

New organ-based tube current modulation method to reduce the radiation dose during computed tomography of the head: evaluation of image quality and radiation dose to the eyes in the phantom study

Jung-Su Kim¹ · Soon-Mu Kwon² · Jung-Min Kim³ · Sang-Wook Yoon⁴

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Abstract A new organ-based tube current modulation (NOB-TCM) method was designed with the intent to decrease tube current by 30% over a prescribed 90° radial arc across the anterior aspect of the radiosensitive organ, without increasing tube current in the remaining radial arc. We compared a reference scan and five other dose-reducing methods with regard to effects on dose, practicality, and image quality to determine the most effective method for the reduction of the radiation dose to the eyes during CT examinations of the head. We compared the radiation doses to the eyes and physical image quality in different regions of interest for TCM and shielding scans. Three types of TCM scans were performed: longitudinal TCM, angular TCM, and NOB-TCM. A bismuth sheet and lead goggles were each applied for the shielding scan. Relative to the reference scan, the dose to the eye was reduced to 25.88% with NOB-TCM, 44.53% with lead goggles, and 36.91% with a bismuth shield. Relative to the reference scan, the mean signal-to-noise ratio (SNR) was decreased to 8.02% with NOB-TCM, 28.36% with lead goggles, and 32.95% with the bismuth shield. The SNR of the anterior region

of interest was decreased to 11.89% with NOB-TCM and 87.89% with the bismuth shield. The average figure of merit was increased by 11.7% with longitudinal TCM and 13.39% with NOB-TCM, compared with the reference scan. NOB-TCM is a superior solution for head CT, including the orbital area, due to the reduction in radiation exposure without significant loss in image quality.

Keywords New organ-based tube current modulation · Radiation dose · Computed tomography · Dose reduction · Image quality

Introduction

Since its public introduction in the early 1970s, computed tomography (CT) has revolutionized not only diagnostic radiology, but also the overall field of medicine. Compared to regular radiographs, head CT scans provide more detailed information about head injuries, strokes, brain tumors, and other brain diseases. CT manufacturers have contributed dose reduction technologies while maintaining image quality such as automatic exposure control and iterative reconstruction algorithms. Iterative reconstruction can allow radiation dose reduction for head and neck. But this algorithm cannot be applied for specific organ dose reduction. Head CT dose optimization is important because of the direct exposure to radiosensitive organs. The eyes, which are radiosensitive organ, are included in the area exposed to radiation during CT scans of the head. In particular, the eye lenses are at risk of radiation exposure when the head and sinuses are scanned, and the radiation effect is thought to represent a deterministic model. During head CT scans, the eyes are exposed to an approximate dose of 50 mGy [1–3]. Recently introduced multi-detector CT

✉ Sang-Wook Yoon
jansons@cha.ac.kr

¹ Department of Radiologic Technology, Chungbuk Health & Science University, Cheongju, Chungcheongbuk-do 28150, Republic of Korea

² Department of Radiologic Technology, Daegu Health College, Daegu 41453, Republic of Korea

³ Department of Radiologic Science, College of Health Science, Korea University, Seoul 02841, Republic of Korea

⁴ Department of Diagnostic Radiology, CHA Bundang Medical Center, CHA University, 351, Yatap-dong, Bundang-gu, Sungnam-si, Gyunggi-do 13496, Republic of Korea

(MDCT) systems provide better image quality and better resolution compared to spiral CT; however, these systems also cause increased radiation exposure during CT procedures [4]. According to the International Commission on Radiological Protection (ICRP) Publication 103, the tissue weighting factors for the breast and thyroid are 0.12 and 0.04, respectively. The International Commission on Radiological Protection recommended that the equivalent dose limit for the lens of the eye be decreased from 150 to 20 mSv/y averaged over 5 years [5]. The eye lens is also considered an organ-at-risk during exposure to lower-dose radiation, especially because of the potential for cataract induction.

