Original Article

Tradeoffs between Radiation Exposure to the Lens of the Eyes and Diagnostic Image Quality in Pediatric Brain Computed Tomography

Vahid Karami[1], Mohsen Albosof[2], Mehrdad Gholami[3], Mohammad Adeli[2], Ali Hekmatnia[4], Mehdi Fallah Bagher Sheidaei[1], Ali Taghizadeh Behbahani[2], Hoda Sadat Sharif[1], Somayeh Jafrasteh[1]

[1]Clinical Research Development Unit, Ganjavian Hospital, Dezful University of Medical Sciences, Dezful, Iran, [2]Department of Biomedical Engineering, Dezful Branch, Islamic Azad University, Dezful, Iran, [3]Department of Medical Physics, Lorestan University of Medical Sciences, Khorramabad, Iran, [4]Department of Radiology, Isfahan University of Medical Sciences, Isfahan, Iran

Abstract

Background: Computed tomography (CT) of the brain is associated with radiation exposure to the lens of the eyes. Therefore, it is necessary to optimize scan settings to keep radiation exposure as low as reasonably achievable without compromising diagnostic image information. The aim of this study was to compare the effectiveness of the five practical techniques for lowering eye radiation exposure and their effects on diagnostic image quality in pediatric brain CT. **Methods:** The following scan protocols were performed: reference scan, 0.06-mm Pbeq bismuth shield, 30% globally lowering tube current (GLTC), reducing tube voltage (RTV) from 120 to 90 kVp, gantry tilting, and combination of gantry tilting with bismuth shielding. Radiation measurements were performed using thermoluminescence dosimeters. Objective and subjective image quality was evaluated. **Results:** All strategies significantly reduced eye dose, and increased the posterior fossa artifact index and the temporal lobe artifact index, relative to the reference scan. GLTC and RTV increased image noise, leading to a decrease signal-to-noise ratio and contrast-to-noise ratio. Except for bismuth shielding, subjective image quality was relatively the same as the reference scan. **Conclusions:** Gantry tilting may be the most effective method for reducing eye radiation exposure in pediatric brain CT. When the scanner does not support gantry tilting, GLTC might be an alternative.

Keywords: *Brain computed tomography, eye lens, image quality, radiation exposure*

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Introduction

Computed tomography (CT) of the brain is the most common and primary imaging examination for a variety of indications, accounting for approximately 75% of all pediatric CT scans.[1-3] A concern is that brain CT contributes to a significant radiation exposure to the lens of the eyes.[4] The estimated lens dose resulting from a <15-year-old pediatric brain CT ranges from 1.4 to 54.9 mGy, depending on the optimization techniques used.[2]

The correlation between CT scanning and the risk of lens opacity is controversial.[5-7] However, results of recent epidemiological studies suggest that the lens of the eyes is more sensitive to radiation than previous estimates.[8-10] The threshold dose needed to induce ophthalmologically detectable lens opacity (cataract formation) seems to be around 500 mGy for adults, which is much lower than previous estimates of 2000–8000 mGy.[11-13] In pediatric patients, this threshold dose maybe even 50% lower because they have high radiation tissue sensitivity.[14] Further, there are potential uncertainties about the threshold dose and the latent period for the formation of radiation-induced cataract; in other words, the process of cataractogenesis may be stochastic with no specific threshold.[11,15] Although a typical lens dose resulting from a pediatric brain CT is lower than those estimated to be cataractogenic, the associated cumulative dose from different scans could be significant. A cohort study including 410,997 children and young adults who underwent CT in the UK between 1985 and 2014 showed that some of the patients experienced over 50 head-region CT examinations.[2] Therefore, it seems quite reasonable and necessary to investigate radiation dose optimization strategies to safeguard patients' safety.

The radiation exposure of the lens can be reduced following several strategies such

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Address for correspondence:
Dr. Vahid Karami, Clinical Research Development Unit, Ganjavian Hospital, Dezful University of Medical Sciences, Dezful, Iran.
E-mail: karami.v@ajums.ac.ir

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as orbital bismuth shield,[15-17] organ-based tube current modulation,[15,18] gantry tilting,[17,19-21] iterative reconstruction techniques,[22] and manipulation of scan settings such as tube current[15] and tube voltage.[23] However, tradeoffs between radiation exposure and diagnostic image quality should be considered.

