

Bismuth Shielding, Organ-based Tube Current Modulation, and Global Reduction of Tube Current for Dose Reduction to the Eye at Head CT¹

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Purpose:

To compare the dose and image quality of three methods for reducing the radiation dose to the eye at head computed tomography (CT): bismuth shielding, organ-based tube current modulation (TCM), and global reduction of the tube current.

Materials and Methods:

An anthropomorphic head phantom was scanned under six conditions: (a) without any dose reduction techniques (reference scanning); (b) with one bismuth eye shield; (c) with organ-based TCM; (d) with reduced tube current to yield the same dose reduction as one bismuth shield; (e) with two layers of bismuth shields; and (f) with organ-based TCM and one bismuth shield. Dose to the eye, image noise, and CT numbers in the brain region were measured and compared. The effect of increasing distance between the bismuth shield and eye lens was also investigated.

Results:

Relative to the reference scan, the dose to the eye was reduced by 26.4% with one bismuth shield, 30.4% with organ-based TCM, and 30.2% with a global reduction in tube current. A combination of organ-based TCM with one bismuth shield reduced the dose by 47.0%. Image noise in the brain region was slightly increased for all dose reduction methods. CT numbers were increased whenever the bismuth shield was used. Increasing the distance between the bismuth shield and the eye lens helped reduce CT number errors, but the increase in noise remained.

Conclusion:

Organ-based TCM provided superior image quality to that with bismuth shielding while similarly reducing dose to the eye. Simply reducing tube current globally by about 30% provides the same dose reduction to the eye as bismuth shielding; however, CT number accuracy is maintained and dose is reduced to all parts of the head.

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In 1991, the International Commission on Radiological Protection estimated that the threshold radiation dose for causing detectable lens opacities was 500–2000 mGy for total dose received in a single brief exposure and 5000 mGy for a total dose received in highly fractionated or protracted exposures (1). These values were retained in the 2007 recommendations of the International Commission on Radiological Protection (2). However, recent studies on the effects of radiation on the lens of the eye challenge these recommendations. Worgul et al (3) reported a dose-effect threshold of less than 1000 mGy for detectable opacities in their study of Chernobyl clean-up workers at 12 and 14 years after exposure. Although these dose levels are much higher than that for a typical computed tomographic (CT) examination of the head (approximately 60 mGy) (4,5), patients can often undergo multiple CT examinations. A study of the risk of cataract formation after exposure to low doses of radiation in a cohort of U.S. radiologic technologists suggested an increasing likelihood of cataract formation with increasing radiation exposure, but with no apparent threshold (6). In addition to the uncertainty regarding a dose threshold for cataract formation, the latency period

for developing lens opacities remains unclear. The DNA damage caused by ionizing radiation in the epithelial cells of the lens appears to remain latent for a relatively long period before expressing itself in the form of opacities or cataracts. A study of cataract formation in adults who were treated with protracted radium irradiation for a skin hemangioma during infancy showed a latency period for the formation of opacities or cataracts of 30–45 years (7). Because uncertainties exist regarding the dose limits required to avoid damage to the lens of the eye and the period after exposure before the damage is expressed, it is prudent to minimize the dose to the eye, especially in children, provided that the diagnostic benefit of the examination is not compromised.

Bismuth shields have been used in CT as one means of protecting superficial organs such as the eye (8,9), thyroid (10,11), and breast (12,13) from radiation delivered during medical CT examinations. During scanning, the shield is placed over the surface of the organ or region of interest (ROI) so that the primary x-ray beam is attenuated by 30%–50% before reaching the patient. Another commonly used dose reduction strategy is tube current modulation (TCM) (14–16). With this technique, tube current is adjusted along the longitudinal (z) axis and/or angularly as the tube rotates around the patient.

Combinations of bismuth shielding and TCM have been investigated in CT of the neck (11) and chest (17). To our knowledge, no investigators have evaluated the dose performance and image

quality with a combination of these two approaches in head CT. Alternatively, the x-ray tube current can be decreased globally throughout the examination to reduce radiation dose not only to the eye but to the entire scanned region. Similar dose reductions and noise increases as those achieved with bismuth shielding can be obtained with a global reduction in the tube current (18,19). This study was performed to compare the dose and image quality of three methods for reducing the radiation dose to the eye at head CT: bismuth shielding, organ-based TCM, and global reduction of the tube current.