The use of a heavy metal in-plane shield protects sensitive organs such as the breast, thyroid, and eye lens [6]. Bismuth shielding is a commercially available option for superficial radiosensitive organ protection [7]. These techniques are mainly used to shield the breast, thyroid, and eye lens during CT to protect the organs at risk from direct exposure. However, bismuth shields are associated with potential image quality issues due to increased image noise over the covered area. Image noise from bismuth shield in head CT examinations will reduce the diagnostic value of images. Therefore, CT manufacturers have developed dose reduction techniques that do not reduce image quality. Tube-current modulation (TCM) techniques automatically adjust the tube current in the xy-plane (angular modulation), along the craniocaudal axis (z-axis modulation), or both, according to the attenuation of the patient and the X-ray beam direction [8]. In organ-based tube current modulation (OB-TCM) techniques, the X-ray tube current is reduced in real-time when the X-ray beam is directed toward the breasts or other dose-sensitive organs such as

the thyroid gland and eye lens. However, the first commercially available OB-TCM was implemented during MDCT to reduce the dose to radiosensitive organs through a 30% decrease in the tube current over a prescribed 90° radial arc across the anterior aspect of the patient, while increasing the tube current in the remaining radial arc. Thus, the patient dose was relatively increased when the patient was shifted downward in the gantry. New organ-based tube current modulation (NOB-TCM) was designed and developed with the intent to decrease the tube current by 30% over a prescribed 90° radial arc across the anterior aspect of the radiosensitive organ without increasing the tube current in the remaining radial arc [9].

In this study, we compared the feasibility of NOB-TCM with other dose reduction methods in terms of its effectiveness for dose reduction to the eye and for image quality during head CT. We used a bismuth shielding material and lead glasses as the in-plane shielding technique. Other dose reduction techniques involved two types of TCMs (longitudinal TCM and angular TCM).

Methods

Scanning technique

This study was performed using a 64 MDCT scanner (Optima660; GE Healthcare, Milwaukee, WI, USA). An anthropomorphic head phantom (PBU-60; Kyoto Kagaku, Kyoto, Japan), CT dose index (CTDI) head phantom (16-cm diameter) and a GE performance phantom were scanned using routine adult head CT protocols (Table 1). Scan protocol was used in all in-plane shielding methods and TCM techniques.

Three types of TCMs were implemented using commercial options, which are as follows: 1, longitudinal TCM (Auto mA); 2, angular TCM (Smart scan); and 3, NOB-TCM (Smart mA). A bismuth sheet and lead goggles were applied for an in-plane shield scan (Table 2). To further compare radiation exposure, additional reference scans that excluded scans of the eyeball region but included CT gantry angle adjustments were performed. The general rotation during a CT scan that includes the eyeball region was $72.3 \pm 7.1^\circ$. Shielding materials were placed on the eyes after acquiring a topogram.

Table 1 Routine adult head CT scanning protocol parameters

Acquisition mode	Axial	Detector configuration	32×0.625 mm
Tube voltage	120 kVp	Distance source to detector	949.147 mm
X-ray tube current	320 mA	Distance source to patient	541.0 mm
Exposure	10 mAs	Convolution kernel	Standard
Spacing between slices	20 mm	Focal spot	1.2 mm
Slice thickness	0.625 mm	Noise index	8.4

Table 2 In-plane shielding techniques

Shielding material	Specification	Model	Manufacturer
Bismuth shield	14×3.5 cm ² , 0.06 mmPb equivalence, 3.4 g/cm ² of bismuth per layer	AttenuRad	F&L Medical Products, Vandergrift, PA, US
Lead glasses	0.07 mmPb equivalence	XR-700	Toray Medical Co., Ltd, Tokyo, Japan