To our knowledge, no clinical-based study has evaluated several dose-reduction strategies in practice. Previous studies have used phantoms to investigate dose-reduction strategies. In patient studies, the dose reduction techniques are limited to 1 or 2 strategies, rendering the comparison of these strategies difficult, if not impossible, because of the methodological differences. Therefore, this study aimed to compare the dose and image quality of orbital bismuth shield, globally lowering the tube current (GLTC), reducing the tube voltage (RTV), gantry tilting, and a combination of gantry tilting and bismuth shielding for reducing the radiation exposure to the lens of the eyes at brain CT. The findings of this research might lead to the understanding of dose optimization strategies in clinical practice.

Methods

This study was reviewed and approved by the Medical Ethics Committee of Dezful University of Medical Sciences (ir.dums.rec. 1398.054). Written informed consent form was obtained from the patients/parents before the study.

Preparation of the unenhanced brain computed tomography dataset

Initially, we retrospectively reviewed 420 pediatric brain CT scans from the picture archiving and communication system (PACS, Medal electronic workstation) of our institution (Afshar CT center) to determine the reference brain CT protocol routinely used in clinical practice. Once the reference scan protocol was known, an experiment was designed to investigate the effects of different optimization techniques on radiation dose received by the lens of the eyes and also the objective and subjective quality of pediatric brain CT scans. For that purpose, a population of pediatric patients was inspected to select the patients that were eligible for the experiment. The patients were deemed eligible to be included in the study if they had to undergo unenhanced brain CT, they were 16 years old or less, they fulfilled the standard positioning requirements of the study and their parents/guardians signed an informed consent form.

The patients that had to undergo life-saving or enhanced brain scans or those that had metallic implants were excluded from the study. The first 20 eligible patients were randomly selected and assigned to a reference group. To investigate the dose reduction techniques, five more groups of patients were needed. Since the primary attenuation coefficients in brain CT depend on the skull bone composition,[24,25] which is age dependent, the assignment of patients to these five groups was not only based on the mentioned criteria but also matching the groups based on patients age. Totally, 107 patients (71 males, 36 females) complied with the mentioned eligibility criteria and therefore were included in this study. A 16-slice Philips-MX CT scanner was used to conduct the scans under six different protocols (including the reference scan), each for a different group of eligible patients as follows:

The reference scan (n = 20)

The reference scan was performed without any dose reduction technique, using the same reference protocol that were routinely used in clinical practice (i.e., sequential mode; kVp: 120; fixed mA: 215; gantry rotation time: 1.5 s; pitch: 0.5; slice thickness: 4.5 mm; field of view: 250 mm; collimation: 12 × 1.5, and gantry tilt: 0°). The scan range was planned from the C2-lamina to the vertex, and the eye lens was included in the scan field.

Bismuth shielding (n = 20)

The CT scanner settings were the same as the reference scan except that a 0.06-mm lead equivalent bismuth shield (AttenuRad Radiation Protection, FandL Medical Products, USA) and a 1-cm shield-to-eyelid spacer placed on the eyes were used.

Globally lowering the tube current (n = 20)

The CT scanner settings were the same as the reference scan, except that the tube current was lowered by 30% (from 215 mA in the reference scan to 150 mA).[15]

Reducing the tube voltage (n = 7)

The CT scanner settings were the same as the reference scan except that the tube voltage was reduced from 120 to 90 kVp. Previous studies on RTV have concurrently increased the tube current by a factor of 3.18,[23] 2.7,[26] and 1.14[27] to compensate for the image noise increase and their results are available. Instead, the tube current remained unchanged in this study, but the scans were piloted on seven patients under 5-year-old (who normally have lower attenuation) and their results were compared with those of their peers among the patients of the reference scan.

Gantry tilting (n = 20)

The CT scanner settings were the same as the reference settings, except that the gantry was tilted along the supraorbital meatal line (SOML) to exclude the eyes from the scan field. A tilt angle of 11°–26° (depending on the patient's head position at the headrest) was used.

Gantry tilting and bismuth shielding (n = 20)

The CT scanner settings were the same as the reference settings except that the gantry was tilted along the SOML and a 0.06-mm lead equivalent bismuth shield was placed directly on the eyes. The eye lens and the bismuth shield were excluded from the scan field. The geometric profiles used in all scan protocols are presented in Figure 1.

