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Initial clinical experience with high-pitch dual-source CT as a rapid technique for thoraco-abdominal evaluation in awake infants and young children

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AIM: To evaluate dual-source high-pitch computed tomography (HPCT) imaging of the chest and abdomen as a rapid scanning technique to obtain diagnostic-quality imaging evaluation of infants and young children without sedation.

MATERIALS AND METHODS: Fifty-three paediatric patients (age 24.1±2 months) who underwent chest or abdomen HPCT (≥1.5) and standard pitch CT (SPCT, <1.5) on a dual-source 128-row multidetector CT system were included in the study. Image quality assessment was performed by two paediatric radiologists for diagnostic confidence, image artefacts, and image noise. Objective image noise was measured.

RESULTS: Most of the CT examinations were performed in children who were >1 year old (n=15 and n=20) followed by ≤1 year old (n=8 and n=10) in SPCT and HPCT, respectively. The mean radiation dose (SSDE) from HPCT was 1.96±1 mGy compared to 2.2±1 mGy for SPCT (p=0.3). No major artefacts were reported and overall image quality of all HPCT examinations was acceptable diagnostically. In addition, objective image noise values were not significantly different between HPCT compared with SPCT (11±3 versus 11±5, p=0.7).

CONCLUSION: Ultra-fast, HPCT can be performed without the need for sedation as a potential alternative to anaesthetised magnetic resonance imaging in infants and young children.

Introduction

Computed tomography (CT) of the abdomen and chest has become a valuable imaging technique in paediatric patients for evaluating thoraco-abdominal focal lesions, identification of infectious sources, tumour staging, and grading of traumatic injuries. It is estimated that 85 million CT examinations are performed annually in US alone, including 10 million paediatric CT examinations.[1,2] Children have higher proportion of dividing cells in their body and smaller body circumference, and so, demonstrate more sensitivity to radiation than adults.[3,4] Furthermore, they have longer future lifespans than adults at the time of exposure, resulting in a longer latency period for expressing

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long-term radiation-induced sequelae. Because of concerns about ionising radiation, many infants and young children are now imaged with magnetic resonance imaging (MRI) instead of CT to assess for thoraco-abdominal pathology; however, due to enclosed nature of MRI scanners and the relatively long scan times, many patients in this age group require deep sedation or anaesthesia to undergo MRI.[5] Although MRI is able to avoid the risks associated with ionising radiation, recent attention has focused on potential risk associated with anaesthetic medication exposure in young children, including preclinical studies associating prolonged anaesthetic drug exposure with apoptotic neurodegeneration in neonatal brains and population studies associating anaesthetic exposure in young children with effects on learning and behaviour.[6–8]

In addition to increased MRI utilisation, substantial efforts have been made for reducing radiation dose in CT imaging of paediatric patients while preserving diagnostic image quality, including the use of tube voltage and tube current reduction protocols in addition to model-based and hybrid iterative reconstruction (IR) algorithms.[9–12] Despite the large reductions in CT dose achievable in paediatric patients, CT imaging of infants and young children remains challenging because of artefacts related to respiration and gross patient movements that can degrade image quality, particular of structures in the lower thorax and upper abdomen. Dual-source CT (DSCT) techniques have been recently introduced that enable acquisition of helical chest CT data with higher table pitch (up to 3.2) and table speed of up to 450 mm/s, which results in lower motion artefacts in adults.[13–16] The fast scan time (<1 second) associated with high-pitch CT (HPCT) performed in children potentially can provide high-quality evaluation of the thorax and abdomen in awake infants and young children as a low radiation alternative to MRI without the need for sedation. Previous studies have reported promising initial results for using free-breathing high-pitch chest DSCT protocol in paediatric patients.[17–20] The purpose of this study is to report a single institution's initial clinical implementation of chest/abdomen CT protocol combining high-pitch mode (HPM) with advanced IR algorithms for non-sedated paediatric patients without breathing instructions, and to compare image quality and radiation dose of this protocol with the standard pitch clinical protocol on the same CT machine.

Materials and methods

Study design

This retrospective single-institutional study is Health Insurance Portability and Accountability Act (HIPAA)-compliant and institutional review board (IRB) approved (protocol no. 2017P000357). The requirement for patient informed consent was waived.