Advances in Knowledge

- Compared with routine head CT examination, CT with bismuth shielding, organ-based tube current modulation (TCM), and global reduction of the tube current reduces the radiation dose to the eye by approximately 30%.
- All three dose reduction techniques lead to a small increase in noise in the brain region (0.5–1 HU) compared to that with a routine head examination.
- A combination of organ-based TCM and bismuth shielding can reduce radiation dose to the eye by almost 50% relative to a routine head examination, but CT number accuracy and image quality (noise and artifact) are sacrificed.

Implications for Patient Care

- Globally reducing the tube current by 30% is superior to bismuth shielding for reducing the radiation dose to the eye because CT number accuracy is maintained and dose is reduced to all parts of the head, not just the eye.
- Organ-based TCM reduces dose to the eye as effectively as bismuth shielding yet provides better image quality.

Materials and Methods

Siemens Healthcare provided the CT scanner used in this work through a research grant to the Mayo Clinic. Two authors (C.H.M. and J.A.C.), employees of the Mayo Clinic, receive grant support from Siemens Healthcare, and one author (K.L.G.) is an employee of Siemens Healthcare. These authors had no access to study data before manuscript drafting. The other authors (J.W., X.D., and S.L.) retained sole control of study data during the entire study and during manuscript drafting.

Reference Scanning

A tissue-equivalent anthropomorphic phantom was placed in a supine position

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Abbreviations:

OSL = optically stimulated luminescence
ROI = region of interest
TCM = tube current modulation

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Guarantors of integrity of entire study, J.W., C.H.M.; study concepts/study design or data acquisition or data analysis/interpretation, all authors; manuscript drafting or manuscript revision for important intellectual content, all authors; manuscript final version approval, all authors; literature research, J.W., J.A.C., K.L.G., C.H.M.; clinical studies, J.W.; experimental studies, all authors; statistical analysis, J.W., X.D.; and manuscript editing, all authors

Potential conflicts of interest are listed at the end of this article.

Figure 1

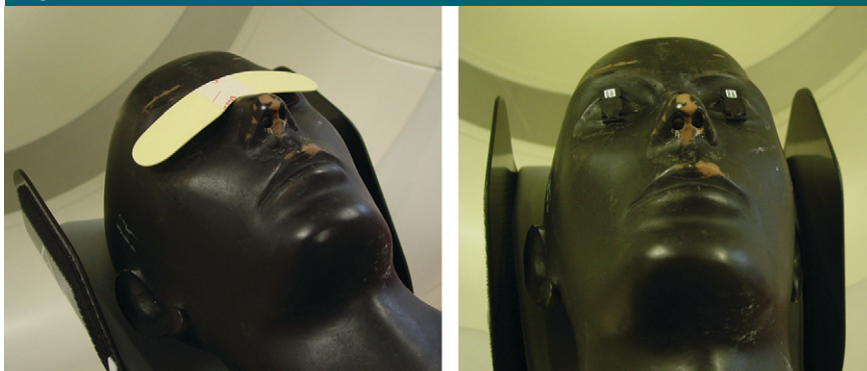


Figure 1: Photograph of phantom, bismuth shield, and dosimeters used in study. **(a)** Bismuth eye shield is placed over the eyes of an anthropomorphic head phantom. **(b)** OSL dosimeters are placed on the eyes for dose measurement.

and scanned by using a clinical dual-source CT scanner (Definition Flash; Siemens Healthcare, Forchheim, Germany) in the single-source mode of operation. A reference scan was obtained, without use of any dose-reduction techniques, by using our clinical routine head examination protocol (spiral acquisition, 120 kVp, 250 effective mAs, rotation time of 1 second, pitch of 0.5, 5-mm-thick sections, 300-mm reconstruction field of view) from vertex to top of C1 lamina.

Bismuth Shielding

One and two layers of bismuth-impregnated latex (3.4 g/cm² of bismuth per layer; AttenuRad, F&L Medical Products, Vandergrift, Pa) were placed over the eyes after the localizer CT radiograph was acquired (Fig 1a).

Organ-based TCM

To reduce the dose to radiosensitive organs such as the breast, thyroid, and lens of the eye, an organ-based TCM technique (XCare, Siemens Healthcare) was implemented on the CT scanner. In this mode, tube current was decreased by 75% from the reference scan's tube current for an angular range of approximately 120° over the anterior surface of the head, symmetric to the median plane of the patient (20). During the remaining 240° of scanning range, tube current was increased by 25% so that the same total tube current time product was applied

over 360°, as was used for the reference scan. In this manner, the same total scanner output was used but allocated more to the lateral and posterior tube positions than to the anterior tube positions.