Dosimetry

The high radiosensitive LiF: Mg, Cu, *P* thermoluminescent dosimeters, commercially known as thermoluminescence dosimeter (TLD) GR200, were used for radiation dose measurements. Before irradiations, the TLDs were calibrated and their correction coefficients were calculated.[28,29] Before and after each use, TLDs were annealed in a Harshaw 3500 TLD reader (Harshaw, Solon, OH) at 245°C for 10 min and then left to cool down to room temperature.[30,31] The patients were positioned at the isocenter of the gantry and the scanogram was performed in lateral projection. The scan range and geometry profile were manually planned to the predefined scan protocol. For each patient, a set of two TLDs were taped on the center (and, if impossible, in the internal corner) of each eyelid and the scan was performed. In the case of the bismuth shield, the shield was located on the eyes, completely covering the TLDs. Given the high radiosensitivity of the TLDs, to ensure that the measured radiation doses are solely attributed to radiation exposure from the CT scanner, it is necessary to measure the natural background radiations and accordingly correct measurement results.[29] We used two TLDs to measure the background radiations. These TLDs were used to compensate the effect of background radiations in measurement results.

Objective assessment of image quality

All 107 brain scans were analyzed using objective measures of image quality. For that purpose, an axial CT image was selected at the level of basal ganglia[19,23,32,33] and six 20-mm^2 circular regions-of-interest (ROI) were placed on the following anatomical locations: 2 ROIs in the gray matter and the subcortical white matter of the frontal lobe; 2 ROIs in the gray matter and the subcortical white matter of the occipital lobe; an ROI in the gray matter of the thalamus, and an ROI in the white matter of the posterior limb of the internal capsule[23,33] [Figure 2]. The mean and the standard deviation (SD) of the CT numbers (in the Hounsfield unit [HU]) were recorded for each ROI, and then, the following image quality measures were calculated:

1. Gray-white matter contrast-to-noise ratio (CNR) = $(GM_{HU}\text{-}WM_{HU})/[(SD^2_{GM} + SD^2_{WM})]^{1/2}$[23,32,33]
2. Gray-matter signal-to-noise ratio (SNR_{GM}) = GM_{HU}/SD_{GM}[23,33]
3. White-matter SNR (SNR_{WM}) = WM_{HU}/SD_{WM}[23,33]
4. Gray-matter noise = SD_{GM}[15,19,33,34]
5. White-matter noise = SD_{WM}.[15,19,33,34]

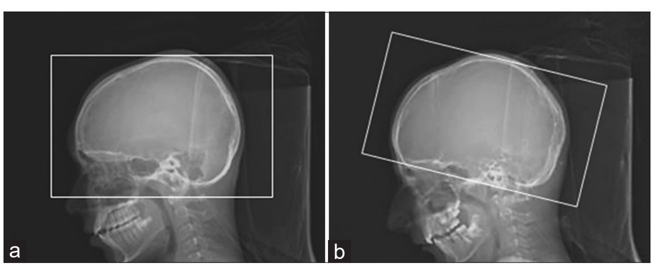

Figure 1: The geometric profiles used in different scan protocols: The reference scan, bismuth shielding, GLTC and RTV (a), gantry tilting and gantry tilting with bismuth shielding (b). GLTC – Globally lowering the tube current, RTV – Reducing the tube voltage

Since the volume CT dose index ($CTDI_{vol}$) is proportional to the inverse square root of the image noise (i.e., $CTDI_{vol} \propto 1/(\sqrt{\text{image noise}})$,[35] a correction factor was used to compensate for the difference in $CTDI_{vol}$ at 90 kVp and 120 kVp. This factor was computed as the square root of the ratio of $CTDI_{vol}$ at two different kVp levels;[23,26,33] for example$\sqrt{[22/52]} = 0.65$.

Further, an ROI with an area of 200-mm^2 was placed at the interpetrous region of the posterior fossa[23,33] as a location highly susceptible to streak and beam hardening artifacts.[36] Two additional ROIs were placed on the right and left temporal lobes as regions susceptible to the streak and beam hardening artifacts caused by the orbital bismuth shield and gantry tilting. The SDs of the CT numbers in the posterior fossa and temporal lobes were recorded and used as the posterior fossa artifact index (PFAI) and temporal lobe artifact index (TLAI), respectively, as they reflect the perturbations of the CT numbers caused by streak and beam hardening artifacts.[33,36]

Subjective assessment of image quality

Two experienced radiologists (A.H and H.S.S) examined the brain scans and collaboratively evaluated the overall quality of the scans, the noise (image graininess) level, introduced artifacts, and gray-white matter differentiation. They evaluated the scans based on the 5-point scoring system used by Park *et al*.[23] as follows:

Scores for image noise: very severe and unacceptable, (1) severe (2), average (3), mild (4), and absent (5).