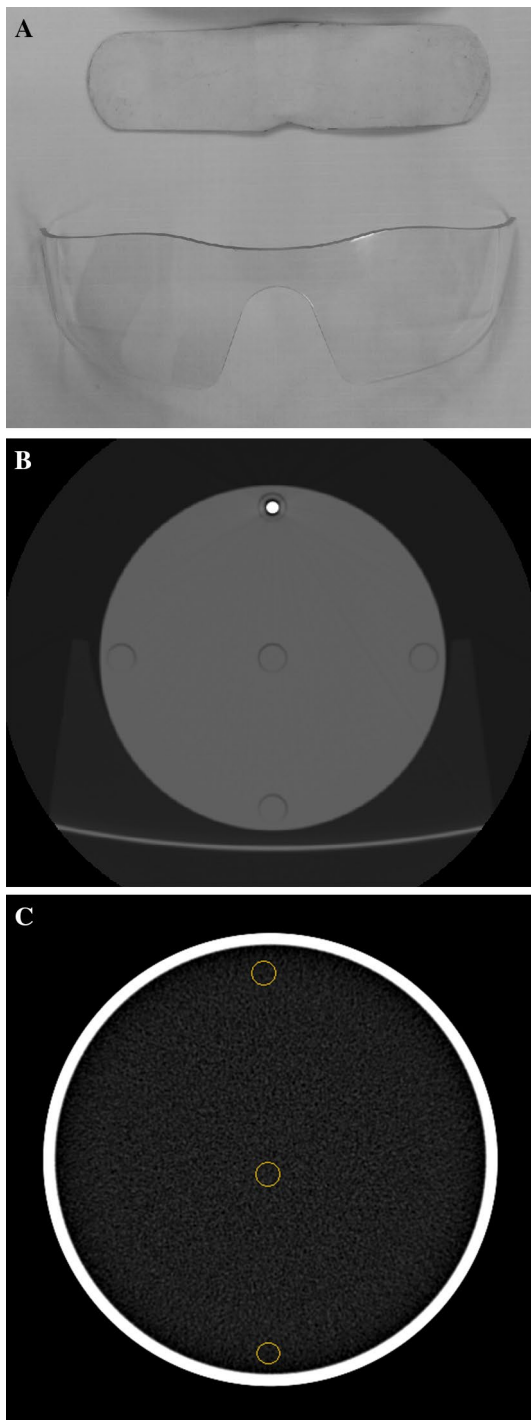


Fig. 1 **a** The bismuth shield and lead glasses used in this study. **b** The computed tomography (CT) dose index head phantom, ionization chamber, and multimeter used in this study. **c** The three regions of interest of GE performance phantom used to measure image noise and CT numbers

To evaluate the radiation, the CTDI volume (CTDI_{vol}) and dose length product (DLP) were calculated based on a scan of the 20-mm central region of the CTDI head

