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Assessing the image quality and eye lens dose reduction using bismuth shielding in computed tomography of brain

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Abstract

Background: Epidemiological studies show that computed tomography (CT) is one of the main sources of ionizing radiations. Shielding of radiosensitive organs is one of the dose reduction methods. This study aimed to assess the eye lens dose reduction and image quality resulting from the use of radio-protective bismuth shield in brain CT imaging.

Methods: Bismuth shields were constructed with two different thicknesses (0.02 and 0.06 cm) and two different geometries including: direct contact with eye (contact setup) and 4 cm above the eye (distant setup). The lens dose was determined using thermo luminescent dosimeter (TLD)-207A chips inside an anthropomorphic head phantom during the CT examinations. Noise, SNR (signal to noise ratio), and CNR (contrast to noise ratio) were calculated to evaluate the image quality.

Results: The lens dose reduction was higher using the shield with 0.06 cm thickness and in ‘contact setup’. On the other hand, the bismuth shield with the thickness of 0.02 cm and in ‘distant setup’ had lower dose reduction and better image quality.

Conclusion: Bismuth shield with the thickness of 0.02 cm and in ‘distant setup’ could decrease the lens dose to the acceptable levels, while providing a better image quality in comparison with the contact shield setup and with 0.06 cm thickness. Using the bismuth shield is a simple and low cost method for protecting the eye lens in brain CT scans with conventional scanners especially in low income or developing countries.

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Introduction

In diagnostic and therapeutic applications of ionizing radiation, the patient dose is one of the great developing concerns due to the probabilities of radiation-induced harmful effects like cancers. Epidemiological studies conducted in the USA showed that computed tomography (CT) is one of the main ionization exposure sources in clinical situations. Brain CT constituted approximately 28.4% (19 million brain CT scans) of CT examinations (67 million CT scans) (1). The eye lens has been considered as one of the most known radiosensitive tissues. Cataract as one of the side effects of ionizing radiation is used to describe any detectable changes in the healthy and transparent lenses. These effects are variable from the small spots to the complete pacification of the lens that leads to blindness. It is well known that cataract could appear after sufficient ionizing radiation exposure (such as charged particles, neutrons, X and gamma rays etc.) (2-4). A lens could be considered as a reproducible tissue with a special cellular system that has no cell elimination mechanism. Ionizing radiations can induce damages, which resulted in production of non-natural fibers. These non-natural fibers did not remove from the lens and migrate toward the rear lens poles. The cataract appears due to the lack of transparency in fibers (2, 3, 5). Some risk factors which are involved in the lens opacity development include: age, diabetes, use of corticosteroids, smoking, and ultraviolet radiation exposure. A fully detailed mechanism of the radiation-induced cataract is not known yet (6,7).

Previous studies reported that lenses have a nonlinear dose-response curve with a specified threshold (8, 9). After low dose exposures, induced opacity remains at a constant level which has a negligible effect on the vision. At higher dose exposures, the induced opacity deteriorates until it leads to blindness. The incident probability of the progressive cataract increased by increasing of radiation dose (2,3).

The exposure threshold to incident radiation-induced cataracts in single (single brief exposure) and fractionated dose irradiation (high and long exposure) are 500 - 2000 mGy and 5000 mGy, respectively reported by International Commission on Radiation Protection (ICRP) in 2007 (10). In April 2011, ICRP recommended the dose limit of 20 mSv per year for the lens of the eye. The previous dose limit for the eye lens was 150 mSv per year. However, for members of the general public, the dose limit was not determined (11).

Recent studies challenge the ICRP reports seriously (12). It was noted that cataracts appear in more than 20-30% of patients after 1Gy or lower exposure. These results showed that there is no threshold for the cataract occurrence, or if any, it ranged from 0 to 0.8 Gy (13-16). In another study, it was suggested that there is no certain threshold for cataract formation (12). Therefore, dose reduction methods have a critical role in brain CT examinations. Several techniques have been well approved to reduce the lens dose in the brain CT (such as gantry tilt technique and tube current modulation), except the available commercial reconstruction algorithms (e.g. model-based iterative reconstruction method).