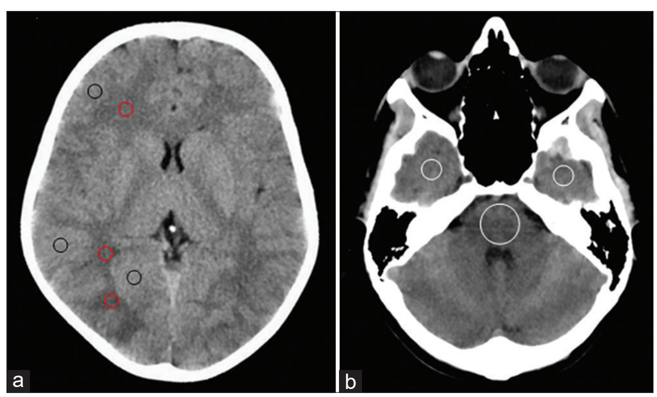

Figure 2: Axial, unenhanced brain scans of an 8-year-old pediatric patient with reference scan settings at the level of basal ganglia (a) and cerebellum (b) with circular ROI used for objective analysis of image quality. The ROIs in the gray matter (black circles) and subcortical white matter (red circles) of the frontal and occipital lobes, in gray matter of the thalamus and white matter of the posterior limb of the internal capsule (a) and the temporal lobes and interpetrous region of the posterior fossa (white circles, b). ROI – Regions-of-interest

Scores for Gray-white matter differentiation: undifferentiated (1), poor (2), average (3), good (4), and perfect (5).

Scores for the introduction of the artifact: Very severe and affecting diagnosis (1), severe but not affecting diagnosis (2), present but acceptable (3), visible but mild (4), and absent (5);

Scores for overall image quality: Unacceptable (1), suboptimal (2), average or acceptable (3), good (4), and excellent (5). To avoid shaping the radiologists' evaluations and reduce potential bias, the images were presented to them in a randomized order and they were not informed of the methodology and objectives of the study.

Statistical analysis

The statistical analyses were performed using the statistical software SPSS (Version 25.0. Armonk, NY: IBM Corp.). Two-sided $P < 0.05$ were considered statistically significant. All values are reported as the mean value ± the SD. The normality of data was evaluated using Shapiro–Wilk test, and then, the independent *t*-test and Mann–Whitney test were applied to compare the outcomes in different scan settings.

Results

Dosimetry

The radiation dose measurements for each scan protocol and their differences from the reference scan are presented in Tables 1 and 2. The mean eye dose varied from 2.81 mGy to 33.41 mGy, depending on the scan protocol used. When compared to the reference scan, the combined use of gantry tilting and bismuth shielding resulted in the highest dose reduction to the eyes (91.58%, $P < 0.0001$).

Objective assessments of image quality

Results of the objective image quality measurements for all scan protocols are presented in Tables 3 and 4. Bismuth shielding caused a statistically significant increase in the PFAI (+1.37 SD, $P < 0.0001$), TLAI (+1.62 SD, $P < 0.0001$) and temporal lobe CT numbers (+1.95 HU, $P = 0.017$), relative to the reference scan. Lowering the tube current by 30%, increased the image noise (+1.10 SD, $P < 0.0001$), PFAI (+1.31 SD, $P = 0.0002$), and TLAI (+1.25 SD, $P < 0.0001$). The SNR (−11.86, $P < 0.0001$) and CNR (−2.31, $P < 0.0001$), however, decreased significantly [Table 3]. RTV from 120 kVp to 90 kVp for pediatric patients <5 years old decreased the gray-and-white matter SNR (−14.5, $P = 0.002$) and CNR (−2.59, $P = 0.002$), [Table 4]. Tilting the gantry along the SOML increased the PFAI (+1.01 SD, $P = 0.001$) and TLAI (+1.11 SD, $P = 0.0001$) by comparison with the reference scan [Table 3].

Subjective assessments of image quality

As shown in Figures 3 and 4, subjective assessments of image quality scores found no significant difference between the reference scan and other protocols, the only exception being the bismuth shielding, which introduced severe visible artifacts around the orbit ($P = 0.023$). An example of axial image in each scan protocol is shown in Figure 5.

