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FULL PAPER

Can a revised paediatric radiation dose reduction CT protocol be applied and still maintain anatomical delineation, diagnostic confidence and overall imaging quality?

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Objective: To compare multidetector CT (MDCT) radiation doses between default settings and a revised dose reduction protocol and to determine whether the diagnostic confidence can be maintained with imaging quality made under the revised protocol in paediatric head, chest and abdominal CT studies.

Methods: The study retrospectively reviewed head, chest, abdominal and thoracoabdominal MDCT studies, comparing 231 CT studies taken before (Phase 1) and 195 CT studies taken after (Phase 2) the implemented revised protocol. Image quality was assessed using a five-point grading scale based on anatomical criteria, diagnostic confidence and overall quality. Image noise and dose-length product (DLP) were collected and compared.

Results: The relative dose reductions between Phase 1 and Phase 2 were statistically significant in 35%, 51% and 54% ($p < 0.001$) of head, chest and abdominal CT

studies, respectively. There were no statistically significant differences in overall image quality score comparisons in the head ($p = 0.3$), chest ($p = 0.7$), abdominal ($p = 0.7$) and contiguous thoracic ($p = 0.1$) and abdominal ($p = 0.2$) CT studies, with the exception of anatomical quality in definition of bronchial walls and delineation of intrahepatic portal branches in thoracoabdominal CTs, and diagnostic confidence in mass lesion in head CTs, liver lesion (>1 cm), splanchnic venous thrombosis, pancreatitis in abdominal CTs, and emphysema and aortic dissection in thoracoabdominal CTs.

Conclusion: Paediatric CT radiation doses can be significantly reduced from manufacturer's default protocol while still maintaining anatomical delineation, diagnostic confidence and overall imaging quality.

Advances in knowledge: Revised paediatric CT protocol can provide a half DLP reduction while preserving overall imaging quality.

The use of CT has been rapidly increasing all over the world during the past two decades, driven by advanced technology and the invention of the multidetector CT (MDCT). Use of MDCT has risen 12-fold in the UK and 20-fold in the USA during this time, and the mean effective dose from all medical X-rays in the USA has increased 7-fold during this period.^{1–3} 6–11% of all CT examinations in developed countries are performed on children aged from 0 to 15 years.^{2,4–6} The organ-absorbed doses reported in adult and paediatric patients undergoing single CT examination are considerably lower than the threshold for initiation of a deterministic effect and the estimated effective doses are still within the annual exposure dose from natural background radiation.⁷ The UK Radiation Protection Division of the Health Protection Agency, the US National Council on Radiological Protection and Measurement and

the US National Academy of Sciences Biological Effects of Ionizing Radiation committees have proposed that, for doses <100 mSv, which is roughly equal to the dose range for multiple CT examinations, the radiation-induced cancers decrease linearly with decreasing dose with no threshold or a so called “linear no-threshold” model.^{3,8,9} There was a linearly increasing risk for all solid cancers with increasing radiation dose and a higher radio sensitivity in children resulting in a larger attributable lifetime cancer risk in this patient group.^{1,3}

Although the association of diagnostic medical radiation exposures in maternal pre-natal, children's post natal and parental pre-conception periods with paediatric cancer risks are summarized in various studies, a CT scan-related cancer risk in children and adolescents has not been

definitively proven.⁶ A retrospective cohort study by Pearce *et al*¹⁰ did, however, find a significant association between estimated cumulative radiation doses delivered by CT scan to the bone marrow and brain and subsequent increased risk of leukaemia and brain tumours in childhood.

Diagnostic reference level (DRL) values are required for CT optimization, and these values are recommended by the International Commission on Radiological Protection; also each region or country is responsible for and authorized to enact details and implementation of their own DRLs.¹¹ Several age-based and weight-based DRLs for paediatric CT have been published.^{12–17} General strategies for CT dose reduction in paediatric healthcare include such things as avoiding a CT scan if adequate clinical information can be obtained from ultrasound or MRI, avoiding multiphase examinations and designing CT protocols to minimize exposure time.¹⁸ Nowadays, many professional societies, regulators and manufacturers have been trying innovative new technologies for reducing radiation dose while maintaining optimal image quality.

Two of the most commonly used image quality parameters in diagnostic imaging are high-contrast (spatial) resolution and low-contrast resolution. Spatial resolution is the ability to distinguish small objects close to one another on an image and is

influenced by various factors such as focal spot size, detector width and ray, pixel size and properties of the reconstruction filter. Low-contrast resolution refers to the visibility of an object against the background. In the absence of artefacts, the low-contrast resolution scan is affected mostly by noise.^{19,20} Although noise derivative is a quality index that is more relevant to assess image quality than image noise, it is difficult to translate in clinical practice.²¹ Image noise is measured by standard deviation (SD) of CT number, and it depends on milliamperes (mA), scan time, kilovoltage peak (kVp), patient size, pitch or table speed, slice thickness and reconstruction algorithm. If the milliampere–seconds value is reduced by 50%, the radiation dose will be reduced by the same amount, with an attendant noise increase of 41%, calculated by the equation ($1/\sqrt{2} = 1.41$, a 41% increase). Tube voltage or beam energy has a direct influence on patient radiation dose. Reducing the peak kilovoltage results in a significant decrease in radiation dose owing to the square law relationship of these two values.^{19,20,22–25} Thus, the image noise and tissue contrast will be affected by adjusting kilovoltage; however, reduced peak tube potential is useful for chest, airway and skeletal studies owing to a high contrast-to-noise ratio requirement in imaging evaluation.¹⁸

