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Article

Reducing the radiation dose to the eye lens region during CT brain examination: the potential beneficial effect of the combined use of bolus and a bismuth shield

C.W.-K. Lai[1]*, H.-Y. Cheung[2], T.-P. Chan[1] and T.H. Wong[3]

[1] Department of Health Technology and Informatics, The Hong Kong Polytechnic University, Hung Hom, HKSAR, P.R. China.
[2] Medical Physics & Research Department, Hong Kong Sanatorium & Hospital, Happy Valley, HKSAR, P.R. China.
[3] Department of Diagnostic & Interventional Radiology, Hong Kong Sanatorium & Hospital, Happy Valley, HKSAR, P.R. China.

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Abstract – *Objective*: Computed Tomography (CT) is the leading contributor to medical exposure to ionizing radiation. Although the use of CT brain scans for patients with head injuries and convulsions has shown a tremendous growth, it has raised substantial concerns in the general public because of the risk of radiation-induced cataracts: the current available strategies to reduce the radiation dose to the eye lens region are limited. Therefore, the present research project was initiated with the aim of evaluating the potential benefit of the combined use of bolus and a bismuth shield on reducing the radiation dose to the eye lens region during CT brain examination. *Materials and methods*: We conducted a series of phantom studies to measure the entrance surface dose (ESD) that is delivered to the eye lens region during CT brain examination under the effect of different scanning and shielding setups. *Results*: Our results indicated, during CT brain examination: (1) a drastic reduction of 92.5% in the ESD to the eye lens region was found when the CT gantry was tilted from 0° (overall ESD = 30.7 mGy) to 30° cranially (overall ESD = 2.4 mGy), and (2) when the CT gantry was positioned at 0° (the common practice in the clinical setting), the setups with the application of a) a bismuth shield, b) a bismuth shield with a face shield (air gap), c) a bismuth shield with bolus, and d) a bismuth shield with bolus and an air gap can result in an acceptable level of image quality with a smaller overall ESD delivered to the eye lens region (overall ESD = 23.2 mGy, 24 mGy, 21 mGy and 19.9 mGy, respectively) than the setup without the bismuth shield applied (overall ESD = 30.7 mGy). *Conclusion*: When the primary beam scanning through the eye lens region is unavoidable during CT brain examination, the combined use of a bismuth shield with bolus and a face shield is an easy-to-use and inexpensive shielding setup to reduce the radiation dose delivered to the eye lens region while maintaining the correct CT number and a low degree of image noise in the resultant image.

Keywords: bolus / bismuth shield / radiation protection / computed tomography

1 Introduction

The radiation dose to patients during medical examinations is of increasing concern to the general public because of the risk of carcinogenesis. According to an epidemiological study in the US, computed tomography (CT) was the leading contributor to medical exposure. In addition, CT brain imaging was the most common CT procedure and constituted approximately 28.4% (19 million) of the total 67 million CT examinations (Mettler *et al.*, 2009).

The major concerns in CT brain examination are the radiation to the eye lens and being overused (Owlia *et al.*, 2014). In 2007, the recommendations of the International Commission on Radiological Protection (ICRP) estimated that the threshold of causing radiation-induced cataracts is 500–2,000 mGy for a single brief exposure, and 5,000 mGy for a highly fractionated and protracted exposure (ICRP, 2007). Today, there are many advanced radiation dose-saving techniques, such as tube current modulation and iterative reconstruction, available on the market. However, not all diagnostic CT centers are equipped with these high-end CT machines, especially in developing countries. Therefore, strategies to reduce the eye lens dose during CT brain examination remain important, despite its application in daily clinical practice being still under debate.

1.1 Current strategies to reduce the eye lens dose during CT brain examination

Previous studies have demonstrated the application of CT gantry tilting during CT brain examination (*i.e.*, tilting the CT gantry toward the supra-orbital line of the patient in order to avoid or minimize the extent of the primary X-ray beam irradiating the patient's orbit) could effectively reduce the overall

* chris.lai@polyu.edu.hk

dose delivered to the eye lens region by approximately 92% (Heaney and Norvill, 2006; Keil *et al.*, 2008; Matsubara *et al.*, 2011). However, there are concerns about the subsequent high incidence of streak artefacts over the posterior cranial fossa (due to the beam hardening effect and partial volume averaging) and the subsequent noticeable degradation in the temporal lobe visualization (Yeoman *et al.*, 1992; Heaney and Norvill, 2006). In this regard, the routine clinical practice of CT brain scans will maintain the CT gantry positioned at 0°, making all or part of the patient's eye lens region inevitably irradiated by the primary X-ray.