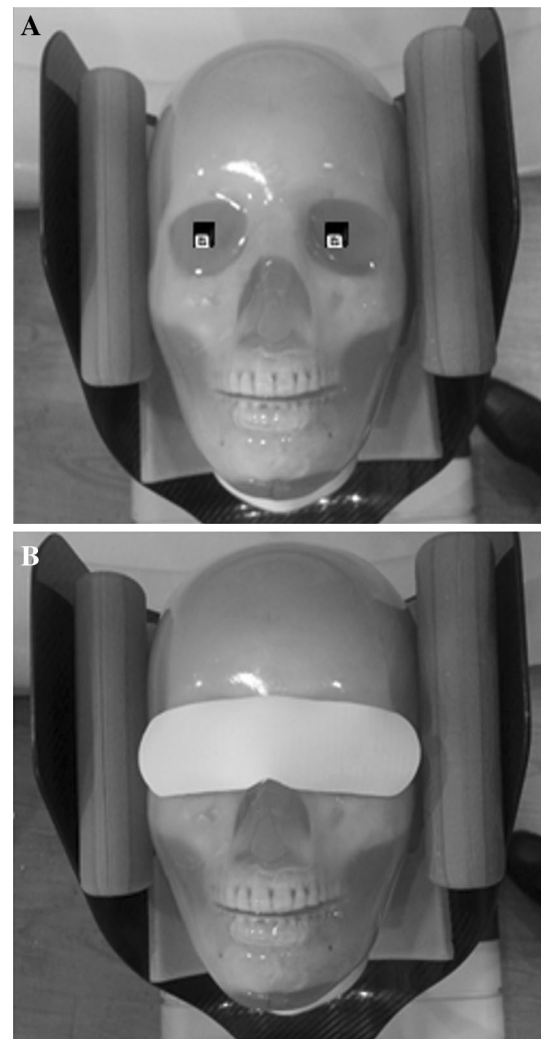


Fig. 2 **a** Nanodot dosimeters are placed on the surfaces of the eye lenses of the anthropomorphic head phantom. **b** A bismuth shield is placed over the eyes of the anthropomorphic head phantom

phantom. A multimeter (mult-O-Meter, Model 601; Unfors Instrument, Billdal, Sweden) was used at the phantom hole for radiation dose measurement (Fig. 1). To measure the radiation dose to the eyes on the anthropomorphic head phantom, 10-mm × 10-mm optically stimulated luminescence dosimeters (nanoDot, Landauer Inc., Glenwood, IL, USA) with ± 5% repeatability and a radiation dosimeter from the same manufacturer (microStar InLight System, Landauer Inc.) were used.

The energy revision coefficient (k) was 1.12 at 120 kV for each component. An optically stimulated luminescent dosimeter was located on the center of the eyeball before each scan. If radiation reduction techniques were used, the eyeball and dosimeter were fully shaded by shielding materials (Fig. 2).

We evaluated the quantitative image quality by measuring the CT number, noise, SNR, and figure of merit (FOM)

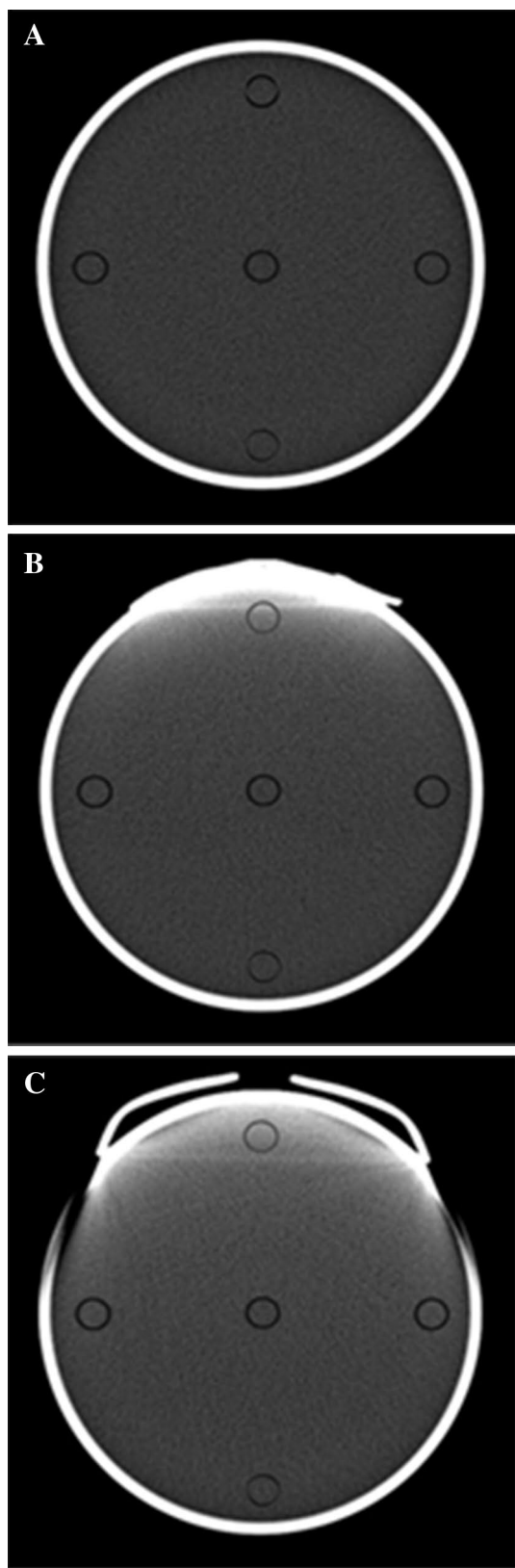


Fig. 3 Images of the GE performance phantom obtained using different scanning techniques. **a** New organ-based tube current modulation image of the phantom. **b** Phantom image obtained with a bismuth shield. **c** Phantom image obtained with lead glasses

