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Eye Lens Radiation Doses to Miscentering Patients and Health-Care Staff From Head Computed Tomography

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A B S T R A C T

The purposes of this study were to assess the effect of patient vertical miscentering on eye lens radiation doses in patients who have undergone head computed tomography (CT) and to measure the absorbed dose to the eye lens in health-care staff who remain in the CT room during the procedure. All measurements were performed in phantoms. Nanodot™ optically stimulated luminescence dosimeters were used to measure radiation doses. For the assessment of the effect of patient vertical miscentering, CT scans were obtained at six different table heights. The radiation doses in the eye lens of health-care staff received when working at three different locations in the CT room were measured. Correction coefficients were applied to determine equivalent dose, Hp(3), in the eye lens. The results revealed that the positioning of patients off the CT scan isocenter during head CT may result in a significantly increased eye lens dose. The phantom eye lens doses can be increased by 43.7% (70 mGy), and image noise increased when the table was 5 cm below the isocenter due to the effect of the bow tie filter and eyes being irradiated directly by the primary beam for a greater proportion of the tube rotation. An estimated eye lens dose of ≤0.1-0.2 mSv was found in phantoms simulating health-care staff, with the dose depending on positioning of the phantom. Health-care staff in the room during CT scans are at risk of a significant eye lens dose, particularly if positioned posterior to the gantry.

Introduction

The use of computed tomography (CT) scanning in emergency departments has increased more than threefold over the last 2 decades (Bellolio et al., 2017; Raja et al., 2014). Head CT is one of the more common emergency CT examinations and plays a critical role in the evaluation of both trauma and nontrauma patients (patients with dizziness, syncope, or cognitive impairment) (Singh Tomar et al., 2013; Sharif-Alhoseini et al., 2011; Wang & You, 2013). Exposure of the eyes to radiation can lead to cataracts (Hamada & Fujimichi, 2015; United Nations Scientific Committee on the Effects of Atomic Radiation, 2008; Vano et al., 2010). Some CT scanners allow the gantry to be tilted to minimize exposure of the eyes, but this facility is not available in all CT scanners. In an emergency CT, health-care staff are frequently required to remain in the CT room during CT scanning to relieve anxiety, operate a manual resuscitator, or care for trauma patients (Kobayashi et al., 2012; Mori et al., 2014a). During head CT, the radiation is scattered from the patient, thus exposing any health-care staff present in the room. Evaluation of eye lens doses received by health-care staff working in interventional radiology has been an area of interest for many years (Boal & Pinak, 2015; Omar et al., 2017; Principi et al., 2015; Stewart et al., 2012; Venneri et al., 2009). The International Commission on Radiological Protection (ICRP) Publication 118 has suggested that the threshold for induction of cataracts is 500 mGy, and to address this, the ICRP has proposed a lower annual occupational radiation dose limit of 20 mSv for the eye lens (Boal & Pinak, 2015; Stewart et al., 2012). However, the eye lens doses received by staff from CT examinations have rarely been studied.

Typically, during head CT scans, the head was placed in a support, with the center of the head at the isocenter. An automatic tube current modulation (ATCM) system handles tube current modulation longitudinally (Kalra et al., 2004; McCollough et al., 2006; Mulkens et al., 2005; Rizzo et al., 2006), whereas the bow tie filter attempts to provide uniform x-ray transmission by correcting

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for the lower attenuation through the periphery of the head. Inappropriate patient centering at the isocenter or miscentering alters the size of the scout image of the head used for planning operation of the CT ATCM systems. Moreover, optimal use of the bow tie filter, which shapes the beam in the axial plane to maintain uniform attenuation across the scan field, is based on the assumption that the patient is properly centered in the scan field. Incorrect centering of the patient can increase the surface dose in regions that are closer to the less-attenuating part of the bow tie filter and increase the noise in the region closer to the more attenuating part of the bow tie filter but also will result in the eyes being irradiated directly by the primary beam for a slightly larger proportion of the scan rotation. Although CT scanners have lasers to aid the radiological technologist in patient positioning, patient miscentering is a common problem in emergency CT. Radiographers are more likely to position the patient incorrectly in the vertical direction than in the horizontal one (Habibzadeh et al., 2012; Toth et al., 2007). Patient miscentering in head CT may result in higher eye lens doses to patients. Many studies have examined the dosimetric effects of patient positioning in CT. However, to the best of the authors' knowledge, no work has yet specifically evaluated the eye dose to patients and the effect of vertical miscentering on eye lens doses.

