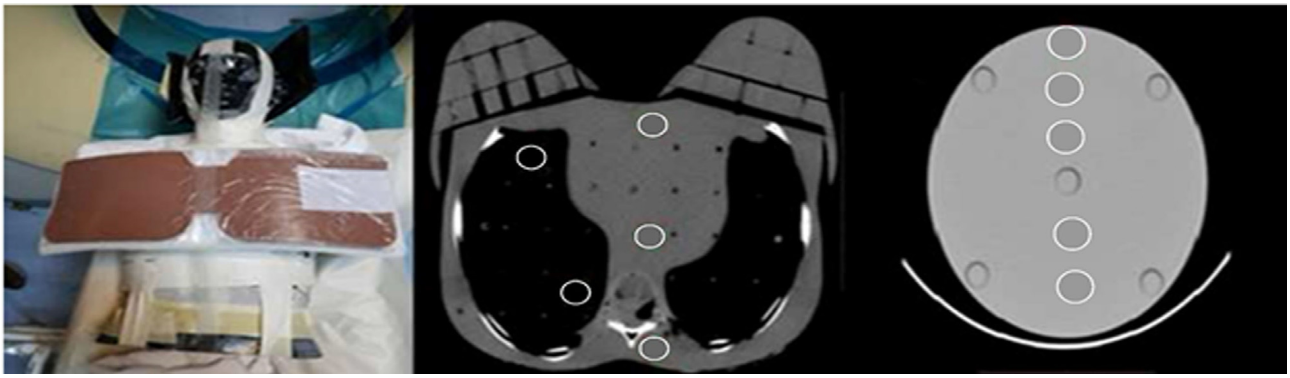

Fig. 1. (A) positioning of a constructed shield for imaging of breast organs using an anthropomorphic phantom; Axial CT images show locations where the ROIs were placed in phantoms: B) Anthropomorphic phantom, C) CTDI phantom (ROI 2 and ROI 4 are not indicated due to the overlap with the adjacent ROIs).

Table 2
Mean entrance skin dose (ESD) of the breast during thoracic CT scans with and without manufactured shields with the thickness of 1 T and 3 T.

	Shield composition	ESD (mGy)	Dose Reduction (%)
1 T	No shielding	22.02 ± 1.12	–
	10%Bi-90%Cu	10.55 ± 0.91	52.1
	50%Bi-50%Cu	10.06 ± 0.77	54.1
	90%Bi-10%Cu	10.82 ± 0.74	50.8
	100%Bi	10.38 ± 0.98	52.8
3 T	10%Bi-90%Cu	5.8 ± 1.1	73.6
	50%Bi-50%Cu	5.85 ± 0.63	73.4
	90%Bi-10%Cu	5.92 ± 0.87	73.1
	100%Bi	6.14 ± 0.85	72.1

3.3. Image quality analysis using an anthropomorphic phantom

The constructed shields were placed over the phantom breast with 1 cm foam as a spacer and different CT images were obtained for image quality assessments. An example of the reconstructed images is indicated in Fig. 3. As can be seen from Fig. 3, the effects of shielding appeared as a foggy area in the beneath of the shield which is visually observable. These degrading effects were quantitatively evaluated in terms of the image noise and CT numbers shifts and measured in different ROIs (Fig. 4). It was observed that the degrading effects of the shields in the anterior region of the thorax were higher than the other regions. The mean CT numbers and image noise in the anterior region of the thorax were 11.9, and 6.8 HU, respectively. Using 10%Bi-90%Cu, 50%Bi-50%Cu, 90%Bi-10%Cu and 100%Bi shields with the thickness of 1 T increased the image noise in the anterior region of the thorax by 0.8 (11%), 1.2 (17%), 1.9 (27%) and 2.7 (40%) HU, respectively. The mean CT number in the anterior region of the thorax with the 10%Bi-90%Cu, 50%Bi-50%Cu, 90%Bi-10%Cu and 100%Bi shields with the thickness of 1 T increased by 5.8, 14.4, 17.7 and 19.2 HU, respectively.

