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ORIGINAL ARTICLE

High-pitch Dual-source Computed Tomography Coupled with Sinogram-affirmed Iterative Reconstruction: Image Quality and Radiation Dose in Children

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ABSTRACT

Objectives: *High-pitch imaging in computed tomography (CT) reduces scan time and radiation dose at the expense of increased noise. Recent advances in iterative reconstruction techniques allow for noise reduction without a significant increase in processing time, by using Sinogram-Affirmed Iterative Reconstruction (SAFIRE). We evaluated the combined effects of high-pitch imaging with SAFIRE in CT of the thorax and abdomen on image quality, diagnostic confidence, and radiation dose in children.*

Methods: *Consecutive CT examinations of the thorax and abdomen performed in young children (age <12 years) on a dual-source CT scanner using standard-pitch, filtered back-projection (group A) between January 2012 and February 2013 were compared retrospectively with those using high-pitch dual-source imaging with SAFIRE between March 2013 and December 2014 (group B). Radiation dose, objective image quality (noise and signal-to-noise ratio), subjective image quality (sharpness, noise, and beam-hardening artifacts), and diagnostic confidence for the two groups were compared by two independent blinded operators.*

Results: *Noise and signal-to-noise ratios of lung parenchyma were similar in the two groups, whereas those of the trachea were better in group B ($p < 0.001$). In the abdomen, both noise and signal-to-noise ratios of the liver and aorta were similar. Sharpness ($p = 0.011$) and noise ($p = 0.005$) were improved in the thorax for group B, but beam hardening worsened ($p = 0.001$). Both independent readers had excellent diagnostic confidence on all CT examinations in both groups. The combination of high-pitch imaging, iterative reconstruction, and reduction of tube current in group B allowed the radiation dose to be significantly lowered in the thorax (1.70 vs 2.71 mGy; $p = 0.012$), and slightly lowered in the abdomen (1.93 vs 3.26 mGy; $p = 0.08$).*

Conclusion: *The combination of high-pitch imaging with an iterative reconstruction algorithm allows the radiation dose to be lowered while offering preserved or even improved diagnostic image quality in paediatric patients.*

Key Words: *Child; Radiation dosage; Radiographic image interpretation, computer-assisted/methods; Tomography, X-ray computed*

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中文摘要

兒童雙源大螺距電腦斷層掃描加上正弦圖確定迭代重建：圖像質量和輻射劑量

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目的：電腦斷層掃描（CT）的大螺距成像以增加噪聲為代價縮短掃描時間和輻射劑量。迭代重建技術的最新進展透過正弦圖確定迭代重建（SAFIRE）容許在不顯著增加處理時間的情況下降低噪聲。本研究評估兒童CT胸腔和腹部造影檢查中的大螺距成像與SAFIRE對圖像質量、診斷可信度和輻射劑量帶來的綜合效果。

方法：回顧性分析兩組數據。A組為2012年1月至2013年2月期間以標準螺距濾波反投影的雙源CT掃瞄進行CT胸腔和腹部檢查的12歲以下兒童，B組為2013年3月至2014年12月期間接受雙源大螺距影像結合SAFIRE CT的12歲以下兒童。由兩名兒科放射學專家以獨立盲性法比較兩組的輻射劑量、客觀圖像質量（噪聲和信噪比）、主觀圖像質量（清晰度、噪聲和射束硬化偽影）和診斷可信度。

結果：兩組的肺實質噪聲和信噪比相當，但在氣管方面B組表現較佳（$p < 0.001$）。在腹部，兩組的肝臟和主動脈噪聲和信噪比亦相當。B組的胸部清晰度（$p = 0.011$）和噪聲（$p = 0.005$）得到改善，但射束硬化則變差（$p = 0.001$）。兩名獨立讀片人均認為兩組的所有CT檢查有良好的診斷可信度。B組使用大螺距成像、迭代重建和減低管電流的結合減低CT胸腔造影的放射劑量（1.70比2.71 mGy，$p = 0.012$），而CT腹部造影的放射劑量則呈下降趨勢（1.93比3.26 mGy，$p = 0.08$）。