In our hospital (Songklanagarind Hospital, Hat Yai, Thailand), we began a revised CT dose reduction protocol in August 2010 that involved lowering kVp and mA, and using dose–length

Table 1. Comparison between the default setting protocol (Phase 1) and the revised radiation dose reduction protocol (Phase 2)^a

CT scanned body part	Phase 1				Phase 2			
	Age/body mass	CTDI	kVp	mAs with automatic tube current modulation ^b	Age/body mass	CTDI	kVp	mA
Head	<18 months	20	120	150	<6 months	14.0	120	90
	18 months to <6 years	25	120	200	6 months to <3 years	22.0	120	135
	6–10 years	32	120	250	3 to <6 years	28.0	120	175
					6 to <12 years	32.0	120	200
					>12 years	50.0	120	315
Chest	<10 kg	3.2	120	50	4 to <10 kg	1.6	80	95
	10 to <30 kg	5.2	120	80	10 to <20 kg	2.0	80	120
	30–50 kg	6.5	120	100	20 to <30 kg	2.4	80	140
					30 to <40 kg	2.8	120	70
					40 to <50 kg	3.5	120	90
					50–64 kg	4.3	120	110
Abdomen	<10 kg	5.2	120	80	4 to <10 kg	2.1	80	130
	10 to <30 kg	7.1	120	110	10 to <20 kg	3.0	80	180
	30–50 kg	7.8	120	120	20 to <30 kg	3.8	120	90
					30 to <40 kg	4.1	120	105
					40 to <50 kg	4.9	120	125
					50–64 kg	5.9	120	150

CTDI, CT dose index; kVp, kilovoltage peak; mA, milliamperes.

^aReproduced from Nievelstein *et al*²³ with permission from Springer-Verlag.

^bAutomatic tube current modulation in chest and abdominal CT.

product (DLP) and DRLs based on the Nievelstein et al²³ protocol and national dose surveys from the UK and Canada^{12,15} (Table 1). The objectives of this study were to compare radiation doses between the default setting and our revised dose reduction protocol and to evaluate whether we could maintain diagnostic confidence in the diagnostic imaging quality with the revised protocol.

METHODS AND MATERIALS

Data collection and dosimetry

Our institutional review board (Human of Research Ethics Committee, Prince of Songkla University, Hat Yai, Thailand) approved the study protocol. Informed consent was waived, and patient confidentiality was protected. We retrospectively reviewed and compared the CT radiation doses of paediatric patients (less than 15 years of age) who underwent head, chest, abdominal and thoracoabdominal CT studies in the Songklanagarind Hospital, Thailand, between 6 months before and 6 months after the dose reduction protocol was initiated. The machine was operated by multislice CT scanner (64-slice system, Phillips Brilliance; Philips Electronics, Petach Tikva, Israel). Phase 1 (January 2010 through June 2010) was the period during which the original default setting protocol parameters from the scanner manufacturer were used, and, during Phase 2 (November 2010 to April 2011), our revised dose reduction protocol regarding MDCT in children was used, a protocol based on current concepts and dose reduction strategies²³ (Table 1). Both kVp and mA were adjusted manually and neither the automatic tube current modulation or automatic exposure control (AEC) were applied for the chest, abdomen and thoracoabdominal CT studies in Phase 2.

The collected data included patient demographic data (age, gender and body mass); indications for scan categorized into four items: trauma, tumour, congenital and infection; and scan parameters: kVp, mA, volume CT dose index (CTDI_{vol}) and DLP. Records with poor image quality from uncertain protocol, technical error, severe motion or streak artefacts resulting in the radiologists being unable to interpret the imaging study were excluded from the study.

The CTDI_{vol} was calibrated using a pencil-shaped ionization chamber either in air or in a dedicated 16- or 32-cm-diameter polymethylmethacrylate phantom. The real-time displays of kVp, mA, CTDI_{vol} and DLP from the CT monitor were recorded in the picture archiving and communication system and retrospectively assessed. A multiplication factor of two was applied to the displayed DLPs for the chest, abdomen and thoracoabdominal scans in all children younger than 15 years, using a DLP based on a 32-cm phantom and adjusted DLP for a 16-cm phantom size, recognizing that smaller sized objects absorb a higher dose using the same parameters.^{23,26,27} All data were manually entered into an excel spreadsheet and analysed into range, minimum, maximum and mean.