Patients

A retrospective institutional radiology database search was performed to identify paediatric patients (age 0–5 years) who underwent clinical chest (n=26) and abdominal CT (n=28) examinations from 2012–2016 on a 128 multidetector row CT machine (Siemens Definition Flash, Siemens Healthcare, Malvern, PA, USA). Clinical indications for all chest and abdominal CT were recorded from the Radiology Information System (RIS). The most common clinical indications for the 18 chest HPCT examination included pulmonary embolism (n=4), chest or mediastinal mass evaluation (n=4), suspected tuberculosis (n=3), worsening dyspnoea (n=2), work-up for chest trauma (n=2), and pneumothorax, abscess, recurrent pneumonia (n=1, each). The most common clinical indications for the eight chest SPCT included suspected or known pulmonary arteriovenous malformation (n=3), chest or mediastinal mass or metastasis evaluation (n=2), dyspnoea (n=2), and work-up for chest trauma (n=1). Clinical indications for 13 abdomen HPCT examinations were abdominal pain (n=5), inflammatory bowel disease (n=3), work-up for abdominal trauma (n=3), abdominal mass evaluation, and intra-abdominal abscess (n=1, each). Indications for the 15 abdomen SPCT included abdominal pain (n=5), abdominal mass evaluation (n=4), inflammatory bowel disease (n=3), intra-abdominal abscess (n=2), and pancreatitis (n=1).

Patient demographic information (age, sex, weight) were retrieved from the PACS and the electronic medical record. Patient imaging parameters and dose information, such as effective tube current, tube voltage and scan pitch, were extracted from an institutional radiation dose software system (Radimetrics, Version 2.6).

Scanning techniques

All CT examinations were undertaken using a 128-row multidetector CT system (SOMATOM Definition Flash, Siemens Healthcare) with either standard pitch mode (SPM; pitch <1.5) or high pitch mode (HPM; pitch ≥1.5), with administration of intravenous contrast (iopamidol 370 mg iodine/ml, Bracco Diagnostics, NJ, USA; administered at 1.6 ml/kg). Filtered back-projection (FBP) or IR were used based on availability to reconstruct the axial images. All imaging parameters were similar between two groups (reference tube voltage, 80 and 100 kV (29 versus 17 examinations were done with 80 kV and 12 versus six examinations with 100 kV on HPM and SPM, respectively) with the exception of scan pitch; mean reference tube current was 191.2±95 mAs on HPM and 94.7±54 mAs on SPM). Gantry rotation time of 0.28 and 0.5 seconds, 39.37 mm table speed per gantry rotation, helical acquisition mode, 128×0.6 mm detector configuration, 5 mm reconstructed section thickness, and 5 mm reconstruction section interval. Patients were scanned on HPM depending on the indication of the CT and the scanner's availability. All high-pitch images were reconstructed using SAFIRE, level 3. ADMIRE was used to reconstruct standard pitch images.

Radiation exposure, scanning length, and time

CT dose index ($CTDI_{vol}$) and dose–length product (DLP) for each examination was recorded from the Radimetrics software. Effective dose (ED) was calculated from the latest publication from the International Commission on Radiological Protection (ICRP) as DLP×k (mSv/mGy/cm) for abdomen and chest. The conversion factor, k, is age dependent and was estimated from the American Association of Physicists in Medicine (AAPM Report 96) on radiation dose[21,22] varied with age and size-specific dose estimate (SSDE) was calculated from $CTDI_{vol}$ using the conversion factors of the AAPM-TG204 publication.[23] The total examination times were retrieved for each examination from the PACS workstation and electronic medical records.

Subjective evaluation for image quality of HPCT and SPCT images

All abdomen and chest CT image datasets were reviewed on a picture archiving and communication systems diagnostic workstation (AGFA Impax ES, AGFA Technical Imaging Systems) for subjective image quality evaluation. Two experienced fellowship-trained paediatric radiologists (with 12 and 20 years of experience) independently assessed all image data sets. Both radiologists were trained on image sets from both HPCT and SPCT techniques (which were subsequently eliminated from analysis) for the grading of different aspects of subjective image quality as well as lesion assessment to understand the evaluation system.