All the shields except the Saba shielding significantly affected the noise and CT numbers in all the studied ROIs. The effects of the Saba shielding with the thickness of 1 T was statistically insignificant on the noise at the regions of the anterior lung ($p = 0.08$) and posterior lung ($p = 0.07$). Also, the Saba shielding effect on the CT numbers shift was not significant in the regions of the posterior chest wall ($p = 0.53$), mediastinum (0.06) and posterior lung ($p = 0.06$). The effects of the 3 T Saba shield were not significant in the noise of the posterior lung ($p = 0.06$) and the CT numbers of the mediastinum ($p = 0.13$). The effects of the 3 T Saba shield on image quality were similar to those of the 1 T Bi shield (Fig. 5). So, 21% higher dose reduction is achievable by using the 3 T Saba shielding instead of the 1 T Bi shield at equivalent image quality.

The results indicated that the Saba shield with the composition of 10%Bi-90%Cu had the lowest effect on image quality in the case of both the image noise and CT numbers shift in comparison to the other shields.

3.4. Image quality analysis by a patient study

For the clinical study, the Saba shield was selected due to its lower impact on the image quality. An axial thoracic CT image of a patient obtained using the Saba shield is shown in Fig. 6. In the intervention group, the first radiologist reported no artifact in the case of all patients in both intervention and control groups. Based on the evaluation results of the second radiologist, artifacts were not seen in 9 patients of the intervention group; only minimal artifacts were seen in 1 patient (score = 1) at the superficial breast tissue. This radiologist also reported one patient in the control group with the minimal artifact of score 1. There was no difference between the groups in the case of image quality. Both radiologists declared that all the CT images are of normal diagnostic quality. Fig. 6

4. Discussion

During CT examinations, radiosensitive organs such as breast, eye, and thyroid receive high doses because of their location. Therefore, it is important to utilize dose reduction techniques for radiosensitive organs during CT imaging. Bismuth shielding, tube current modulation (TCM), automatic exposure control (AEC) and iterative reconstruction are techniques used for dose reduction in CT scanners. However, these techniques have some limitations and also are not available in all CT scanners [34].

4.1. Comparison of Saba shielding efficiency with Bi shielding

4.1.1. Dose reduction

For dose reduction measurements, two methods have been used in previous works including organ dose measurements or entrance skin dose (ESD) measurements whereas the latter method was used in our study. The dose measurements showed significant ESD reduction using manufactured breast shields with the thickness of 1 T (50.8–54.1%). Dose reduction efficacy of all the manufactured shields with the thickness of 1 T was approximately the same as expected.

Our dose reduction results are in accordance with Hopper [8], Alonso [3], and Einstein [22] studies. The minor differences between this study and that of Hopper, Alonso, and Einstein could be attributed to the variations in scanning techniques and breast sizes. The shielding efficacy of our manufactured shields with the thickness of 1 T is better than, Tappouni and Mathers [7], Hohl [20], Lambert and Gould [23], Yilmaz [21], Catuzzo [16] and Wang [27] ones. Shielding efficacy of the manufactured shields suggests that they can be used as good dose saving filters for clinical applications. By increasing the thickness of the manufactured shields from 1 T to 3 T, the shielding efficacy was

