



Use of bismuth shield for protection of superficial radiosensitive organs in patients undergoing computed tomography: a literature review and meta-analysis

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Abstract

The study aimed to assess the effect of bismuth (Bi) shielding on dose reduction and image quality in computed tomography (CT) through a literature review. A search was conducted in the following databases: Web of Science, PubMed, Google Scholar, and Scopus. Studies that reported estimated dose reduction with bismuth shielding during imaging of the eye, thyroid, and breast were included, and a meta-regression analysis was used to examine the influence of the CT scanner type on the dose reduction. The studies included a total of 237 patients and 34 pediatric and adult anthropomorphic phantoms for whom the radiation dose was reported. Bismuth shielding was recommended in 88.89% of the studies based on the maintenance of appropriate image quality under shielding. Noise associated with Bi shielding was 7.5%, 263%, and 23.5% for the eye, thyroid, and breast, respectively. The fixed-effects pooled estimate of dose reduction was 34% (95% CI: 13–55; $p < 0.001$) for the eye, 37% (95% CI 14–61; $p < 0.001$) for the thyroid, and 36% (95% CI 36–55; $p < 0.001$) for the breast. The image quality, usage of foams, CT scanner type, beam energies, and backscatter radiation were important factors that directly affected the efficacy of Bi shielding to reduce the radiation dose at the superficial radiosensitive organs.

Keywords Bismuth shielding · Computed tomography · Dose reduction · Image quality

1 Introduction

Several methods have been employed to minimize the radiation dose in patients undergoing computed tomography (CT) imaging [1]; these include the use of lead-free shields [2, 3] and tube current modulation (TCM) [4]. As a result of rapid improvement in the technical performance of CT imaging and expansion of its clinical use [5], CT has become one of the most important tools in medical imaging [6, 7]. CT usage has increased exponentially over the years, from 3 million scans in 1980 to 67 million scans in 2006, which represents

600% growth during that period [8, 9]. Patients undergoing CT imaging have significant exposure to ionizing radiation, and use of shields is recommended as a method to reduce radiation-induced damage.

The breasts are directly exposed during thoracic CT imaging and the inferior aspect of the breast may be exposed to nearly 20–50 mGy of radiation [10, 11]. Recent findings have indicated that the breast tissue in female individuals and the lens were more radiosensitive than previously reported [12]. Women with high-density breasts are at high risk for breast cancer compared to women with low-density breasts [13]. Breast cancer is the second most common cancer [14], and currently, the most prevalent cancer in women [15]. CT imaging of the head typically exposes the patient to a radiation dose of 30–70 mGy [16]. Therefore, during CT examination of the thorax and head, measures to decrease the radiation dose to the breast, eye, and thyroid should be taken since although rarely the organs of interest, they are radiosensitive and always included in the scanning field [17, 18].

Bismuth (Bi) shielding was originally described by Hopper et al. in 1997 and confirmed [19, 20] as a technique

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to minimize the dose during radiographic examinations, which enables protection of the superficial organs from exposure to radiation. Bi shield is a commercially accessible reusable product contained in sterile plastic bags for use in CT imaging to protect superficial organs such as the eye, thyroid, and breast from radiation through medical CT examinations [21]. The Bi shield is placed over the surface of the organ or region of interest (ROI) during the scanning, which causes approximately twofold attenuation of the primary X-ray beam before it reaches the patient. Since the Bi shield is usually located within the scan volume, the effects on both the radiation dose and image quality must be considered. There is increasing concern about these effects, particularly to influence the image quality. Bi shielding causes beam-hardening artifacts, and may also increase the CT numbers recorded under the shield. Recently, the use of Bi shields has been recommended as an alternative method for decreasing the radiation dose to superficial organs which are radiosensitive including the thyroid, eye, breast, and gonads.

The combined method of TCM and use of Bi shield is recommended, in which the Bi shield is placed on the radiosensitive organ of the patient after acquiring the scout image; if the Bi shield is placed before acquiring the scout image, the algorithm for current adjustment is offset by the attenuation due to the shield, and the efficacy of the Bi is reduced [22]. Additionally, to achieve significant dose reduction without generating image noise and artifact, foams can be used to increase the space between the Bi shields and superficial organs, which sufficiently reduces the image noise under shielding.

Despite the capability of Bi shields to achieve relatively large dose reduction, the benefit of routine or specialized use of these shields remains unclear. Diagnostic imaging technologists in the field should consider both the image quality and dose reduction besides the actual dose. Radiologists and medical physicists face the challenge to acquire images of adequate quality with lowest radiation exposure to the patient, in agreement with the as low as reasonably achievable (ALARA) principle. Currently, the focus is on developing methods to reduce the radiation dose during CT examinations without compromising the image quality; therefore, it is necessary to review the results of previous studies.

To the best of our knowledge, there is no comprehensive literature review on Bi shielding. In this study, we conducted a literature review and meta-analysis of published studies with the aim to evaluate the effects of Bi shielding on the radiation dose to superficial radiosensitive organs such as the eye, thyroid, and breast, quality of the medical images acquired through diagnostic imaging procedures, and the effects of the scanner type and X-ray beam energy on the efficacy of Bi shielding.

2 Methods and materials

Systematic literature review and meta-analysis were conducted and reported according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta Analyses) guideline [23].

2.1 Search strategy and study selection

To identify published studies involving the use of Bi shielding as a radiation protection method for radiosensitive organs such as the eye, thyroid, and breast during diagnostic imaging, an organized literature search was performed of the databases including Web of Science, PubMed, Google Scholar, and Scopus from more than 2 decades ago until April, 2018; the search was limited to articles published in English. Two researchers screened the titles and abstracts of all the retrieved references; the full text of relevant articles was reviewed.

2.2 Inclusion criteria

Articles were included in the review based on the following inclusion criteria: (1) original quantitative research published in a peer-reviewed journal; (2) actual experimental procedure, and not simulation such as Monte Carlo methods using Geant 4; (3) assessment of the effect of Bi shielding on radiation protection; (4) shielding from X-ray, not particle or gamma ray. A flow chart of the study selection is shown in Fig. 1.

2.3 Statistical analysis

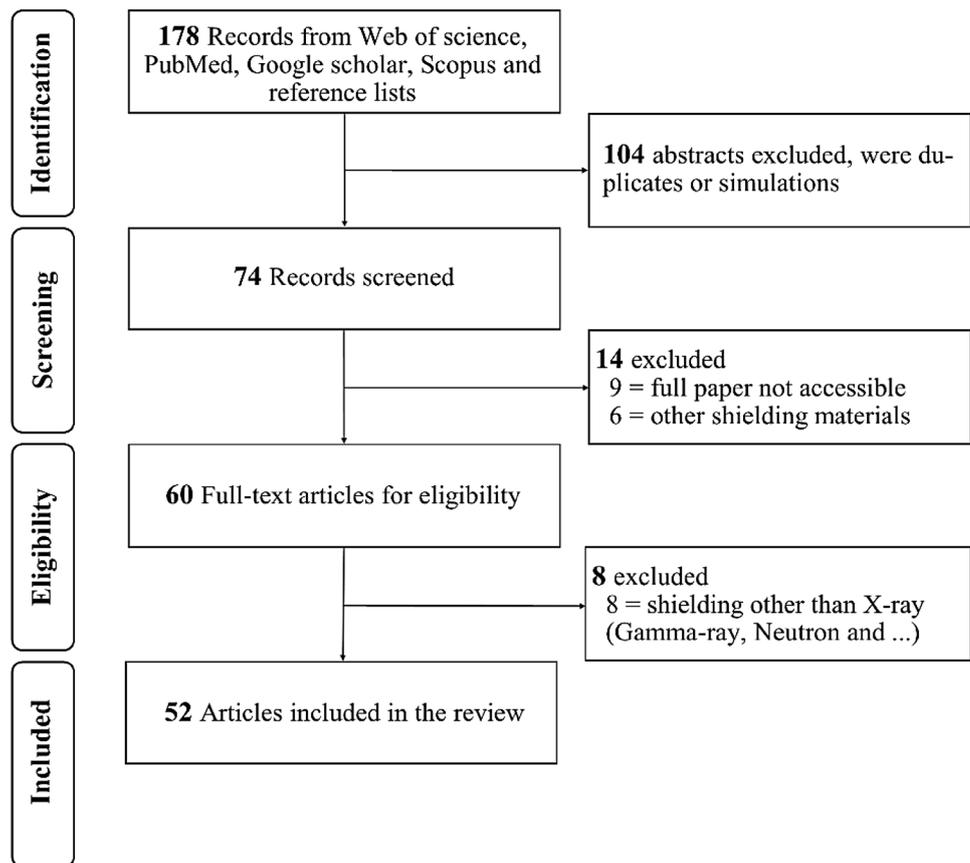
The percentage of reports for each organ including the eye, thyroid, and breast was calculated. Cochran's Q test and I^2 test were used to calculate the percentage of heterogeneity; the level of significance was set at $p < 0.05$. A fixed-effects model was used to estimate the pooled effect size. Meta-regression analysis was used to determine the relationship between dose reduction and CT scanner type for the eye, thyroid, and breast separately. STATA version 14.1 (Stata-Corp LLC, TX, USA) software was used for all analyses.

3 Results

3.1 Search results and study selection

Totally, 178 relevant articles were identified through the literature search; of these, some studies did not involve usage of shielding materials and devices of interest (Fig. 1).

Fig. 1 Flow diagram of study selection



Therefore, 52 studies that examined the effectiveness of Bi shielding during imaging were considered as relevant and included in the systematic review. In total, CT images of 237 patients and results of dose measurements using 34 pediatric, adult, and female anthropomorphic phantoms were included. The most frequent protocols were those for imaging of the head, neck, and chest. Various types of scanners were used, of which the most common types were 16-slice (Siemens Medical Solutions, Henkestr, Erlangen, Germany), 64-slice (several different manufacturers), 256-slice (Siemens Medical Solutions, Malvern, PA, USA; Revolution CT, GE Healthcare, Chicago, IL, USA), 320-slice (Aquilion ONE, Toshiba Medical Systems, Otawara, Tochigi, Japan), and 4-slice multi-detector computed tomography (MDCT) scanners (Toshiba Medical Systems, Otawara, Tochigi, Japan), which were used in 11, 8, 2, 1, and 1 studies, respectively; other scanner types included a periapical X-ray device (Belmont 303-H, Takara Belmont Corp., Chuo-ku, Osaka, Japan) in one study, panoramic imaging device (Planmeca Promax, Helsinki, Finland) in two studies, cone beam computed tomography (CBCT) scanner (Planmeca ProMax 3D Mid, Helsinki, Finland) in one study, PQ5000 CT scanner (Marconi Medical Systems, Cleveland, OH, USA) in two studies, GX Xpress CT machine (Toshiba Medical Systems, Otawara, Tochigi, Japan) in one study, and Symbia

T2 dual-head hybrid SPECT/CT system (Siemens, AG, Henkestr, Erlangen, Germany) in one study. The radiation dose was measured using a CT dose index (CTDI) phantom with pencil-shaped ionization chamber, and thermo-luminescent dosimeter (TLD) and metal-oxide-semiconductor field effect transistor (MOSFET) dosimeter in most studies. In most of the studies, quantitative evaluation of the image quality was limited to measuring the level of noise defined as the standard deviation of CT values and determined at both the anterior and posterior ROI in the scanning volume.