Global Reduction of Tube Current

The tube current was reduced over all 360° to achieve the same dose reduction to the eye as was obtained with one layer of bismuth shielding. Because dose is linearly proportional to the tube current–time product (milliamperere second), the decreased tube current–time product was calculated as follows: $\text{Ref-mAs} \times (\text{Bi_Dose}/\text{Ref_Dose})$, where Ref-mAs is the tube current–time product in the reference scan and Bi_Dose and Ref_Dose are the doses measured at the eye of the phantom with and without bismuth shielding, respectively.

In total, scans were obtained under six conditions: (a) without the use of any dose reduction technique (reference scan), (b) with one bismuth eye shield, (c) with organ-based TCM, (d) with globally decreased tube current, (e) with two layers of bismuth eye shields, and (f) with organ-based TCM and one bismuth eye shield. The same effective milliamperere second was used for all scan modes except that performed with a global decrease in tube current. In addition, we investigated the effect of increasing the distance between the bismuth shield and the lens of the eye (0, 2, 3, and 4 cm) on

dose and image quality by placing foam pads between the phantom surface and the bismuth shield.

Dosimetry

Optically stimulated luminescence (OSL) dosimeters (Dot dosimeter; Landauer, Glenwood, Ill) were used to measure the radiation dose to the eye for each CT scan (21). The radiation-sensitive area was about 5.4 mm in diameter and about 2 mm thick. An OSL dosimeter was placed over the center of each eye (Fig 1b) for each scan. The accumulated dose was determined with an OSL reader (MicroStar, Landauer) before and after each CT acquisition, and the difference was recorded as the dose to the eye. OSL dosimeters were calibrated with a 0.6-mL (2-cm-long) ionization chamber (10 × 5–0.6; Radcal, Monrovia, Calif) by using the same scan configuration (Appendix E1, online). When bismuth eye shields were applied, the OSL dosimeters were completely covered by the shield. Dose measurements for each scan were performed twice, and average values for both scans and both eyes were used for analysis.

Image Noise and CT Number Accuracy

Image noise was evaluated by using the standard deviation of CT numbers in ROIs of approximately 100 mm² in the intracranial region. CT numbers within each ROI and their standard deviations were averaged over five adjacent images along the z direction. For methods involving bismuth shielding, the shield was present on all five images included in the analysis. A total of eight ROIs were separated into three groups on the basis of their distance from the anterior midline (Fig 2), as follows: (a) anterior area, two ROIs 9 cm below the surface; (b) central area, three ROIs 13.5 cm below the surface; and (c) posterior area, three ROIs 18 cm below the surface. The average noise within each group was compared among the six scanning techniques. The average CT numbers within the ROIs were also recorded, averaged within each group, and compared among different scanning techniques. Statistical analysis was performed with a paired two-tailed

unequal variance *t* test (Excel; Microsoft, Redmond, Wash) by comparing the mean and standard deviations of CT numbers from the same ROI group between the reference and dose reduction scanning techniques. $P < .05$ was considered to indicate a statistically significant difference.

Results

Similar dose reduction was achieved with bismuth shielding and organ-based TCM (26.4% and 30.4%, respectively, relative to the reference scan) (Table 1). By globally lowering the tube current–time product from 250 to 177 mAs, a similar dose reduction was achieved (30.2%, relative to the reference scan). When two layers of bismuth shields were used, dose to the eye was reduced by about 42.4% from the reference scan. Use of one layer of bismuth eye shields together with organ-based TCM provided a dose reduction of around 47.0%. All scanning modes showed symmetrical doses between the two eyes.