Both radiologists were blinded to the findings and independently assessed the images in two separate study sessions. Chest CT examinations were evaluated on lung and mediastinal windows (lung: width, 1500 HU; level, −600 HU; mediastinal: width, 350 HU; level, 50 HU). Abdominal CT examinations were assessed on liver and soft tissue windows (liver: width, 150 HU; level, 88 HU; soft tissue: width, 125 HU; level, 35 HU). In addition to the default preselected lung and mediastinal settings, radiologists were also allowed to change the window width and level according to their comfort level of assessment.

Image artefacts (such as stair step and motion artefacts) on a four-point grading scale (1=no artefacts, 2=minor artefacts not interfering with diagnostic decision making, 3=major affecting visualisation of major structures, diagnosis still possible, 4=artefacts affecting diagnostic information), image noise on a five-point scale (1= unacceptable, 2= above average, 3= average, 4= less than average, 5= minimal) and overall image quality on a five-point grading scale (1= unacceptable, 2= suboptimal, 3= average, 4= above average, 5= excellent) were assessed for all chest and abdominal CT examinations. Grades 1 to 2 were considered "non-acceptable" and grades 3 to 5 as "acceptable" for chest and abdomen overall image quality. Image quality characteristics assessed in the present study have been described in the European Guidelines on Quality Criteria for Computerized Tomography document (EUR 16262).[24]

Objective image quality evaluation

The CT images were analysed for mean attenuation values, image noise (standard deviation of attenuation) and CNR (contrast to noise ratio). The regions of interest (ROIs, 20–30 mm) were manually placed over the pulmonary arteries, paraspinal muscle and lung for chest CT examinations (average attenuation of left and right pulmonary arteries − average attenuation of paraspinal muscles)/(average noise in left and right lungs) and over the liver and intraperitoneal fat (average attenuation of liver − average attenuation of intraperitoneal fat)/average noise in intraperitoneal fat) for abdominal CT images. The ROI was replicated and placed on the exact same location throughout the entire study.

Statistical analysis

Dose analysis was performed on all cases with archived doses. Overall dose was compared using a two-sample *t*-test. CT attenuation and quantitative objective noise data (parametric variables) were analysed using Student's *t*-test and Wilcoxon signed rank test for subjective image quality and lesion evaluation (nonparametric) variables. *p*-Values <0.05 were considered significant. The inter-reader agreement (using kappa statistics) categorisation was as follows: poor, <0.2; fair, 0.2 to <0.4; moderate, 0.4 to <0.6; good, 0.6 to <0.8; and very good, 0.8 to 1.

Results

Patient characteristics

Fifty-two patients were included in the present study, including 30 patients (31 total scans; 18 chest CT and 13 abdomen CT) with HPCT (defined as scan pitch ≥ 2) and 22 patients (23 total scans; 8 chest CT and 15 abdomen CT) with SPCT (defined as scan pitch <2). A total of 54 chest (n=26) and abdomen CT (n=28) examinations were analysed. Patients in both groups were classified into two subgroups based on different age groups (Table 1). There was no significant statistical difference between the age, weight, and patient diameter between SPCT and HPCT groups. All HPCT and SPCT examinations were performed in awake patients without sedation. The average patient age was 27.8±2 in the SPCT group and 21.3±2 months in the HPCT group. Twenty-nine of 52 patients (56%) were female. No HPCT case received sedation while three patients underwent anaesthesia in SPCT group (Fig 1).

Radiation doses, scanning length, and examination time

Based on the dose reports, the average $CTDI_{vol}$, DLP, SSDE and estimated effective dose values in HPCT examinations

Table 1
Baseline patient characteristics.

Age (year)	High-pitch mode			Standard-pitch mode		
	n	Weight (kg)	Patient Diameter (mm)	*n*	Weight (kg)	Patient Diameter (mm)
<1	10	6±2	116±2	8	9±6	120±1
1–5	21	16.4±1	146±1	15	15±6	144±2
	31			23		

n is the number of CT scans.