3.2 Principal finding

The main finding of the literature review was that Bi shielding significantly reduced the radiation dose in pediatric and adult patients. All studies recommended the use of Bi shields to reduce the radiation dose to superficial radiation-sensitive organs: 27 studies provided clear opinion on Bi shielding; 24 studies strongly recommended the use of Bi shields; three studies reported that Bi shielding was not necessary or advisable, and recommended other solutions. Thus, 88.9% of the studies recommended the use of Bi shields, whereas 11.1% of the studies did not. Hopper et al. [20] reported that Bi shields decreased the average radiation dose by 48.5%. Most of the studies investigated the effect of Bi shields on

image quality: The use of Bi shields affected the image quality, which suggests that it is important to determine the comparative effects on the image quality through shielded versus non-shielded approaches.

3.3 Bismuth shielding and eye protection

A total of 15 studies evaluated Bi shielding as a method for reducing radiation dose to the ocular lens during CT imaging of the head (Table 1); in all of these studies, the radiation dose was measured with lens protection placed on the head phantom. The dose reduction at the eye varied from 21 to 50% (36.28±6.22) depending on the scanner, exposure condition, and shield design. A forest plot of the studies on dose reduction at the eye that were included in the meta-analysis is shown in Fig. 2. The fixed-effects pooled estimated value of dose reduction for the eye was 34% (95% CI 13–55; $p < 0.001$). Meta-regression analyses to determine the relationships between factors such as the detector row number and dose reduction at the eye indicated that by increasing the number of detector rows of the CT scanner, the efficacy of Bi shielding was increased, which suggests a relationship

between increased number of the CT scanner detector and dose reduction at the eye; however, the relationship was not statistically significant (Fig. 3).

Ciarmatori et al. [35] reported that Bi shielding can reduce the entrance surface dose by 21–29% during head CT examinations, and Wang et al. [33] reported that Bi shielding and TCM reduced the radiation dose to the ocular lens by 26.4%. Hopper et al. [24] indicated that the use of Bi-coated shielding at one-, two-, and three-layer thickness over the eyes decreased the radiation dose by 48.5%, 59.8%, and 65.4%, respectively.

3.4 Bismuth shielding and thyroid protection

A total of 15 studies investigated Bi shielding as a method to reduce the radiation dose to the thyroid (Table 2). All studies reported a dose reduction at the thyroid of 25–84% (49.73±16.90) depending on the scanner, exposure condition, patient’s body weight, and shield design. Meta-analysis indicating the fixed-effects pooled estimate of dose reduction of 37% (95% CI: 14–61; $p < 0.001$) at both the thyroid and breast is shown in Fig. 4. The meta-regression of dose

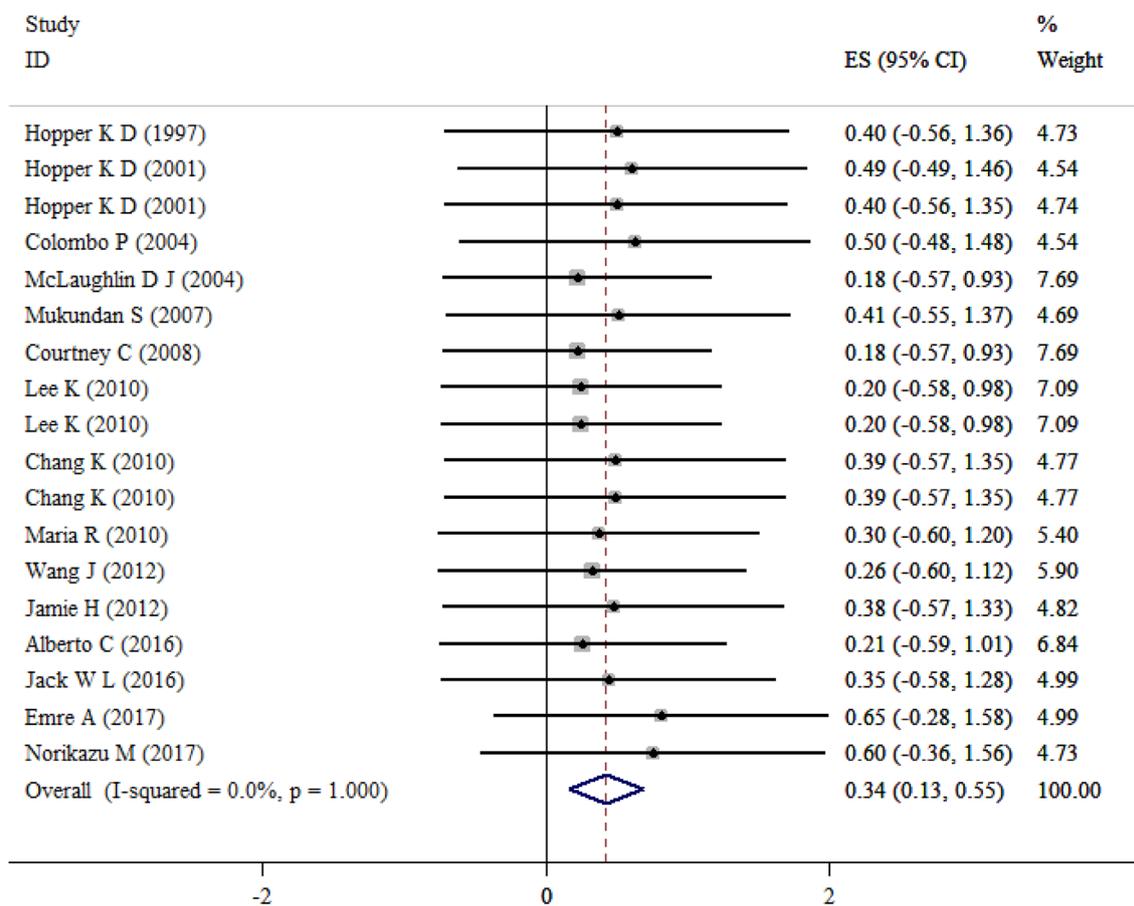


Fig. 2 Forest plot of studies on dose reduction for the eye. Heterogeneity ($I^2 = 0$); ES estimation, CI confidence interval

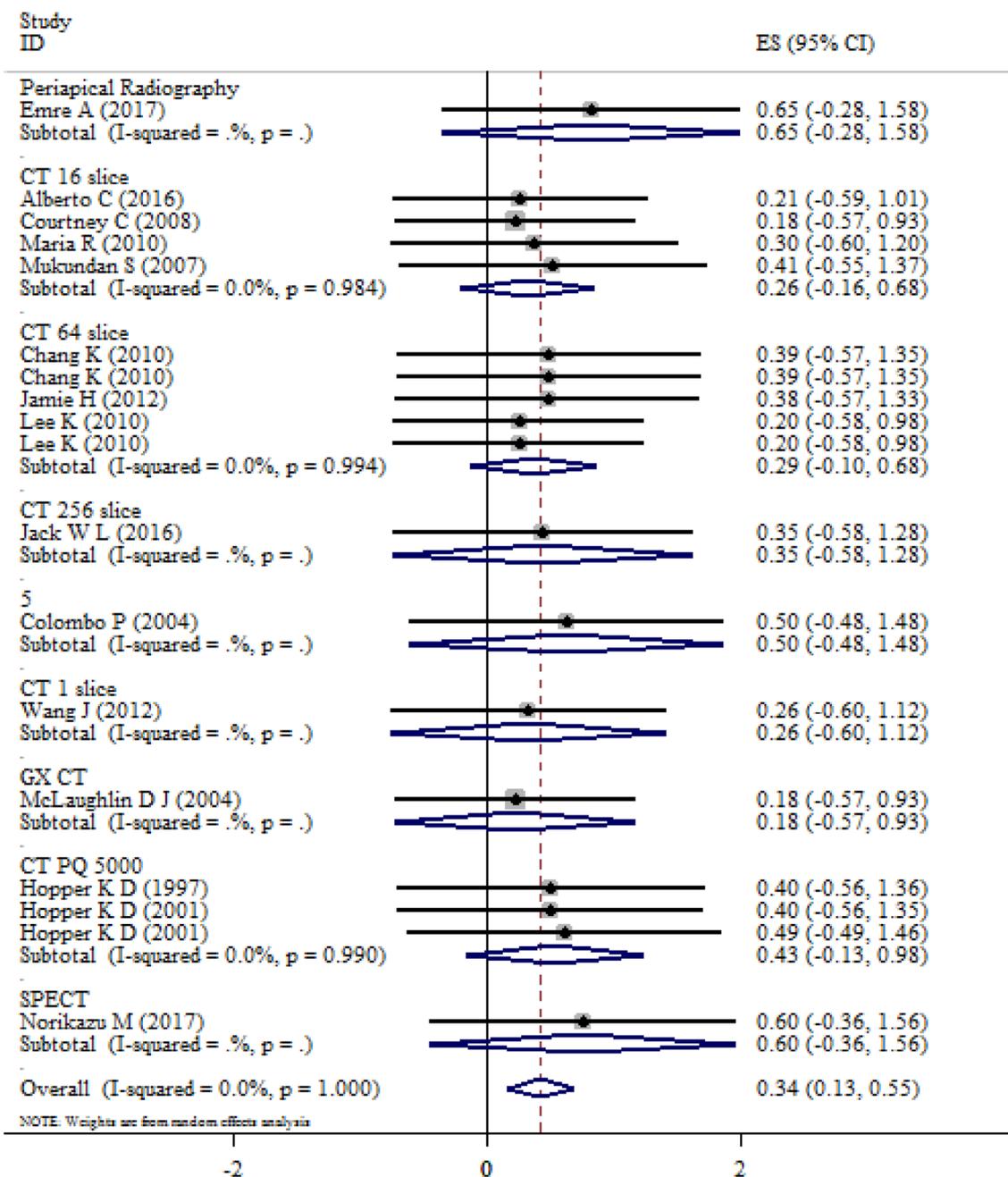


Fig. 3 Forest plot of dose reduction for the eye based on categorizing studies by scanner type

reduction at the thyroid as a function of the CT scanner detector number is plotted in Fig. 5; the relationship was not statistically significant ($p > 0.809$).