Assessment of image quality

Qualitative assessment

All imaging studies were reviewed in blinded random order and independently by two experienced paediatric radiologists (SK

Table 2. Five-point grading scale^a

Score	Anatomical criteria	Diagnostic confidence	Overall quality
1	Not possible	Non-diagnostic	Non-acceptable, repeat scan
2	Difficult	Low	Low
3	Acceptable	Acceptable	Acceptable
4	Good	Good	Good
5	Excellent	Excellent	Excellent
NA	Not applicable		

^aReproduced with permission from the International Atomic Energy Agency.²⁸

and PT). The guidelines for image quality assessment were adapted from the standard International Atomic Energy Agency (IAEA) protocol (IAEA-TECDOC-1621).²⁸ The quality of each image was assessed in terms of anatomical criteria, diagnostic confidence and overall quality using a five-point scale grade for each element (Table 2). If there was a greater than two grading score discrepancy by the two assessors, the image was reviewed again until an agreement between these assessors was reached. The anatomical assessments were divided into head, chest and abdominal areas (Table 3). Diagnostic confidence was assessed in terms of clinical disease or pathological lesions in each head, chest and abdominal study (Table 4). Both chest and abdominal regions were assessed in the cases with contiguous thoracic and abdominal CT studies in one acquisition.

Quantitative assessment

The image noise value was defined as the SD of the mean density by using a region-of-interest methodology in a standard 5- to 15-mm² circular region and measured at the level of the body of the lateral ventricles, the thoracic descending aorta at the level of the carina and the abdominal aorta at the level of the hepatic portal hilum in the head, chest and abdominal CT examinations, respectively. The noise measurement was performed in the same cross-section in each region of the studies. 4-mm and 3- or 2-mm reconstructed slice thicknesses were used in head and body CT studies, respectively. A threshold of 20 HU was used as defining an acceptable image quality.^{29,30}

Table 3. Anatomical criteria^a

Brain	Chest	Abdomen
Grey-white differentiation	Delineation of lung fissures	Delineation of intrahepatic portal branches
Delineation of ventricular contours	Delineation of outline of great vessels	Delineation of splenic vein
Delineation of basal ganglia	Definition of bronchial walls	Delineation of external bowel contours
Definition of gyri		

^aReproduced with permission from the International Atomic Energy Agency.²⁸

Statistical analysis

Different findings between the Phase 1 and Phase 2 images were compared to check for any significant differences by using Student's *t*-test for age and body mass and χ^2 or Fisher's exact test for gender and indication. Wilcoxon's rank-sum test was used to compare quality scores, and weighted κ statistic was used to assess inter-rater agreement between the two phases. In addition, inter-observer agreement of image quality was assessed by κ -value to evaluate the conspicuity of the image quality in each phase. Linear regression was used to compare the mean radiation doses and noise level. The statistical significance level was set at 0.05.

RESULTS

Demographic data

232 and 204 paediatric CT studies were performed in Phases 1 and 2, respectively. 10 CTs (2.3%) were excluded from the study owing to uncertain CT protocol (8 studies), misregistration (1 study) and severe motion artefact (1 study), leaving a total of 426 CTs for the study (231 in Phase 1 and 195 in Phase 2). There were no statistically significant differences in the demographic data or indications for CT scanning between Phase 1 and Phase 2, except the "infection/others" category in indications for scan was higher in Phase 1 than in Phase 2 (Table 5). Three patients had an "other" indication for their CT studies. Two patients in Phase 1 were referred, one for evaluation of ruptured appendicitis and one owing to complications of acute pancreatitis, and one patient in Phase 2 had an undetermined pancreatic head lesion.

Imaging quality

Anatomical criteria

There were no statistically significant differences in most anatomical aspects between the two phases except in the delineation of definition of the bronchial walls and intrahepatic portal branches in the thoracoabdominal CT studies. The anatomical quality scores in delineation of the intrahepatic portal branches were slightly lower while the definition of the bronchial walls was slightly better after applying the dose reduction protocol in the thoracoabdominal studies (Table 6).

Diagnostic confidence

The diagnosis of mass lesions in the brain, liver lesions (<1 cm) and splanchnic venous thrombosis in the abdominal studies were made with more confidence after the implementation of the revised dose reduction protocol with statistical

Table 4. Diagnostic confidence^a

Brain	Chest	Abdomen
Bleeding	Nodule (3 mm)	Liver lesion (>1 cm)
Infarction	Emphysema	Splanchnic venous thrombosis
Mass lesion	Mediastinal lymph node	Pancreatitis
	Aortic dissection	Retroperitoneal lymph node

^aReproduced with permission from the International Atomic Energy Agency.²⁸

Table 5. Patient demographic data and indications for scan

Patient characteristic	Phase 1 (n = 231)	Phase 2 (n = 195)	p-value
Age (years)	6.5 ± 4.8 ^a	5.8 ± 4.5 ^a	0.090
Body mass (kg)	21.1 ± 13.7 ^a	20.8 ± 13.3 ^a	0.800
Sex			0.200
Male	119 (52%)	111 (57%)	
Female	112 (48%)	84 (43%)	
Indication			0.008
Trauma/seizure	26 (11%)	32 (16%)	
Tumour	151 (65%)	138 (71%)	
Congenital	18 (8%)	14 (7%)	
Infection/others	36 (16%)	11 (6%)	

^aData are mean ± standard deviations. Significant p-values are in italic.

significance, while the diagnosis of pancreatitis in the abdominal studies and emphysema and aortic dissection in the thoracoabdominal studies were statistically significantly worse (Table 7).