The primary purposes of this study were to assess the effect of miscentering of the patient x-ray couch on the eye lens dose in patients undergoing head CT examinations using the ATCM system and to measure the radiation doses to the eye lenses of staff remaining in the CT room when performing CT examinations. The secondary purposes were to determine whether the eye lens doses to patients are likely to approach the radiation absorbed dose threshold of 500 mGy, at which point there is a 1% risk of cataract induction, and whether the doses to staff remaining in the CT room received from emergency head CT are likely to approach the annual occupational lens dose limit of 20 mSv recommended by ICRP (Boal & Pinak, 2015; Stewart et al., 2012).

Materials and methods

Computed Tomography Scanner

Measurements were performed on a GE Brivo 16-slice CT scanner. The ATCM system used was called Smart mA. This system provides longitudinal (z-axis) and rotational (x-y plane) tube current modulation. The quality of the image recorded depends on a selected noise index, which is defined as the standard deviation of the pixel values in the uniform water phantom. The system allows the user to set the minimum and maximum values of the tube current and estimates the tube current from the attenuation level of the scan projection radiograph or scout image. The settings used in CT imaging protocols for clinical head scans were used (Table 1). The CT gantry tilt on the scanner could not be modified.

Phantoms

An anthropomorphic head phantom with complete cervical spine (RSD Model RS-108; Radiology Support Devices, NC, USA) was used for measuring the absorbed dose in the eye lens and image noise for patients undergoing CT scans of the head. The phantom is 30 cm long, starting from the skull vertex and continuing to the seventh cervical spine. The phantom comprises a skeleton encased in polymethyl methacrylate (PMMA). The anteroposterior and lateral diameters measured at the external auditory meatus (EAM) are 19 and 14 cm, respectively. For the staff eye lens dose measurement, a female Alderson radiation therapy (ART) phantom (RSD Model ART 300; Radiology Support Devices, NC, USA) was used to simulate a patient laid on the X-ray couch, forming the source of the scatter radiation. The ART phantom represents a 155-cm-tall, 50-kg female.

Dosimeters

A 100-mm-long ionization chamber with a 3 cm^3 active volume (Model 10X5-3CT; Radcal Corporation, CA, USA) with an electrometer (Model 9010) was used for measurement of the distribution of the dose profile in the x-y plane by the characteristic of the bow tie filter. A NanoDot™ (Al_2O_3:C) dosimeter (Landauer, Inc., IL, USA) was used for dose measurement (Lavoie et al., 2011; Scarboro et al., 2015). The lower limit of detection is 50 μGy, and the useful energy range is 5 keV to 20 MeV, with an accuracy of ±10%. NanoDot™ dosimetry is based on the raw signal and a series of correction coefficients. The correction coefficients in terms of signal fading, dose linearity, and angular dependence are reported to be <3% for CT dosimetry (Scarboro et al., 2015). The calibration and correction coefficients were provided by the company.

OSLD Readout

The dosimeters were read by a microStar reader (Landauer, Inc., IL, USA) in which a light-emitting diode is exposed to the detector, and, subsequently, the emitted luminescence is detected. At 24 h after irradiation, each NanoDot™ was read three successive times, and the Optically stimulated luminescence dosimeter (OSLD) signal was corrected for signal depletion for multiple readouts and individual sensitivity. The average reading was corrected for energy dependence. The base and background doses, which are the residual signal of each nanodot and the dose of the unexposed nanodot, respectively, were subtracted to yield the actual dose. The dose equivalent at 3-mm depth, Hp(3), is regarded as the

Table 1
Details of the routine computed tomography head protocol

Scout protocol	Tube voltage	120 kVp
	Tube current	10 mA
	Tube position	90° (Lateral)
	Scout length	300 mm
Scan protocol	Targeted noise level	NI = 5.37
	Minimum and maximum mA	120-180 mA
	Tube voltage	120 kVp
	Collimation	20 mm
	Pitch factor	0.562
	Slice thickness	1.25 mm
	Filter reconstruction	Standard
	Iterative reconstruction	30% adaptive statistical iterative reconstruction (ASIR)
	Rotation time	1 sec

appropriate quantity for monitoring the eye lens as the lens is covered by approximately 3 mm of soft tissue. The correction coefficients for responses to the effective energy of the CT X-rays, and converting air kerma at the active volume of the NanoDot™ to the eye lens dose equivalent, Hp(3) were applied as recommended by the International Electrotechnical Commission standard 62387 (International Electrotechnical Commission, 2012).