Kim et al. [45] investigated the effect of Bi shields at different thickness levels on the exposure dose and reported a dose reduction of 84% at 0.12 mm thickness, 92% at 0.25 mm thickness, and 96% at 0.5 mm thickness, suggesting that the efficacy of the shield increases with increasing thickness. In one study, the use of Bi shielding

in orthopantomography (OPTG) and CBCT scanning was associated with higher radiation dose to the thyroid gland [37]. Inkoom et al. [44] investigated the effect of Bi shielding on the radiation dose to the thyroid and image quality in CT imaging with fixed exposure parameters using pediatric anthropomorphic phantoms representing a newborn and 10-year-old child, and reported dose reduction at the thyroid of 17% and 35%, respectively.

Table 1 Studies on imaging (CT, SPECT/CT, CBCT, X-ray) performed on a patient/phantom using a bismuth shield at the eye with focus on the radiation dose and image quality

Reference (Date)	Region scanned (Organ assessed)	Patient type	Scanner	Dosimeter	Bismuth shield (with foam)	Dose reduction	Image quality	Recommended
[19] (1997)	(Orbit, thyroid and breast)	Anthropomorphic body phantom	CT scanner PQ2000 or PQ5000	TLD-100	Commercially available from F & L Medical, (Yes)	57% (breast), 60% (thyroid), 40% (eye), 51% (testes)	Did not effect on diagnostic CT image	Yes
[24] (2001)	Head (Eye)	Head phantom and human studies (30)	CT scanner (PQ5000, Marconi Medical Systems, OH)	TLD-100	Commercially available from F & L Medical (No)	48.5% and 39.6% average dose reduction in phantom and patient, respectively	No significant artifact caused by the eye shielding	Yes
[25] (2004)	Chest and head (Breast and eye)	Anthropomorphic phantom (Alderson Rando)	-	-	Bismuth shield (Attenu-Rad F&L Medical Products) (Yes)	34% of the breast and 50% to the lens	Quality is only slightly reduced	Yes
[26] (2004)	Chest and brain (Breast and eye)	40 patients	GX Xpress CT machine (Toshiba Medical Systems, Japan)	TLD-100	Bismuth shield (Attenu-Rad Radioprotective Garments) (Yes)	18% and 56% dose reduction for eye and thyroid, respectively	Without detriment to image quality	Yes
[27] (2007)	Head (Eye)	5-Year-old pediatric anthropomorphic phantom	16 MDCT scanner (Light Speed, GE)	MOSFET	Bismuth impregnated latex (1.7 g Bi/cm ² , eq to 0.45 mg/cm ³ of lead) (Yes)	39%, 42%, and 41% at 140, 120, and 100 kVp, respectively	-	Yes
[28] (2008)	Chest (20 organ locations breast and lung, etc.)	5-Year-old child anthropomorphic phantom	16-MDCT scanner (Light-Speed GE)	MOSFET dosimeter	2-ply bismuth (1.7 g/cm ²) (F & L Medical Products) (Yes)	Average of 18.0%	Image quality was acceptable	-
[29] (2010)	Chest, head and neck (Breast, eye and thyroid)	Rando (Fluke Biomedical WA, USA)	64-channel MDCT (Dose-Right with Brilliance 2.0, Philips)	TLD - 100	Bismuth compound (F&L, Vandergrift PA, USA) (Yes)	20%, 12% and 22% dose reduction in eye, thyroid and breast, respectively	34%, 7% and 10% increase SD of HU(ROI). 84%, 85% and 79% reduction SD of HU after making 1-cm gap from the patient	Yes
[30] (2010)	Chest, head and neck (breast, eye and thyroid)	PMMA phantom, (76-419-4150, Fluke Biomedical, Cleveland, OH, USA)	-	CT ionization chamber	Bismuth compound (F&L Vandergrift, PA, USA) (Yes)	34-46% and 41-55% at the 12 o'clock positions of the head and body phantom	The artifact on the reconstructed images was minimal when the distance between the shielding and the organs was > 1 cm	Yes
[31] (2010)	Head (eye)	A pediatric anthropomorphic phantom (Atom Phantoms, Cirs Norfolk VA, USA)	16-slice CT scanner (Siemens, Forchheim, Germany)	TLD-100	Bismuth shield (Attenu-Rad Radio protective Garments, F&L Medical Products, USA) (Yes)	In 0.5 cm, 1 cm, and 2 cm away from the eyes of the phantom, dose reduction was 32%, 30% and 29%, respectively	All scans were thought to contain diagnostic information for the report	Yes

Table 1 (continued)

Reference (Date)	Region scanned (Organ assessed)	Patient type	Scanner	Dosimeter	Bismuth shield (with foam)	Dose reduction	Image quality	Recommended
[32] (2011)	Head (eye and thyroid)	Anthropomorphic phantom of 1-year-old child	CT equipment from three different producers, namely Siemens, Philips, and GE	TLD-100	Bismuth shields for eyes and thyroid (Somatex, Germany) (-)	Reduction in eye dose No. 1 (18–20%), No. 2 (56–65%), No. 3 it was only 4% For thyroid No. 1 (25%), No. 2 (22%) and No. 3 had no reduction	Image quality was acceptable	Yes
[33] (2012)	Head (eye)	Tissue-equivalent anthropomorphic Phantom	Dual-source CT scanner (Definition Flash; Siemens Germany)	OSLD (Dot dosimeter)	(3.4 g/cm ² of bismuth per layer; AttenuRad, F&L Medical Products) (-)	26.4%	Image noise in the brain region was slightly increased	No
[34] (2012)	Head and chest (eye and breast)	Male CT Torso Phantom	64-slice Discovery HD750 (GE)	MOSFET dosimeter	Kiran CT Eye and Breast Shields (Kiran Americas, New Jersey, USA) (Yes)	Reduced dose by 38% and 50%, respectively, for eye and breast	A 35% increase in image noise was measured	-
[35] (2016)	Head (Eye)	CTDI phantom and an anthropomorphic phantom	Light Speed L16 (General Electric, Milwaukee USA)	CTDI assessment and TLDs	Bismuth shield (3x14 cm ² , 0.06 mm Pb eq AttenuRad, Vandergrift PA, USA) (Yes)	21% (in the “4-cm” set-up) and by 29% (in the “con-tact” set-up)	No artifacts	Yes
[36] (2016)	Chest, head and neck (breast, eye and thyroid)	Female anthropomorphic phantom	256-MDCT scanner (Revolution CT, GE Healthcare)	OSLD (Screened Nanodots, Landauer)	Single-layer bismuth-impregnated latex shields (0.06-mm lead-equivalent AttenuRad, F & L Medical Products) (Yes)	35%, 42%, and 37% in the head, neck, and chest regions, respectively	Anterior image noise increased by 0.1, 9.5, and 0.7 HU in the head, neck, and chest regions, respectively	-
[37] (2017)	Head (eye lens and thyroid gland)	Standard head phantom	Periapical radiography X-ray device, a panoramic radiography device, and a CBCT scanner	TLD-100	Bismuth eye and thyroid shields (F&L Medical Co) (No)	In PR technique, 65% and 63% dose reduction for eye and thyroid, respectively	-	-
[38] (2017)	Brain (eye)	Phantom	Symbia T2 dual-head hybrid SPECT/CT camera (Siemens)	CTDI	Bismuth shield (0.15-mm lead equivalent) (No)	60%	The SPECT images was acceptable	Yes

MOSFET metal oxide semiconductor field effect transistors, TLD thermos luminescent dosimeters, ROI region of interest, CT computed tomography, MDCT multi-detector computed tomography, eq equivalent, PMMA poly-methyl meth acrylate, OSLD optically stimulated luminescence dosimeters, CTDI computed tomography dose index, SPECT single-photon emission computed tomography.

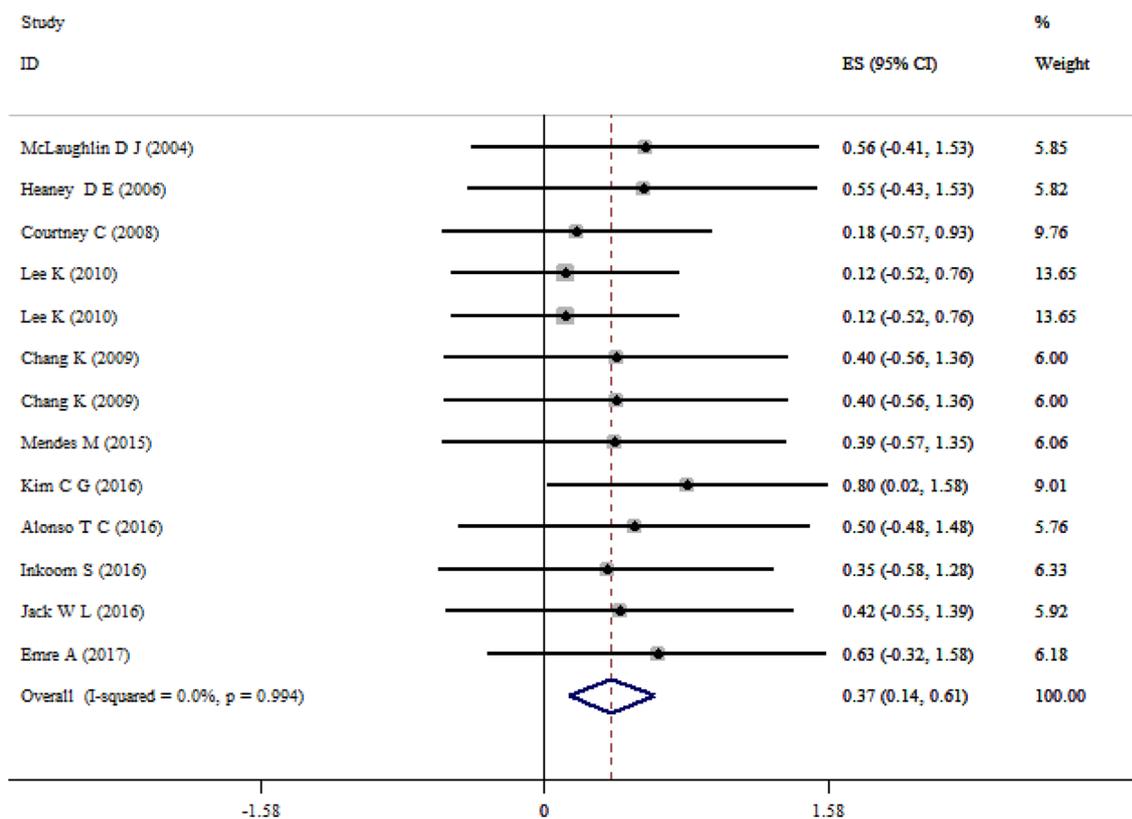


Fig. 4 Forest plot of studies on dose reduction for the thyroid. Heterogeneity ($I^2 = 0$); ES estimation; CI confidence interval

3.5 Bismuth shielding and breast protection

A total of 20 studies explored the effectiveness of Bi shielding to reduce the radiation dose to the breast (Table 3). All the studies concluded that Bi shielding was effective in reducing the radiation dose to the breast during thoracic CT imaging. The results indicated a dose reduction of 15–57% (39.05 ± 11.98) depending on the scanner type, exposure condition, and shield design. The forest plot of the studies on dose reduction for the breast that was included in the meta-analysis is shown in Fig. 6. The fixed-effects pooled estimate of dose reduction for the breast was 36% (95% CI 17–55; $p < 0.001$). Meta-regression analysis of the efficacy of Bi shield for breast protection as a function of the CT scanner detector number is shown in Fig. 7.