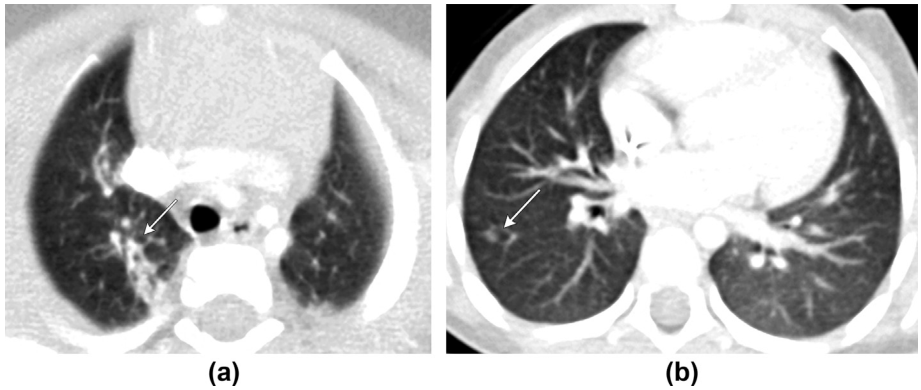

Figure 1 Axial dual-energy CT images of (a) a sedated 3-year-old male patient (pitch: 1.1, CTDI: 3 mGy and DLP: 67 mGy·cm) demonstrated right upper lobe opacity (arrow) and left lung volume loss due to subsegmental atelectasis and (b) a 4-year-old female patient (pitch: 3, CTDI: 1.3 mGy and DLP: 36 mGy·cm) showed subcentimetre pulmonary nodule (measuring 5 mm, arrow) in the superior segment of the right lower lobe who scanned on a dual-source multidetector scanner. The patient was awake and followed no breathing instructions.

showed no statistical significance compared with SPCT studies (1.8±0.5 versus 2±0.8 mGy, 49±2 versus 55.2±3 mGy·cm, 1.96±1 versus 2.2±1 mGy and 2.6±0.9 versus 2.6±1 mSv, respectively, $p=0.3$ for all values; Table 2; Fig 2). The mean total examination time was significantly lower in the chest HPCT group compared to chest SPCT group (10.7±3 versus 15.1±5 minutes, $p=0.03$). The mean total examination time in the abdomen HPCT group was 25% lower compared to SPCT group, which approached statistical significance (7.5±3 versus 10±2 minutes, $p=0.08$).

HPCT diagnostic acceptability

Two radiologists rated the overall quality of chest and abdominal images, as well as the motion artefacts and noise of CT examinations using a five-point scale. The interobserver agreement (kappa-value) for overall image quality, artefact and noise were 0.98 ($p=0.1$), 0.84 ($p=0.3$) and 0.94 ($p=0.05$), respectively.

HPCT subjective and objective image quality assessment

Objective noise measurements based on fat and muscle demonstrate a 30% decrease in mean objective image noise (standard deviation of attenuation values) associated with chest HPCT compared to SPCT (10.3±2 versus 14±7 HU) that was not significant ($p=0.7$). Mean objective image noise was 11±3 versus 10.8±4 HU in abdomen HPCT and abdomen SPCT, respectively. Mean CNR was 20% lower in abdomen SPCT compared to HPCT (15.2±5 and 20.7±7), also not statistically significant ($p=0.1$; Fig 3).

Discussion

The aim of the present study was to assess a new paediatric CT protocol that enables chest and abdomen HPCT, without breathing instruction, on a dual-energy CT with regards to subjective image quality, motion artefacts, and radiation dose, in comparison to standard-pitch CT. Dual-source CT utilises two X-ray tubes to perform simultaneous image acquisition and decrease scan time. Higher pitch results in some loss of image quality due to *z*-directional gaps leading to fewer photons contributing to each axial image because of faster table movement.[25–27] One way to minimise this loss of image quality is through the use of dual-source CT machines (e.g., Flash mode) in which gapless *z*-sampling can occur at pitch values up to 3 or more due to two X-ray sources simultaneously imaging the patient. Dual-energy HPCT has been shown to diminish motion artefacts, improve image quality, and enable diagnostic scanning at higher pitch values compared with HPCT performed on single-source scanners.[14,16,28–30] Dual-energy HPCT with a pitch of 3.0 enables examination of the paediatric chest in <0.5 seconds.[13] A recent study by Atli *et al.* reported 60% shorter mean scan time when using dual-energy HPCT protocol (pitch=3.0) compared to standard-pitch protocol (pitch=1.5) in paediatric abdomen imaging.[31] In adults HPCT has been shown to reduce motion

Table 2
Comparison of radiation exposure in mSv and mGy.cm by patient age between high-pitch and standard-pitch mode examinations.