結論：大螺距成像結合迭代重建可降低輻射劑量，且為兒童患者維持甚至提高診斷圖像質量。

INTRODUCTION

Use of computed tomography (CT) in children has increased.[1] Children have a longer life expectancy and are more susceptible to the detrimental effects of radiation; hence, the ‘as low as reasonably achievable’ (ALARA) principle in radiation protection should be applied. Dose-reduction strategies include automated tube-current modulation, low-tube potential, high-pitch imaging, and prospective electrocardiographic gating. A reduction in dosage, however, may result in increased image noise and artifacts, which affect image interpretation. In children, a slight increase in noise may still be acceptable as long as diagnostic information is preserved.[2]

The second-generation dual-source CT scanner (SOMATOM Definition Flash CT; Siemens Healthcare, Forchheim, Germany) is a 128-slice multidetector-row CT with high temporal resolution of 75 ms. It has two tube/detector pairs with a fast gantry rotation time of 0.28 s to shorten scanning time, an important consideration in children who cannot hold their breath.[3] The Flash spiral high-pitch scan mode reduces the average examination time to 0.49 s in paediatric patients, potentially negating the need for sedation.

Iterative reconstruction (IR) techniques remove noise more effectively than solely filtered back-projection techniques for image reconstruction. In addition, IR allows various dose-reduction methods to be incorporated, including tube-current modulation and reduction. Although IR techniques are traditionally more time-consuming and more expensive to perform, recent technological advances have shortened its reconstruction time for more widespread clinical use.

Different CT manufacturers have different IR algorithms, including IRIS/SAFIRE (Siemens, Forchheim, Germany), ASIR/VEO (GE Healthcare, Wisconsin, USA), iDose (Philips, Amsterdam, Netherlands) and AIDR 3D (Toshiba, Tokyo, Japan).[4] Some are based on blending IR with filtered back-projection (hybrid IR techniques), whereas others are based on domain space reconstruction alone.[5]

SAFIRE (Sinogram-affirmed Iterative Reconstruction) is one of the latest hybrid reconstruction techniques. Its major strength lies in its fast image processing in both the image data space and raw data domain. On each iterative cycle, data are reprojected in the sinogram space for validation and correction, resulting in improved images. SAFIRE has 5 preset strengths ranging from 1 to 5, with 5 having the greatest noise reduction. However, the image will also appear more pixelated or blotchy at higher strengths. In general, S2 or S3, regarded as medium strengths, are most appropriate for clinical practice because they give the best diagnostic confidence in both adult and paediatric patients.[6,7] At the Queen Elizabeth Hospital, Hong Kong, the Siemens SOMATOM Definition Flash CT scanner was used from January 2012 to March 2013, with standard-pitched image acquisition and traditional filtered back-projection for image reconstruction, for CT examinations of the thorax and abdomen in young children (age <12 years). After March 2013 the high-pitched flash-scanning mode and SAFIRE were used.

Previous studies have shown an improvement in image quality with SAFIRE in cardiovascular CT angiography in neonates and children.[8-10] To the best of our knowledge, no studies have investigated the effects of both high-pitch imaging and IR on paediatric CT of the thorax and abdomen for any clinical indication.[7] The purpose of this retrospective study was to investigate the combined effects of high-pitch imaging and IR in CT of the thorax and abdomen on image quality, diagnostic confidence, and radiation dose in young children.

METHODS

The study was approved by the Kowloon Central Cluster / Kowloon East Cluster Research Ethics Committee (Ref No. KC/KE-16-0076/ER-3), which waived the requirement for informed patient consent for this audit study. Retrospective data were collected from consecutive CT examinations of the thorax and abdomen performed in young children (age <12 years) on the Siemens SOMATOM Definition Flash CT at the Queen Elizabeth Hospital between January 2012 and December 2014. The first group (group A) comprised CT datasets obtained between January 2012 and February 2013 by standard-pitch scanning and a filtered back-projection algorithm. The second group (group B), comprised CT datasets obtained between March 2013 and December 2014 by high-pitch flash-scanning and the SAFIRE algorithm. Images from all CT examinations in group B were reconstructed with IR with a preset strength of S2. Both contrast and non-contrast CT scans were included in the study. When a contrast scan was performed, data from the contrast scan were used for data analysis. If multiple contrast phases were used, the venous phase was chosen for analysis.