The appropriateness of using commercial bismuth shields during CT brain examination is still under debate (Colletti *et al.*, 2013). The primary purpose of their use is to reduce the radiation dose to the superficial organs, including the eye lens (Perisinakis *et al.*, 2005), thyroid gland (Hohl *et al.*, 2006) and breast tissue (Colombo *et al.*, 2004) during CT examinations. However, there are several concerns associated with the use of them, including an adverse effect on the image quality and CT number accuracy, a waste of information-carrying photon exits from the patient and on their way to the detectors, and an increased incidence of streak artefacts when they are placed in direct close contact with the patient's skin (Heaney and Norvill, 2006; Leswick *et al.*, 2008; Vollmar and Kalender, 2008; Kalra *et al.*, 2009; Lee *et al.*, 2010). Furthermore, problems related to hygiene and extra running costs further limit their use in the routine clinical setting.

On the other hand, many radiological technologists overcame the aforementioned drawbacks by offsetting a bismuth shield from the patient's skin, also called the air-gap technique, to control scatter radiation (Perisinakis *et al.*, 2005) and streak artefacts (Yeoman *et al.*, 1992) produced by the in-plane bismuth shield during CT examinations. Also, despite the drastic advancement in the latest CT systems with advanced strategies in reducing the overall radiation dose to the patient, making the implementation of bismuth shields less frequent (Kalra *et al.*, 2004, 2005; Lee *et al.*, 2010), the efficacy of reducing the eye lens dose during CT brain imaging by a bismuth shield and organ-based tube current modulation was similar (Wang *et al.*, 2012).

1.2 Our proposed new strategy to reduce the eye lens dose during CT brain examination

To date, no study has been done to investigate the efficacy of the application of soft-tissue-simulating material and a bismuth shield on shielding the superficial organ dose during CT examination. There are many commercial soft-tissue-simulating materials available in the healthcare market, including bolus, nylon®, orange articulation wax, red articulation wax, PMMA, modeling clay, bee wax, paraffin 1, paraffin 2 and pitch. We chose to use bolus in the present study, because it has a mass density of 1.112 g cm^{-3} and a radiation attenuation factor of 8% more than the ICRP's brain within the energy range of less than 150 keV (Ferreira *et al.*, 2010). The intrinsic properties of bolus favor its application in our study because it does not flow, creep or sag out of shape during the examination. It can also be cut with scissors to fit the patient, and is easily layered when needed.

One of the means to observe the eye lens dose is through the determination of the entrance surface dose (ESD) to the eye lens regions. We hypothesize that offsetting the bismuth shield by a certain thickness of soft-tissue-simulating material (bolus) can attenuate a certain low-energy range of X-ray photons to achieve a radiation dose reduction to superficial organs. Therefore, the aim of the present study was to investigate the effect of the combined use of bolus and a bismuth shield on reducing the radiation dose to the eye lens region during CT brain examination with Adaptive Statistical Iterative Reconstruction.

2 Materials and method

2.1 CT System and Rando® Phantom

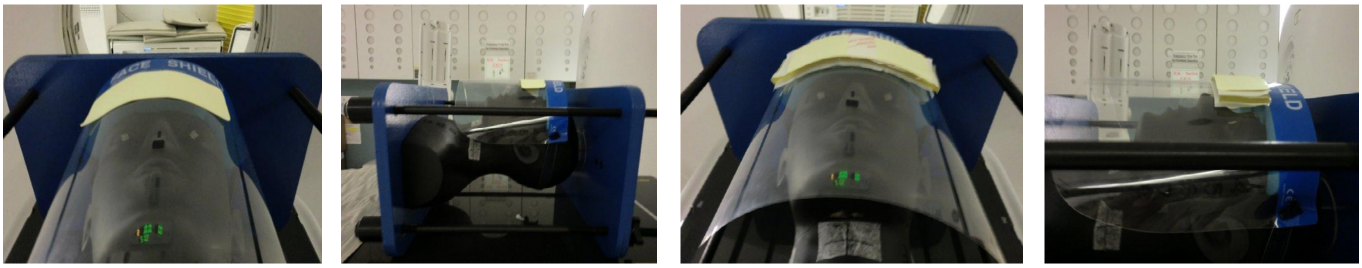
Discovery™CT750 HD with Adaptive Statistical Iterative Reconstruction (ASiR) and a carbon fiber flat tabletop (GE Medical Systems, LLC) were used in the present study. Slices No.1 to No.13 of an anthropomorphic phantom (RANDO® Woman) were selected and packed together tightly to simulate the head and neck region of a patient.