Overall exposure	High-pitch mode		Standard-pitch mode		*p*-Value
	ED (mSv)	DLP (mGy.cm)	ED (mSv)	DLP (mGy.cm)	
Radiation exposure by patient age (year)					
<1	2.9±0.8	51.3±37	2.5±0.8	32±22	0.5
1–5	2.4±1	46±14	2.8±1	67±30	0.1
Average	2.6±0.9	49±2	2.6±1	55±32	0.3

ED, effective dose; DLP, dose–length product.

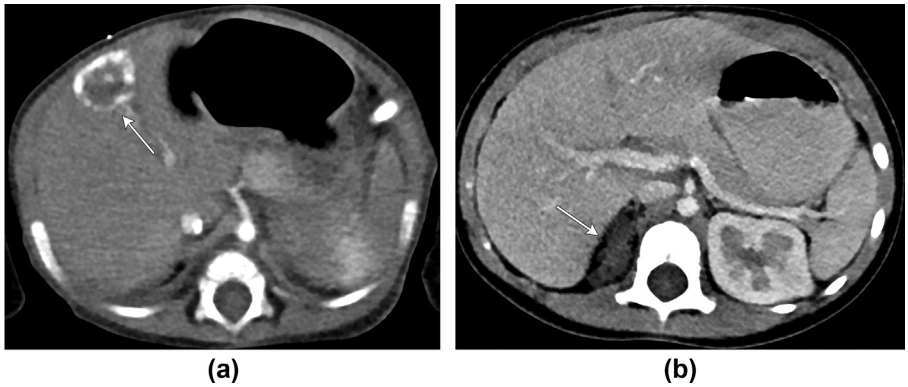

Figure 2 Transverse contrast enhanced CT in (a) an awake 3-month-old female patient (pitch: 0.95, CTDI: 2.1 mGy, and DLP: 45 mGy·cm) shows 2.4 cm haemangioma (arrow) and in (b) a non-sedated 2-year-old female patient (pitch: 3, CTDI: 1.8 mGy, and DLP: 31 mGy·cm) demonstrates a multilobulate soft-tissue structure, measuring up to 3.1×1.4 cm (arrow), consistent with multicystic dysplastic kidney. The contrast to noise ratio value was 10% lower in SPCT compared to HPCT (13.8 versus 15.3).

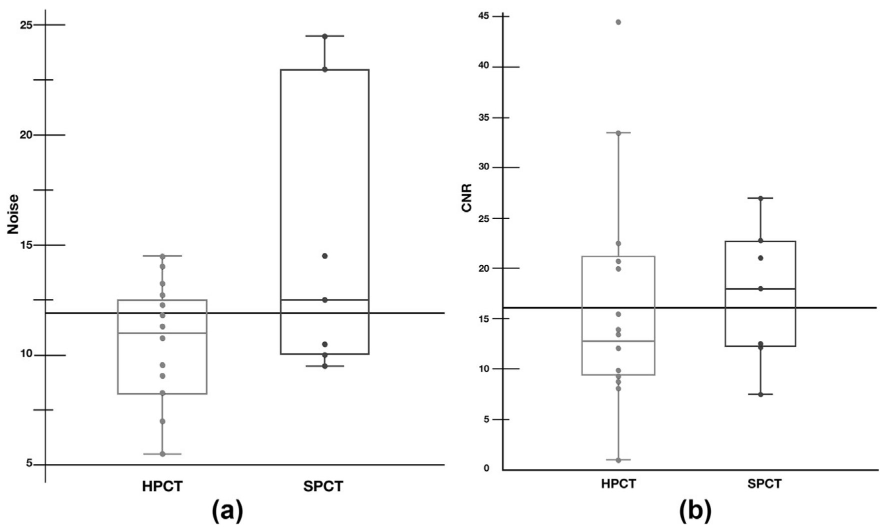

Figure 3 Boxplots graph showing objective image quality parameters in both high-pitch (HPCT) and standard-pitch (SPCT) groups. (a) Image noise, and (b) contrast-to-noise ratio. Note there is no significant difference in noise or CNR between the groups (p=0.1 and p=0.6, respectively).