During both periods, all CT examinations were performed with advanced CT dose technologies—namely, automated current modulation, automated tube voltage, and region-specific dose reduction. Automated Current Modulation (Care Dose; Siemens Healthcare) provided real-time current (mA) modulation adapted to body thickness. Automated Tube Voltage (Care KV, Siemens Healthcare) selected the optimal individualised kV setting with pre-set kV value based on age, bodyweight, and reference settings for calculation. X-Care (Siemens Healthcare) was used to reduce dose to the most dose-sensitive body regions, such as breast, thyroid, and lens. Imaging protocols for thoracic and abdominal CT were standardised. Thoracic CT included scanning from the supraclavicular region to the liver. Abdominal CT included scanning from the lung base to the iliac crest. The scan range was also standardised. The imaging settings are shown in Tables 1 and 2. The major changes in the CT protocol in group B were the application of a lower reference current (ref mA), higher pitch acquisition, and reconstruction with the IR technique.

Data Measurement and Statistical Analysis

All examination datasets within the study period were anonymised. The images of all datasets were

Table 1. Imaging settings of thoracic computed tomography in the two study groups.

Setting	Group A	Group B
Care kV mode	On	On
Tube current (ref mA)	110	80
Voltage (ref kV)	120	120
Pitch	0.6	2.8
Gantry rotation(s)	0.28	0.28
Coverage	0.6 x 64	0.6 x 64

Table 2. Imaging settings of abdominal and pelvic computed tomography in the two study groups.

Setting	Group A	Group B
Care kV mode	On	On
Tube current (ref mA)	210	120
Voltage (ref kV)	120	120
Pitch	1.4	3.0
Gantry rotation(s)	0.5	0.28
Coverage	0.6 x 64	0.6 x 64

Table 3. Image quality assessment based on European Guidelines on Quality Criteria for Computed Tomography.[11]

Sharpness	1 = very sharp 2 = questionable 3 = noticeable blur	Beam-hardening artifacts	1 = less than usual 2 = optimal level 3 = artifacts affect interpretation
Noise	1 = less than usual 2 = optimal noise 3 = noise affects interpretation	Diagnostic confidence	1 = fully confident 2 = probably confident 3 = limited confidence

independently reviewed by two paediatric radiologists (K.S.T, H.Y.L) who were blinded to the clinical information, examination details, and prior imaging findings and reports, as well as the results of qualitative assessment. Images were reviewed on the hospital's picture archiving and communication system.

Qualitative Analysis

Subjective image quality assessment was conducted by two paediatric radiologists, each with 10 years' experience in radiology. Qualitative image quality was based on the European Guidelines on Quality Criteria for Computed Tomography.[11] The assessed quality criteria included subjective sharpness, subjective noise, beam-hardening artifacts, and diagnostic confidence (Table 3).[12]

Quantitative Analysis

Objective image quality was obtained from the hospital's picture archiving and communication system and measured in terms of mean noise (defined as standard deviation of CT number in Hounsfield units) and signal-to-noise ratio (defined as mean CT number in Hounsfield units divided by image noise). These values were calculated from identical regions of interest in selected anatomical regions by placing a region-of-interest circle with an area of 0.2 to 0.5 cm^2 according to patient size and area of interest. In the thorax, the selected regions included lung parenchyma, trachea, paraspinal muscle, and subcutaneous tissue (Figure 1). In the abdomen, they included the liver, aorta, paraspinal muscle, and subcutaneous tissue (Figure 2).