Experimental Setup

Bow Tie Filter Measurement

Bow tie filter profile measurement was carried out to examine the radiation attenuation across the fan beam. The X-ray tube was positioned at 90° (lateral position), with the beam directed horizontally. The ionization chamber was supported and suspended in the air. A scout mode was used, with the size of the field of view selected for the head CT protocol. The exposure settings were 120 kV, 100 mA, and 200 mm scan length. The table was first adjusted for the ion chamber centered at the scanner isocenter. Output measurements were taken across the scan field of approximately 400 mm by raising and lowering the table in 10 mm increments.

Effects of Patient Miscentering

Institutional ethics review board approval was obtained, and informed consent was not needed because the subjects of this study were phantoms. For CT scanning at the isocenter level, the head phantom was in the supine position on the table, with its EAM aligned at the center of rotation (isocenter). OSLDs were taped at the surface of both the eyes. A scout image was taken using the X-ray tube positioned at 90° (lateral). To examine the influence of miscentering on patient dose and image noise, the head phantom was placed in the head support, with the center of the phantom at the isocenter; the vertical positioning of the table was then varied through 2, 3, and 5 cm below the isocenter to 1 and 3 cm above. Scout imaging and scans were repeated using new sets of OSLDs.

The values of the volume CT dose index ($CTDI_{vol}$) and dose length product (DLP) were recorded from the CT scanner's display. The mA per image was read from the digital imaging and communications in medicine header. The image noise in terms of the standard deviation of the CT number was measured using ImageJ (Rueden et al., 2017). A 1.25-cm-thick stack of 30 images around the middle slice of the imaging area was measured using circular regions of interest (ROIs) of 100 mm^2 that were placed on the PMMA matrix and avoided the bones. Fourteen different locations along the central, vertical, and horizontal directions of the phantom were measured as illustrated in Figure 1. The measured noise for ROI numbers 1-3, 4-7, 8-10, and 11-14 were averaged and defined as the values of image noise for the anterior, middle, posterior, and lateral portions of the phantom, respectively. A paired sample t-test was used to determine whether the values of measured noise at each position and table height were statistically significantly different from those at the isocenter. The statistical package for the social sciences (SPSS) statistics software (SPSS version 17.0 for Windows) was used to perform all statistical tests, at a 5% level of significance.

Staff Lens Dose Measurement

The ART phantom was in the supine position on the table at the isocenter level to simulate the patient and source of the scatter radiation. A custom-made phantom to simulate a health-care staff member remaining in the CT room was developed using a silicon mannequin. The distance from the eyes to the floor was 147 cm, which was approximately equivalent to the average Thai female's height of 159 cm. A lead apron and thyroid collar were wrapped tightly around the phantom but without x-ray−protective eyewear.

Figure 1. Region of interest locations for measurements of image noise.

Two OSLDs were taped over the phantom's eyes. Three positions for staff were simulated: facing the gantry on the right (A) and left sides (B) next to the table and standing at the rear of the gantry (C) (Figure 2). Positions A and B are common for operating a manual resuscitator while C is for supporting or immobilizing uncooperative patients. For A and B, the distance from the midchest of the phantom to the center of the gantry's bore was 80 cm while that for position C was 50 cm.

Results

Bow Tie Filter Dose Profile

The fan beam profile measured in the scout mode is provided in Figure 3. The dose plateaued for a distance of ±8 cm relative to the isocenter and then sharply declined beyond that point.

Effects of Patient Miscentering on Radiation Dose and Image Noise

The modulations to tube current values, starting from the base of the skull for individual scans, are illustrated in Figure 4. The dynamics of the tube current modulation for all eight table height position settings followed similar patterns and were limited by the minimum and maximum tube current setting values (120-180 mA). The ATCM was not a factor in the measurements of patient lens dose as the tube current was at a maximum throughout the region of the eyes. The average mA, $CTDI_{vol}$, and DLP obtained for individual table height settings are provided in Table 2 and were within ±2% of those at the isocenter. The average dose to the two eye lenses in the phantom positioned at the isocenter was 48.7 mGy. The doses were 9.5-34% lower when the table heights were 1-3 cm above the isocenter but 9.5%-44% higher when table heights were 2-5 cm below the isocenter.