Table 3 Doses to the eye in the anthropomorphic head phantom with different scanning techniques

Scan technique	CTDI _{vol} (mGy)	Eye dose (mGy)	Eye-dose reduction (%)
Reference scan	57.59	45.51 ± 1.93	–
Longitudinal TCM	50.4	43.11 ± 1.34	5.06
Angular TCM	50.26	43.51 ± 0.11	4.18
New OB-TCM	48.2	33.66 ± 1.21	25.88
Lead glasses	57.59	25.19 ± 1.12	44.53
Bismuth	57.59	28.65 ± 1.08	36.91
Angle scan	52.2	4.61 ± 0.23	89.85

CTDI_{vol} computed tomography dose index volume, TCM tube current modulation, OB organ-based

at the GE performance phantom images. FOM was defined by the following equation that included the SNR and exposure dose (X_{inc}):

$$FOM = \frac{SNR^2}{X_{inc}} \quad (1)$$

A higher FOM value results in better image quality capability in terms of SNR at a lower exposure. Using Image J software (1.46r; National Institutes of Health, Bethesda, MD, USA), pixel values were acquired based on a ROI size of 100 pixels around the centers of three holes (anterior hole, mid-central hole, posterior hole) located inside the GE performance phantom (Fig. 3). SNR was defined by the following equation as the ratio of the power of a signal (meaningful information) and the power of background noise (unwanted signal). CT number of ROI was signal and standard deviations of ROI was background noise.

$$SNR = \frac{P_{signal}}{P_{noise}}$$

Results

Compared with the reference scan, the doses to the eye were reduced to 25.88% with NOB-TCM, 44.53% with lead goggles, and 36.91% with the bismuth shield (Table 3). Table 4 presents the CTDI_{vol} and DLP at the CTDI head phantom using different TCM techniques. The CTDI_{vol} and DLP at the CTDI head phantom were reduced to 9.39% with NOB-TCM.

The noise indicates differences in the CT number and the signal in the three-point ROI (anterior hole, mid-central hole, posterior hole) with respect to radiation exposure to the GE performance phantom (Table 5). A miscellaneous

Table 4 CTDI_{vol} and DLP in different scanning techniques at the CTDI head phantom

Scanning techniques	CTDI _{vol}		DLP	
	(mGy)	Rate of change (%)	(mGycm)	Rate of change (%)
TCM				
Longitudinal-TCM	57.43	0.28	114.86	0.29
Angular-TCM	57.27	0.56	114.54	0.56
New OB-TCM	52.18	9.39	104.37	9.39
Reference scan	57.59	–	115.19	–

CTDI_{vol} computed tomography dose index volume, DLP dose length product, TCM tube current modulation, OB organ-based

Table 5 Signal of ROIs in the GE performance phantom with different scanning techniques

Scanning techniques	Anterior hole	Mid-central hole	Posterior hole	Average CT number
TCM				
Longitudinal-TCM	115.32 ± 0.08	118.48 ± 0.14	114.03 ± 0.20	115.9 ± 1.9
Angular-TCM	115.56 ± 0.12	118.61 ± 0.13	115.30 ± 0.12	116.5 ± 1.6
New OB-TCM	115.27 ± 0.18	118.55 ± 0.04	113.78 ± 0.19	115.9 ± 2.1
Shielding scan				
Bismuth	242.68 ± 5.55	123.75 ± 0.04	115.84 ± 0.12	160.8 ± 60.1
Lead glasses	438.86 ± 4.79	126.41 ± 0.05	118.11 ± 0.14	227.8 ± 154.5
Reference scan	114.73 ± 0.12	118.73 ± 0.09	114.02 ± 0.20	115.8 ± 2.2