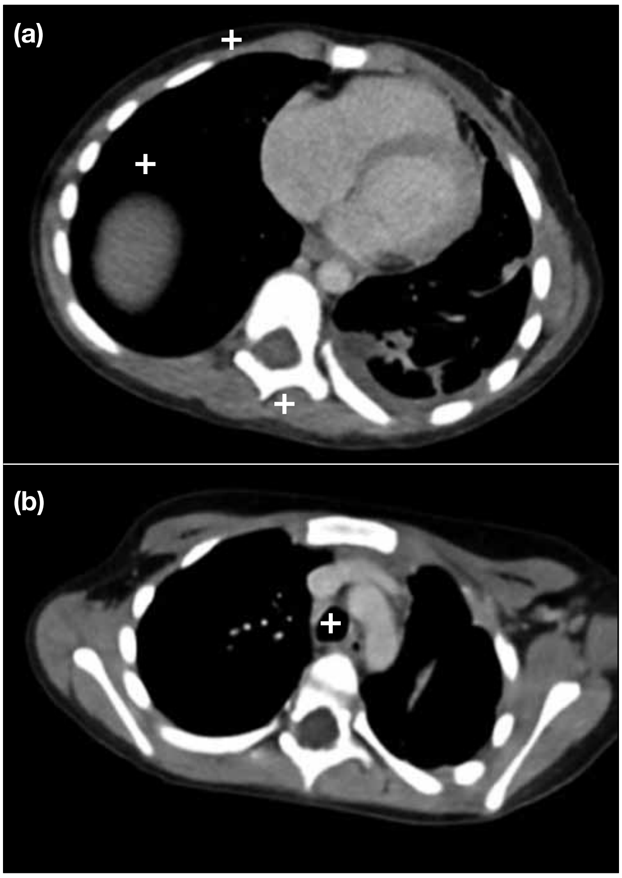

Figure 1. In the thorax, mean noise and signal-to-noise ratio were measured from regions of interest (crosses) in anatomical regions including (a) lung parenchyma, paraspinal muscle, subcutaneous tissue, and (b) trachea.

Radiation Dose Measurements

Radiation dose was obtained from our picture archiving and communication system and measured in terms of volume CT dose index ($CTDI_{vol}$). A CTDI phantom, with diameter of 32 cm as preset by the manufacturer (Siemens Healthcare), was used as a reference for CT dose value estimation. The dose-length product was also retrieved. If the radiation dose in the thorax and abdomen in combined examinations could not be obtained separately, it was excluded from radiation dose analysis.

Continuous variables including age, radiation dose, and objective image quality are expressed in mean ± standard deviation and were analysed by the independent *t* test. Subjective image quality and sex ratio are expressed in percentages with between-group difference analysed by Pearson's Chi-square test. The potential disparity of subjective image quality assessment between independent radiologists was evaluated by intraclass correlation coefficient.

RESULTS

A total of 165 paediatric thoracic and abdominal CT image datasets were obtained on the hospital's Siemens SOMATOM Definition Flash CT machine during the study period from January 2012 to December 2014. There were 50 CT datasets (35 for the thorax, 15 for the abdomen) in group A and 115 CT datasets (84 for the thorax, 31 for the abdomen) in group B. There was no significant demographic difference in terms of mean age (3.07 vs 2.68 years; $p = 0.483$) or sex ratio (M:F = 1.17:1 vs 1.13:1; $p = 0.910$), as shown in Table 4.

Figure 2. In the abdomen, mean noise and signal-to-noise ratio were measured from regions of interest (crosses) in anatomical regions including liver, aorta, paraspinal muscle, and subcutaneous tissue.

Radiation Dose Measurements

Radiation dose in the thorax, as measured by mean $CTDI_{vol}$, was significantly lower in group B than in group A (1.70 vs 2.71 mGy; $p = 0.012$). In the abdomen, mean $CTDI_{vol}$ was also lower in group B than in group A, although statistical significance was not observed ($CTDI_{vol}$ = 1.93 vs 3.26 mGy; $p = 0.08$). Some patients (6 in group A, 8 in group B) who underwent combined thoracic and abdominal examination were excluded, as $CTDI_{vol}$ evaluation for each body region was not possible. The dose-length product also showed a slight reduction for group B, despite not achieving statistical significance (Table 4).

Quantitative Analysis

Objective image quality assessments between the two groups are shown in Table 5. In the thorax, there was no difference between group A and group B in the lung parenchyma in terms of noise (11.8 and 10.3, respectively; $p = 0.186$) and signal-to-noise ratio (72.6 and 75.3, respectively, $p = 0.672$). Objective image quality was better in group B than group A at the trachea, with improved noise (4.1 vs 21.8; $p < 0.001$) and signal-to-noise ratio (459.4 vs 135.3; $p < 0.001$).

Table 4. Patient characteristics in the two study groups.