Statistical information for the meta-analyses performed for the eye, thyroid, and breast is presented in Table 4. In one study, a radio-protective garment composed of Bi and latex attenuated the delivered radiation dose by 50% [48]. One study evaluating the effectiveness of Bi to reduce the radiation dose to both the superficial and deep glandular breast tissues in human participants and phantoms reported a dose reduction of 17% at the deep glandular tissue during MDCT imaging performed by a radiologist [54].

Data analyses revealed that thyroid shielding was more effective than eye shielding and breast shielding with respect to dose reduction (Fig. 8).

3.6 Bismuth shielding and image quality

Some studies suggested that image quality should be considered when assessing dose reduction strategies: a total of 29 studies performed qualitative or quantitative assessment of the impact of dose reduction on image quality. Of these studies, 21 studies reported an absence of significant change in the image quality, whereas 8 studies reported noticeable changes in the image quality; thus, 72.41% of studies reported acceptable image quality through Bi shielding, and 27.59% of studies reported that Bi shielding had a negative effect on the image quality. Some studies reported the presence of noise of the Bi shields at 12-o'clock and 6-o'clock positions. When the Bi shield was placed on the CT phantom, the noise was highest at the 12-o'clock position and lowest at the 6-o'clock position in all of the organs, and there were differences in the noise at 12-o'clock vs. 6-o'clock position for the head, neck, and chest phantoms (Fig. 9). Noise enhancement was highest for the 12-o'clock position because this position

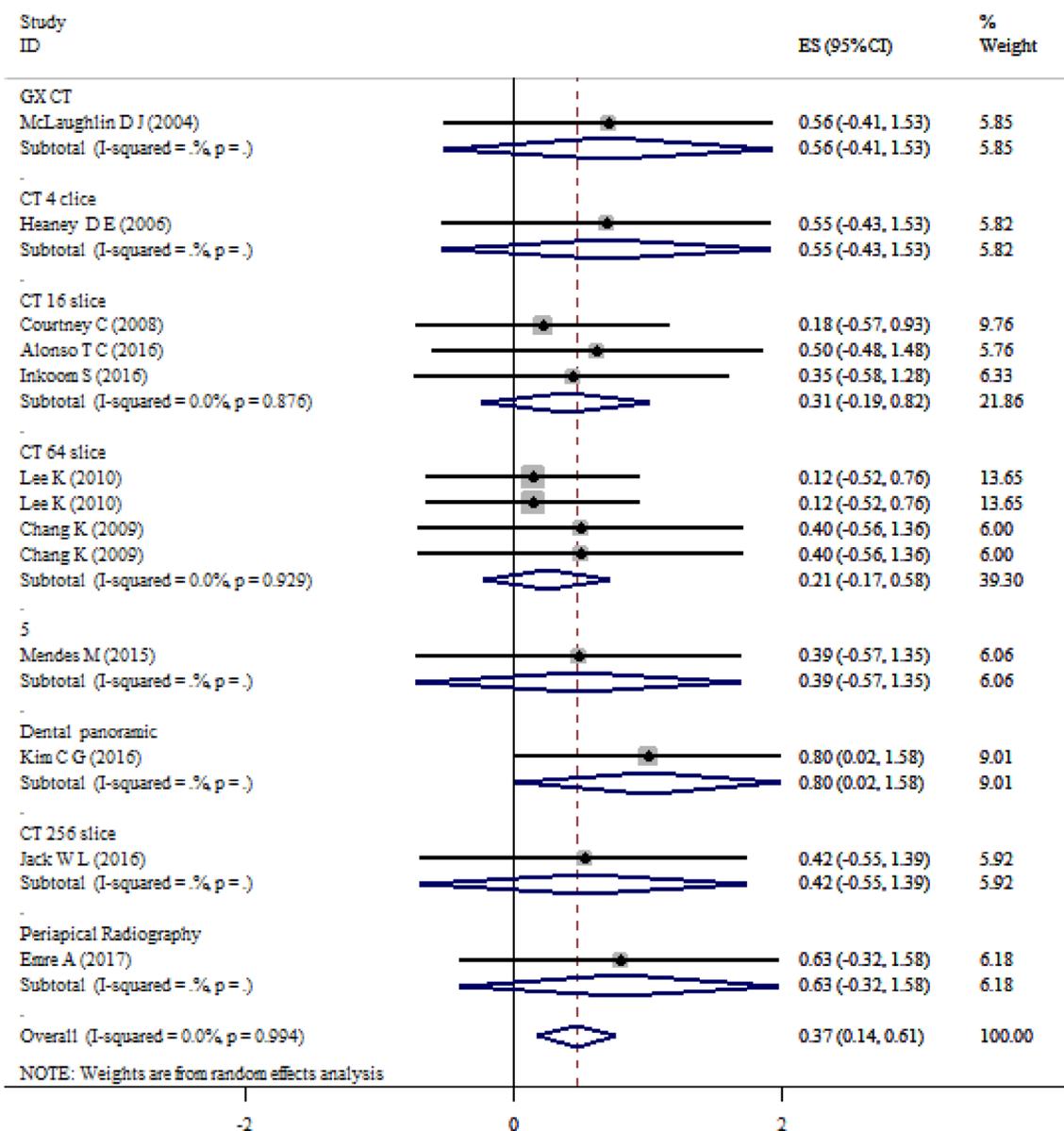


Fig. 5 Forest plot of dose reduction for the thyroid based on categorizing studies by scanner type

is located just under the Bi shield, which indicated that the change in image quality due to Bi shielding was limited in the range of 1–2 cm distance from the shield, and streak artifacts mainly appeared at the location where the shield was placed. The average noise value of the Bi shield placed on the head, neck, and chest phantoms was approximately 7.15%, 263%, and 23.5%, respectively, depending on the tube voltage, number of scanner detector, and shielding type [33, 48, 50, 51, 55, 56]. The increase in noise (263%) was greatest for the thyroid under Bi shielding, which may be explained by the passage of radiation beams through dense areas such as the spine and skull base, and the emission of backscatter radiation beams in

the presence of the Bi shield at the thyroid (or eye). Aytugur et al. [37] reported an increase in the radiation dose to the thyroid of 602.9% through OPTG scanning under Bi shielding, which may also be explained by the presence of backscatter radiation. Other studies [25, 51] reported a decrease in the image quality at regions immediately behind the breast shield, but not at the areas of diagnostic interest for thoracic CT, and a significant increase in the image noise at only the anterior portions of the lung. Kalra et al. [60] reported that Bi shielding was associated with increased image noise and CT attenuation values; streak artifacts were present at 0 and 1 cm distance between the shield and phantom's surface, but not at 2 and 6 cm

Table 2 Studies on imaging (CT, X-ray) performed on a patient/phantom using a bismuth shield at the thyroid with focus on the radiation dose and image quality

Reference (date)	Region scanned (Organ assessed)	Patient type	Scanner	Dosimeter	Bismuth shield (with foam)	Dose reduction	Image quality	Recommended
[26] (2004)	Chest and brain (thyroid and eye)	Forty patients	GX Xpress CT machine (Toshiba Medical Systems, Japan)	TLD-100	Bismuth shield (Attenu-Rad Radioprotective Garments) (Yes)	18% and 56% dose reduction for eye and thyroid, respectively	Without detriment to image quality	Yes
[39] (2006)	Neck and chest (thyroid and breast)	Anthropomorphic 'Rando' head phantom	Four-slice CT Scanner (Toshiba medical systems)	TLD-100	1 mm thick (0.18 mm Pb equivalence) and had a bismuth content of 50% by weight (-)	Reduction in thyroid dose for neck and chest scans was 55% and 47%, respectively. And dose reduction in breast was 23%	-	Yes
[40] (2006)	Chest (thyroid and breast)	Female Alderson-Rando Phantom	16-row MDCT scanner	TLD-100	4-ply in-plane bismuth shield (Yes)	47% organ-dose reduction for the thyroid and 32% for the breast	Without deteriorating image quality	Yes
[28] (2008)	Chest (20 organ locations breast and lung, ...)	5-Year-old child anthropomorphic phantom	16-MDCT scanner (Light-Speed GE)	MOSFET dosimeter	2-ply bismuth (1.7 g/cm ²) (F & L Medical Products) (Yes)	Average of 18.0%	Image quality was acceptable	-
[29] (2010)	Chest, head and neck (breast, eye and thyroid)	Rando (Fluke Bio-medical WA, USA)	64 channel MDCT (Dose-Right with Brilliance 2.0, Philips)	TLD - 100	Bismuth compound (F&L, Vandergrift, PA, USA) (Yes)	20%, 12% and 22% dose reduction in eye, thyroid and breast, respectively	34%, 7% and 10% increase SD of HU(ROI), 84%, 85% and 79% reduction SD of HU after making 1-cm gap from the patient	Yes
[30] (2009)	Chest, head and neck (breast, eye and thyroid)	PMMA phantom, (76-419-4150, Fluke Biomedical, Cleveland, OH, USA)	-	CT ionization chamber	Bismuth compound (F&L Vandergrift, PA, USA) (Yes)	34-46% and 41-55% at the 12 o'clock positions of the head and body phantom	The artifact on the reconstructed images was minimal when the distance between the shielding and the organs was > 1 cm	Yes
[32] (2011)	Head (eye and thyroid)	Anthropomorphic phantom of 1-year-old child	CT equipment from three different producers, namely Siemens, Philips, and GE	TLD-100	Bismuth shields for eyes and thyroid (Somatex, Germany) (-)	For thyroid No. 1 (25%), No. 2 (22%) and No. 3 had no reduction	Image quality was acceptable	Yes
[41] [2015]	Chest, head and neck (breast, eye and thyroid)	Head and body PMMA phantoms	GE (Brightspeed Elite CT scanner)	Pencil ionization chamber	Commercial bismuth shields for the eye lens, thyroid and breast (Kiran) (Yes)	36% for eye lens, 39% for thyroid and 45% for breast shields	-	-