Streak artifacts were observed in the orbit with bismuth shielding (Fig 3b) but were not present with organ-based TCM (Fig 3c) or global tube current reduction (Fig 3d). No scanning technique produced noticeable artifacts in the brain region. All five dose reduction techniques increased image noise in the anterior and central regions of the brain ($P < .05$ for all) relative to that on the reference scan (Table 2). The two scanning modes with the largest dose reductions (two layers of bismuth eye shields and combination of bismuth eye shield and organ-based TCM) produced the highest noise; however, the average absolute increase relative to the reference scan was not larger than 2 HU (Table 2). Use of one layer of bismuth shielding or organ-based TCM did not significantly increase image noise in the posterior region of the brain relative to that on the reference scan ($P > .05$ for both), whereas global reduction of the tube current caused a small but statistically significant increase in image noise in the posterior region (1.1 HU; $P < .05$) (Table 2). CT numbers within the brain were artificially increased when bismuth shields

Figure 2

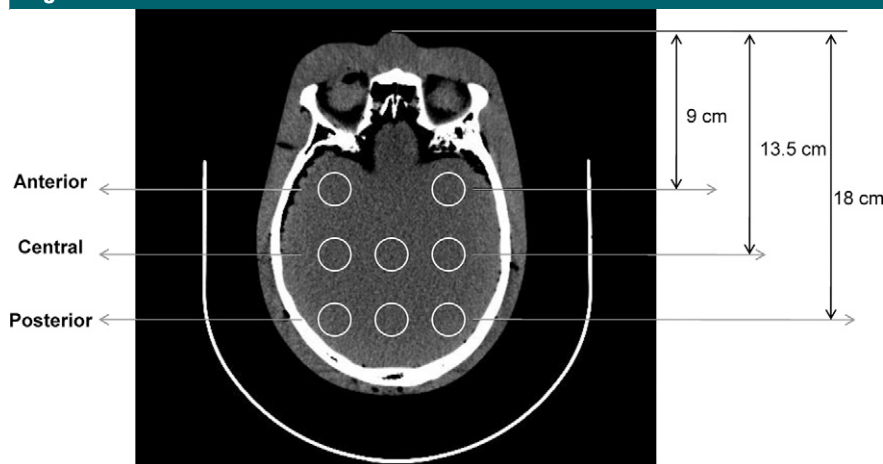


Figure 2: Image illustrates the eight ROIs used to measure image noise and CT numbers. The three rows of ROIs were grouped according to distance from the anterior phantom surface.

Table 1

Doses to the Eye Surface with Different Scanning Techniques

Scanning Technique	CTDI _{vol} (mGy)*	Dose to the Eye (mGy) [†]	Mean Absolute Difference between Two Eyes (mGy)
Reference	38.18	32.16 ± 1.62	0.14
Bismuth shielding (one layer)	38.18	23.66 ± 0.41	0.38
Organ-based TCM	37.57	22.39 ± 0.47	0.51
Decreased tube current	27.19	22.44 ± 0.98	1.64
Bismuth shielding (two layers)	38.18	18.53 ± 0.66	0.79
Bismuth shielding and organ-based TCM	37.88	17.05 ± 0.44	0.68

* CTDI_{vol} = volume CT dose index.

[†] Data are averages ± standard deviations.

were used (Table 2). In the anterior region, one layer of bismuth shielding caused an increase in CT numbers from 16.2 to 19.5 HU ($P < .05$), whereas two layers of bismuth shielding increased the average CT numbers from 16.2 to 28.1 HU ($P < .05$). No significant change in CT numbers was found with organ-based TCM ($P = .25$) or global tube current reduction ($P = .15$). The combination of one layer of bismuth shielding with organ-based TCM increased the mean CT number of this region from 16.2 to 18.8 HU ($P < .05$). In the central and posterior regions, the influence of bismuth shielding on CT numbers was smaller than that within the anterior region. However, the use of two layers of bismuth eye shields still increased CT numbers 31%

in the central region ($P < .05$) and 8% in the posterior region ($P < .05$).

With increased separation between the bismuth shield and the eye lens, artifacts near the orbit region were largely decreased. The larger separation led to a slight increase in the dose to the eye (Fig 4). Image noise was increased in the anterior and central regions of the brain, and CT numbers were artificially increased in the anterior region at all distances between the shield and the eye lens (Fig 4).