artefacts.[14] An anthropomorphic study concluded that for the images acquired with lower dose, both IR systems were seen to shift the noise power spectra curves towards the lower frequencies. The greater shift distance in the ADMIRE dataset compared to the SAFIRE dataset indicates that both IR algorithms are applied more aggressively when the overall level of noise is higher, and less aggressively when there is little noise. The noise properties of examinations reconstructed with ADMIRE IR algorithm show no significant improvement in maintaining noise structure compared to examinations reconstructed with SAFIRE, which is consistent with what has been shown in previous studies.[32,33]

One important application of HPCT in children is as a cross-sectional imaging alternative to MRI that does not require sedation. MRI is increasingly utilised in children because of its lack of ionising radiation exposure[5]; however, the long scan times and enclosed space of MRI machines often mandates deep sedation or general anaesthesia to obtain diagnostic quality MR images in infants and young children. In addition to the potential risks associated with anaesthetic medication exposure, the requirement for anaesthesia for MRI is associated with increased financial cost and wait times.[34]

This single institutional study is a retrospective analysis of initial clinical experience with paediatric HPCT imaging of the thorax and abdomen in awake young children focusing on radiation dose data, image quality, and diagnostic acceptability. In addition, subjective and objective assessments of HPCT image noise, lesion conspicuity, and artefacts were excellent, with objective noise values 30% lower in chest HPCT compared with SPCT while similar noise values were observed between abdomen HPCT and SPCT. Qualitative evaluation of HPCT overall image quality by blinded readers yielded only one out of 31 (3.2%) HPCT studies rated unacceptable due to suboptimal visibility of the abdominal structures such as adrenals, gall bladder, bowels, and peritoneum by a single reader, with no studies rated unacceptable by both. These results build on prior studies reporting similar have reported that image noise values for chest HPCT and SPCT.[16,35]

The present study confirms the diagnostic utility of HPCT for thoraco-abdominal evaluation of infants and young children without the need for sedation. The scan pitch of $\geq$2 results in a scan time of a fraction of a second, allowing thoraco-abdominal evaluation of infants and young children who are free-breathing without significant motion artefacts. All of the HPCT examinations in the present study cohort were diagnostically acceptable for answering the clinical question of interest, with no patient requiring repeat imaging for technical reasons. The use of HPCT has great potential to improving clinical workflow in paediatric patients by decreasing scan wait times compared with MRI and avoiding the need for anaesthetic medication exposure and recovery.[13]

Limitations of the present study include its retrospective nature, with the relatively small number of patients reflecting the fact that all studies were acquired as part of routine clinical care. The overall practice pattern at the authors' institution (as with many paediatric practices) is weighted toward the use of MRI for body cross-sectional imaging in young children because of lack of ionising radiation, with CT generally utilised in patients who require scanning urgently or who may not tolerate anaesthetic medications or the MRI system environment. The reason for the choice of CT over MRI was generally not documented in the electronic medical records, so we are unable to perform subset analysis based on reason why CT was chosen over MRI. In addition, because of the retrospective nature of this study, exact CT acquisition times were not available for each study, and total examination times as recorded on the EMR and PACS were used for scan time comparison. The present results show a reduction in scan time associated with HPCT, which was significant for chest CT examinations and approached significance for abdominal CT. Finally, the authors' institution has multiple CT vendors and only studies performed on a single scanner type were chosen to minimise equipment-related variation. Future studies with larger numbers of patients will be needed to validate these findings. In addition, studies focusing on CT performed for specific indications (e.g. pulmonary embolus chest CT or renal stone abdominal CT) are needed to quantify the dose savings associated with HPCT in specific patient populations. Lack of respiratory rate record as a variable might have influence on the choice of protocol.

In conclusion, the dual-energy HPCT protocol in the present study enables free-breathing examination of the paediatric chest and abdomen in <0.5 and 1.6 seconds while maintaining excellent subjective and objective image quality in combination with IR compared to a conventional pitch. The proposed protocol can routinely be used in non-sedated paediatric patients.

Conflict of interest

The authors declare no conflict of interest.

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