The average values of the image noise levels measured at different phantom locations are provided in Figure 5. The values of measured noise were 6.81-7.92 Hounsfield units (HU). There were significant differences, at the level of $p < .05$, in the image noise

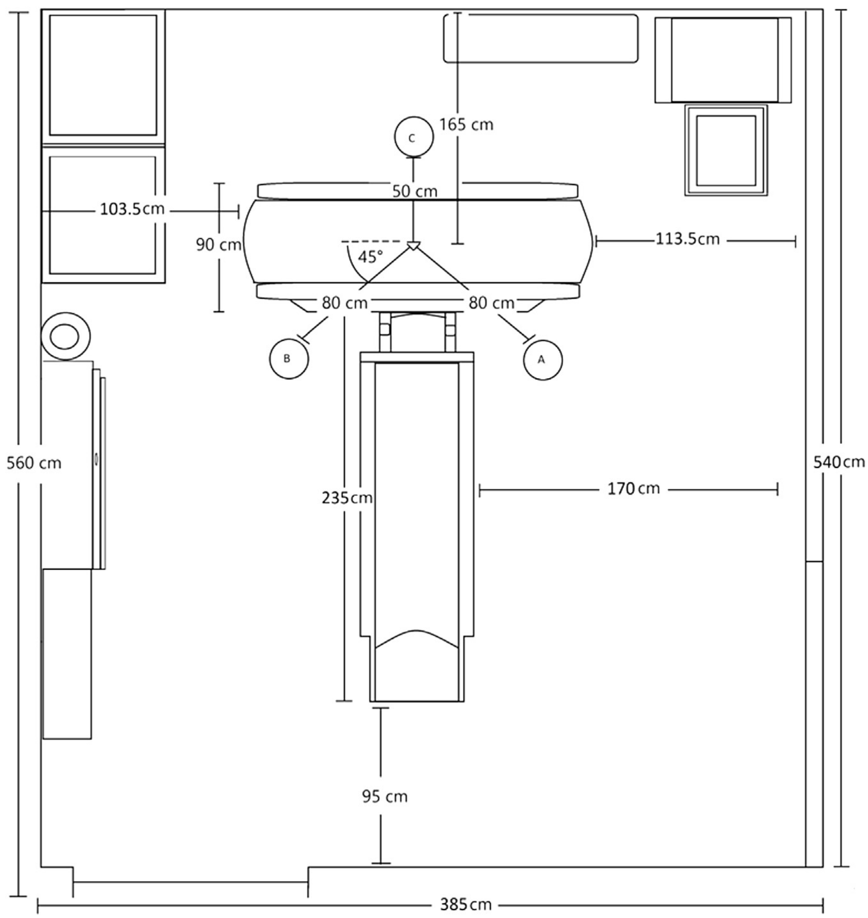

Figure 2. Health-care staff positions A, B, and C during computed tomography examination used for the assessment.

levels measured at the posterior portion of the phantom and the overall image noise for the table height of 5 cm below the isocenter.

Eye Lens Doses to Health-care Staff Present in the Computed Tomography Room during the Computed Tomography Scan

Details on equivalent eye lens doses to staff are provided in Table 3. The mean equivalent dose at the eye lens was approximately 0.1 mSv per examination when the staff were standing next to the table (positions A and B) but was approximately twofold higher when the staff were standing at the rear of the gantry (position C).

Discussion

Radiation dose to the eye lens is a topic of interest to CT professionals at the present time. The present study focused on eye lens doses received by patients and staff from head CT scans as this is one of the more common CT examinations in emergency

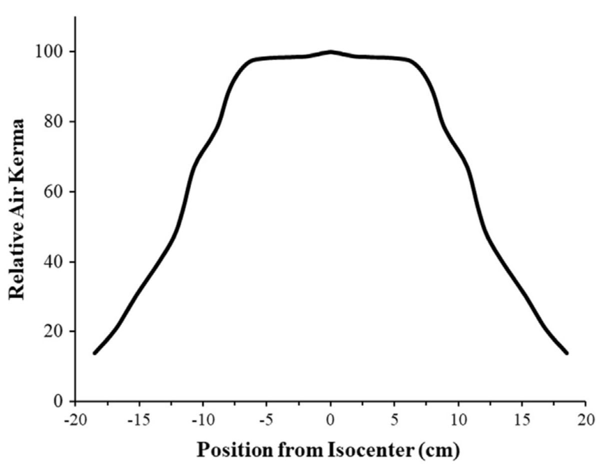

Figure 3. Bow tie filter dose profile.