2.2 Bismuth eye shield, face shield and bolus

Dedicated commercial face shields were used to achieve a 4-cm air gap above the phantom's eye surface. Commercial bismuth-impregnated shields (0.5 mm thick and 3.4 g cm^{-2} of bismuth, AttenuRad, F&L Medical Products) were used as the eye shields. Two pieces of 0.5-cm-thick commercial bolus (BOLX-II, Action Products Inc., USA) were cut to the same size as the bismuth shield before use.

2.3 Thermoluminescent dosimeters (TLDs)

A total of 150 pieces of TLD-100 (LiF: Mg, TI, Thermo Scientific™) was used to evaluate the radiation dose. They were all annealed and calibrated in accordance with the manufacturer's recommended protocol. The TLDs were first annealed using a TLD annealing oven for 1 h at 400 °C and stabilized at 100 °C for another 3 h, then read by a Rialto TLD reader (NE Technology Ltd., UK). The linearity of the TLDs was tested over the dose range of 200 mR to 600 mR and the results showed a good linear change. In order to convert the TLD read-out signal (in Coulombs) to the radiation dose (in gray), we performed TLD calibration at a fixed dose rate of 1 Gy. By utilizing a beam shape ionization chamber (model: 20X6-6, Radcal® Corporation) and a diagnostic X-ray tube (Toshiba Medical Systems) with the following parameters: tube voltage 120 kVp and tube current 2 mAs (the lowest possible tube current of the unit), the individual dose calibration factor for each TLD was then determined. To minimize the anode heel effect and X-ray backscatter effect during calibration, the beam shape ionization chamber and TLDs were aligned perpendicular to the anode-cathode direction, and placed at a level of 20 cm above the X-ray table. Overall, the uncertainty associated with each TLD calibration and reading in our laboratory was less than 3–4% up to 30 days of storage.



(a) (b) (c) (d)

Fig. 1. An illustration of the configuration of Setup C and Setup E. The configuration of the Setup C: with one-ply of a bismuth shield placed on top of a face shield only (frontal view (a) and lateral view (b)); and Setup E: with one-ply of a bismuth shield and 1-cm-thick bolus placed on top of a face shield (frontal view (c) and lateral view (d)).

2.4 Determination of the ESD to the eye lens region

After calibrations were made, all TLDs were annealed again prior to exposure. 145 pieces of calibrated TLDs were used for irradiation, and the remaining five TLDs were used to measure the background radiation during the study. Within 15−24 h after exposure, all TLDs were tempered for 1 h at 100 °C, and then read by the same TLD reader. The net count (coulombs) of individual TLDs was obtained by subtracting the residual and background counts, and then converted to the ESD using its individual dose calibration factor In the present study, the overall ESD to the eye lens region of the phantom was calculated as the average of the ESD to the right and left eye regions, and was assumed to be equal to the absorbed dose delivered to the eye lens.

2.5 CT brain acquisition protocol

The CT scout view was acquired before each axial scan in order to determine the starting and ending position of the brain scan. After the CT scout view was obtained, 10 TLDs (5 TLDs on each eye) were placed along the surface of the eyes of the anthropomorphic phantom, together with the application of the bismuth shield, bolus and/or face shield before acquisition. All scans were performed on the phantom from the level at the base of the skull to the vertex using the following parameters: axial acquisition, tube voltage 120 kVp, tube current 280 effective mAs, rotational time of 1 s, 20 mm collimation and standard brain reconstruction kernel algorithm with Adaptive Statistical Iterative Reconstruction (ASiR) setup ss30 slice 30%. The acquired data were reconstructed in 0.625-mm-thick images along the z-axis for image quality evaluation.

At first, the ESD to the eye lens region was determined when the CT gantry was kept at 0° (the routine practice of CT brain imaging) and the acquisition procedures were repeated five times using the following Setups A to E:

- nothing applied (Setup A)
- bismuth shield (Setup B)
- bismuth shield + face shield (Setup C)
- bismuth shield + bolus (Setup D)
- bismuth shield + bolus + face shield (Setup E)

The configurations of Setup C and Setup E are illustrated in Figure 1.