Tube current modulation and gantry tilt techniques are preferred to the bismuth shield due to their proper lens dose reduction while maintaining image quality. However, these methods are not available in most of the commercial scanners due to their cost of implantation and attenuation characteristics. The dose reduction technique with a high attenuation filter (like bismuth) could be a fair alternative method for CT examinations (17,18). The artifact is considered as the main problem of the bismuth shielding method (19,20). In this study by changing the composition and thickness of the bismuth shield, the efficiency of the new eye shields was evaluated. Our aim was to find an optimal eye lens shield with effective protection for the patient's eye lenses and fewer image artifacts or noise in comparison with common bismuth shields.

Materials and methods

Construction of the eye shields

Eye shields were designed and built based on the thickness of 1T that reduces primary radiation by 63%. Two different eye shields of 1T and 3T were constructed using bismuth powder distributed homogenously in silicone gel. The silicone was chosen as the base for the radio-protective lens shield, due to its low cost, flexibility and durability. A mold made of Plexiglas with dimensions of 14 × 3 × 1 cm^3 was used to form the radio-protective eye shields. The mold used for the construction of the eye shields is shown in Figure 1. Shields thicknesses were 0.0191 and 0.0573 centimeters without considering the base gel and 0.02 and 0.06 centimeters with considering base gel for 1T and 3T shields respectively. The dimensions of these shields were 3 × 14 cm^2.

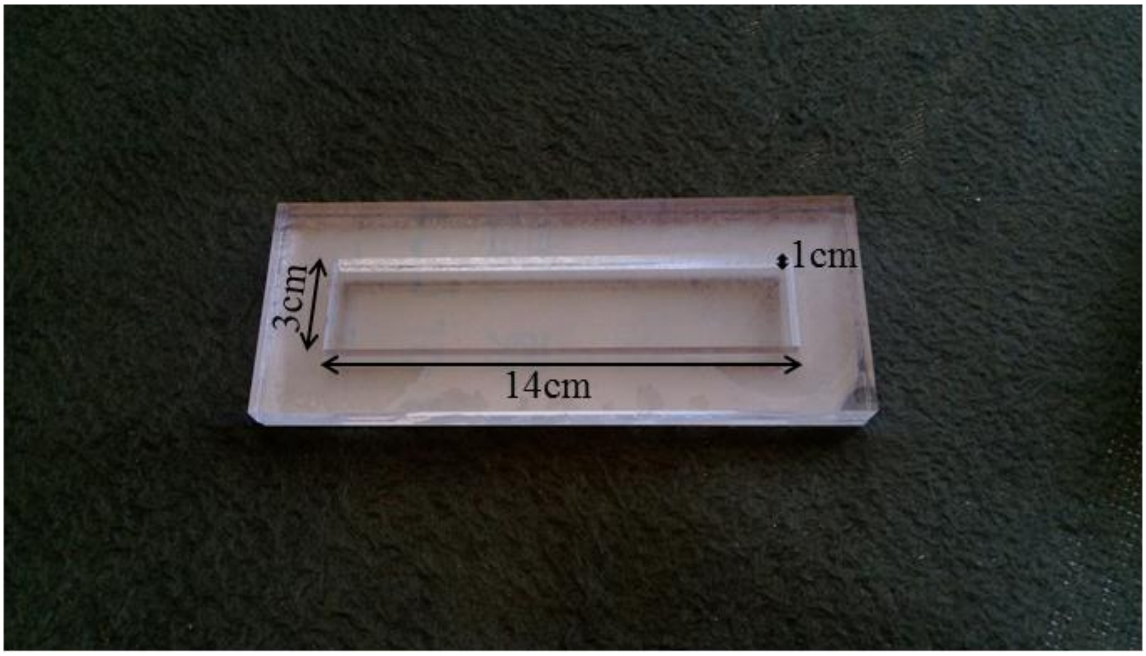

Figure 1. The mold made of Plexiglas used for the construction of the eye shields

The required mass of the bismuth powders were 8.22 and 24.65 grams for 1T and 3T shields, respectively. The bismuth powder (CAS 7440-69-9, molar mass 208.98 g/mol, Merck Co., Germany) was mixed in 25 grams of the industrial silicon using a slow speed mixer (300-500 rpm). Finally, 5% silicon hardener with identification number 3335 (or 1 g) was added to the medium and transferred immediately into the prepared mold. The distributions of metal powders inside the shield slab were evaluated using a SEM system (XL30, Philips Co. Massachusetts, USA).

The attenuation efficiencies and CT image qualities were obtained using the lens shields with mentioned thicknesses on an anthropomorphic head phantom and CTDI phantom.