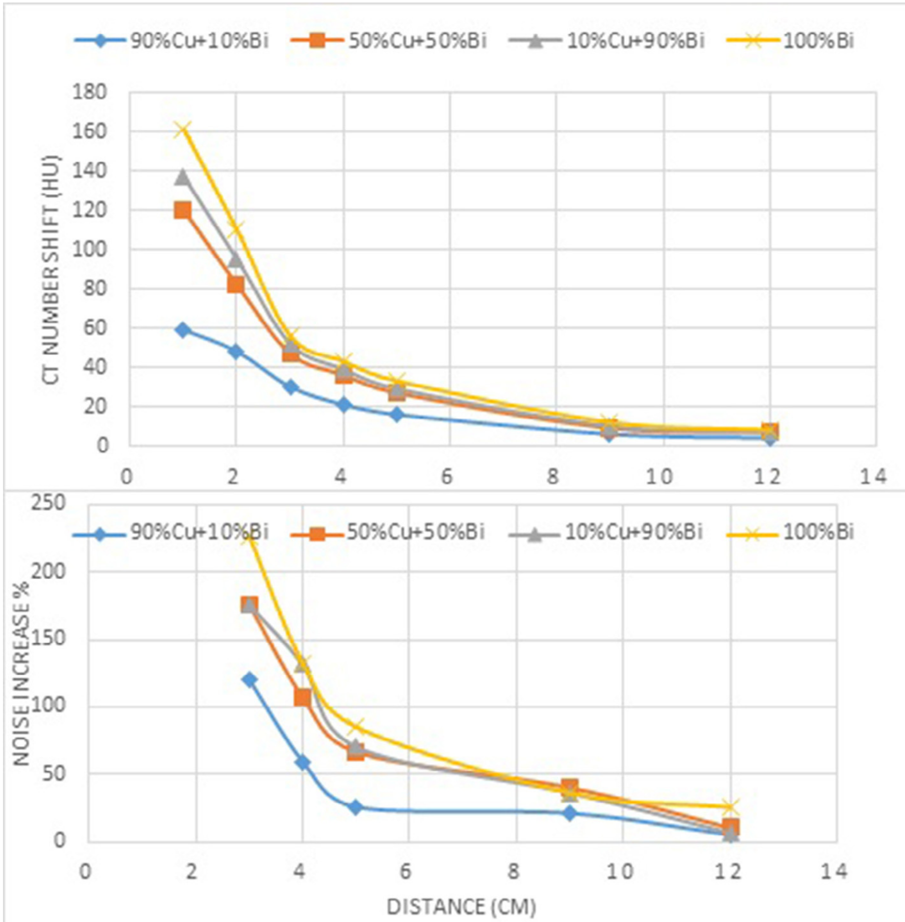

Fig. 2. (Top) Effect of different shields on CT numbers shift in the uniform CTDI phantom, (bottom) Effect of different shields on image noise increase from reference dose mode in the uniform CTDI phantom.

increased significantly.

4.1.2. Effect on noise and CT number Shift: Uniform phantom study

We used a CTDI phantom as a uniform phantom for preliminary evaluations of the efficiency of the newly constructed shields. The shields were constructed in a rectangular form with different weight percentages of the Bi and Cu to find which combination had the best efficiency. The results indicated that increasing the Cu weight percentage in the shield composition significantly decreased the image noises and CT numbers distortion. Increasing the Cu weight percentage in the shield composition from 0 to 90% resulted in 105% reduction in the image noise and 21% reduction in the CT numbers shift at a region with the distance of 3 cm from the shield.

The reason for this effect seems to be due to the lower atomic number of the Cu than Bi. Having a high atomic number leads to more reduction of the high energy photons from the x-ray beam. This causes a reduction in the SNR which, in turns, leads to higher noise in the image.

The results indicated that the shield with 10% Bi and 90% Cu had the lowest degrading effects on the image quality. The shield with this composition was named Saba shield and used in the anthropomorphic phantom and the patient study for more evaluation.

The distance between the shield and phantom had a vital role in image quality. Both the Saba and Bi shields indicated severe noise and CT numbers shift in the contact position. However, the noise and CT numbers shift decreased rapidly by increasing the distance between the shields and the phantom. In the case of Bi shield, the noise decreased from 2296% down to 85% and the CT numbers shift decreased from 161 HU down to 33 HU by moving the shield from the contact position to the distance of 5 cm. In the case of the Saba shield, the noise decreased from 522% down to 25% and the CT numbers shift decreased from 59 HU down to 16 HU by moving the shield from the contact position to the distance of 5 cm. The Saba shield had no noise and only 6HU shift in the CT numbers at the distance of 9 cm.

During thoracic CT examinations, the breasts tissue are not the target organs for imaging, whereas they make a distance of 3–7 cm between the shield and chest. So, by using a spacer with a width of 3 cm, a 6–10 cm distance will be made between the shield and the target tissues including lungs, sternum, and mediastinum. As a result, using the Saba shield with a spacer of 3 cm will protect breast tissue without degrading image quality.