Table 2 (continued)

Reference (date)	Region scanned (Organ assessed)	Patient type	Scanner	Dosimeter	Bismuth shield (with foam)	Dose reduction	Image quality	Recommended
[42] (2016)	Neck (Thyroid)	Whole body human phantom (skull phantom)	Dental panoramic (GENORAY GDP-1)	Glass rod detector	Bismuth shielding sheets were made to be 0.12 mm, 0.25 mm, 0.5 mm thick (No)	84%, 92% and 96% with 0.12, 0.25 and 0.5 mm thickness shielding, respectively	Bismuth shielding of 0.12 mm thickness is thought to be appropriate	Yes
[43] (2016)	Chest (lungs, breasts and thyroid)	Alderson Rando female anthropomorphic phantom	Bright Speed 16 Select GE Healthcare CT	TLD-100	1-mm-thick piece of bismuth (Yes)	Approximately 47%, 30%, and 50% in the lungs, breasts and thyroid, respectively	–	Yes
[44] (2016)	Neck (thyroid)	Four pediatric anthropomorphic phantoms	16-slice CT scanner (Siemens, Germany)	TLD-100	Thyroid shields (AttenuRad CT; F&L Medical Products USA) (Yes)	Dose reduction of 17% (newborn) and 35% (10 years old)	Noise was increased	No
[36] (2016)	Chest, head and neck (breast, eye and thyroid)	Female anthropomorphic phantom	256-MDCT scanner (Revolution CT, GE Healthcare)	OSLD (Screened Nanodots, Landaur)	Single-layer Bismuth-impregnated latex shields (0.06-mm lead-equivalent AttenuRad, F&L Medical Products) (Yes)	35%, 42%, and 37% in the head, neck, and chest regions, respectively	Anterior image noise increased by 0.1, 9.5, and 0.7 HU in the head neck, and chest regions, respectively	–
[37] (2017)	Head (eye lens and thyroid gland)	Standard head phantom	Periapical radiography X-ray device, a panoramic radiography device, and a CBCT scanner	TLD-100	Bismuth eye and thyroid shields (F&L Medical Co) (No)	In PR technique, 65% and 63% dose reduction for eye and thyroid, respectively In OPTG technique, 205% and 602% dose increasing for eye and thyroid, respectively In CBCT technique, 38% dose increasing for eye and thyroid	–	–

MOSFET metal oxide semiconductor field effect transistors, TLD thermos luminescent dosimeters, ROI region of interest, CT computed tomography, MDCT multi-detector computed tomography, *eq* equivalent, PMMA poly-methyl meth acrylate, OSLD optically stimulated luminescence dosimeters, CTDI computed tomography dose index, PR periapical radiography, OPTG orthopantomography, CBCT cone beam computed tomography

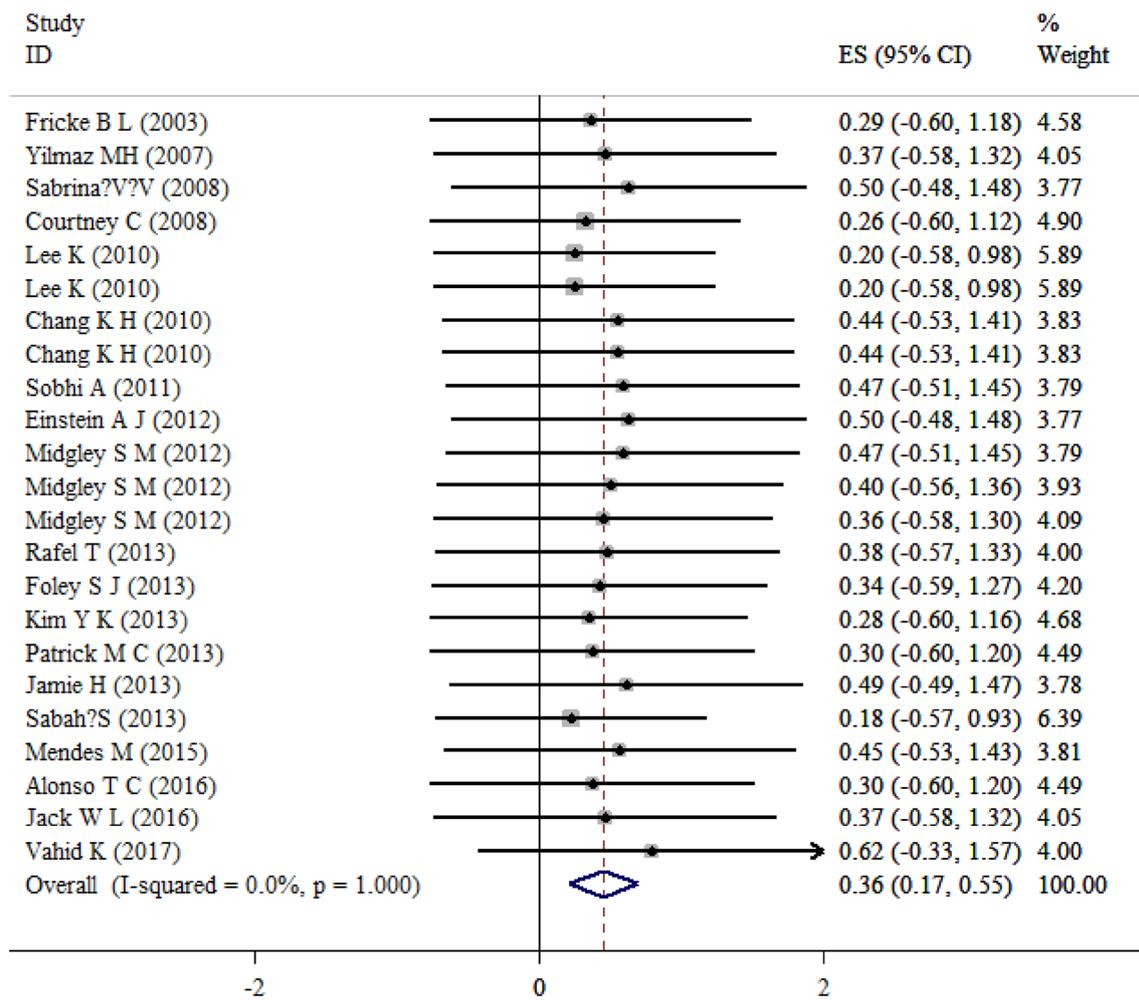


Fig. 6 Forest plot of studies on dose reduction for the breast. Heterogeneity ($P = 0$); ES estimation, CI confidence interval

distance from the shield. These studies reported a frequent occurrence of beam-hardening and streak artifacts due to use of Bi shields; nevertheless, the diagnostic accuracy was not limited and the overall image quality was considered acceptable.

3.7 Solutions for improving the image quality under Bi shielding

The image noise directly below the Bi shield is higher than that recorded at central or posterior position away from the shield, which indicates that some material placed between the shield and organ could reduce the noise at near (anterior) and far (posterior) positions from the Bi shield. Nevertheless, the image noise below the shield did not significantly affect the image quality required for making a diagnosis. A total of 28 studies investigated the effect of increasing distance between the shield and organ. All studies investigating

the impact of the distance between the shield and patient or phantom surface reported that the use of foam was clearly effective in reducing noise. Foam placed between the shield and organ enables capture of X-rays at the location, anchors the shield, and is easy to work with; thus, foam reduces the image noise by preventing direct contact between the shield and surface of the patient. Additionally, the studies recommended that the image quality readers (radiologists and technologists) should be familiar with the correct usage of Bi shielding and its effect on noise.

CT numbers may be used for complementary diagnosis such as in coronary calcium scoring and characterizing of renal cyst and adrenal mass. In these cases, the investigator should use caution because the presence of the shield can result in a change in the CT number of the ROI. Chang et al. [30] reported the presence of minimal artifacts at greater than 1 cm distance from the Bi shields to organ such as the breast, thyroid, or eye, in agreement with the usefulness Bi shielding at a distance. Wang et al. [33] reported that the use