	Group A (standard pitch)	Group B (high pitch)	p Value
No. of CT datasets	50	115	
No. of thorax CT examinations	35	84	
With contrast	15	63	
Non-contrast	20	21	
No. of contrast-enhanced abdomen CT examinations	15	31	
Age, mean (SD), y	3.07 (3.54)	2.68 (2.55)	0.483
Sex, M:F (No.:No.)	1.17:1 (27:23)	1.13:1 (61:54)	0.910
Radiation dose			
Thorax	(n = 29*)	(n = 76*)	
$CTDI_{vol}$, mean (SD), mGy	2.71 (1.98)	1.70 (0.90)	0.012
DLP, mean (SD), mGy·cm	54.87 (51.54)	45.41 (36.62)	0.371
Abdomen	(n = 9*)	(n = 23*)	
$CTDI_{vol}$, mean (SD), mGy	3.26 (1.96)	1.93 (0.86)	0.08
DLP, mean (SD), mGy·cm	78.80 (63.09)	62.35 (38.49)	0.481

Abbreviations: CT = computed tomography; $CTDI_{vol}$ = volume CT dose index; DLP = dose-length product; F = female; M = male; SD = standard deviation.
* Excluded combined thorax-abdomen studies in which radiation dose could not be separately evaluated.

Table 5. Results of objective image quality assessment for the two study groups.*

Region	Variable	Group A	Group B	p Value
Thorax				
Lung parenchyma	Noise	11.8 (6.0)	10.3 (3.6)	0.186
	SNR	72.6 (38.1)	75.3 (28.2)	0.672
Trachea	Noise	21.8 (29.7)	4.1 (4.5)	< 0.001
	SNR	135.3 (138.8)	459.4 (358.9)	< 0.001
Paraspinal muscle	Noise	6.50 (2.50)	6.68 (2.09)	0.756
	SNR	12.0 (5.97)	11.8 (5.43)	0.861
Subcutaneous tissue	Noise	7.22 (3.04)	5.38 (1.87)	0.002
	SNR	14.1 (7.25)	18.0 (10.6)	0.051
Abdomen				
Abdominal aorta	Noise	7.66 (4.13)	6.81 (2.78)	0.476
	SNR	24.7 (12.7)	35.6 (69.6)	0.550
Liver	Noise	5.94 (2.58)	5.11 (1.80)	0.209
	SNR	26.1 (20.6)	26.1 (14.1)	0.996
Paraspinal muscle	Noise	5.92 (3.00)	8.99 (14.00)	0.407
	SNR	15.7 (9.0)	14.4 (12.0)	0.709
Subcutaneous tissue	Noise	8.07 (3.60)	5.76 (3.15)	0.031
	SNR	10.8 (9.2)	14.0 (12.7)	0.379

Abbreviation: SNR = signal-to-noise ratio.
* Data are shown as mean (standard deviation).

Table 6. Results of subjective image quality assessment for the two study groups*

Thorax	Group A (n = 38)	Group B (n = 84)	p Value
Sharpness = 1	69%	88%	0.011
Sharpness = 2	31%	12%	
Sharpness = 3	–	–	
Noise = 1	6%	31%	0.005
Noise = 2	94%	65%	
Noise = 3	–	4%	
Beam hardening = 1	69%	35%	0.001
Beam hardening = 2	29%	43%	
Beam hardening = 3	3%	22%	
Abdomen	**Group A (n = 17)**	**Group B (n = 31)**	**p Value**
Sharpness = 1	73%	58%	0.528
Sharpness = 2	27%	39%	
Sharpness = 3	–	3%	
Noise = 1	100%	10%	0.346
Noise = 2	–	87%	
Noise = 3	–	3%	
Beam hardening = 1	80%	77%	0.781
Beam hardening = 2	13%	19%	
Beam hardening = 3	7%	3%	

* Scoring of 1, 2, and 3 based on European Guidelines on Quality Criteria for Computed tomography[11] (see Table 3).

There was also improved noise in the subcutaneous tissue (5.38 vs 7.22; p = 0.002). None of the results in group B showed reduced objective quality. In the abdomen, noise and signal-to-noise ratio showed no significant difference in the abdominal aorta, liver, or paraspinal muscle, whereas noise in subcutaneous tissue was improved in group B compared with group A (5.76 vs 8.07; p = 0.031). Again, there was no significant deterioration of quality in any of the regions assessed.

Qualitative Analysis

Effects on subjective image quality are shown in Table 6. In the thorax, subjective image quality was improved in group B in terms of sharpness (p = 0.011) and noise (p = 0.005), with 19% and 25% more scores of '1', respectively. Nonetheless, beam hardening worsened in group B, with a 34% reduction in scores of '1' ($p = 0.001$). In the abdomen, no difference was found between the two groups in terms of sharpness ($p = 0.528$), noise ($p = 0.346$), or beam hardening ($p = 0.781$).