4.1.3. Effect on noise and CT Numbers: Anthropomorphic phantom and patient study

All the constructed shields were examined using an anthropomorphic phantom. The shields were placed over the breast organ using a 1 cm spacer. In the anterior chest wall ROI, the noise and CT numbers shift were 11% and 5.8 HU for the Saba shield and 40% and 19.2 HU for the Bi shield, respectively. The noise of the Saba shield in the anterior lung, posterior lung, and mediastinum was equal to 2%, 0.7%, and 9%. The Saba shield caused no change in the CT numbers of the mediastinum; only 2 HU shift in the CT numbers of the anterior lung and 1 HU shift in the CT numbers of the posterior lung was observed. The results of the anthropomorphic phantom study were in accordance with the results of the uniform phantom study indicating that the 1 T Saba shield has no degrading effect on the image quality.

The effects of the 1 T Saba shield on the image quality were

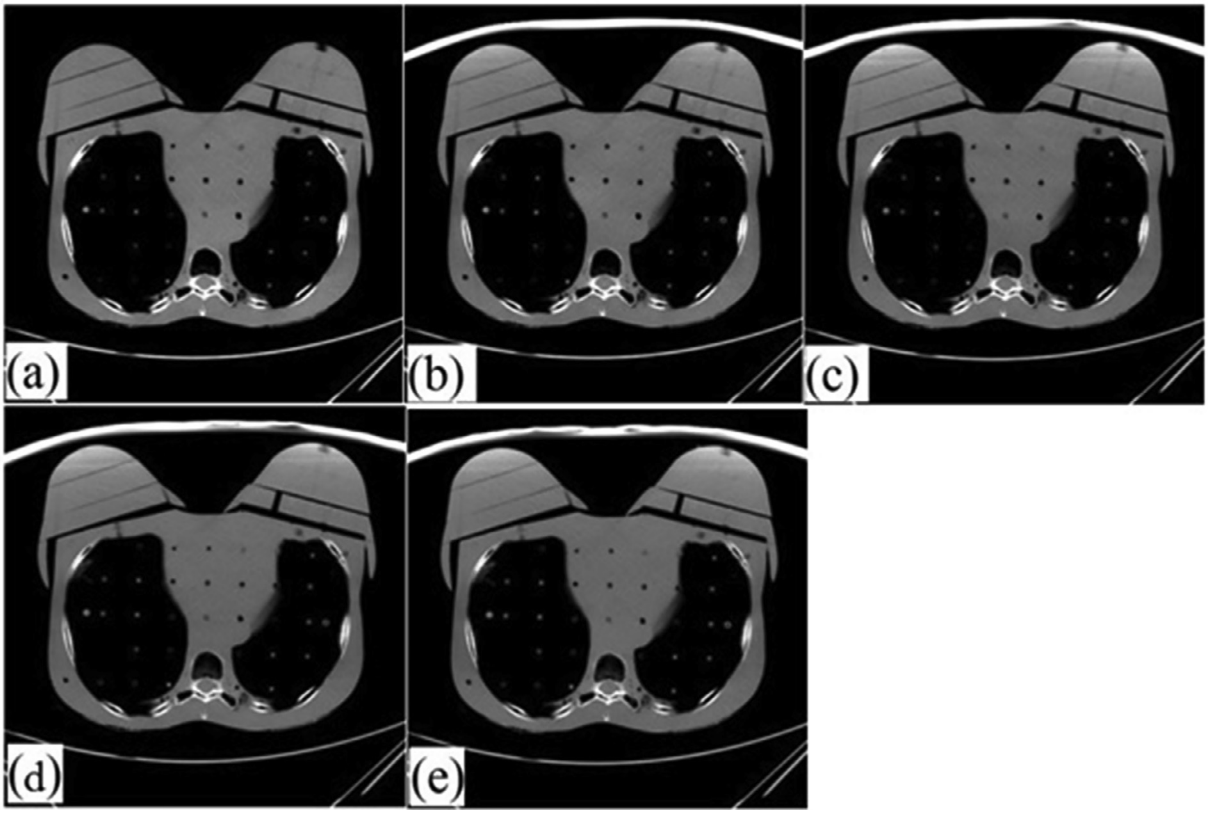

Fig. 3. Reconstructed images of the anthropomorphic phantom (a) without shield, (b) with the shield of 90% Cu and 10% Bi (Saba shielding), (c) with shield of 50% Cu and 50% Bi, (d) with shield of 10% Cu and 90% Bi, (e) with shield of 100% Bi.