X-ray computed tomography (CT)

Imaging of the anthropomorphic head phantom and CTDI phantom was performed using a 16-slice CT scanner

(Brilliance, Philips, Germany) with radiation and technical parameters including: kVp= 120, mA=250, resolution=3mm, pitch=0.313, rotation time=0.5sec.

Evaluation of the lens dose during the CT examinations

The lens doses were determined using thermo luminescent dosimeter (TLD)-207A (LiF:p,CuMg, PTW, Germany) chips inside the anthropomorphic head phantom during the CT examinations. Two blocks made of foam were developed for positioning of the thermo luminescent dosimeters on the right and left eyes as shown in Figure 2.

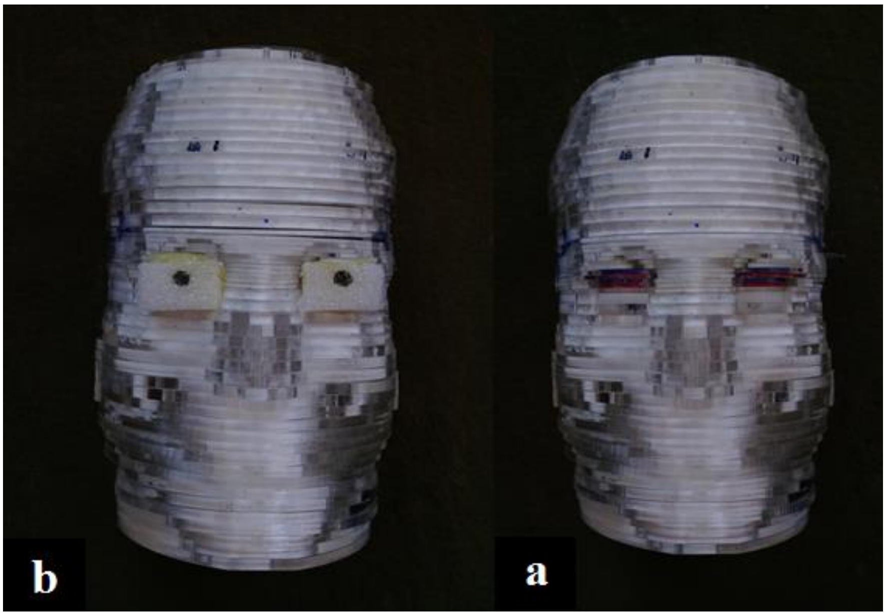

Figure 2. The embedded foam blocks for positioning of the thermo luminescent dosimeters on the right and left eyes of the anthropomorphic head phantom. a) Anthropomorphic head phantom without embedded foam blocks. b) Anthropomorphic head phantom with embedded foam blocks

The lens doses were determined in two scanning geometries: 1) the lens shield placed directly on the face (Contact setup) 2) the lens shield placed at 4 cm above the eye (distant shield setup). For each CT examination with eye shields, the same scanning geometry was provided using an in-house developed holder made of foam. The attenuation characteristics of the foams are similar to air. So, it has the least effect on the image quality and lens dose values.

Evaluation of the image quality

The image quality of the CT data was evaluated using a CTDI head phantom. The image quality was studied for both of scanning geometries. Seventy regions of interests (ROIs) with the dimension of 3x3 pixels were selected along the favored direction. In each ROI, the average and standard deviation of the signal intensities (Hounsfield unit value) were considered as the signal and noise values, respectively. The SNR, CNR and noise parameters were measured as the image quality indices. SNR and CNR parameters were defined by Eqs 1 and 2, respectively:

$$\mathrm{SNR}=\frac{\bar{S}}{\mathrm{Noise}} \qquad (1)$$

$$\mathrm{CNR}=\frac{I_{phantom}-I_{air}}{\sqrt{\sigma_{phantom}^{2}+\sigma_{air}^{2}}} \qquad (2)$$

Where $\bar{S}$ and I are averaged Hounsfield units in each of the divided ROIs and σ represents the standard deviation of these ROIs.

The image quality of the CT data was evaluated along three profiles (included left, central and right profiles) in the anterior-posterior direction with an in-house MATLAB (ver. 2010a, The MathWorks TM, Natick, Massachusetts, United States) based code.

The phantom surface was also divided into three regions included top, medium and bottom sides. The defined areas and extracted profiles in the CT images for both of "Contact" and "distant shield" setups are shown in Figure 3.

Results

Construction of the eye shields

Approximately uniform distributions of the bismuth metal powders could be seen in the constructed shields (Figure 4).