CT computed tomography, ROI region of interest, CTDI CT dose index, TCM tube current modulation, OB organ-based

increase (<1%) in the average CT number relative to the reference scan (115.8) was observed with every TCM. Trends were also observed with regard to the differences in the CT numbers at each hole, positive values at the anterior hole, and negative values at the mid-central hole. Regarding radiation shields, the average CT numbers were increased by 38.86% with a bismuth shield, and 96.72% with lead glasses, compared with the reference scan. In particular, the CT numbers at the anterior hole with a bismuth shield and lead glasses exhibited dramatic increases of 111.52 and 282.52%, compared with the reference scan.

The noise and SNR values of each ROI were compared with those of the reference scan; the average SNR was decreased to 8.02% with NOB-TCM, 28.36% with lead goggles, and 32.95% with the bismuth shield, respectively (Table 6). The SNR of the anterior hole was decreased to 11.89% with NOB-TCM and 87.89% with the bismuth shield. Average increases in noise of 0.90, 6.29, and 8.38% relative to the reference scan were observed with longitudinal-TCM, angular-TCM, and NOB-TCM, respectively. In particular, the ROI noise increased notably at the posterior hole with longitudinal-TCM and angular-TCM. However, a similar notable increase at the anterior hole was observed for NOB-TCM. In addition, huge increases in average noise were observed with the bismuth shield (499.10%) and lead glasses (411.08%), especially at the anterior hole (Table 7; Fig. 4).

The average FOM was increased by 11.7% with longitudinal TCM and by 13.39% with NOB-TCM, compared with the reference scan. However, angular TCM, bismuth shield, and lead glasses were associated with decreases of 0.8, 9.2, and 3.6%, respectively (Fig. 5).

Discussion

By the early 1990s, CT scans of the brain and body contributed approximately 20% of the collective dose of radiation to the general population [10]. As of 2006, the number of CT examinations was reported to have increased by 10% per year over the past 10–15 years, and accounts for 49% of the total collective radiation dose administered to patients undergoing radiological examination; this corresponds to a 120-fold increase in the CT collective dose since the 1980s [11]. Eye lens is radiosensitive organ. In ICRP Publication 60, the limit on equivalent dose to eye lens of 150 mSv in a year was based on a dose threshold of 0.5–2 Gy for a single exposure [12]. In 2011 the ICRP recommended that the occupational dose limit for an equivalent dose for the lens of the eye to be reduced from 150 to 20 mSv per year, averaged over defined periods of 5 years, with no single year exceeding 50 mSv. The new limit is a substantial reduction of the previously recommended annual eye lens limit of 150 mSv. In ICRP report

Table 6 SNR at ROIs in the GE performance phantom with different scanning techniques

Scanning techniques	Anterior hole	Mid-central hole	Posterior hole	Average SNR
TCM				
Longitudinal-TCM	42.45 ± 0.56	32.66 ± 0.65	30.36 ± 0.43	35.2 ± 5.45
Angular-TCM	37.66 ± 0.56	32.65 ± 0.66	29.20 ± 0.53	33.2 ± 3.64
New OB-TCM	33.63 ± 0.70	30.56 ± 0.21	32.01 ± 1.50	32.1 ± 1.58
Shielding scan				
Titanium	46.57 ± 1.55	34.33 ± 0.65	29.06 ± 0.55	36.7 ± 7.65
Bismuth	4.62 ± 0.21	31.81 ± 0.33	33.85 ± 0.41	23.4 ± 13.79
Lead glasses	10.09 ± 0.29	28.32 ± 0.36	36.60 ± 0.98	25.0 ± 11.47
Reference scan	38.17 ± 0.90	32.28 ± 0.73	34.11 ± 0.52	34.9 ± 2.63