Then, with the CT gantry tilted 30° cranially (without the bismuth shield or bolus), the ESD to the eye lens region was determined again (Setup F).

Where:

- both Setup A and Setup F have NO bismuth shield, bolus or face shield applied;
- Setup B has a bismuth shield placed directly on top of the orbits (NO bolus or face shield);
- Setup C has a bismuth shield placed on top of the face shield orbits (NO bolus);
- Setup D has a bismuth shield and 0.5-cm-thick bolus placed directly on top of the orbits (NO face shield);
- Setup E has a bismuth shield and 1-cm-thick bolus placed on top of a face shield.

2.6 Image quality analysis

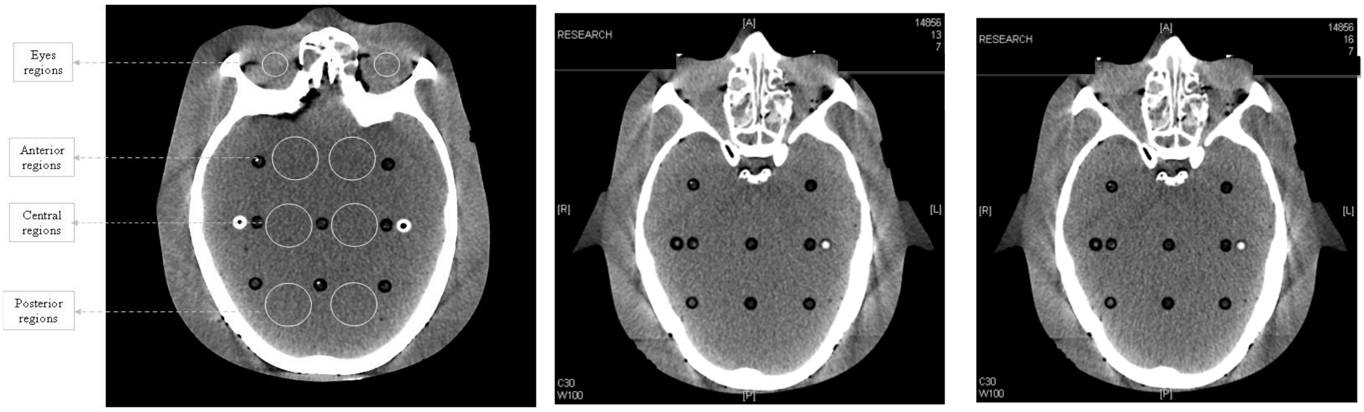
All images produced by the Setups A to E were assessed in two aspects: the correctness of the CT number and the standard deviation (SD) of the CT number in four predefined zones (over the eye region, the anterior cerebral, central cerebral and posterior cerebral). Eight regions of interest, six of 274 mm^2 in the intracranial regions and two of 86 mm^2 in the orbits, were used to determine the correctness of the CT numbers and their standard deviation using a Centricity Radiology RA 600 workstation (GE Medical Systems, LLC) (Figure 2).

2.7 Data analysis

All results were analyzed using IBM SPSS v21. 0.0. The Mann-Whitney U-test was used to compare the group mean, and the level of significance was set at $p < 0.05$.

3 Results

The present study measured the radiation dose deposited in the five thermoluminescent dosimeters (TLDs) that were placed on the surface of each eye of the physical phantom to



(a) (b) (c)

Fig. 2. Sample images acquired by (b) the Setup A (no shielding) and (c) Setup E (with bismuth, face shield and bolus). An illustration of the location of the eight predefined regions of interest used for the determination of the CT number and image noise (a). A sample image obtained from Setup A and Setup E, showing no visually noticeable artifacts or discrepancy of image noise level between the two setups.

Table 1. The Entrance Surface Dose (ESD) delivered to the eye lens regions under different scanning and shielding setups. The ESD to the right eye, left eye and both eye lens regions were measured by thermoluminescent dosimeters under six different scanning and shielding Setups, A, B, C, D, E and F. SD: standard deviation; CV: coefficient of variation. The Mann-Whitney U-test was performed to compare the right, left and overall ESD in the Setup A with the other setups.