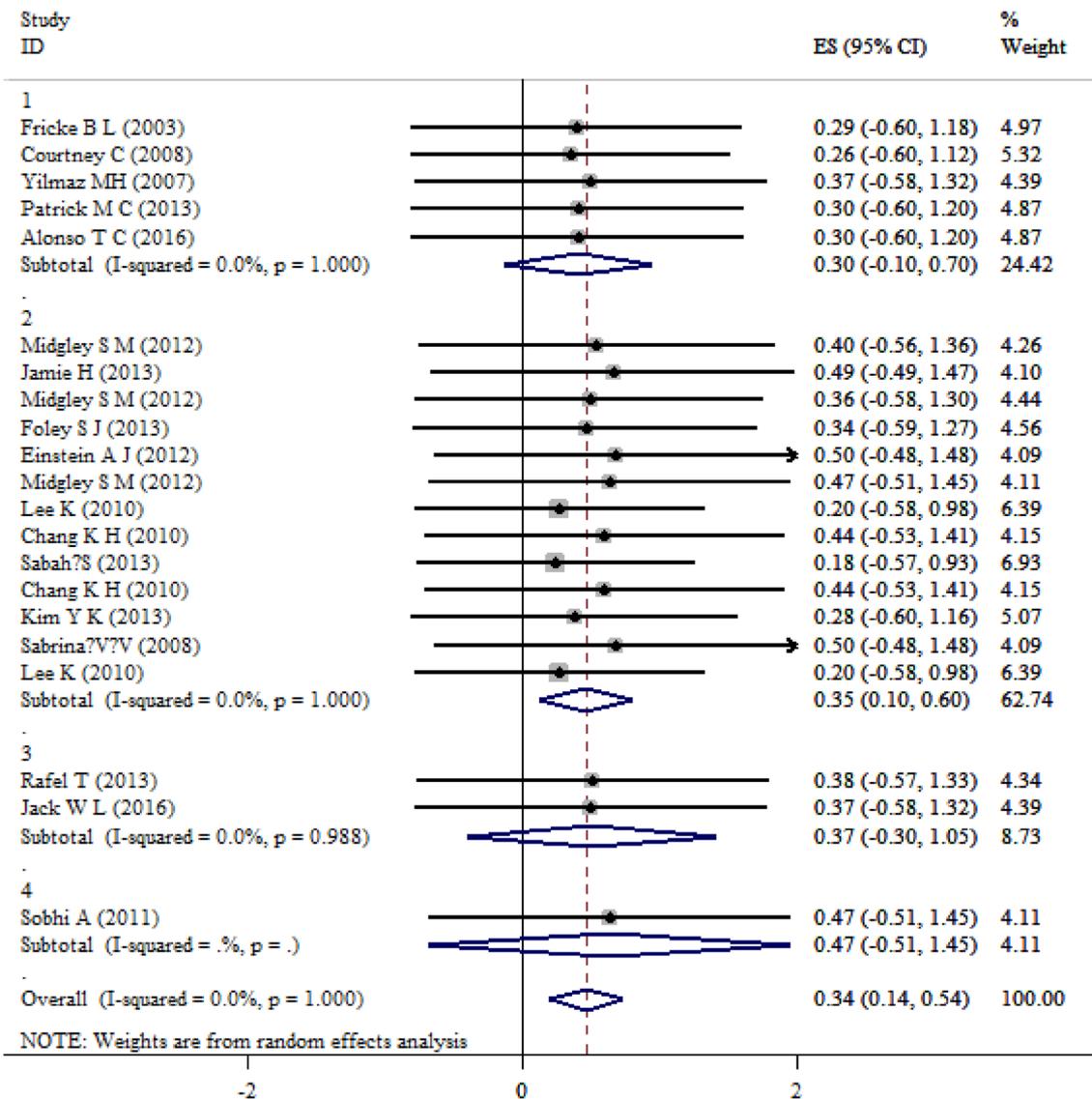


Fig. 7 Forest plot of dose reduction for the breast based on categorizing studies by scanner type

of a piece of foam to increase the distance between the Bi shield and ocular lens reduced artifacts near the orbit.

3.8 Bismuth shielding and beam energies

The degree of attenuation is entirely dependent on the atomic structure (the atomic number) of the material and energy of the photons in the beam; imaging devices produce a spectrum of output energy. Some studies reported that the Bi shield caused a decrease in the overall beam intensity alone, similar to the effect of TCM [61, 62]; however, TCM cannot always be used because tube current is limited by the patient's body weight, device type, exposure condition, as well as the image quality. Standard XCOM data were presented according to the mass attenuation coefficients

of Bi; the probability of photoelectric interaction at low energy level of 20–40 keV is about ten times higher than at 60–140 keV [63]. Bi shielding reduces the surface dose to the patient through variation of the beam shape, especially by reducing the level of low-energy photons at the surface of the organ; while these photons do not have an important role in forming the image, they increase the radiation dose to superficial organs and tissues such as the breast, eyes, and thyroid. TCM and Bi shielding have clear differences in effect on the beam shape variation, which is useful when a low-energy beam is used. Moreover, at the same dose to the superficial organ, TCM generates higher image noise than Bi shielding. The XCOM data showed that the attenuation was minor for intermediate energies of 80–90 keV and weak above the K-absorption edge of 90.52 keV for Bi [64].

Table 3 Studies on imaging (CT, X-ray) performed on a patient/phantom using a bismuth shield at the breast and one study using shielding at the pelvis with focus on the radiation dose and image quality

Reference (date)	Region scanned (Organ assessed)	Patient type	Scanner	Dosimeter	Bismuth shield (with foam)	Dose reduction	Image quality	Recommended
[46] (2003)	Chest (breast and lung)	Anthropomorphic diametric phantom	MDCT scanner (Light-Speed, GE)	TLD-100	Bismuth-coated latex sheets (F & L Medical Products (Yes))	Respectively, 6.7% and 29% decrease to the lung and breast	No noise	Yes
[47] (2007)	Chest (breast)	Anthropomorphic diametric phantom	16-MDCT scanner (Sensation 16, Siemens Medical Solutions, Germany)	TLD-100	Bismuth-coated latex sheets (Cone Instruments Inc., Solon, OH) (Yes)	37.12%	-	Yes
[48] (2008)	Chest (breast)	Semi-anthropomorphic thorax phantom	CT system (Sensation 64, Siemens Medical Solutions, Germany)	Ionization chamber type 30,009	Bismuth garments (0.060 mm Pb eq, Dyna Medical Corporation, London, Ontario) (-)	50%	Noise increased up to 40% and image quality was impaired by artifacts	No
[28] (2008)	Chest (20 organ locations breast and lung, etc.)	5-Year-old child anthropomorphic phantom	16-MDCT scanner (Light-Speed GE)	MOSFET dosimeter	2-ply bismuth (1.7 g/cm ²) (F & L Medical Products (Yes))	Average of 26%	Image quality was acceptable	-
[45] (2009)	-	Customized slab phantom	X-raytube (SRO 33,100 ROT 350, Phillips Medical Systems, Germany)	Ion chamber (10 × 5-0.18, Radcal Corporation, Monrovia, CA)	A 2-ply (0.5 mm) and a 4-ply (1.0 mm) bismuth shield (F & L Medical Products (Yes))	23% (2-ply) and 40% (4-ply)	-	-
[29] (2010)	Chest, head and neck (breast, eye and thyroid)	Rando (Fluke Biomedical, WA, USA)	64-channel MDCT (Dose-Right with Brilliance 2.0, Philips)	TLD - 100	Bismuth compound (F&L, Vandergrift, PA, USA) (Yes)	20%, 12% and 22% dose reduction in eye, thyroid and breast, respectively	34%, 7% and 10% increase SD of HU(ROI). 84%, 85% and 79% reduction SD of HU after making 1-cm gap from the patient	Yes
[30] (2010)	Chest, head and neck (breast, eye and thyroid)	PMMA phantom, (76-419-4150, Fluke biomedical, Cleveland, OH, USA)	-	CT ionization chamber	Bismuth compound (F&L Vandergrift, PA, USA) (Yes)	34-46% and 41-55% at the 12 o'clock positions of the head and body phantom	The artifact on the reconstructed images were minimal when the distance between the shielding and the organs was > 1 cm	Yes

Table 3 (continued)

Reference (date)	Region scanned (Organ assessed)	Patient type	Scanner	Dosimeter	Bismuth shield (with foam)	Dose reduction	Image quality	Recommended
[49] (2011)	Eight different clinical coronary CTA protocols	Adult thoracic anthropomorphic phantom	A 320-MDCT scanner (Aquilion ONE, Toshiba medical systems)	MOSFET and TLDs	Bismuth breast shield (ARB42-medium, Dyna Medical) (Yes)	46.8%	–	Yes
[50] (2012)	Chest (breast)	Whole-body anthropomorphic phantom	64 detector-row scanner (Light-speed VCT XT, GE Healthcare, Waukesha, Wisconsin)	MOSFET	4-ply bismuth shielding (AttenuRad ARB42 and ARB 53 F&L Medical Products) (Yes)	46–57%	Image noise was modestly but significantly increased	–
[51] (2012)	Chest protocols (esophagus, lung and breasts)	A torso phantom	64-CT scanner (Siemens, Erlangen, Germany)	Pencil chamber	F & L Medical Products (Yes)	53–63% (female breast), 82–85% (lung), 79–84% (esophagus) and 76–80% (effective dose) with larger dose reductions at lower kVp	Image quality is preserved when breast shields are placed after the scout no closer than 10 mm from the skin	Yes
[52] (2013)	Chest (breast)	Anthropomorphic Phantom	256-MDCT (Siemens Medical solutions, Malvern, PA)	NanoDots (Lan-dauer Inc., Glenwood, IL)	Bismuth breast shield (F & L Medical Co., Vandergrift, PA; 0.060 mm Pb eq) (Yes)	Dose reduction 38%	Image quality was acceptable	Yes
[53] (2013)	Chest (breast and lung)	Anthropomorphic phantom	64-slice MDCT scanner (Siemens)	TLD-100	60*42 cm bismuth-based in-plane breast shield (Yes)	Mean reductions 33–37% for the breast, 1–15% for the lung and 28–37% for the skin	Noise was increased	–
[54] (2013)	Chest, head and neck (breast)	Patient and female anthropomorphic phantom (Rando Phantom)	MDCT scanner (Siemens Healthcare)	Dosimeter (Rad-checkplus, Fluke Biomedical)	Bismuth breast shield (AttenuRad, F&L Medical Products) (Yes)	Dose in the breast surface and in the deep was reduced 16.0% and 28.1%, respectively	Image quality was acceptable	–

Table 3 (continued)

Reference (date)	Region scanned (Organ assessed)	Patient type	Scanner	Dosimeter	Bismuth shield (with foam)	Dose reduction	Image quality	Recommended
[55] (2013)	Chest (breast)	Water-filled Phantom with two attached symmetric breast phantoms	16-MDCT time-of-flight PET/CT system (Gemini, Philips Healthcare)	Patient skin dosimeter	1-mm-thick bismuth impregnated in synthetic rubber with 0.25 inch of foam (Yes)	30%	Noise and artifacts increased	Yes
[34] (2013)	Head and chest (eye and breast)	Male CT Torso Phantom	64-slice Discovery HD750 (GE)	MOSFET dosimeter	Kiran CT Eye and Breast Shields (Kiran Americas, New Jersey, USA) (Yes)	38% and 50%, respectively, for eye and breast	A 35% increase in image noise was measured	–
[56] (2013)	ECG-gated coronary CT angiography	72 women (mean [± SD] age, 53 ± 9 years)	64-MDCT scanner (LightSpeed VCT, GE Healthcare)	–	Bismuth-coated in-plane latex breast shields (AttenuRad, Cone Instruments) (Yes)	–	Slightly increased noise but did not adversely affect	–
[57] (2013)	Chest (breast)	5-Year-old specially designed ATOM Dosimetry Phantom	64-slice MDCT (Siemens Medical Solutions, Erlangen, Germany)	Pencil ionization chamber	Bismuth breast shield, 0.03-mm Pb equivalent; F&L Medical Products, Vanderg-rift, PA (Yes)	15% reduction to the breast	No qualitative differences were noted	–
[41] (2015)	Chest, head and neck (breast, eye and thyroid)	Head and body PMMA phantoms	GE (Bright Speed Elite CT scanner)	Pencil ionization chamber	Commercial bismuth shields for the eye lens, thyroid and breast (Kiran) (Yes)	36% for eye lens, 39% for thyroid and 45% for breast shields	–	–
[43] (2016)	Chest (lungs, breasts and thyroid)	Alderson Rando female anthropomorphic phantom	Bright Speed 16 Select GE Healthcare CT	TLD – 100	1-mm-thick piece of Bismuth (Yes)	Approximately 47%, 30%, and 50% in the lungs, breasts and thyroid, respectively	–	Yes