Correlation between the two readers was considered moderate to good, with intraclass correlation coefficients of between 0.620 and 0.850. Both independent readers had good diagnostic confidence on all CT examinations (100% with score of '1') in both groups.

DISCUSSION

The first step to reduce radiation exposure in children is judicious use of CT examination and increasing awareness among clinicians and the general public of the importance of minimising radiation exposure.[2,13] Alternative imaging tests—for example, MRI or ultrasonography—may sometimes be more appropriate in children.[14] When a CT examination is justified, steps should be taken to optimise the scanning variables.[2] For instance, automated tube modulation, lower user-defined kV settings (automated tube voltage), and dose reduction for sensitive body regions are recent advances in CT techniques, contributing to lowering radiation dose to children. After dose reduction, the choice of post-processing technique is crucial to ensure that the images are of sufficient diagnostic quality. When examining the paediatric age group, clinicians are usually willing to accept some degree of noise to keep the radiation dose low, as long as diagnostic confidence is not affected.

As there is a linear inverse relationship between pitch and radiation dose, dual-source CT allows high-pitch imaging, and thus faster scanning and dose reduction.[15] The incurred noise from dose-reduction strategies can be remedied by a noise-reduction technique, such as IR. Our study results showed that the combination of high-pitch dual-source CT scanning and SAFIRE allowed us to lower the radiation dose while preserving or even improving image quality. The only deterioration in subjective image quality was in terms of worsening of beam-hardening artifacts in the thorax, especially around the shoulder girdle. This effect can be attributed to the increased artifacts at the scapula, a finding consistent with other reports in the literature.[16] Diagnostic confidence was not affected.

Our initial results are promising. The reduction in radiation dose was achieved by a combination of high-pitch scanning and a reduction in our assigned tube current (ref mA). Radiation dose in terms of $CTDI_{vol}$ was significantly lowered in the thorax and slightly lowered in the abdomen, albeit not achieving statistical significance. The dose-length product also showed a slight reduction, without being statistically significant. The non-significant findings are likely related to the small sample size and the use of a low IR strength (S2) in our study. We were conservative in choosing S2 IR strength, from 5 different strengths. With more imaging experience, we may be able to gradually move towards a higher IR strength, and thereby achieve further radiation reduction.

Lee et al[7] compared subjective and objective image quality of full-dose images by filtered back-projection and corresponding half-dose images produced with different strengths of SAFIRE (S1-S5) in paediatric abdominal CT. Although image noise decreased inversely with SAFIRE strength, their images appeared blotchy and pixelated at S5, making the images unsuitable for diagnostic evaluation. Overall, S4 images produced the best objective image quality, whereas S3 images produced the best subjective imaging quality. Nonetheless, the optimal strength should be tailored to each institution's need and requires further validation in our centre.

There are several limitations in this study. Although there was no difference between groups in age or sex, the bodyweight or body mass index were not retrieved and may vary widely in paediatric patients of the same age and sex. In addition, this was a retrospective study and the scanning protocol was not standardised for contrast use or number of phases. Lack of standardisation could be a potential confounding factor during the calculation of noise and signal-to-noise ratio. All cases of abdomen CT had the portovenous phase performed and were therefore unaffected. In the thorax, different contrast phases were used, including arterial and venous phases. We believe that the effects were minimal in our regions of interest such as lung parenchyma, trachea, subcutaneous tissue, and paraspinal muscle, owing to minimal contrast enhancement in these regions. Another limitation was the small sample size, especially for abdominal cases. Future prospective studies with a larger sample size, a higher IR strength, and a standardised recruitment and imaging protocol are advised for better evaluation.

The current CT imaging protocol with high-pitch imaging and SAFIRE is confined to paediatric patients younger than 12 years. A regular audit is planned in our centre in order to review image quality and radiation dose under the current imaging protocol. Further research is required before extending use of the protocol to older children, as beam-hardening artifacts may increase with body size.

CONCLUSION

A combination of high-pitch dual-source imaging with an IR algorithm allows radiation dose to be lowered while offering preserved or even improved diagnostic image quality. Further optimisation of blending may allow further dose reduction in the future.