		Scanning and shielding setups					
		A Gantry at 0° No shielding	**B Gantry at 0° + bismuth**	**C Gantry at 0° + bismuth**	**D Gantry at 0° + bismuth**	**E Gantry at 0° + bismuth + face shield + bolus**	**F Gantry at 30° No shielding**
ESD to the right eye lens region (mGy)	Mean ± SD	30.4 ± 2.0	21.1 ± 2.3	24.6 ± 7.5	22.2 ± 5.5	19.4 ± 4.5	2.4 ± 0.1
	(p value)	(reference scan)	(*ns*)	(*ns*)	(*ns*)	(*ns*)	($p < 0.001$)
	CV	6.6	10.8	30.5	24.7	23.4	3.4
ESD to the left eye lens region (mGy)	Mean ± SD	31.0 ± 3.1	25.2 ± 8.5	23.4 ± 4.0	19.9 ± 2.7	20.4 ± 12.2	2.3 ± 0.1
	(p value)	(reference scan)	(*ns*)	(*ns*)	(*ns*)	(*ns*)	($p < 0.001$)
	CV	10.1	33.9	33.9	13.7	12.2	5.2
Overall ESD to the eye lens region (mGy) (p value)		30.7 (reference scan)	23.2 (*ns*)	24.0 (*ns*)	21.0 (*ns*)	19.9 (*ns*)	2.4 ($p < 0.001$)
Relative reduction in the overall ESD to the eye lens region when compared with Setup A (%)		(reference scan)	24.4	21.8	31.6	35.2	92.5

assess the ESD to the eye lens regions during CT brain examination under different scanning and shielding setups. In this study, the CT Dose Index -Volume ($CTDI_{vol}$) was 48.41 mGy (Setups A to E) and 55.9 mGy (Setup F) when acquisitions were acquired with the CT gantry positioned at 0° and 30°, respectively. Interestingly, due to the compensatory shorter scan length used during the acquisition in the Setup F, the dose-length product in the Setup F was found to be equal to that in the Setups A to E (670.77 mGy.cm).

Setup A (the CT gantry was positioned at 0° and no bismuth shield or bolus were applied) was used as the reference scan to determine the relative reduction of the overall ESD in the eye lens region by additional shielding and gantry tilting. The overall ESD to the eye lens region under different scanning and shielding setups, and the relative reduction in the overall ESD when compared with Setup A are summarized in Table 1. The mean, standard deviation (SD) and coefficient of variance (CV) in the CT numbers measured in the four predefined zones of the resultant images are summarized in Table 2. Finally, with reference to the Setup A, the relative deviation in the mean CT number and image noise level (SD of CT numbers) in Setups B, C, D and E were calculated and are summarized in Table 3.

4 Discussion and conclusion

CT brain imaging is a major source of radiation exposure to the eye lens when the scan range falls within the eye lens region. This study is a preliminary study to determine the

Table 2. The mean and SD of the CT number in different zones of images acquired by different shielding setups. The mean and SD of the CT numbers in different zones of images under different shielding Setups A, B, C, D and E. SD: standard deviation. The Mann-Whitney U-test was performed to compare the mean CT number in Setup A with the other setups.

Image quality in different zones	CT Number (Hounsfield Unit)	Different shielding setups: A Gantry at 0° No shielding	B Gantry at 0° + bismuth	C Gantry at 0° + bismuth + face shield	D Gantry at 0° + bismuth + bolus	E Gantry at 0° + bismuth + face shield + bolus
Eye region	Mean ± SD (p value)	33.6 ± 5.7 (reference scan)	50.4 ± 5.7 ($p < 0.001$)	29.7 ± 5.0 (*ns*)	41.3 ± 5.2 (*ns*)	30.8 ± 5.6 (*ns*)
Anterior cerebral region	Mean ± SD (p value)	17.2 ± 4.7 (reference scan)	18.5 ± 4.9 (*ns*)	16.8 ± 5.0 (*ns*)	17.4 ± 4.9 (*ns*)	17.2 ± 5.2 (*ns*)
Central cerebral region	Mean ± SD (p value)	21.7 ± 4.9 (reference scan)	22.8 ± 5.0 (*ns*)	21.3 ± 5.0 (*ns*)	21.9 ± 5.1 (*ns*)	21.3 ± 5.1 (*ns*)
Posterior cerebral region	Mean ± SD (p value)	25.9 ± 4.9 (reference scan)	27.0 ± 5.2 (*ns*)	25.6 ± 5.0 (*ns*)	26.0 ± 5.4 (*ns*)	25.6 ± 5.2 (*ns*)

Table 3. The relative change in the mean of the CT number and image noise level (SD of the CT number) under the Setups B to E. When compared with the Setup A (the reference scan) where no bismuth shield was applied, the relative change in the mean CT number and image noise level in the resultant images in different zones of the head after the application of different shielding setups (Setups B to E) are summarized in Table 3.