Table 3 (continued)

Reference (date)	Region scanned (Organ assessed)	Patient type	Scanner	Dosimeter	Bismuth shield (with foam)	Dose reduction	Image quality	Recommended
[36] (2016)	Chest, head and neck (breast, eye and thyroid)	Female anthropomorphic phantom	256-MDCT scanner (Revolution CT, GE Healthcare)	OSLD (Screened Nanodots, Landauer)	Single-layer Bismuth-impregnated latex shields (0.06-mm lead-equivalent AttenuRad, F & L Medical Products) (Yes)	35%, 42%, and 37% in the head, neck, and chest regions, respectively	Anterior image noise increased by 0.1, 9.5, and 0.7 HU in the head, neck, and chest regions, respectively	Yes
[58] (2017)	Pelvis radiography	95 pediatric girls	Radiographic unit (VARIAN Radiography system, USA)	TLD GR - 200	Commercially available 0.06-mm lead equivalent bismuth (Yes)	62%	Image quality remained diagnostically acceptable	Yes
[59] (2018)	Chest (breast)	Standard female Phantom	16-slice MDCT	TLD - 200	Bismuth-silicon composite shield (Yes)	37.6% reduction to the breast	15.7% image noise increased	Yes

MOSFET metal oxide semiconductor field effect transistors, *TLD* thermos luminescent dosimeters, *ROI* region of interest, *CT* computed tomography, *MDCT* multi-detector computed tomography, *eq* equivalent, *PMMA* poly-methyl meth acrylate, *OSLD* optically stimulated luminescence dosimeters, *CTDI* computed tomography dose index

Only a few studies investigated the effect of energy on the performance of Bi shielding. As the beam energy increased, the dose decreased gradually (Fig. 10). At low beam energy, Bi shielding was more effective in reducing the radiation dose, which may be explained by the variation in shape of the X-ray spectrum at increasing value from 80 to 120 keV [27, 30, 51]. In each case, the mean dose reduction at 80 keV was considerably higher than those at other energy levels; whereas, dose reduction at 120 keV was generally the lowest. The difference in mean dose reduction was not significant only for the thyroid due to the presence of backscatters beams. Based on this result, Bi shielding is particularly indicated at low energy levels. The patient's condition should be considered when deciding the exposure settings. In obese patients, the operator has a limited choice of tube current or lower energy setting; however, in normal patients, setting of optimum exposure conditions is possible depending on the skill of the technologist.

3.9 Bismuth shield and backscattered radiation

Differences in dose reduction at various parts of the radiation-sensitive tissue(s) under shielding are shown in Fig. 11. In the eye, thyroid, and breast, the highest percentage of mean dose reduction occurred at the 12-o'clock position, whereas the lowest percentage of mean dose reduction occurred at the 6-o'clock position, and there were gradual decreases in the dose reduction with increases in the distance from the shield. Thus, the studies concluded that Bi shielding was effective for the protection of superficial organs [28, 34, 35, 41, 44, 48, 49, 61]. Aytugar et al. [37] reported that there was an increase in the dose to the thyroid and eye under Bi shielding in OPTG and CBCT imaging. In OPTG scanning, since the irradiation is performed at posterior anterior (PA) orientation, the X-ray beams pass through dense areas such as the spine and skull base; therefore, higher exposure factors should be selected. These beams may cause backscatter radiation that interacts with the Bi shield especially at the level of the thyroid and eye [37]. The dose reduction at 6-o'clock position (deeper part of the body) was less than that at the surface (Fig. 11). Kim et al. [45] reported that in general, there was reduction in the radiation dose although the dose to the thyroid was increased due to backscatter.

4 Conclusion

In conclusion, the presence of a Bi shield was effective to decrease the patients' surface radiation dose by decreasing the low-energy photons delivered at the surface. Comparison among the doses to the eye, thyroid, and breast showed that Bi shielding has potential for use in dose reduction, especially at the thyroid, without significantly lowering the

Table 4 Meta-regression showing the effect of CT scanner type on dose reduction for three sensitive organs

Dose reduction	Coef.	Std. err.	<i>t</i>	P> t	[95% Conf. Interval]
Scanner type (eye)	0.01489	0.08076	0.18	0.857	−0.19873 0.72447
Scanner type (thyroid)	0.02604	0.10474	0.25	0.809	−0.21089 0.26299
Scanner type (breast)	0.04751	0.14446	0.33	0.746	−0.25485 0.34988

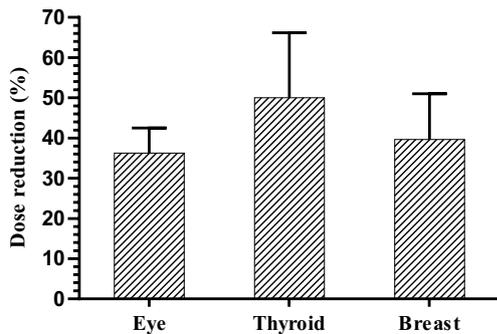


Fig. 8 Comparison of the dose reduction (mean ± SD) achieved using bismuth shielding among the eye, thyroid, and breast. Error bars represent the standard deviation (SD)

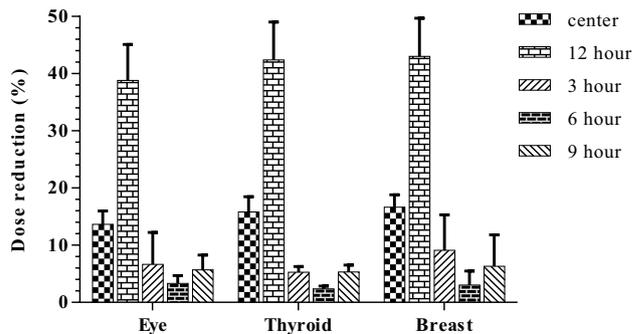


Fig. 11 Comparison of the dose reduction (mean ± SD) achieved using bismuth shielding at different parts of the eye, thyroid, and breast. Error bars represent the standard deviation (SD)

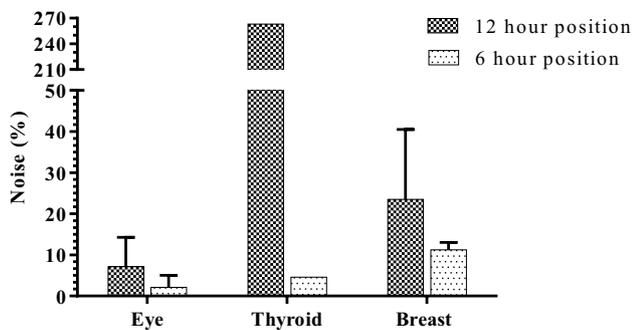


Fig. 9 Comparison of the noise (mean ± SD) from the bismuth shield among the eye, thyroid, and breast at the 12-o'clock position and 6-o'clock position. Error bars represent the standard deviation (SD)

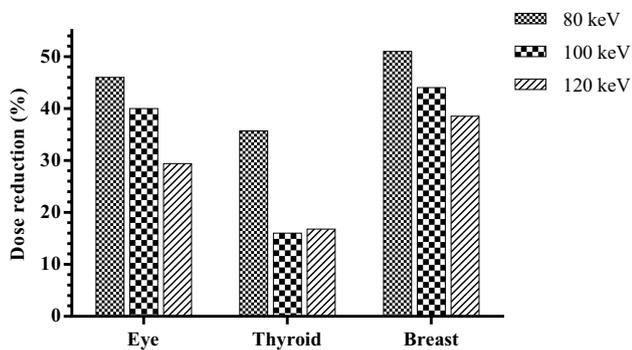


Fig. 10 Comparison of the dose reduction (%) achieved using bismuth shielding among the eye, thyroid, and breast at different energy levels

image quality. Image quality, usage of foam, beam energies, and backscatter radiation were important factors that directly affected the efficacy of Bi shielding. The image noise assessed for imaging with and without Bi shield indicated that the increase in the noise level under Bi shielding was acceptable for making the diagnosis. Additionally, foam of optimum 1–2 cm thickness was recommended to decrease the noise in images acquired with bismuth shielding.

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Compliance with ethical standards

Conflict of interest The author declares that she has no conflicts of interest.

References

- Mehnati P, Ghavami M, Heidari H. Reducing radiation doses in female breast and lung during CT examinations of thorax: A new technique in two scanners. *J Biomed Phys Eng.* 2017;7(3):217.
- Mehnati P, Malekzadeh R, Sooteh MY, Refahi S. Assessment of the efficiency of new bismuth composite shields in radiation dose decline to breast during chest CT. *Egypt J Radiol Nucl Med.* 2018;49(4):1187–9.
- Mehnati P, Sooteh MY, Malekzadeh R, Divband B. Synthesis and characterization of nano Bi₂O₃ for radiology shield. *Nanomedicine.* 2018;5(4):222–26.