Discussion

Techniques for decreasing the radiation dose to the eye can be used provided that the resultant image quality is

Figure 3

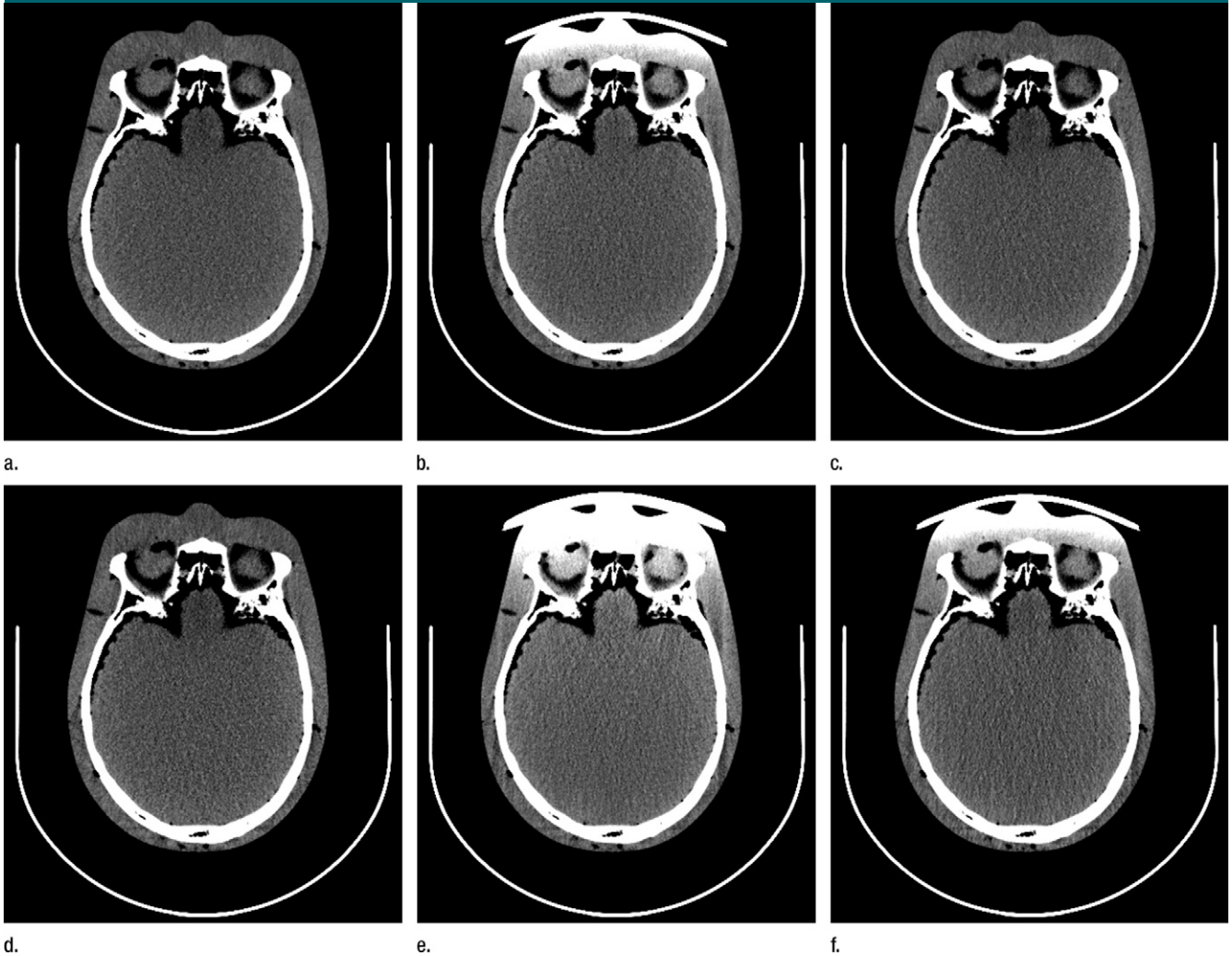


Figure 3: Examples of reference CT scan and scans obtained with five dose reduction techniques (for all images, window width = 120 HU and window level = 40 HU). **(a)** Reference scan of anthropomorphic head phantom. **(b)** Scan with one bismuth shield. **(c)** Scan with organ-based TCM. **(d)** Scan with globally decreased tube current. **(e)** Scan with two layers of bismuth shields. **(f)** Scan with one bismuth shield and organ-based TCM.