Discussion

The exposure settings should be customized for pediatric patients to deliver the lowest radiation dose required for diagnostic image quality.[1,37] While dedicated pediatric scan settings are widely available in most CT scanners,[38] their

Table 1: The mean and standard deviation of the eye dose and the percentage of dose reduction in different scan settings for pediatric patients under 16 years of age

Examined protocols	Eye dose (mGy)	Dose reduction (%)	P^a
Reference scan	33.41±7.14	-	-
Bismuth shielding	24.04±3.73	28.04	<0.0001
Globally lowering the tube current	23.02±3.76	31.09	<0.0001
Gantry tilting	7.63±5.70	77.16	<0.0001
Gantry tilting and bismuth shielding	2.81±0.89	91.58	<0.0001

[a]*P*-value between the reference scan and other protocols

Table 2: The mean and standard deviation of the eye dose and the percentage of dose reduction in reference scan and reducing tube potential setting for pediatric patients under 5 years of age

Examined protocols	Dose (mGy)	Dose reduction (%)	*P*
Reference scan	29.55±5.07	-	-
Reducing tube voltage	20.38±2.01	31.03	0.013

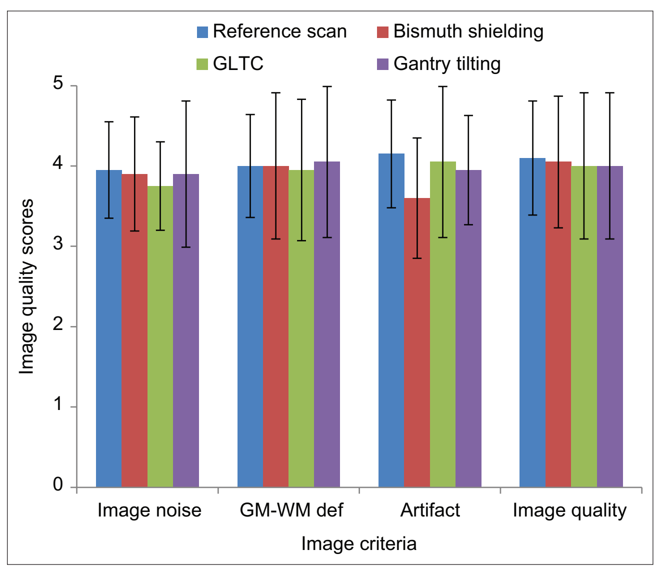

Figure 3: The mean and SD of the subjective image quality scores in different scan protocols for pediatric patients under 16 years old (SDs are shown as error bars). SD – Standard deviation; GLTC – Globally lowering tube current; GM-WM – Gray matter-white matter

Table 3: Objective image quality measures in different scan protocols for pediatric patients under 16 years of age

Image quality descriptors	Reference scan	Bismuth shielding	Difference[a] P^a	GLTC	Difference[b] P^b	Gantry tilting	Difference[c] P^c
GM, HU[d]	33.71±0.94	33.75±1.14	+0.04 0.776	33.63±1.22	−0.08 0.825	33.82±1.32	+0.11 0.762
GM, SD (noise)[d]	1.30±0.30	1.34±0.39	+0.04 0.935	2.42±0.47	+1.12 <0.0001	1.42±0.63	+0.12 0.447
WM, HU[d]	25.22±0.81	25.20±0.91	−0.02 0.948	25.13±1.58	−0.09 0.823	25.24±0.93	+0.02 0.944
WM, SD (noise)[d]	1.21±0.38	1.24±0.39	+0.03 0.794	2.29±0.63	+1.08 <0.0001	1.29±0.37	+0.08 0.504
CNR[d]	4.87±1.19	4.86±1.29	−0.01 0.791	2.56±0.66	−2.31 <0.0001	4.5±1.22	−0.37 0.343
SNR[d,e]	25.04±5.13	24.74±5.82	−0.30 0.871	13.18±2.7	−11.86 <0.0001	25.42±8.70	+0.38 0.745
Noise[d,f]	1.26±0.23	1.29±0.31	+0.03 0.683	2.36±0.37	+1.10 <0.0001	1.36±0.39	+0.10 0.329
PF, HU[g]	27.58±4.06	29.31±2.88	+1.73 0.149	27.74±2.97	+0.16 0.889	28.51±3.17	+0.93 0.426
PFAI[g]	4.20±0.70	5.57±0.75	+1.37 <0.0001	5.51±1.23	+1.31 0.0002	5.21±1.05	+1.01 0.001
TL, HU[h]	33.35±2.97	35.30±1.81	+1.95 0.017	33.41±3.18	+0.06 0.808	34.38±2.08	+1.03 0.214
TLAI[h]	3.51±0.80	5.13±0.54	+1.62 <0.0001	4.76±0.91	+1.25 <0.0001	4.62±0.88	+1.11 0.0001

[a]Between bismuth shielding and the reference scan; [b]Between GLTC and the reference scan; [c]Between gantry tilting and the reference scan; [d]At the level of the basal ganglia; [e]Averaged between G-and-WM SNR; [f]Averaged between G-and-WM noise; [g]At the level of posterior fossa; [h]At the level of temporal lobe. GM – Gray matter; WM – White matter; CNR – Contrast-to-noise ratio; SNR – Signal-to-noise ratio; PF – Posterior fossa; PFAI – PF artifact index; TL – Temporal lobe; TLAI – Temporal lobe artifact index; GLTC – Globally lowering the tube current; HU – Hounsfield unit; SD – Standard deviation