insignificant in many regions. The 3 T Saba shield had the same effects on the image quality as the 1 T Bi shield; however, the dose reduction of the 3 T Saba shield was about 21% higher than the 1 T Bi shield. So by using the 3 T Saba shield instead of the conventional 1 T Bi shield, a 21% higher dose reduction can be achieved at the same image quality. Also, if higher image quality is required, the 1 T Saba shielding can be used.

In the patient study, the 1 T Saba shield had no degrading effect on the image quality based on the reports of two radiologists. The results of the clinical trial were in accordance with the results of the phantom studies.

4.1.4. Patient's radiation exposure wasting

When the x-ray tube is beneath the patient, the shield does not reduce the patient dose, but rather absorbs some photons exiting from the patient before they can reach the detector. The amount of wasted radiation is another concern about the applicability of physical shielding. The amount of the noise increase is a good indicator for the amount of the wasted radiation as we know the wasted radiation is related to the SNR loss and the SNR loss has a linear relation with the noise increase. So, when a little increase in image noise exists, this means that the amount of wasted radiation is not considerable. In this study, the results indicated that the Saba shield had several times less noise in the images than the Bi shield; also, the noise of the Saba shield was statistically insignificant in most of the ROIs (p-value < 0.05). Considering the amount of image noise, it can be concluded that the problem of radiation wasting has been fixed using the Saba shield.

In other words, when the X-ray tube is beneath the patient, the photons first interact with the patient's body before reaching the shield. This cause the X-ray beam to harden (low energy photons are absorbed inside the body and high energy photons pass through the body). Due to the hardening effect, the high energy photons will mostly remain in the spectrum, which, in turn, will easily pass through the shield. The mass attenuation coefficient of the copper is very low for the high energy photons, whereas the Bi has high mass attenuation coefficient for the high energy photons and also it has a K-edge in 90.5 Kev. Due to the considerable difference in the mass attenuation coefficients between the Saba and Bi shields in the higher energies, the Saba shield has several times less radiation wasting in comparison to the Bi shield.

4.2. Tube current modulation or Saba shielding?

The Bi shield had several disadvantages and for this reason, many researchers preferred and recommended the tube current modulation method for protecting the breast tissues. The disadvantages and shortcomings of the Bi shield have been fixed in the Saba shield. Now, it is necessary to revise and compare the benefits and possible drawbacks of the Saba shield with those of the tube current modulation method to decide which one is best suited for dose reduction of the breast organ during thoracic CT examinations. The Saba shielding is flexible, cheap and user-friendly for use and, more importantly, it can be used in any scanners worldwide without the special need for technologists training.

The tube current modulation method can give dose reduction equivalent to the Bi shielding without degrading effect on the image quality. However, this technique has several major limitations: 1) It increases the radiation dose to the more posteriorly located organs such as lungs [23]. Research by Hoang et al. reported dose increases of 29% to the upper lungs and 15–20% to the spinal bone marrow [31]. Increasing the dose of radiosensitive organs such as lungs and bone marrow is a major concern challenging the applicability of this technique for thoracic CT, because of the equality of weighting factors for the lung and breast tissue, based on ICRP 103. 2) A portion of larger breasts may position out of the anterior scan region, where the increased tube current would result in the increased dose to the breasts [9,12]. 3) In the case of off-center positioning of the patient, the breast organ may receive more radiation dose from the increased tube current