No statistically significant difference in overall quality assessment between the two groups was found. Both imaging readers rated overall quality as acceptable or above average in all CT studies after the revised dose reduction protocol (Table 7).

Image noise

There were statistically significant increases in imaging noise after applying the revised dose reduction CT protocols in almost all of the CT studies except for the chest CTs (Table 8).

Examples of abdominal CT studies in Phase 1 and Phase 2 are displayed in Figure 1a,b.

Dose reduction

As a consequence of implementation of the revised reduction dose CT protocol, the relative radiation dose and DLP were statistically significantly reduced in all CT studies particularly chest and abdominal CT studies (Table 8).

DISCUSSION

Since children are more sensitive to radiation and at a relatively greater risk of carcinogenesis than are adults, it is even more important to avoid unnecessary radiation exposure in this group than in the adult population. An optimal CT radiation dose in MDCT studies can be achieved by modifying the acquisition parameters, using the automatic exposure control, and adjusting acquisition parameters for patient size or iterative reconstruction.^{24,31} There are many different AEC systems, and all have different default settings, as the CT equipment manufacturers have not reached any consensus concerning optimal default settings.²⁵ Nievelstein *et al*²³ created the first paediatric MDCT optimizing guideline protocols with scanners from various manufacturers by adjusting tube voltage and CT dose

Table 6. Comparison of anatomical quality scores between before (Phase 1) and after (Phase 2) implementation of the revised dose reduction protocol

Anatomical criteria	Brain (<i>n</i> = 140)			Chest (<i>n</i> = 89)			Abdomen (<i>n</i> = 114)			Thoracoabdomen (<i>n</i> = 83)		
	Phase 1 (<i>n</i> = 73)	Phase 2 (<i>n</i> = 67)	<i>p</i> -value	Phase 1 (<i>n</i> = 43)	Phase 2 (<i>n</i> = 46)	<i>p</i> -value	Phase 1 (<i>n</i> = 67)	Phase 2 (<i>n</i> = 47)	<i>p</i> -value	Phase 1 (<i>n</i> = 48)	Phase 2 (<i>n</i> = 35)	<i>p</i> -value
Grey-white differentiation	3.1	3.1	0.4	3.8	3.6	0.1	3.8	3.6	0.50	4.0	3.8	0.070
Delineation of ventricular contours	3.8	3.9	0.2	3.7	3.7	0.9	3.9	3.9	0.40	3.9	3.9	0.300
Delineation of basal ganglia	3.0	3.0	0.8	4.0	3.9	0.6	4.0	3.7	0.07	4.0	4.1	0.010
Definition of gyri	3.0	3.0	0.8							3.9	3.7	0.004
										3.9	3.9	0.200
										3.8	3.7	0.300

Significant *p*-values are in *italic*.

Table 7. Comparison of diagnostic confidence and overall quality between before (Phase 1) and after (Phase 2) implementation of the revised dose reduction protocol

Diagnostic confidence	Brain (<i>n</i> = 140)			Chest (<i>n</i> = 89)			Abdomen (<i>n</i> = 114)			Thoracoabdomen (<i>n</i> = 83)		
	Phase 1 (<i>n</i> = 73)	Phase 2 (<i>n</i> = 67)	<i>p</i> -value	Phase 1 (<i>n</i> = 43)	Phase 2 (<i>n</i> = 46)	<i>p</i> -value	Phase 1 (<i>n</i> = 67)	Phase 2 (<i>n</i> = 47)	<i>p</i> -value	Phase 1 (<i>n</i> = 48)	Phase 2 (<i>n</i> = 35)	<i>p</i> -value
Bleeding	4.0	4.0	0.300	4.0	4.0	0.5	4.0	4.1	0.003	4.1	4.0	0.1
Infarction	3.7	3.7	0.700	4.1	4.1	0.9	3.9	4.1	0.002	4.1	4.0	0.03
Mass effect	4.0	4.2	<0.001	3.3	3.3	0.8	3.2	3.1	0.010	3.6	3.6	0.3
Definition of gyri	3.0	3.0	0.800	3.9	3.8	0.3	3.8	3.8	0.900	4.0	3.8	0.01
										4.0	4.0	0.7
										3.9	3.9	0.1
										3.2	3.1	0.1
										3.9	3.9	0.5
Overall quality	3.4	3.4	0.7	3.9	3.8	0.3	3.8	3.8	0.700	4.0	3.9	0.1
										3.8	3.8	0.2

Significant *p*-values are in *italic*.