4. Funama Y, Awai K, Hatemura M, et al. Automatic tube current modulation technique for multidetector CT: is it effective with a 64-detector CT? *Radiol Phys Technol.* 2008;1(1):33–7.
5. Morris P, Perkins A. Diagnostic imaging. *The Lancet.* 2012;379(9825):1525–33.
6. Mehnati P, Tirtash MJ, Ghavami M. CT role in the assessment of existence of breast cancerous cells. *J Biomed Phys Eng.* 2016. <https://doi.org/10.22086/jbpe.v0i0.384>
7. Muhogora W, Ahmed N, Alsuwaidi J, et al. Paediatric CT examinations in 19 developing countries: frequency and radiation dose. *Radiat Prot Dosim.* 2010;140(1):49–58.
8. Broder J, Warshauer DM. Increasing utilization of computed tomography in the adult emergency department, 2000–2005. *Emerg radiol.* 2006;13(1):25–30.
9. Broder J, Fordham LA, Warshauer DM. Increasing utilization of computed tomography in the pediatric emergency department, 2000–2006. *Emerg radiol.* 2007;14(4):227–32.
10. Smith-Bindman R, Lipson J, Marcus R, et al. Radiation dose associated with common computed tomography examinations and the associated lifetime attributable risk of cancer. *Arch Intern Med.* 2009;169(22):2078–86.
11. Saravanakumar A, Vaideki K, Govindarajan K, et al. Assessment of regional pediatric computed tomography dose indices in Tamil Nadu. *J Med Phys.* 2017;42(1):48.
12. Kleibl Z, Kristensen VN. Women at high risk of breast cancer: molecular characteristics, clinical presentation and management. *The Breast.* 2016;28:136–44.
13. Alizadeh Riabi H, Mehnati P, Mesbahi A. Evaluation of mean glandular dose in a full-field digital mammography unit in Tabriz, Iran. *Radiat Prot Dosim.* 2010;142(2–4):222–27.
14. Ferlay J, Steliarova-Foucher E, Lortet-Tieulent J, et al. Cancer incidence and mortality patterns in Europe: estimates for 40 countries in 2012. *Eur J cancer.* 2013;49(6):1374–403.
15. DeSantis C, Ma J, Bryan L, et al. Breast cancer statistics, 2013. *CA Cancer J Clin.* 2014;64(1):52–62.
16. McCrohan JL, Patterson JF, Gagne R, et al. Average radiation doses in a standard head examination for 250 CT systems. *Radiology.* 1987;163(1):263–68.
17. Seidenfuss A, Mayr A, Schmid M, et al. Dose reduction of the female breast in chest CT. *AJR Am J Roentgenol.* 2014;202(5):W447–W52.
18. Mehnati P, Amirnia A, Jabbari N. Estimating cancer induction risk from abdominopelvic scanning with 6-and 16-slice computed tomography. *IJRB.* 2017;93(4):416–25.
19. Hopper KD, King SH, Lobell M, et al. The breast: in-plane X-ray protection during diagnostic thoracic CT—shielding with bismuth radioprotective garments. *Radiology.* 1997;205(3):853–58.
20. Hopper KD ed Orbital, thyroid, and breast superficial radiation shielding for patients undergoing diagnostic CT. *Seminars in Ultrasound, CT and MRI;* 2002: Elsevier.
21. Mehnati P, Sooteh MY, Malekzadeh R, Divband B, Refahi S. Breast conservation from radiation damage by using nano bismuth shields in chest CT scan. *Crescent J Med Biol Sci.* 2018; 5:4.
22. Spampinato S, Gueli AM, Milone P, et al. Dosimetric changes with computed tomography automatic tube-current modulation techniques. *Radiol Phys Technol.* 2018;11(2):184–91.
23. Moher D, Liberati A, Tetzlaff J, et al. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Ann Intern Med.* 2009;151(4):264–69.
24. Hopper KD, Neuman JD, King SH, et al. Radioprotection to the eye during CT scanning. *AJNR Am J Neuroradiol.* 2001;22(6):1194–98.
25. Colombo P, Pedroli G, Nicoloso M, et al. Evaluation of the efficacy of a bismuth shield during CT examinations. *Radiol Med (Torino).* 2004;108(5–6):560–68.
26. McLaughlin D, Mooney R. Dose reduction to radiosensitive tissues in CT. Do commercially available shields meet the users' needs? *Clin Radiol.* 2004;59(5):446–50.
27. Mukundan S Jr, Wang PI, Frush DP, et al. MOSFET dosimetry for radiation dose assessment of bismuth shielding of the eye in children. *AJR Am J Roentgenol.* 2007;188(6):1648–50.
28. Coursey C, Frush DP, Yoshizumi T, et al. Pediatric chest MDCT using tube current modulation: effect on radiation dose with breast shielding. *AJR Am J Roentgenol.* 2008;190(1):W54–61.
29. Lee K, Lee W, Lee J, et al. Dose reduction and image quality assessment in MDCT using AEC (D-DOM & Z-DOM) and in-plane bismuth shielding. *Radiat Prot Dosim.* 2010;141(2):162–67.
30. Chang K-H, Lee W, Choo D-M, et al. Dose reduction in CT using bismuth shielding: measurements and Monte Carlo simulations. *Radiat Prot Dosim.* 2009;138(4):382–88.
31. Raissaki M, Perisinakis K, Damilakis J, et al. Eye-lens bismuth shielding in paediatric head CT: artefact evaluation and reduction. *Pediatr Radiol.* 2010;40(11):1748–54.
32. Gbelcová L, Nikodemova D, Horvathova M. Dose reduction using bismuth shielding during paediatric CT examinations in Slovakia. *Radiat Prot Dosim.* 2011;147(1–2):160–63.
33. Wang J, Duan X, Christner JA, et al. Bismuth shielding, organ-based tube current modulation, and global reduction of tube current for dose reduction to the eye at head CT. *Radiology.* 2012;262(1):191–98.
34. Huggett J, Mukonoweshuro W, Loader R. A phantom-based evaluation of three commercially available patient organ shields for computed tomography X-ray examinations in diagnostic radiology. *Radiat Prot Dosim.* 2012;155(2):161–68.
35. Ciarmatori A, Nocetti L, Mistretta G, et al. Reducing absorbed dose to eye lenses in head CT examinations: the effect of bismuth shielding. *Australas Phys Eng Sci Med.* 2016;39(2):583–89.
36. Lambert JW, Gould RG. Evaluation of a net dose-reducing organ-based tube current modulation technique: comparison with standard dose and bismuth-shielded acquisitions. *AJR Am J Roentgenol.* 2016;206(6):1233–40.
37. Aytugar E, Kose TE, Gumru B, et al. Are bismuth shields useful in dentomaxillofacial radiology practice for the protection of eyes and thyroid glands from ionizing radiation? *Iran J Radiol.* 2017. <https://doi.org/10.5812/iranjradiol.40723>.
38. Matsutomo N, Fukunaga M, Onishi H, et al. Corneal dose reduction using a bismuth-coated latex shield over the eyes during brain SPECT/CT. *J Nucl Med Technol.* 2017;45(3):214–18.
39. Heaney D, Norvill C. A comparison of reduction in CT dose through the use of gantry angulations or bismuth shields. *Australas Phys Eng Sci Med.* 2006;29(2):172–78.
40. Hohl C, Wildberger J, Süß C, et al. Radiation dose reduction to breast and thyroid during MDCT: effectiveness of an in-plane bismuth shield. *Acta Radiol.* 2006;47(6):562–67.
41. Mendes M, Costa F, Figueira C, et al. Assessment of patient dose reduction by bismuth shielding in CT using measurements, GEANT4 and MCNPX simulations. *Radiat Prot Dosim.* 2015;165(1–4):175–81.
42. Kim C-G. The development of bismuth shielding to protect the thyroid gland in radiations environment. *Indian J Sci Technol.* 2016;9:25.
43. Alonso TC, Mourão AP, Santana PC, et al. Assessment of breast absorbed doses during thoracic computed tomography scan to evaluate the effectiveness of bismuth shielding. *Appl Radiat Isot.* 2016;117:55–7.
44. Inkoom S, Papadakis AE, Raissaki M, et al. Paediatric neck multidetector computed tomography: the effect of bismuth

- shielding on thyroid dose and image quality. *Radiat Prot Dosim.* 2016;173(4):361–73.
45. Kim S, Yoshizumi TT, Frush DP, et al. Dosimetric characterisation of bismuth shields in CT: measurements and Monte Carlo simulations. *Radiat Prot Dosim.* 2009;133(2):105–10.
 46. Fricke BL, Donnelly LF, Frush DP, 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(2):407–11.
 47. Yilmaz MH, Yaşar D, Albayram S, et al. Coronary calcium scoring with MDCT: the radiation dose to the breast and the effectiveness of bismuth breast shield. *Eur J Radiol.* 2007;61(1):139–43.
 48. Vollmar SV, Kalender WA. Reduction of dose to the female breast in thoracic CT: a comparison of standard-protocol, bismuth-shielded, partial and tube-current-modulated CT examinations. *Eur Radiol.* 2008;18(8):1674–82.
 49. Abadi S, Mehrez H, Ursani A, et al. Direct quantification of breast dose during coronary CT angiography and evaluation of dose reduction strategies. *AJR Am J Roentgenol.* 2011;196(2):W152–W58.
 50. Einstein AJ, Elliston CD, Groves DW, et al. Effect of bismuth breast shielding on radiation dose and image quality in coronary CT angiography. *J Nucl Cardiol.* 2012;19(1):100–08.
 51. Midgley S, Einsiedel P, Langenberg F, et al. Assessment of patient dose and image quality for cardiac CT with breast shields. *Radiat Prot Dosim.* 2012;151(3):463–68.
 52. 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 radiology.* 2012 (2013).
 53. Foley SJ, McEntee MF, Rainford LA. An evaluation of in-plane shields during thoracic CT. *Radiat Prot Dosim.* 2013;155(4):439–50.
 54. Kim YK, Sung YM, Choi JH, et al. 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(3):537–44.
 55. Colletti PM, Micheli OA, Lee KH. To shield or not to shield: application of bismuth breast shields. *AJR Am J Roentgenol.* 2013;200(3):503–07.
 56. Hulten E, Devine P, Welch T, et al. Comparison of coronary CT angiography image quality with and without breast shields. *AJR Am J Roentgenol.* 2013;200(3):529–36.
 57. Servaes S, Zhu X. The effects of bismuth breast shields in conjunction with automatic tube current modulation in CT imaging. *Pediatr Radiol.* 2013;43(10):1287–94.
 58. Karami V, Zabihzadeh M, Shams N, et al. Radioprotection to the Gonads in Pediatric Pelvic Radiography: Effectiveness of Developed Bismuth Shield. *Int J Pediatr.* 2017;5:6.
 59. Mehnati P, Arash M, Akhlaghi P. Bismuth-silicon and bismuth-polyurethane composite shields for breast protection in chest computed tomography examinations. *J Med Phys.* 2018;43(1):61.
 60. Kalra MK, Rizzo SM, Novelline RA. Reducing radiation dose in emergency computed tomography with automatic exposure control techniques. *Emerg radiol.* 2005;11(5):267–74.
 61. McCollough CH, Wang J, Berland LL. Bismuth shields for CT dose reduction: do they help or hurt? *JACR.* 2011;8(12):878–79.
 62. Geleijns J, Wang J, McCollough C. The use of breast shielding for dose reduction in pediatric CT: arguments against the proposition. *Pediatr Radiol.* 2010;40(11):1744–47.
 63. Berger M. XCOM: photon cross sections database. <http://www.nist.gov/pml/data/xcom/index.cfm>. 2010.
 64. Kim S, Frush DP, Yoshizumi TT. Bismuth shielding in CT: support for use in children. *Pediatr Radiol.* 2010;40(11):1739–43.

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