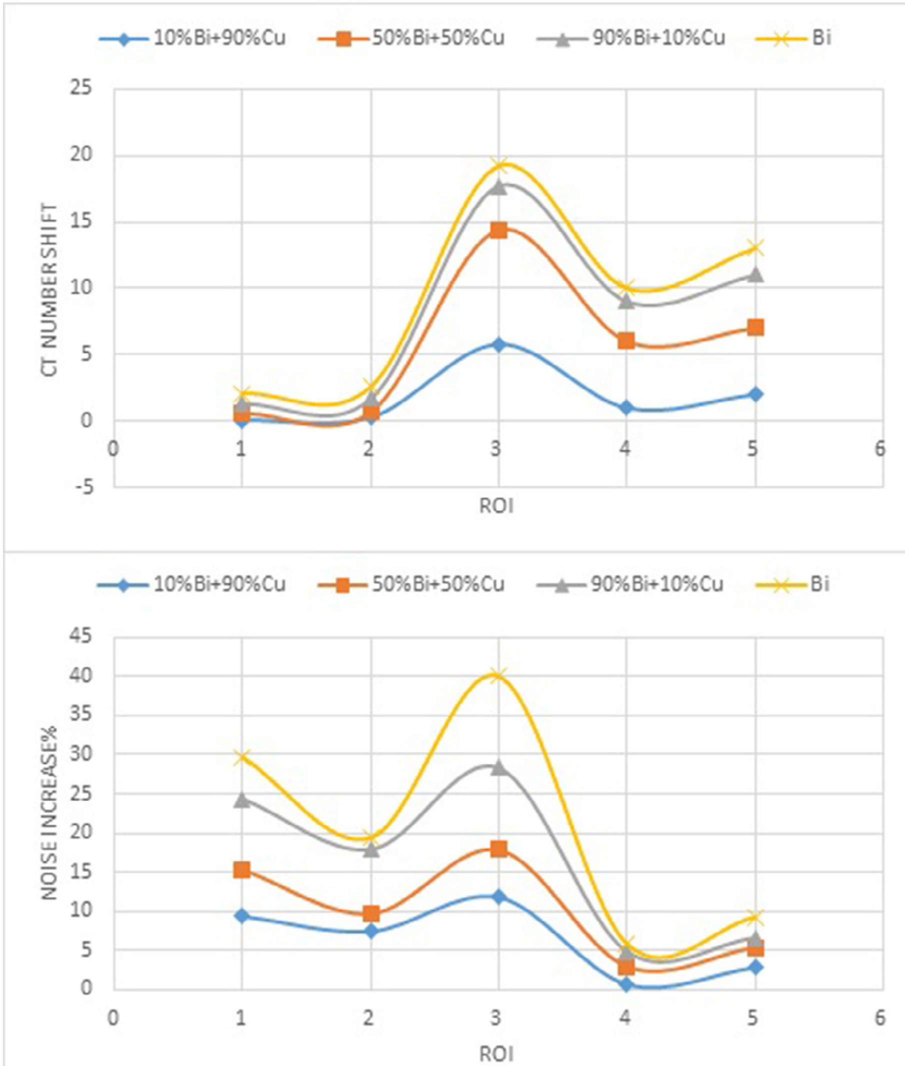

Fig. 4. (top) CT number shift and (bottom) noise increase from reference dose mode at different ROIs: (1) Mediastinum, (2) posterior chest wall, (3) Anterior chest wall, (4) Posterior lung, and (5) Anterior lung in the anthropomorphic phantom.

[9]. Lai et al. reported a 50% increase in the dose of the breast due to the positioning of a phantom off-center during thoracic CT examination using tube current modulation [35]. 4) Adjusting patients in the center of the gantry is a time-consuming process and need training for careful implementation by the technologist. 5) This technology is not available in all scanners and this issue is commonplace in the case of low-income countries which mostly use the old generation of scanners [11]. 6) Tube current modulation decreases all photons including high energy and low energy photons in the anterior regions; however, physical shields reduce mostly low energy photons and do not change high energy photons considerably. Removing the low energy photons is of interest because they are mostly contributing to patient dose rather than image quality.

Of those, increasing the dose of the posteriorly located organs is of great concern that should be considered carefully by the scientific community. In fact, the tube current modulation method decrease breast cancer chance; on the other hand, it increases the lung cancer probability. This means that the tube current modulation method is no longer beneficial for the patient's safety and only increase the cost of the imaging in the case of thoracic CT examinations.