Table 8. Comparison of image noise and dose-length product (DLP) between before (Phase 1) and after (Phase 2) implementation of the revised dose reduction protocol

Noise/dose	Brain	<i>n</i>	Chest	<i>n</i>	Abdomen	<i>n</i>	Thoracoabdomen	<i>n</i>
Noise								
Phase 1 (± standard deviation)	3.8 ± 0.8	71	19.3 ± 6.8	38	15.2 ± 4.4	65	12.9 ± 3.5	44
Phase 2 (± standard deviation)	4.6 ± 0.8	61	17.0 ± 6.3	37	21.0 ± 4.5	47	14.8 ± 3.4	35
<i>p</i> -value	<0.001		0.100		<0.001		0.020	
Dose (DLP, mGycm)								
Phase 1 (range)	890 (630–1160)	73	92 (56–131)	43	228 (150–314)	67	255 (203–355)	48
Phase 2 (range)	575 (445–1040)	67	45 (33–76)	46	105 (90–159)	47	163 (123–230)	35
<i>p</i> -value	<0.001		<0.001		<0.001		<0.001	
Dose reduction (%)	35.4		51.1		53.9		36.1	

Significant *p*-values are in italic.

indexes (CTDI_s) based on age or body weight category. National surveys from several countries also provide good standards for optimizing scanning protocols with reasonable radiation doses.^{11–15} However, the most important concern is how to balance radiation dose reduction and imaging quality. Several studies have reported on the relationship between optimizing radiation reduction CT protocols and image quality in adults and paediatric patients.^{24,32–34} The thorax has low pulmonary absorption of radiation and high intrinsic contrast, therefore, low-dose chest CTs have been widely practically used. The low-dose chest CT in adults can provide a lower radiation dose, while retaining satisfactory image quality and even reduced contrast material usage.^{30,34,35} The same result has been found in paediatric chest CT studies, through applying a weight-based protocol that significantly increased noise (41–55%) but still achieved acceptable image quality.³⁶ Another study found that not only were radiation doses in a low kilovoltage technique reduced, but the contrast-to-noise ratio also increased by 40% when decreasing the voltage from 140 to 80 kVp.³⁷ Frush *et al*³⁷ found that even with a decreased simulated tube current <40 mA, the high visibility structures in abdominal CT scans had no loss of detection, while the low visibility structures were reduced in detection to a level ≤ 80 mA. In addition, Siegel *et al*³¹ reported that different phantom sizes had effects of varying tube current and voltage on radiation dose, image noise and image contrast. They found that as tube voltage and tube current were reduced, the radiation dose decreased while imaging contrast increased and the effect was greater in smaller sized phantoms. On the other hand, image noise increased when tube voltage and tube current were decreased, but the effect was seemingly minimal in smaller phantoms. Their findings indicate that the radiation dose can be decreased while retaining acceptable image quality, particularly in smaller patients or while performing paediatric contrast-enhanced CT examinations.

To our knowledge, this is the first study to examine and compare both qualitative and quantitative aspects of image quality after applying a practical paediatric CT dose reduction protocol. Our study clearly showed that there were no statistically significant differences in overall imaging quality for anatomical

interpretation and diagnostic confidence between before and after applying our dose reduction protocol. The delineation of bronchial walls were overall better defined in the anatomical criteria with the revised protocol, with statistical significance in partly thoracoabdominal scans because we applied CT parameters (CTDI, kVp and mA) following the abdominal CT protocol which has clearly higher CTDI, kVp and mA than that of the chest CT protocol. However, diagnosing pancreatitis and aortic dissection was statistically significantly worse in terms of diagnostic confidence, since the organs of interest in these conditions are located in the centre of the abdomen, which has physically the lowest level of contrast-to-noise ratio, and most of the CT studies were evaluated in the venous phase. Such scans are, of course, normally required primarily in emergency conditions, and, for such emergency conditions, we recommend other specific modified protocols such as the AEC, iterative reconstruction, more scanning phases or the CT angiography technique, which should be applied in life-threatening conditions or where high accuracy is needed.

Measured noise was statistically significantly increased in the scans of the head (21%; $p < 0.001$), abdomen (38%; $p < 0.001$) and thoracoabdomen (14.7%; $p < 0.02$) after using the dose reduction protocol. Only the abdominal scans showed slightly higher noise than the acceptable threshold noise level (20 HU) at 21 HU; however, subjective quality assessment found no statistically significant differences between before and after applying the revised protocol. Interestingly, measured noise in the chest CTs slightly decreased after changing the protocols, although without statistical significance. This might have been a result of increased contrast-to-noise ratio after reducing tube voltage and the lowest level of noise at the periphery which measures the noise area at the descending aorta.^{31,38} Reduction of radiation dose is correlated with increasing image noise in a physical way. This was clearly seen in this study, as after applying an age- and weight-based reduction protocol, the radiation dose was remarkably decreased with statistically significant differences in all scanning parts. Particularly in the chest and abdominal studies, the DLPs could be decreased up to 51% ($p < 0.001$) and 54% (0.001), respectively, while still