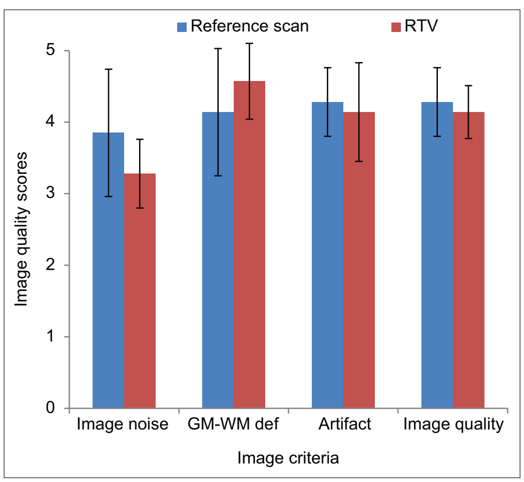

Figure 4: The mean and SD of the subjective image quality scores in the reference scan and the reduced tube potential for pediatric patients under 5 years old (SDs are shown as error bars). SD – Standard deviation; GM-WM – Gray matter-white matter; RTV – reducing tube voltage

clinical use is commonly ignored.[39,40] This situation would result in greater radiation exposure than is needed for pediatric patients.[38,39] In our study, 387 out of 420 (92%) screened pediatric brain CT scans were performed using preprogrammed adult scan settings. Furthermore, there was no evidence of the gantry tilting at all. This emphasizes the need for optimization of the current pediatric scan settings. Results of a similar study by the international atomic energy agency on pediatric CT practice in 146 CT facilities in 40 countries of Asia, Europe, Latin America, and Africa showed that in 40% of the facilities, the specific body size exposure settings were not used and in 13% of them, the same exposure settings were used for all age groups.[38]

In this study, the mean eye dose in the reference scan was 33.41 mGy which is higher than 2.17–18.9 mGy reported by Tahmasebzadeh *et al.* for the ≤15 years old pediatric patients.[41] This discrepancy may stem from differences in the radiation dose measurement methods and the scan settings used (kVp, mAs, and pitch). Bismuth shields have been used to reduce radiation exposure of the eyes in pediatric brain CT.[19,42] In our study, a bismuth shield with a 1-cm shield-to-eyelid spacer decreased the eye dose by 28% relative to the reference scan, that is consistent with others.[15,16,43] The clinical effectiveness of bismuth shields however has been questioned.[30,34,44] Shields may cause streak and beam-hardening artifacts,[34] increase noise[15,19] and CT numbers[15,43] of the images, especially in the anterior regions of the head.[15] In a phantom study, Wang *et al.* reported a statistically significant increase in image noise and CT numbers, even in the intracranial regions, when orbital bismuth shield to be used.[15] Similarly, Geleijns *et al.* revealed a 1–2 SD increase in image noise due to the orbital bismuth shield.[34] These findings are consistent with our results in the posterior fossa and temporal lobes [Table 3]. In fact, photons coming from the

Table 4: Objective image quality measures in the reference scan and the reduced tube potential for pediatric patients under 16 years of age

Image quality descriptors	Reference scan	Reducing tube potential	Difference *P*
GM, HU[a]	32.87±0.62	36.37±0.79	+3.50 0.002
GM, SD (noise)[a,b]	1.13±0.22	2.51±0.56	+1.38 0.002
WM, HU[a]	24.41±0.38	26.19±1.59	+1.78 0.018
WM, SD (noise)[a,b]	1.04±0.38	2.20±0.34	+1.16 0.002
CNR[a]	5.64±1.29	3.05±0.71	−2.59 0.002
SNR[a,c]	28.21±6.68	13.71±1.63	−14.50 0.002
Noise[a,d]	1.09±0.25	2.35±0.27	+1.26 0.002
PF, HU[e]	28.43±3.98	31.55±3.69	+3.12 0.179
PFAI[e]	3.82±0.63	5.62±1.17	+1.80 0.015
TL, HU[f]	31.40±3.44	34.38±1.30	+2.98 0.073
TLAI[f]	3.35±0.73	4.88±1.04	+1.53 0.018