In conclusion, it seems that the Saba shielding outperforms the tube current modulation method because of its great dose saving without any other complications to the image quality or patient safety. These surprising results of the Saba shielding in the case of image quality is due to the selection of the Cu as the main X-ray absorbing material in the shield composition. The Saba shield is a targeted shield acting as a high pass filter for the X-ray photons in the energies used in the radiology. The main X-ray absorbing material in the Saba shield composition is not limited to the Cu and few other materials including Mn, Fe, Ni, and Zn has the attenuation properties similar to those of the Cu and, hence they may be used in the composition of the Saba shield.

5. Study limitations

Our study has some limitations in the case of dose measurements. The dose measurements with TLDs were done in the breast surface and skin entrance dose (SED) was used for evaluation and comparison of the Saba and Bi shields. For better estimation of organs doses, TLDs may be inserted into the phantom at the corresponding position of the right and left lungs and breasts to measure the organ dose reductions. Also, the effect of physical shielding on beam quality was not considered and the energy correction factor is needed for obtaining accurate absolute dose values. However, it should be noted that the main aim of this study was to compare the degrading effect of the Saba shield with those of the Bi shield on image quality. To do so, it was important to construct both shields with identical dose reduction abilities. However, measuring the

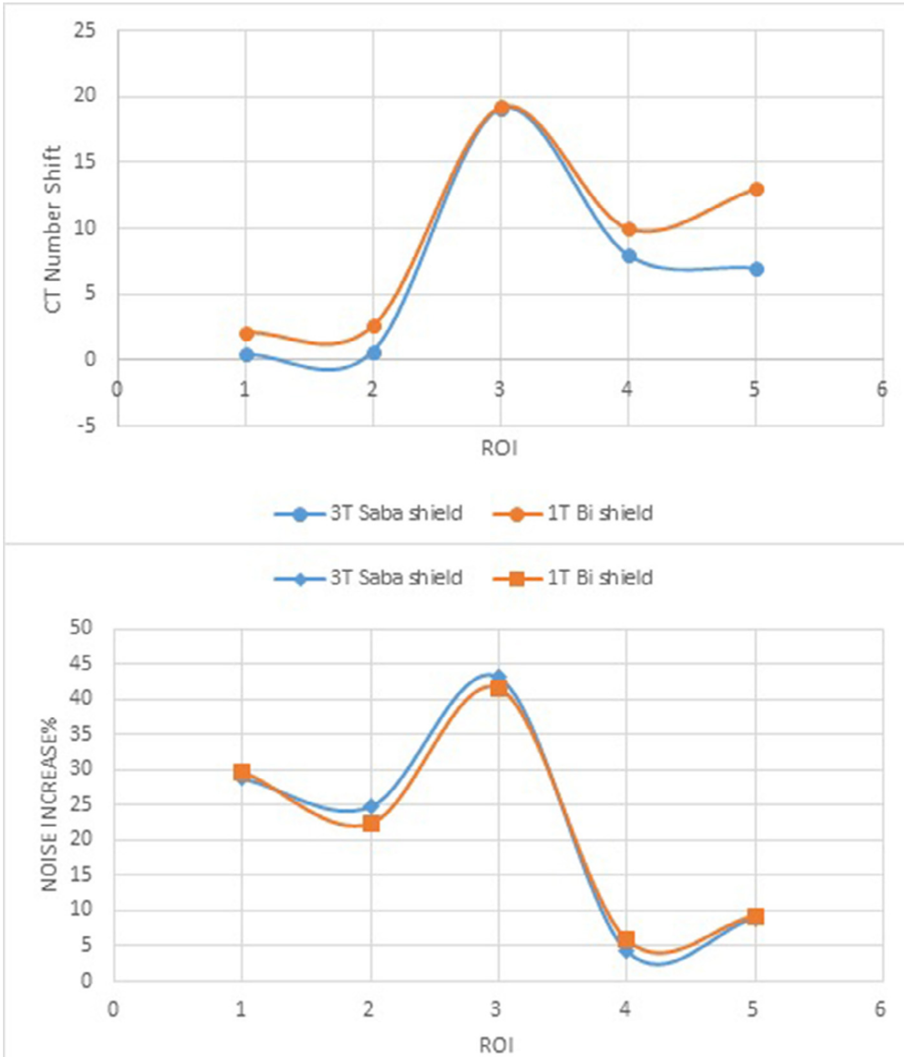

Fig. 5. Comparison of (top) CT number shift and (bottom) noise between 1 T Bi shield and 3 T Saba shield in different ROIs: (1) Mediastinum, (2) posterior chest wall, (3) Anterior chest wall, (4) Posterior lung, and (5) Anterior lung in the anthropomorphic phantom.

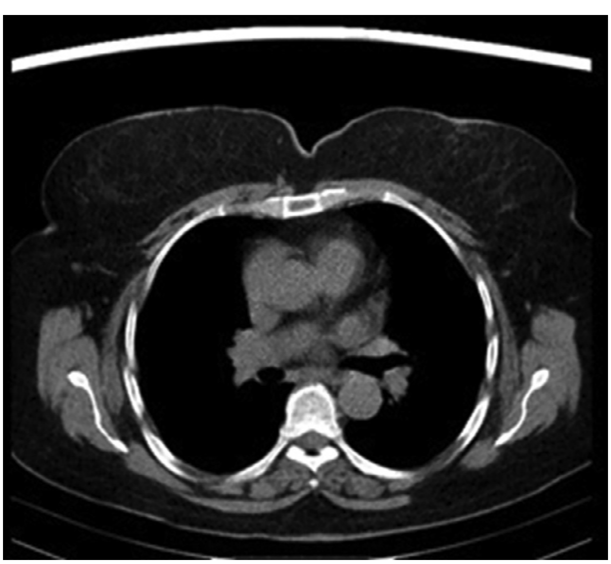

Fig. 6. Example of axial thoracic CT image obtained with Saba shielding.

absolute doses were not useful in this study since dose reduction is considered. So, the energy dependence uncertainty does not affect the results of this study because this uncertainty was applied in the case of the both Saba and Bi shield.