Table 2

Image Noise and CT Numbers in Brain Regions with Different Scanning Techniques

Scanning Technique	Anterior Region		Central Region		Posterior Region	
	Noise	CT Number	Noise	CT Number	Noise	CT Number
Reference	5.7 ± 0.4	16.2 ± 1.8	5.7 ± 0.4	16.1 ± 0.7	6.0 ± 0.6	20.3 ± 2.0
Bismuth shielding (one layer)	6.4 ± 0.6	19.5 ± 2.4	6.4 ± 0.5	17.7 ± 0.9	6.0 ± 0.5*	20.4 ± 2.1*
Organ-based TCM	6.2 ± 0.4	15.4 ± 1.3*	6.2 ± 0.4	16.0 ± 0.6*	6.2 ± 0.6*	20.1 ± 2.0*
Decreased tube current	6.5 ± 0.7	15.0 ± 1.7*	6.8 ± 0.6	16.1 ± 0.9*	7.1 ± 0.6	20.4 ± 1.8*
Bismuth shielding (two layers)	7.5 ± 1.2	28.1 ± 2.1	6.9 ± 0.6	21.1 ± 1.3	6.4 ± 0.5	22.0 ± 2.2
Bismuth shielding and organ-based TCM	6.7 ± 0.7	18.8 ± 2.9	6.9 ± 0.7	17.2 ± 1.7	6.6 ± 0.7	20.4 ± 2.3*

Note.—Data are averages ± standard deviations (in Hounsfield units). *P* values were calculated to test whether there was a significant difference between the noise or CT number value with reference scanning and that with other techniques. Except where noted, all *P* values were less than .05.

* *P* > .05.

Figure 4

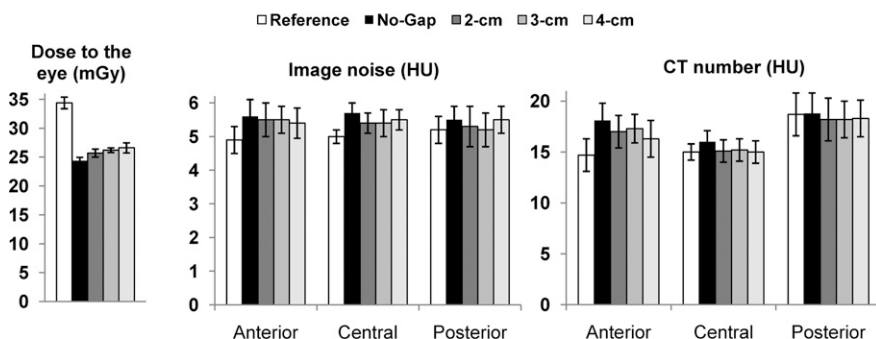


Figure 4: Left, Radiation dose to the eye with bismuth shielding at different distances from the eye surface. Error bars represent the variation of measurement between two eyes. Middle, image noise and, right, CT number in the brain regions for reference scan and scans with bismuth shields placed at varying distances from phantom surface. Error bars represent the variation of measurements in five adjacent images along the z direction.

acceptable. When feasible, many practices exclude the lens of the eye from the primary x-ray beam by aligning the scan along the supraorbital meatal line. However, tilting the gantry to accomplish this is not possible with all CT scanners or for all scan modes.

Bismuth shields have been used clinically in head CT to reduce the dose to the lens of the eye. The dose reduction observed in our study was consistent with that reported by others (9,18,22). A variety of TCM techniques have also been used to adapt the radiation dose to individual patient size (23–25). Owing to the relatively symmetrical shape of the head in the axial plane, TCM on the basis of attenuation changes in the axial plane does not provide significant dose reduction to the eye. In this work, organ-based TCM was used to reduce dose to the anterior surface of the head and, hence, the eye and provided dose reduction comparable to that with bismuth shielding.

The similarity between bismuth shielding and organ-based TCM is that these two methods both reduce x-ray photons coming directly toward the eye from the anterior direction. Both techniques have practical limits to the amounts of dose reduction achievable. With bismuth shielding, the application of a more highly attenuating shield or multiple layers of shields achieves a larger dose reduction; however, the streak artifacts, changes in CT number, and

increase in image noise become limiting factors, as shown in this study. For organ-based TCM, the tube current for anterior projections must remain sufficient to avoid the CT number variations associated with partial scan reconstructions. Considering limitations on the amount of dose reduction that is practical for these approaches, investigators have explored combining bismuth shielding and TCM to further reduce radiation dose to superficial organs such as the thyroid and breast (11,17). Our results confirmed that the dose reduction to the eye achieved by combining bismuth shielding and TCM was greater than that with either of the methods alone (47.0% vs 26.4% or 30.4%). In contrast to TCM reported in those studies (11,17), the organ-based TCM technique implemented in this study has the advantage that the tube current for the anterior x-ray tube position is not affected by the presence of the bismuth shield; organ-based TCM adjusts the tube current on the basis of only the angular position of the x-ray tube, independent of the object's attenuation. This avoids the risk that the TCM technique on a given CT scanner will increase the tube current in response to the increased attenuation from the bismuth shielding. Combining bismuth shielding and organ-based TCM provides a predictable strategy for reducing dose to the eye.