Data are shown as averages ± standard deviations

ROI region of interest, TCM tube current modulation, OB organ-based

Table 7 Noise at ROIs in the GE performance phantom with different scanning techniques

Scanning techniques	Anterior ROI noise	Mid-central ROI noise	Posterior ROI noise	Average noise
TCM				
Longitudinal-TCM	2.72 ± 0.04	3.63 ± 0.08	3.76 ± 0.06	3.37 ± 0.48
Angular-TCM	3.07 ± 0.05	3.63 ± 0.08	3.95 ± 0.07	3.55 ± 0.38
New OB-TCM	3.43 ± 0.07	3.88 ± 0.03	3.56 ± 0.17	3.62 ± 0.22
Shielding scan				
Bismuth	52.70 ± 3.60	3.89 ± 0.04	3.42 ± 0.04	20.01 ± 24.01
Lead glasses	43.51 ± 1.50	4.46 ± 0.06	3.23 ± 0.08	17.07 ± 19.38
Reference scan	3.01 ± 0.07	3.68 ± 0.08	3.34 ± 0.05	3.34 ± 0.29

Data are shown as averages ± standard deviations

ROI region of interest, TCM tube current modulation, OB organ-based

118, the threshold value for the absorbed dose to the eye lens was set at 0.5 Gy for acute or protracted exposure [13]. For members of the public, the dose limit was recommended as a maximum of 15 mSv per year [14]. Eye lens turbidity can be induced at radiation exposure doses below the brain CT radiation value of 0.5–2 Gy, and cataracts and secondary vision disorders can be induced at values of 4 Gy or higher [12, 15]. However, current studies suggest that eye lenses are much more radiation sensitive than earlier reports indicated [16].

The older OB-TCM method used to reduce the radiation dose to the eye resulted in a reduction in CT radiation output at the anterior side of the head, whereas radiation at the posterior side was increased as a compensatory mechanism to ensure image quality. Therefore, a reasonable reduction in the total amount of X-ray radiation to the head was not achieved. NOB-TCM can reduce the tube current to the anterior side of the head (i.e., radiosensitive eye location) and maintain the radiation doses to other areas of the body. Therefore, this technique reduces the dose to the eye and head more effectively without a loss of image quality.

In this study, NOB-TCM was applied to an anthropomorphic head phantom, and a decrease in CTDI_{vol} of 16.31% (48.20 mGy) relative to the reference scan (57.59 mGy)

was observed; this was the largest decrease among the measured CTDI_{vol} values obtained with all tested TCM methods. This finding differs considerably from the result obtained by Want et al. in which OB-TCM yielded a 1.6% dose reduction [16]. According to radiation exposure measurements obtained with a photosensitive fluorescent dosimeter in our study, NOB-TCM reduced radiation exposure by 25.88%. Radiation shielding methods reduce the dose from a primary X-ray beam by 30–50% when placed on the surface of the target organ [16].

In this study, an in-plane shielding CT examination with bismuth shields yielded a 36.91% reduction in radiation exposure, which was similar to the dose reduction rates reported for other studies and much higher than that obtained with NOB-TCM. Similarly, shielding with lead glasses led to a 44.53% dose reduction. However, a scan that excluded the eye region and adjusted the gantry scanning angle yielded the highest reduction rate of 89.85% (4.61 mGy), compared with the reference scan. These results suggest that excluding the eye region from the CT scan is the best solution for reducing radiation exposure to the eyes. However, NOB-TCM or shielding materials are alternative solutions in cases of head CT involving the orbital region.