Another limitation of this study was that the amount of the wasted radiation by the Saba shield has not measured quantitatively and we are going to measure it in our future studies. The number of participants in the clinical trial is another limitation for this study and a clinical trial with more participants may be advantageous in future studies.

6. Conclusions

In this study, we aimed to explore a new shield to reduce the breasts dose as the conventional Bi shielding without degrading image quality during thoracic CT examinations. To do so, several shields were constructed using different combinations of Cu and Bi and their efficiency was compared with those of the conventional Bi shield. The results of the uniform and anthropomorphic phantom studies indicated that the shield with 10% Bi and 90% Cu had the lowest impact on the image quality. A 1 T thickness of this new shield, named Saba shield, reduced the breast skin entrance dose equal to 50% similar to a 1 T bismuth shield, whereas the Saba shield effects on the image noise and CT numbers shift were several times lower than the Bi shield. Also, the 1 T Saba shield with provided 21% higher dose reduction than the 1 T Bi shield at the equivalent image quality.

In the anthropomorphic phantom study, the maximum observed shifts in the CT numbers were less than 6 HU for the 1 T Saba shield; also, the maximum observed noise increase from the reference dose mode was less than 11%. Based on the reports of two expert radiologists, the results of the clinical trial were in accordance with those of the phantom studies and no artifacts were observed in the reconstructed images when the 1 T Saba shield was used.

Declaration of Competing Interest

All authors declare that they have no conflict of interest.

Acknowledgments

Valiallah Saba contributed to the idea, conception, and design and construction method of the new shield. He also evaluated the efficiency of the shield in the case of uniform phantom and patient study. Mohammad Keshtkar evaluated the efficiency of the shield using an anthropomorphic phantom. The CT imaging was carried out at the Radiology Department of the Imam Reza hospital. Therefore, the authors express their sincere appreciation to the above institutes for their financial help and technical assistance.

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