Figure 1. (a) Abdominal CT study of a 10-month-old girl using the default setting protocol of a 64-slice system (Phillips Brilliance) [body mass, 8.5 kg; CT dose index (CTDI) = 4.7 mGy; window level = 55 HU and window width = 426 HU] at the level of portal vein hilum shows measured noise at the abdominal aorta about 14.12 HU. (b) Example of abdominal CT study of a 10-month-old girl using the default setting protocol of a 64-slice system, Phillips Brilliance (body mass, 8.7 kg; CTDI = 2.07 mGy; window level = 83 and window width = 426) at the level of portal vein hilum shows measured noise at the abdominal aorta about 22.11. A, area; C, window centre; DFOV, display field of view; FFS, feet first supine; M, mean; P, posterior; RD, radial distance; SD, standard deviation; THK, slice thickness; W, window width; Z, image zoom.

(a)

(b)

achieving acceptable image quality. For longer scan lengths covering both the chest and abdomen in a single contrast examination, the mean radiation dose in the default setting protocol using the AEC was lower than that of the summative mean radiation dose of separated chest and abdominal CT studies. This resulted from eliminating the overlapping and over-ranging effects providing isotropic reconstruction, imaging

reformation and reduced radiation exposure.²³ After applying the dose reduction protocol using the abdominal CT parameters on the thoracoabdominal scans, the mean radiation dose was slightly higher than that of the additive radiation dose of separated chest and abdominal scans. However, the mean radiation dose in Phase 2 could be reduced up to 36% while still achieving acceptable image quality with statistical significance compared with Phase 1.

In addition, our study also showed that the radiation doses in all age groups in the brain, chest and abdominal examinations were lower than those found in a preliminary national dose survey for paediatric MDCTs in Thailand conducted in 2010 and reported in 2012.¹⁷ However, the DRLs of those studies were based on age group, and a more accurate comparison of radiation doses should be based on weight-based DRLs instead of age group because of rapidly changing sizes in toddlers and teenagers. A few published weight-based DRLs in chest and abdominal CT studies have also shown much lower radiation doses than those of age-based DRLs.^{15,16} The weight-based DRL is also more practically useful when adjusting tube voltages and tube currents, although some studies have suggested that abdominal circumference is the most accurate and useful parameter to optimize abdominal CT images in children owing to a wide variation in paediatric body shapes.³⁹

Limitations of the study

First, our study results cannot with confidence be applied to scanning machines from other CT manufacturers or different operating AEC systems. Although the use of an AEC system achieves the decreased radiation exposure, to maintain a constant noise level in areas of high tissue density requires increasing the tube current leading to higher radiation exposure than without the AEC system or manual adaptation.^{23,25} Furthermore, a specific universal paediatric AEC system protocol is still lacking, and our modulation technique should be applied with user-defined settings based on their own scanners and be used with caution in paediatric examinations. Secondly, the number of patients in our study aged less than 1 year was not high enough, particularly the lower numbers receiving head and abdominal studies, because we normally use ultrasound instead of a CT scan to minimize radiation exposure in this age group, thus further studies are required to establish the appropriate dose reduction protocols while maintaining diagnostic image quality. In addition, since we used two paediatric radiologists, it might be argued that our scores were higher than might be found in general radiologists. We suggest further studies including a larger group of radiologists or general or non-paediatric radiologists to eliminate possible bias in the findings and quality score.

CONCLUSION

Paediatric age- and weight-based CT dose reduction protocols can significantly reduce the half relative radiation dose while maintaining adequate anatomical details, diagnostic confidence and overall image quality.