Image quality must be taken into consideration when evaluating dose

reduction strategies. Hopper et al (8) showed that artifacts caused by the eye shield were not projected into the brain region. Geleijns et al (18) reported a modest increase in image noise of about 1–2 HU with the eye shield. These findings agree with our results (Fig 3b, Table 2). Even though the use of a piece of foam to increase the distance between the bismuth shield and the eye lens can reduce artifacts near the orbit, image noise was still increased in the brain region (Fig 4). This reflects a fundamental limitation of the bismuth shielding strategy: Photons coming from both the anterior and posterior directions are attenuated by the shield. Although this reduces dose to the anterior surface, the removal of photons from the beam exiting the patient leads to the loss of useful information for creating images and wastes radiation dose (26). In addition, we found that the CT numbers were increased with bismuth shielding, even in the intracranial area (9 cm below the shield) (Table 2, Fig 4). This variation of CT number accuracy could have an influence on quantitative diagnostic tasks such as brain perfusion analysis. There are several other disadvantages of bismuth shielding. Owing to the high attenuation of bismuth shields, even a small amount of patient motion during scanning could cause severe streaking artifacts, and pediatric patients may not cooperate with wearing the shield. Furthermore, because the shield comes in contact with the patient, infection control procedures must be used.

Organ-based TCM showed a similar noise increase as bismuth shielding but preserved CT number accuracy. If further dose reduction to the eye is desired, the combination of bismuth shielding and organ-based TCM may be considered because image quality with this approach was comparable to that achieved by using one layer of bismuth shielding.

Globally decreasing the tube current by 30% provided the same dose reduction to the eye as did bismuth shielding. The noise in the brain region was slightly higher (~1 HU) than that with bismuth shielding in the posterior part of the brain. If this noise level is

diagnostically acceptable, reducing the tube current (over 360°) is superior to bismuth shielding because it does not change the CT number of brain tissue or require any additional steps in placing and cleaning the bismuth shield. In addition, it can be applied on scanners not equipped with organ-based TCM. It is important to note that the radiation dose from all directions, and not just to the anterior surface, is reduced.

There were several limitations in this work. First, the phantom used in our study represented only an adult head. However, cranial calcification is complete in children aged 3 years and older and adult scanning techniques are appropriate. For younger children, a less calcified skull provides x-ray attenuation more similar to that of a toddler or infant torso, where the use of bismuth shielding has been previously evaluated and is in good agreement with the results with an adult head phantom (27). Thus, our conclusions appear valid for any age group. Second, the dose evaluation was limited to the eye lens. It has been previously shown that the radiation dose to the brain does not change with bismuth eye shielding (18). Although the radiation dose to the posterior and lateral aspects of the head is increased with use of organ-based TCM, a thorough dose evaluation was not performed here because it has been described elsewhere (20). Our focus was restricted to the eye lens because cataracts caused by cumulative dose to the eye remain a specific consideration, even with low-dose head CT, especially in patients with stroke or brain tumor who are likely to undergo numerous CT examinations (5). Thus, the decision with regard to what dose reduction strategy is best overall is determined by the dose to the eye lens. To avoid increasing the dose to the brain in organ-based TCM, the tube current could be reduced in the anterior direction but kept the same in other directions relative to the reference scan. However, this scanning configuration is not currently available with any commercial CT scanners and hence was not able to be evaluated here. Third, image quality was evaluated on the basis of quantitative measurement of CT numbers in a

phantom. Rigorous observer performance studies with use of patient images are required to confirm that the proposed dose reduction strategies do not have a negative effect on clinically relevant diagnostic tasks. Finally, statistical comparisons of the measured image noise values were performed by using a paired *t* test, which in a small sample size is an appropriate test only if the data are normally distributed. However, this may not be the case for average noise values because noise values (standard deviations) are typically not normally distributed.

In conclusion, organ-based TCM provided similar dose reduction to the eye as bismuth shielding but better image quality. In addition, globally reducing tube current by about 30% not only achieves the same dose reduction to the eye as bismuth shielding but also reduces dose to the brain and maintains CT number accuracy.

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