[a]At the level of the basal ganglia; [b]Calculated using corrected noise; [c]Averaged between G-and-WM SNR; [d]Averaged between G-and-WM noise; [e]At the level of the posterior fossa; [f]At the level of the temporal lobes. GM – Gray matter; WM – White matter; CNR – Contrast-to-noise ratio; SNR – Signal-to-noise ratio; PF – Posterior fossa; PFAI – PF artifact index; TL – Temporal lobe; TLAI – Temporal lobe artifact index; HU – Hounsfield unit; SD – Standard deviation

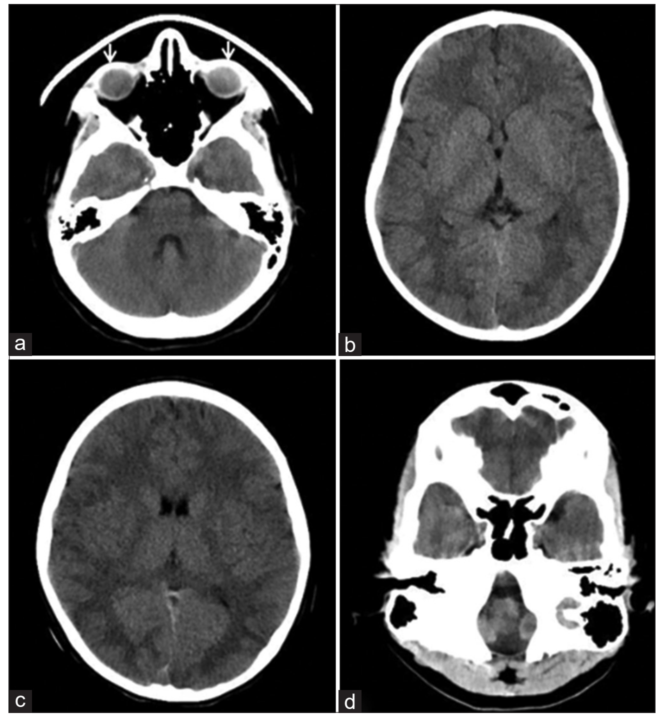

Figure 5: An example of axial image in each scan setting: (a) an axial scan of a 15-year-old pediatric patient with an orbital bismuth shield and a 1-cm shield-to-eyelid spacer. There are severe artifacts around the orbit (arrows), (b) an axial scan of a 8-year-old pediatric patient with 30% GLTC, (c) an axial scan of a 10-year-old pediatric patient with tube voltage of 90-kVp, (d) an axial scan of a 15-year-old pediatric patient with gantry tilted along the SOML at the levels of temporal lobes. GLTC – Globally lowering the tube current, SOML – Supraorbital meatal line

anterior and posterior directions of the head are attenuated by the shield before reaching the detector and hence, increase CT numbers and image noise due to the waste of useful radiation. As shown in Figure 5, the shield caused severe visible artifacts around the orbit, which have very little impact on CT diagnostic features as they fall outside the regions of diagnostic interest.[19,42,45]

GLTC can be used to reduce radiation exposure of the radiosensitive tissues during CT examinations.[15,46] In our study, a 30% decrease in the tube current resulted in a 31% reduction in the eye dose from the reference scan, which confirms Wang *et al*.[15] In consistence with previous phantom-based studies,[15] in our study, the GLTC increased the gray-and-white matter noise at the level of basal ganglia, the posterior fossa and the temporal lobes, whereas the mean CT numbers were relatively similar to the reference scan ($P > 0.05$). The corresponding subjective image quality scores however did not significantly change between the two groups of images [Figure 3]. It seems that the GLTC is superior to the bismuth shield because it provides similar or even higher dose reduction levels without concerns associated with the use of the bismuth shield, such as increasing the CT numbers of the brain tissue,[15,43,47] introduction of streaks and beam-hardening artifacts below the shield,[34,47] wasting the useful radiation,[44,48,49] the need for regular sterilization of the shield,[15] unavailability of the shield in some facilities,[38] and additional costs. In addition to the eyes, GLTC would reduce radiation exposure of the brain tissue as well. Moreover, even small movements of a restless pediatric patient during the scan can create severe streak artifacts due to the use of high attenuation materials. The GLTC may be limited by increasing the image noise; however, its reduction by 30% does not subjectively compromise diagnostic image quality, as our study showed [Figure 3]. The combined use of GLTC with iterative reconstruction algorithms is reported to significantly compensate for this increased image noise.[44]