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REFERENCES

- Brenner D, Elliston C, Hall E, Berdon W. Estimated risks of radiation-induced fatal cancer from pediatric CT. *AJR Am J Roentgenol* 2001; **176**: 289–96. doi: [10.2214/ajr.176.2.1760289](https://doi.org/10.2214/ajr.176.2.1760289)
- Brenner DJ, Hall EJ. Computed tomography—an increasing source of radiation exposure. *N Engl J Med* 2007; **357**: 2277–84.
- Hall EJ, Brenner DJ. Cancer risks from diagnostic radiology. *Br J Radiol* 2008; **81**: 362–78. doi: [10.1259/bjr/01948454](https://doi.org/10.1259/bjr/01948454)
- Fujii K, Aoyama T, Koyama S, Kawaura C. Comparative evaluation of organ and effective doses for paediatric patients with those for adults in chest and abdominal CT examinations. *Br J Radiol* 2007; **80**: 657–67. doi: [10.1259/bjr/97260522](https://doi.org/10.1259/bjr/97260522)
- Mettler FA Jr, Wiest PW, Locken JA, Kelsey CA. CT scanning: patterns of use and dose. *J Radiol Prot* 2000; **20**: 353–9.
- Linet MS, Kim KP, Rajaraman P. Children's exposure to diagnostic medical radiation and cancer risk: epidemiologic and dosimetric considerations. *Pediatr Radiol* 2009; **39**(Suppl. 1): S4–26.
- Huda W, Vance A. Patient radiation doses from adult and pediatric CT. *AJR Am J Roentgenol* 2007; **188**: 540–6. doi: [10.2214/AJR.06.0101](https://doi.org/10.2214/AJR.06.0101)
- National Research Council, Committee on the Biological Effects of Ionizing Radiations. *Health risks from exposure to low levels of ionizing radiation (BEIR VII: Phase 2)*. Washington, DC: National Academic Press; 2006.
- Kleinerman RA. Cancer risks following diagnostic and therapeutic radiation exposure in children. *Pediatr Radiol* 2006; **36**(Suppl. 2): 121–5. doi: [10.1007/s00247-006-0191-5](https://doi.org/10.1007/s00247-006-0191-5)
- Pearce MS, Salotti JA, Little MP, McHugh K, Lee C, Kim KP, et al. Radiation exposure from CT scans in childhood and subsequent risk of leukaemia and brain tumours: a retrospective cohort study. *Lancet* 2012; **380**: 499–505. doi: [10.1016/S0140-6736\(12\)60815-0](https://doi.org/10.1016/S0140-6736(12)60815-0)
- Diagnostic reference levels in medical imaging: review and additional advice. *Ann ICRP* 2001; **31**: 33–52.
- Shrimpton PC, Hillier MC, Lewis MA, Dunn M. National survey of doses from CT in the UK: 2003. *Br J Radiol* 2006; **79**: 968–80. doi: [10.1259/bjr/93277434](https://doi.org/10.1259/bjr/93277434)
- Verdun FR, Gutierrez D, Vader JP, Aroua A, Alamo-Maestre LT, Bochud F, et al. CT radiation dose in children: a survey to establish age-based diagnostic reference levels in Switzerland. *Eur Radiol* 2008; **18**: 1980–6. doi: [10.1007/s00330-008-0963-4](https://doi.org/10.1007/s00330-008-0963-4)
- Galanski M, Nagel HD, Stamm G. Pediatric CT exposure practice in the federal republic of Germany: results of a nationwide survey in 2005–2006. [Cited July 2014.] Available from: http://www.mh-hannover.de/fileadmin/kliniken/diagnostische_radiologie/download/Report_German_Paed-CT-Survey_2005_06.pdf
- Watson DJ, Coakley KS. Paediatric CT reference doses based on weight and CT dosimetry phantom size: local experience using a 64-slice CT scanner. *Pediatr Radiol* 2010; **40**: 693–703. doi: [10.1007/s00247-009-1469-1](https://doi.org/10.1007/s00247-009-1469-1)
- Järvinen H, Merimaa K, Seuri R, Tyrväinen E, Perhoma M, Savikurki-Heikkilä P, et al. Patient doses in paediatric CT: feasibility of setting diagnostic reference levels. *Radiat Prot Dosimetry* 2011; **147**: 142–6.
- Kritsaneepaiboon S, Trinavarat P, Visrutaratna P. Survey of pediatric MDCT radiation dose from university hospitals in Thailand: a preliminary for national dose survey. *Acta Radiol* 2012; **53**: 820–6. doi: [10.1258/ar.2012.110641](https://doi.org/10.1258/ar.2012.110641)
- Paterson A, Frush DP. Dose reduction in paediatric MDCT: general principles. *Clin Radiol* 2007; **62**: 507–17. doi: [10.1016/j.crad.2006.12.004](https://doi.org/10.1016/j.crad.2006.12.004)
- Goldman LW. Principles of CT: radiation dose and image quality. *J Nucl Med Technol* 2007; **354**: 213–25; quiz 226–8. doi: [10.2967/jnmt.106.037846](https://doi.org/10.2967/jnmt.106.037846)
- McNitt-Gray ME. Tradeoffs in CT image quality and dose. [Cited July 2014.] Available from: http://www.oucom.ohio.edu/ou-microct/Downloads/Tradeoffs_in_CT_Image_Quality_and_Dose_9794-13379.pdf
- Brisse HJ, Brenot J, Pierrat N, Gaboriaud G, Savignoni A, De Rycke Y, et al. The relevance of image quality indices for dose optimization in abdominal multi-detector row CT in children: experimental assessment with pediatric phantoms. *Phys Med Biol* 2009; **54**: 1871–92. doi: [10.1088/0031-9155/54/7/002](https://doi.org/10.1088/0031-9155/54/7/002)
- McNitt-Gray ME. AAPM/RSNA physics tutorial for residents: topics in CT. Radiation dose in CT. *Radiographics* 2002; **22**: 1541–53. doi: [10.1148/rg.226025128](https://doi.org/10.1148/rg.226025128)
- Nielsenstein RA, van Dam IM, van der Molen AJ. Multidetector CT in children: current concepts and dose reduction strategies. *Pediatr Radiol* 2010; **40**: 1324–44. doi: [10.1007/s00247-010-1714-7](https://doi.org/10.1007/s00247-010-1714-7)
- Tamm EP, Rong XJ, Cody DD, Ernst RD, Fitzgerald NE, Kundra V. Quality initiatives: CT radiation dose reduction: how to implement change without sacrificing diagnostic quality. *Radiographics* 2011; **31**: 1823–32. doi: [10.1148/rg.317115027](https://doi.org/10.1148/rg.317115027)
- Lee CH, Goo JM, Ye HJ, Ye SJ, Park CM, Chun EJ, et al. Radiation dose modulation techniques in the multidetector CT era: from basics to practice. *Radiographics* 2008; **28**: 1451–9. doi: [10.1148/rg.285075075](https://doi.org/10.1148/rg.285075075)
- Thomas KE, Wang B. Age-specific effective doses for pediatric MSCT examinations at a large children's hospital using DLP conversion coefficients: a simple estimation method. *Pediatr Radiol* 2008; **38**: 645–56. doi: [10.1007/s00247-008-0794-0](https://doi.org/10.1007/s00247-008-0794-0)
- Shrimpton PC, Wall BF. Reference doses for paediatric computed tomography. *Radiat Prot Dosimetry* 2000; **90**: 249–52.
- International Atomic Energy Agency. *Dose reduction in CT while maintaining diagnostic confidence: a feasibility/demonstration study. Document no. IAEA-TECDOC-1621*. Vienna, Austria: International Atomic Energy Agency; 2009.
- Tsapaki V, Aldrich JE, Sharma R, Staniszevska MA, Krisanachinda A, Rehani M, et al. Dose reduction in CT while maintaining diagnostic confidence: diagnostic reference levels at routine head, chest, and abdominal CT—IAEA-coordinated research project. *Radiology* 2006; **240**: 828–34.
- Sigal-Cinqualbre AB, Hennequin R, Abada HT, Chen X, Paul JF. Low-kilovoltage multi-detector row chest CT in adults: feasibility and effect on image quality and iodine dose. *Radiology* 2004; **231**: 169–74. doi: [10.1148/radiol.2311030191](https://doi.org/10.1148/radiol.2311030191)
- Siegel MJ, Schmidt B, Bradley D, Suess C, Hildebolt C. Radiation dose and image quality in pediatric CT: effect of technical factors and phantom size and shape. *Radiology* 2004; **233**: 515–22. doi: [10.1148/radiol.2332032107](https://doi.org/10.1148/radiol.2332032107)
- Shah R, Gupta AK, Rehani MM, Pandey AK, Mukhopadhyay S. Effect of reduction in tube current on reader confidence in paediatric computed tomography. *Clin Radiol* 2005; **60**: 224–31. doi: [10.1016/j.crad.2004.08.011](https://doi.org/10.1016/j.crad.2004.08.011)
- Singh S, Kalra MK, Moore MA, Shailam R, Liu B, Toth TL, et al. Dose reduction and compliance with pediatric CT protocols adapted to patient size, clinical indication, and number of prior studies. *Radiology* 2009; **252**: 200–8. doi: [10.1148/radiol.2521081554](https://doi.org/10.1148/radiol.2521081554)
- Mayo JR, Hartman TE, Lee KS, Primack SL, Vedal S, Müller NL. CT of the chest: minimal tube current required for good image quality with the least radiation dose. *AJR Am J Roentgenol* 1995; **164**: 603–7. doi: [10.2214/ajr.164.3.7863879](https://doi.org/10.2214/ajr.164.3.7863879)