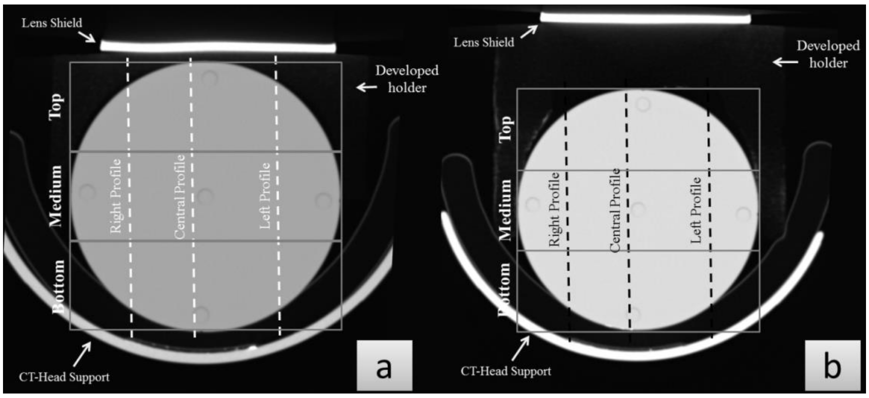

Figure 3. Defined areas and extracted profiles in the CT images for image quality assessment. a) "Contact" setup. b) "Distant shield" setup.

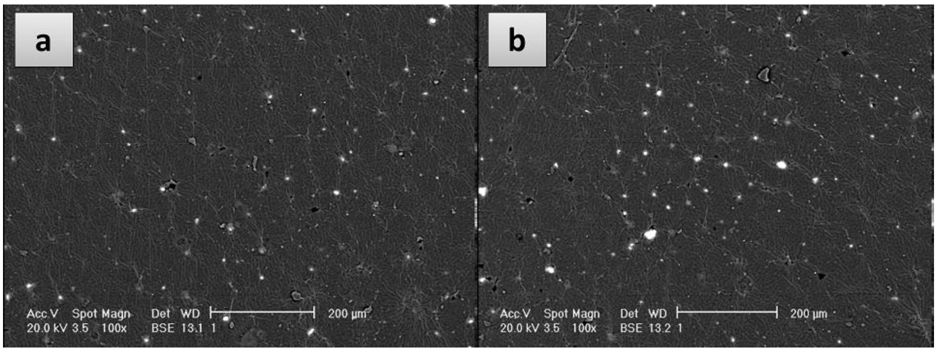

Figure 4. The distribution of bismuth metal powders in the silicone base for two eye shields with the magnification of 500X. a) The eye shield with the thickness of 0.02 cm. b) The eye shields with the thickness of 0.06 cm.

Evaluation of the lens dose during the CT examinations using the lens shields

Entrance skin doses (ESD) of the left and right eye lenses resulted from the CT examinations with different thicknesses of 0.02 cm and 0.06 cm in two scanning geometries included “Contact” and “Distant shield” setups are listed in Table 1.

Table 1. Entrance skin dose values of the left and right eye lenses resulted from the CT examinations with and without the lens shields

Thickness	Studied position	Shielding status	ESD (mSv)	ESD relative attenuation (%)
0.02 cm Bi	Left eye	Without Shielding	18.85±1.37	-
		Distant shield	12.20±0.46	35.24±5.30
		Contact	11.76±0.42	37.63±5.04
	Right eye	Without Shielding	19.13±1.39	-
		Distant shield	13.16±0.87	31.25±6.74
		Contact	11.48±0.69	40.02±5.66
0.06 cm Bi	Left eye	Without Shielding	18.85±1.37	-
		Distant shield	10.76±0.70	42.91±5.57
		Contact	10.30±0.63	45.33±5.20
	Right eye	Without Shielding	19.13±1.39	-
		Distant shield	10.21±0.64	46.63±5.11
		Contact	9.35±1.49	51.13±8.53

Evaluation of the image quality using the lens shields

The average SNRs, CNRs and noise values of the studied profiles (included left, central, and right profiles) are listed in Tables 2, 3 and 4, respectively for eye shields with the thicknesses of 0.02 cm (1T) and 0.06 cm (3T).