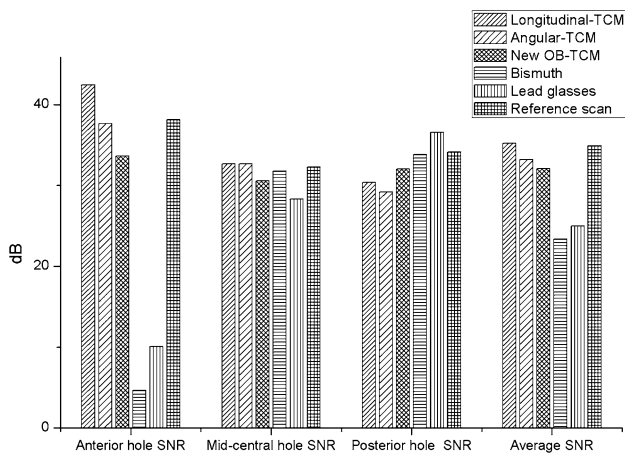


Fig. 4 Signal-to-noise ratios (SNRs) of the GE performance phantom with different scanning techniques. *TCM* tube current modulation, *OB* organ-based

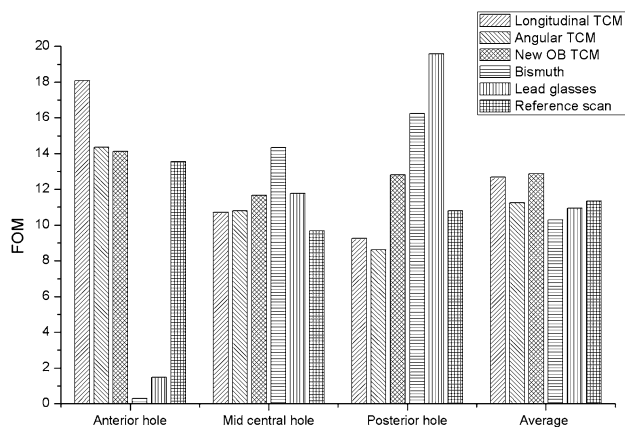


Fig. 5 Figures of merit (FOMs) at the GE performance phantom achieved with different scanning techniques. *TCM* tube current modulation, *OB* organ-based

In the evaluation of the image quality with the GE performance phantom conducted in this study, CT numbers obtained with NOB-TCM differed little from the reference scan (0.47% increase at the anterior hole, 0.21% decrease at the posterior hole). However, with NOB-TCM, the noise was increased by 13.9% at the anterior hole and 6.5% at the posterior hole from the reference scan. The CT-number and noise was increased to a greater extent at the anterior hole than at the posterior hole. The SNR value decreased by 11.86% at the anterior hole and 6.16% at the posterior hole, with an average SNR decrease of 8.02% from the reference scan. This result was due to a reduction in tube current at the anterior region on the GE performance phantom images.

The bismuth shield and lead glasses reduced radiation exposure to a greater extent than NOB-TCM. However,

these techniques also increased the CT number and noise value at the anterior hole, compared to the reference scan. Accordingly, the SNR at the anterior hole and average SNR were decreased. These characteristics resulted in greater variation than that achieved with NOB-TCM. This large-scale reduction in radiation exposure not only affected the CT numbers of images, but also increased the noise. This technique may have a negative effect on the image quality.

The average FOM of the GE performance phantom image was increased with longitudinal-TCM and NOB-TCM, when compared with the reference scan. In contrast, the average FOM of the GE performance phantom image was decreased with the bismuth shield and lead glasses. Because a high FOM value indicates a relatively better system performance from the ROI of radiation exposure and SNR, the TCM can improve the image quality rather than the reference CT scan. Considering the FOM, the TCM was more efficient than bismuth and lead glasses shield scans. The NOB-TCM was still the most effective technique for combined dose reduction to the eye and image quality.

Conclusion

The NOB-TCM was more efficient than in-plane shielding techniques in terms of reducing the radiation dose to the eyes and ensuring image quality. This method can be used to reduce the radiation dose to the eyes when the head CT includes the orbital area.

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Compliance with ethical standards

Conflict of interest Author Jung-Su Kim declares that he has no conflict of interest. Author Soon-Mu Kwon declares that he has no conflict of interest. Author Jung-Min Kim declares that he has no conflict of interest. Author Sang-Wook Yoon declares that he has no conflict of interest.

Ethical approval All procedures performed in studies involves phantom study.

Informed consent Informed consent is not required for this phantom study.

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