REFERENCES

1. Smith-Bindman R, Miglioretti DL, Johnson E, Lee C, Feigelson HS, Flynn M, et al. Use of diagnostic imaging studies and associated radiation exposure for patients enrolled in large integrated health care systems, 1996-2010. JAMA. 2012;307:2400-9. cross ref
2. Strauss KJ, Goske MJ, Kaste SC, Bulas D, Frush DP, Butler P, et al. Image gently: Ten steps you can take to optimize image quality and lower CT dose for pediatric patients. AJR Am J Roentgenol. 2010;194:868-73. cross ref
3. Kehl HG, Kiski D, Maintz D, Stege D, Vebus V, Kotthoff S, et al. Reduced radiation dose of thoracic and cardiac dual source computer tomography with high-pitch protocol in infants and children. Pediatr Res. 2011;70:249. cross ref
4. Cho YJ, Schoepf UJ, Silverman JR, Krazinski AW, Canstein C, Deak Z, et al. Iterative image reconstruction techniques: cardiothoracic computed tomography applications. J Thorac Imaging. 2014;29:198-208. cross ref
5. Khawaja RD, Singh S, Otrakji A, Padole A, Lim R, Nimkin K, et al. Dose reduction in pediatric abdominal CT: use of iterative reconstruction techniques across different CT platforms. Pediatr Radiol. 2015;45:1046-55. cross ref
6. Song JS, Choi EJ, Kim EY, Kwak HS, Han YM. Attenuation-based automatic kilovoltage selection and sinogram-affirmed iterative reconstruction: effects on radiation exposure and image quality of portal-phase liver CT. Korean J Radiol. 2015;16:69-79. cross ref
7. Lee M, Kim MJ, Han KH, Lee MJ. Half-dose abdominal CT with sinogram-affirmed iterative reconstruction technique in children—comparison with full-dose CT with filtered back projection. Pediatr Radiol. 2015;45:188-93. cross ref
8. Tricarico F, Hlavacek AM, Schoepf UJ, Ebersberger U, Nance JW Jr, Vliegenthart R, et al. Cardiovascular CT angiography in neonates and children: image quality and potential for radiation dose reduction with iterative image reconstruction techniques. Eur Radiol. 2013;23:1306-15. cross ref
9. Zheng M, Zhao H, Xu J, Wu Y, Li J. Image quality of ultra-low-dose dual-source CT angiography using high-pitch spiral acquisition and iterative reconstruction in young children with congenital heart disease. J Cardiovasc Comput Tomogr. 2013;7:376-82. cross ref
10. Nie P, Li H, Duan Y, Wang X, Ji X, Cheng Z, et al. Impact of sinogram affirmed iterative reconstruction (SAFIRE) algorithm on image quality with 70 kVp-tube-voltage dual-source CT angiography in children with congenital heart disease. PloS One. 2014;9:e91123. cross ref
11. European guidelines on quality criteria for computed tomography. Available from: http://www.drs.dk/guidelines/ct/quality/htmlindex.htm. Accessed 24 Apr 2016.
12. Han BK, Grant KL, Garberich R, Sedlmair M, Lindberg J, Lesser JR. Assessment of an iterative reconstruction algorithm (SAFIRE) on image quality in pediatric cardiac CT datasets. J Cardiovasc Comput Tomogr. 2012;6:200-4. cross ref
13. Goske MJ, Applegate KE, Bell C, Boylan J, Bulas D, Butler P, et al. Image Gently: providing practical educational tools and advocacy to accelerate radiation protection for children worldwide. Semin Ultrasound CT MR. 2010;31:57-63. cross ref
14. Donnelly LF. Reducing radiation dose associated with pediatric CT by decreasing unnecessary examinations. AJR Am J Roentgenol. 2005;184:655-7. cross ref
15. Primak AN, McCollough CH, Bruesewitz MR, Zhang J, Fletcher JG. Relationship between noise, dose, and pitch in cardiac multi-detector row CT. Radiographics. 2006;26:1785-94. cross ref
16. Hsieh J. Computed Tomography Principles, Design, Artifacts, and Recent Advances. 2. Bellingham, WA: Society of Photo Optical Instrumentation Engineering; 2009.