Table 2. The average SNRs of the studied profiles (included left, central, and right profiles) for the CT data obtained using the lens shields with the thicknesses of 0.02 cm and 0.06 cm

		Shielding	Left		Center		Right	
			$\overline{SNR}$	% Change	$\overline{SNR}$	% Change	$\overline{SNR}$	% Change
0.02 cm	Bi	Without Shielding	536.31	-	516.67	-	603.67	-
		Contact	419.07	-21.86	420.58	-18.60	387.07	-35.88
		distant shield	445.50	-16.93	373.98	-27.62	484.26	-19.78
0.06 cm	Bi	Without Shielding	536.31	-	516.67	-	603.67	-
		Contact	227.02	-57.67	211.02	-59.16	229.53	-61.98
		distant shield	251.17	-53.17	238.69	-53.80	292.42	-51.56

Table 3. The average CNRs of the studied profiles (included left, central, and right profiles) for the CT data obtained using the lens shields with the thicknesses of 0.02 cm and 0.06 cm

		Shielding	Left		Center		Right	
			$\overline{CNR}$	% Change	$\overline{CNR}$	% Change	$\overline{CNR}$	% Change
0.02 cm	Bi	Without Shielding	329.88	-	327.04	-	339.91	-
		Contact	225.44	-31.66	215.75	-34.03	215.90	-36.48
		distant shield	269.45	-18.32	248.58	-23.99	278.63	-18.03
0.06 cm	Bi	Without Shielding	329.88	-	327.04	-	339.91	-
		Contact	78.59	-76.17	77.68	-76.25	79.99	-76.47
		distant shield	164.08	-50.26	155.86	-52.34	172.20	-49.34

Table 4. The noise values of the studied profiles (left, central, and right profiles) for the CT data obtained using the lens shields with the thicknesses of 0.02 cm and 0.06 cm

		Shielding	Left		Center		Right	
			$\overline{Noise}$	% Change	$\overline{Noise}$	% Change	$\overline{Noise}$	% Change
0.02 cm	Bi	Without Shielding	2.52	-	2.56	-	3.32	-
		Contact	3.37	33.54	4.39	71.22	3.77	13.63
		distant shield	3.50	38.93	5.14	100.55	3.17	-4.36
0.06 cm	Bi	Without Shielding	2.52	-	2.56	-	3.32	-
		Contact	7.17	184.48	8.60	235.51	6.55	97.49
		distant shield	5.53	119.23	6.19	141.68	5.12	54.23

Discussion

Dose reduction in CT imaging has different methods. They include automatic exposure control or tube current modulation (TCM), using filters, gated irradiation, increasing pitch value, sequential scanning, gantry tilting, and voltage reduction (21). Angular and longitudinal TCM methods reduce the dose parameters ($CTDI_{vol}$) based on the attenuation on different angular and longitudinal projections (22). These methods reduce the radiation dose in all the regions of the selected slice and they do not differentiate between various organs. It is necessary to mention that using shields is independent from the angular or longitudinal TCM reduction methods. In the TCM methods, tube current is regulated based on the attenuation of the related slices and all tissues positioned on these slices receive lower doses compared to the standard CT scan. On the other hand, when the shields are positioned nearly in front of a specific organ or tissue, this organ will receive a significant lower dose in comparison with other organs in the same slices. Therefore, using the TCM could reduce the slice/slices doses that have lower attenuation and using filter can reduce the specific tissue dose that is positioned near the shield. Shields and angular (or longitudinal) TCM methods can be used with each other during the CT scan, but the shield must be removed during scout or localizer imaging for determining the attenuation of different slices and angular projections. In the on-line angular TCM method which uses the previous projection of attenuation values for current modulation in subsequent projections, it seems that using shields will affect the TCM and increase the tube current in shielded relevant slices, therefore it is better to ignore the use of shields in real time TCM. Organ-based TCM is another TCM method that reduces the specific structure dose by reducing the exposure about 50% in 120 degrees around the structure, while increases the exposure about 25% in remaining 240 degrees. The positioning of the patient is critically important in this method. The patient's central line must be the same as the scanner's central line. Misalignments will lead to big errors and overexposing of radiosensitive structures in this method. Furthermore, apart from the good positioning of the patient, the availability of CT scanners with organ-based TCM is rare due to the high cost of these scanners especially in low income or developing countries. Thus, using the bismuth shield is a simple and low cost method for protecting the eye lens in brain CT scans with conventional scanners.