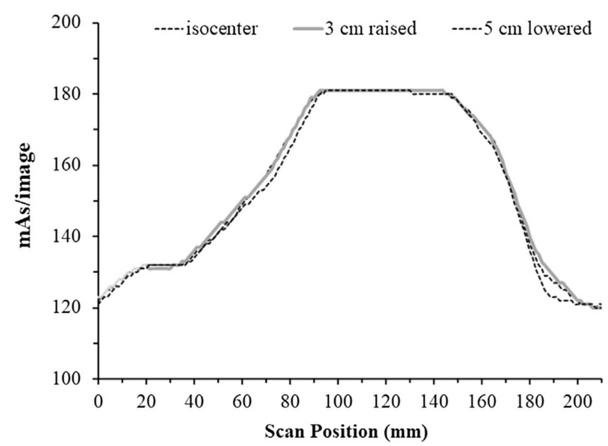

Figure 4. Tube current modulations for scans at different table heights.

Table 2
Scanner's dose display and absorbed dose (mGy) for the phantom eye lens obtained for individual table height positions

Table position	Scanner's dose display			Absorbed dose (mGy)			
	Average mAs	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)	Right eye	Left eye	Average	% Difference
+3 cm	154	47.38	1059	29.60	35.08	32.34	−33.6
+1 cm	153	47.08	1052	43.51	44.69	44.10	−9.46
Isocenter	154	47.38	1059	47.82	49.59	48.71	–
−2 cm	153	47.08	1052	52.53	54.10	53.31	9.46
−3 cm	153	47.08	1052	58.21	62.13	60.17	23.5
−5 cm	152	46.77	1034	68.21	71.74	69.97	43.7

$CTDI_{vol}$ = computed tomography dose index; DLP = dose length product.

departments. Owing to the serious condition of some emergency patients and poor co-operation from others, health-care staff are required to remain in the CT room during scanning to monitor patients in need of intensive care. Moreover, because this medical imaging task needs to be performed rapidly, miscentering of the patient x-ray couch during CT scanning is a common problem.

Effects of Patient Miscentering on the Dose and Image Quality

The $CTDI_{vol}$ and DLP remained relatively constant even when the phantom was scanned in off-center positions. This was because the lateral scout image (tube position of 90°) was used for the ATCM; therefore, there was no magnification of the scout image when the table heights were adjusted. To examine the effect of the X-ray tube position together with table height adjustment, two additional scout images were also taken at the isocenter and at table height of 2 cm above the isocenter by positioning the X-ray tube at 0° (anteroposterior). It was confirmed that the $CTDI_{vol}$ increased from 47.51 mGy to 50.24 mGy when the table heights were moved closer to the X-ray tube. This was because the projected area of the phantom was magnified in the scout image. The results suggest that the use of a lateral scout image offers advantages over the AP scout image for head CT using ATCM.

There were no significant differences in the image noise levels for scans at the different table heights, except when the table was 5 cm lower than the isocenter (Figure 5). Because the central region of the bow tie filter is approximately ±8 cm from the isocenter (Figure 3) when the table is positioned at 5 cm below the isocenter, the posterior peripheral portion of the phantom was moved forward to the edge of the bow tie filter. Therefore, the values of measured noise at the posterior portion of the phantom were substantially higher than those at the anterior portion. Photons are

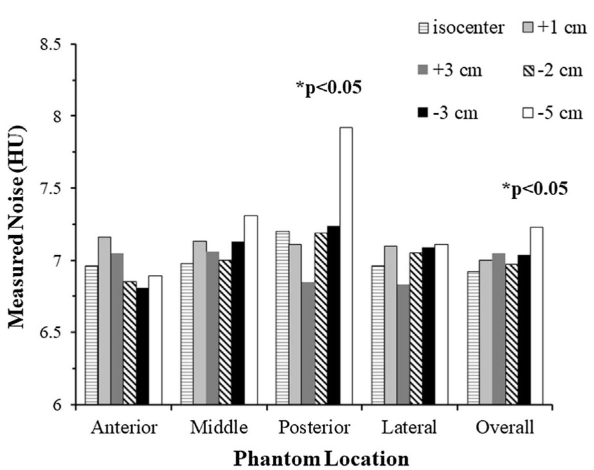

Figure 5. Image noise levels measured at different phantom locations and table heights.

more attenuated by the edge of the bow tie filter, resulting in a reduction in the relative photon fluence, which in turn increases the image noise. These effects were not noticed when the table heights were adjusted by ±3 cm as the phantom's scan area remained in the central area of the bow tie filter. However, this one "statistically significant" outcome may simply be the result of sample error. In addition, the difference in the image noise (i.e., standard deviation) of this one statistically significant value compared with that of the other values was <1 HU, which is not clinically significant.