RTV from 120 kVp to 100 kVp and 80-kVp has been used to reduce radiation exposure in pediatric brain CT.[23,24,26,27,42] In our study, RTV from 120-kVp to 90-kVp was associated with a 31% reduction in the eye dose ($P = 0.013$) that is moderate to 21.8% reported by Mukundan *et al*. for RTV from 120 to 100 kVp.[42] In line with our findings, Park *et al*. showed that using 80-kVp instead of 120 kVp for pediatric brain CT significantly increased the PFAI, gray-white matter contrast (difference in HU) and gray-and-white matter CT number and noise ($P < 0.001$), and decreased gray-and-white matter SNR ($P < 0.05$).[23] In our study, 90 kVp instead of 120 kVp significantly decreased gray-white matter CNR (−2.59, $P = 0.002$) that confirms Nagayama *et al*.,[27] however contrasts with Ben-David *et al*.[26] and Park *et al*.[23] In opposite to ours, in these studies, the authors have concurrently increased the tube current-time-product by a factor of 3.18[23] and 2.7[26] to compensate for the increased image noise. However, the RTV experiment had limitations. The only options that the CT scanner offered for the tube voltage were 90, 120, and 140 kVp. Since 120 kVp was used in the reference scan group, 90 kVp was the only option below 120 kVp that could be used for the experiment. In addition, the 90 kVp may not be ethically recommended for older pediatrics due to image quality deterioration by increasing image noise. Therefore, only younger pediatrics (≤5 years old), who have lower attenuation coefficients, were included in this group to guarantee the image quality. Since only seven patients in the reference scan group ($n = 20$) were ≤5 years old, only seven patients were included in the RTV group to match the populations. This led to a smaller sample size; therefore, the RTV results might not be generalizable. The validity of the RTV results should be evaluated using a larger sample in future studies.

The European guidelines recommend that the eye lens should be excluded from the scan field by tilting the gantry along the SOML. Furthermore, the slice thickness is recommended to be 5 mm for the hemispheres, but it should be lowered to 2 mm for the posterior fossa to reduce interpetrous artifacts.[50] When gantry tilting is applied, the eye dose is solely due to scattered radiations.[17] In our study, gantry tilting caused a statistically significant eye-dose reduction of 77% from the reference scan that is consistent with 75%–88% reported in the previous studies.[17,19,51-53] In some scanners, gantry tilting is not possible. In these cases, a head support may be useful to keep the patient's chin down such that the SOML is perpendicular to the CT table. For patients who could not follow this practice, the GLTC may be useful. However, there are challenges associated with the clinical use of gantry tilting. In some studies, the introduction of beam-hardening artifacts in the posterior fossa and impairment of the visualization of the temporal lobes have been reported,[43,51] whereas other reports rejected these drawbacks.[20,54] In our study, gantry tilting along the SOML resulted in a 1–2 SD increase in the PFAI and TLAI from the reference scan ($P < 0.001$). In the case of subjective image quality, no significant differences were found between the two groups of images ($P > 0.68$) [Figure 4]. Some facilities have used thin slices and/or raised the tube voltage in the skull base and petrous region to overcome interpetrous artifacts; however, these techniques were demonstrated to be unsuccessful in other studies.[36,55]

We also examined whether the combined use of gantry tilting and bismuth shielding brings any additional benefit. This practice caused a 14.4% additional dose reduction than gantry tilting alone (91.58% vs. 77.18%). This is consistent with a dose reduction of 18% reported by McLaughlin and Mooney.[17] Given the small reduction in the eye dose together with the cost of the shield and infection control considerations before each use, justification for the combined use of bismuth shield and gantry tilting may be questionable. Furthermore, since the shield was located outside the scan field, image quality assessment was inconsequential.

This study faced several limitations. (1) The experiment was performed using a single CT scanner in one facility, (2) Given that the CT scanner represents three options for tube voltage selection of 90, 120, and 140 kVp, the only available choice to study the RTV protocol was 90-kVp. However, there were ethical limitations for the use of 90 kVp in larger pediatrics since it might increase the risk of scan repetition by increasing the image noise. Therefore, only smaller pediatrics (≤5 years old) which have lower attenuation coefficients, were included in the RTV group to guarantee the image quality.

Conclusions

In this study, five practical techniques for reducing eye radiation dose during pediatric brain CT were investigated. All the techniques decreased the eye dose significantly; however, they gave rise to the increase of PFAI and TLAI by ~1–2 SD. Further, GLTC and RTV increased the image noise at the level of basal ganglia, leading to lower CNR and SNR. On the bright side, the subjective image quality remained relatively unaffected except for bismuth shielding which caused severe artifacts around the orbit. Gantry tilting along the SOML could be the most effective method for lowering eye radiation exposure in pediatric brain CT. When the scanner does not support gantry tilting, GLTC might be an alternative.

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Conflicts of interest

There are no conflicts of interest.

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