35. Zhu X, Yu J, Huang Z. Low-dose chest CT: optimizing radiation protection for patients. *AJR Am J Roentgenol* 2004; **183**: 809–16. doi: [10.2214/ajr.183.3.1830809](https://doi.org/10.2214/ajr.183.3.1830809)
36. Kim JE, Newman B. Evaluation of a radiation dose reduction strategy for pediatric chest CT. *AJR Am J Roentgenol* 2010; **194**: 1188–93. doi: [10.2214/AJR.09.3726](https://doi.org/10.2214/AJR.09.3726)
37. Frush DP, Slack CC, Hollingsworth CL, Bisset GS, Donnelly LF, Hsieh J, et al. Computer-simulated radiation dose reduction for abdominal multidetector CT of pediatric patients. *AJR Am J Roentgenol* 2002; **179**: 1107–13. doi: [10.2214/ajr.179.5.1791107](https://doi.org/10.2214/ajr.179.5.1791107)
38. Dong F, Davros W, Pozzuto J, Reid J. Optimization of kilovoltage and tube current-exposure time product based on abdominal circumference: an oval phantom study for pediatric abdominal CT. *AJR Am J Roentgenol* 2012; **199**: 670–6. doi: [10.2214/AJR.10.6153](https://doi.org/10.2214/AJR.10.6153)
39. Reid J, Gamberoni J, Dong F, Davros W. Optimization of kVp and mAs for pediatric low-dose simulated abdominal CT: is it best to base parameter selection on object circumference? *AJR Am J Roentgenol* 2010; **195**: 1015–20. doi: [10.2214/AJR.09.3862](https://doi.org/10.2214/AJR.09.3862)