The dose to the eye lens increased significantly when the table heights were lowered. This was, again, because the location of the eye lenses, which were approximately 10 cm anterior to the center of the phantom, was beyond the edge of the bow tie filter. When the table height was lowered, the eye lens was moved closer to the isocenter, and when the table was lowered by 5 cm, the lens was projected onto the central thinnest part of the bow tie filter in which the photons are less attenuated during the scan rotation at which the absorbed dose could be as high as 44% (70 mGy). In addition, the lower position of the head resulted in the eyes being irradiated directly by the primary beam for a greater proportion of the tube rotation. However, the eye lens doses decreased when the table was raised. This is due to the fact that the lens was moved toward the edge of the bow tie filter, during periods of lateral exposure, and could even lay outside the beam for a portion of the time, resulting in greater radiation attenuation. Information from the literature review found that the average patient miscentering error is approximately ±2 cm (Li et al., 2007; Sukupova et al., 2016; Toth et al., 2007) therefore, the eye lens doses vary within ±24%, and image noise levels are acceptable.

Overall, the results indicated that the average eye lens dose was well below the 500 mGy threshold at which there is a 1% risk of cataract (Stewart et al., 2012), which confirms that the technique is clinically safe for emergency patients, even for repeated head CT scans that are often performed to observe the progress of the intracranial injury. However, 7-15 examinations could exceed this threshold. Caution should be exerted if repeated scans are planned, particularly if CT angiography and CT perfusion examinations are performed in addition.

Eye Lens Doses to Health-care Staff Present in the Computed Tomography Room during the Computed Tomography Scan

The eye lens doses were highest for the position C because the staff member was positioned closer to the X-ray tube and the

Table 3
Equivalent doses to the eye lens per examination

Position	Equivalent dose for eye lens Hp(3) (mSv)		
	Right eye	Left eye	Average
A	0.097	0.127	0.112
B	0.098	0.084	0.091
C	0.227	0.221	0.224

scatter radiation toward the eye was most intense when the x-ray tube was placed above the patient. Doses for the positions A and B were lower than those for the position C because they were shielded by the gantry (Wallace et al., 2012) and were exposed for a small percentage of the total scan time. It was observed that the left and right eyes were slightly more exposed to radiation for positions A and B, respectively. This is likely to be due to the health-care staff being in the oblique position where the proximal eye was shielded by the gantry.

Owing to the equivalent eye dose limit values recommended by the ICRP, since the staff received 0.1-0.2 mSv of equivalent dose per examination, they would be able to remain in the CT room during CT scanning for 100-200 examinations per annum before reaching the dose limit, when standing at the rear of the gantry or next to the table. This implied that the risk of eye lens damage for staff was very low. Although the measurement was made only at 147 cm from the floor, it would still be small and not pose a meaningful risk certainly for a taller person where the distance from the scattering object would be greater. Even for a shorter person, with the lens closer to the patient and assuming an inverse square law increase, the dose would increase only slightly.

However, this depends on the staff workload in the case of emergency CT. A study in Japan found that the mean frequency for remaining in the CT room during CT examination was 1-2 times per month (Mori et al., 2014a). Staff remaining in the CT room should wear a lead apron and thyroid collar, but x-ray–protective eyewear made of 0.75-mm lead-equivalent glasses are also recommended, where available, to protect the eye lens (Goren et al., 2013; Mori et al., 2014b).

There are some limitations to this study. First, the study was performed in only one CT scanner with a routine CT scan protocol. The results are not generalizable to other CT scanners or different CT technologies. Second, only a single measurement was taken for each position of the phantom. Third, the staff eye lens dose measurements were performed only for the distance of the eyes to the floor of 147 cm, which was equivalent to the average Thai female's height; therefore, these measurements may not represent staff that are taller or shorter. Finally, although there is only a small variation in head size for adult patients, only the standard size of head phantom was used in this study.

Conclusion

The doses for patient and staff eye lenses received from emergency head CT examination were lower than the threshold of 500 mGy for cataracts and the staff limit on the equivalent dose of 20 mSv as recommended by the ICRP. However, the positioning of patients off the CT scan isocenter during head CT may result in a significantly increased eye lens dose. Health-care staff present in the CT room during the procedure are at risk of a significant eye lens dose, particularly if positioned posterior to the gantry. Wearing x-ray–protective eyewear made of 0.75-mm lead-equivalent glasses is recommended for protection where these are available.

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