		Different shielding setups: B Gantry at 0° + bismuth	C Gantry at 0° + bismuth + face shield	D Gantry at 0° + bismuth + bolus	E Gantry at 0° + bismuth + face shield + bolus
Percentage change in the mean CT Number relative to the Setup A (%)					
Zones	Eyes	+50	–11.6	+22.9	–8.3
	Anterior	+7.6	–2.3	+1.2	No change
	Central	+5.1	–1.8	+0.9	–1.8
	Posterior	+4.2	–1.2	+0.3	–1.2
Percentage change in the image noise level relative to the Setup A (%)					
Zones	Eyes	No change	–12.3	–8.8	–1.8
	Anterior	+4.3	+6.4	+4.3	+10.6
	Central	+2.0	+2.0	+4.1	+4.1
	Posterior	+6.1	+2.0	+10.2	+6.1

efficacy of using soft-tissue-simulating material and a bismuth shield together for eye lens dose protection during CT brain examination. When compared with the ESD to the eye lens region in the reference scan (30.7 mGy), we found (1) a cranial gantry tilt of 30° (Setup F) can significantly reduce the amount of the overall ESD to the eye lens region (2.4 mGy), which corresponds to a relative reduction of 92.5%, and (2) when the primary radiation scanning through the eye lens region was unavoidable during acquisition (as in the Setups A to E, where the CT gantry was positioned at 0°), with the application of an in-plane bismuth shield with bolus and an air gap (Setup E), the overall ESD to the eye lens region was 19.9 mGy, which corresponds to a relative reduction of 35.2% (Table 1).

Apart from examining the radiation dose to the eye lens region, the correctness of the CT number and image noise level of the resultant image were also important when considering the efficacy of bismuth shield application (Wang *et al.*, 2012). Generally, the bismuth shield application would lead to a beam hardening effect and starvation of information-carrying photons, resulting in an incorrect CT number being calculated during acquisition (Lee *et al.*, 2011; Kim *et al.*, 2013). The mean of the CT number and the SD of the CT numbers collected from the Setup A (no bismuth shield or bolus applied) can thus be used as the reference value of the CT number and image noise level in the present study. When we compared the correctness of the CT number under different shielding setups (Setups B to E) with the reference scan (Setup A), we found the image obtained by Setup B had a significant drift in the mean CT number over the eye region (50.4 HU) when compared with the reference scan (33.6 HU). Besides, the Setup B tends to produce a greater extent of drifts in the mean CT number in all four zones than in the Setups C, D and E.

Furthermore, our results demonstrated a trend (where an in-plane bismuth shield was applied) that the extent of drifts in the mean of the CT number were gradually reduced from the eye regions to the posterior cerebral regions in the Setups B to E (Table 2).

In the Setups B to E, a certain amount of information-carrying X-ray photons were being cut off by the in-plane bismuth shield, and the overall image noise level in the brain regions of the image should therefore inevitably increase due to increased scatter formation and X-ray photons deprived by the bismuth shield. Interestingly, the image noise level over the eye region in the Setup B was similar to that in the reference scan (the relative change in the SD of the CT number is zero), while the image noise levels over the eye region in the Setups C, D and E were found to be improved when compared with the reference scan (the relative reduction in the SD of the CT number ranged between 1.8% and 12.3%). It may probably be due to the effective noise control by the Adaptive Statistical Iterative Reconstruction (ASiR) (Hara *et al.*, 2009; Vorona *et al.*, 2013; Goenka *et al.*, 2014). However, the image noise level over the cerebral regions (anterior, middle and posterior cranial zones) in the Setups B, C, D and E was slightly increased when compared with the reference scan (the relative increment in the SD of the CT number ranged between 2.0% and 10.6%), but all changes were not visually noticeable and did not affect the radiologist's diagnosis. Sample images comparing the image quality in the Setup A (no shielding) and Setup E (with the bismuth, face shield and bolus) are shown in Figure 2.

In conclusion, the application of bolus with an in-plane bismuth shield can reduce the radiation dose in the eye lens region during CT brain examination. In the present study, the combined use of two pieces of 0.5-cm-thick bolus and a commercial bismuth shield that was placed on top of a dedicated face shield (Setup E) can reduce the overall ESD to the eye lens region, and maintain acceptable image quality in the resultant image. Further work on the role of different combinations of materials and thickness of soft-tissue-simulating material and shields in reducing the eye dose is warranted.

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