In this study, the effect of the lens shielding was evaluated regarding to the dose reduction and image quality in two different geometries and with two different thicknesses. Lower lens doses were achieved in the "contact" setup in comparison with the "Distant shield" setup. By increasing the thickness from 0.02 cm to 0.06 cm for two scanning geometries, the dose reduction percentage increased from 38.82±5.36% to 48.23±7.06% and from 33.24±6.06% to 44.77±5.34%, respectively.

Higher degeneration was observed for SNR and CNR parameters where the eye shield was placed directly on the face. Therefore, it seems better to use the eye shields placed at the 4 cm distance from the face. It can be concluded that a shield with lower thickness produces a better image quality in terms of SNR and CNR. Based on the clinical application of the CT data, we should decide between the dose reduction and the image quality (included CNR reduction of 30-45%, and SNR reduction of 25-40%), due to the thickness increasing from 0.02 cm to 0.06 cm for the eye shield. Higher CNR and SNR values were observed for the lateral profiles in comparison to the central one. But the noise was lower in the lateral profiles.

For the eye shields in the "Contact" setup, the signal intensities in the central and lateral profiles increased by increasing the shield thickness from 0.02 cm to 0.06 cm (about 11% and 8%, respectively). In the "distant shield" setup, the signal intensities were also increased by 3% in the central and lateral profiles. In the upper part of the profiles, a significant signal increase was observed. Lower signal intensities were observed for the lateral profile than the central one. The artifact in thicker shields has been reported previously (18,22-24). There were no artifacts in the CT data when the lens shields were placed on the distant shield setup (at the 4 cm distance from the face).

Several studies have evaluated bismuth shielding as a dose reduction method (21,25-33). The reported dose reductions vary from 20% to 50% depending on the scanner, technique and shield design. Mendes et al (30) evaluated the dose reduction obtained with and without a bismuth shield covering the eyes using the acrylic head phantom. The percentage dose reduction was 36%, verifying the dose reduction capabilities of bismuth eye shields. However, image quality was disrupted in these studies due to the bismuth shield structure. We used the bismuth powder in a silicone gel base for reducing the metal artifacts.

In another study by Wang et al (22), the effect of the bismuth shield thickness was evaluated using both a single-layer and double-layer of bismuth shielding on a phantom. They reported a 26.4% and 42.4% dose reduction for the single and double-layered shields, respectively. While this study confirms that increasing the bismuth shield thickness will increase the dose reduction, but the image quality will be disrupted. This finding is consistent with our results.

Hopper et al (34), studied the ability of bismuth in reducing radiation to the lens during the routine cranial CT. In the phantom study, the eye dose was reduced by 48.5%, 59.8%, and 65.4% using 1T, 2T, and 3T, respectively. In the patient study, average dose reductions of 39.6%, 43.5%, and 52.8% were obtained using 1T, 2T, and 3T thicknesses of bismuth shield, respectively (34).

Several studies recommend not using bismuth shielding for the impact of the shielding on the image quality due to the produced artifacts which extend into the brain, affecting mainly the orbits, inferior frontal lobe and anterior temporal regions (19,24). In some cases, these artifacts not only make images inappropriate for diagnostic purposes, but also increases the number of scans (19,34). Several studies have shown a drift in CT numbers between 50% and 65% (22,25,27). In addition, there are also many studies that support the use of bismuth, suggesting no significant impact on the image quality (19,20,27). Majority of previous studies suggest that creating a small gap between the eye and the shield is a good approach to preserve the image quality to an acceptable diagnostic level (9,17,19,25,31). For instance, in a study by Raissaki et al (31), by using the folded gauzes for elevating the shield, artifacts were reduced to a negligible level. Distances of 5, 10 and 20 millimeters were evaluated and a dose reduction of 32%, 30% and 29% were reported respectively, compared to the 32% dose reduction following direct placement of the shield. We found similar results with previous investigations regarding a small gap for artifact reduction with a new design of bismuth shield.

Conclusion

In this study, the image quality of the CT scans using the bismuth shields with the thickness of 1T and 3T was evaluated. The attenuation characteristics and the CT image qualities obtained using the lens shields were evaluated with different thicknesses of 0.02 cm and 0.06 cm. 1T eye shield in 'Distant setup' could decrease the lens dose magnitudes at an acceptable level, while providing a better image quality in comparison to the "contact shield" setup. According to the results, using the bismuth shield is a simple and low-cost method for protecting the eye lens in brain CT scans with conventional scanners especially in low income or developing countries.

Conflict of interest

The authors declare no conflict of interest.

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