High-Pitch Computed Tomography of the Lung in Pediatric Patients: An Intraindividual Comparison of Image Quality and Radiation Dose to Conventional 64-MDCT

High-pitch Computertomografie der Lunge bei Kindern: Ein intraindividueller Vergleich der Bildqualität und Strahlendosis zur konventionellen 64-MDCT

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Key words
- thorax
- CT
- artifacts

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Zusammenfassung
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Ziel: Ziel der Studie war die Häufigkeit von typischen Artefakten der high-pitch Computertomografie (HPCT) bei low-dose Untersuchungen von Kindern im Vergleich zur MDCT zu evaluieren und die effektive Dosis (D_{eff}) zu berechnen.

Material und Methoden: 35 Patienten (17 Jungen, 18 Mädchen; Durchschnittsalter 112 ± 69 Monate) wurden in diese retrospektive Studie eingeschlossen. Bei allen Patienten wurden zwei CT-Untersuchungen mit jeweils gleicher Röhrenspannung und -strom im mittleren Zeitabstand von 87 Tagen durchgeführt: entweder zuerst die MDCT gefolgt von der HPCT oder in umgekehrter Reihenfolge. Die Bildqualität wurde durch 2 Radiologen im Konsensus intraindividuell verglichen. Der Gesamtartefaktscore (0–8) wurde definiert als Summe der Artefakte durch Bewegung, Atmung sowie Pulsation am Herzen bzw. den pulmonalen Gefäßen (0 – keine; 1 – geringe; 2 – deutliche Artefakte). Die D_{eff} wurde entsprechend den Europäischen Leitlinien zur Qualitätssicherung in der MDCT berechnet. Zur Auswertung der Unterschiede zwischen den Gruppen wurde die Mann-Whitney U Teststatistik angewandt. Die Korrelation von ordinalen Variabeln wurde mittels der Spearmans Rangkorrelation getestet.

Ergebnisse: Die Scanzeit war für die HPCT im Vergleich zur MDCT signifikant niedriger ($0,72 \pm 0,13$ s vs. $3,65 \pm 0,81$s; p < 0,0001). In 28 von 35 (80 %) HPCT Untersuchungen traten keine Artefakte auf, wohingegen bei der MDCT bei allen Untersuchungen Artefakte erkennbar waren. Die Häufigkeit von Pulsations- und Atmungsartefakten war in der MDCT höher im Vergleich zur HPCT (100 % vs. 17 % und 31 % vs. 6 %). Der Gesamtartefaktscore korreliert signifikant mit dem Patientenalter für die MDCT (r = –0,42; p = 0,01) aber nicht für die HPCT (r = –0,32; p = 0,07). Die berechnete D_{eff} war signifikant niedriger für

Abstract
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Purpose: The aim of this study was to investigate frequencies of typical artifacts in low-dose pediatric lung examinations using high-pitch computed tomography (HPCT) compared to MDCT, and to estimate the effective radiation dose (E_{eff}).

Materials and Methods: Institutional review board approval for this retrospective study was obtained. 35 patients (17 boys, 18 girls; mean age 112 ± 69 months) were included and underwent MDCT and follow-up scan by HPCT or vice versa (mean follow-up time 87 days), using the same tube voltage and current. The total artifact score (0–8) was defined as the sum of artifacts arising from movement, breathing or pulsation of the heart or pulmonary vessels (0 – no; 1 – moderate; 2 – severe artifacts). E_{eff} was estimated according to the European Guidelines on Quality Criteria for Multislice Computed Tomography. The Mann-Whitney U test was used to analyze differences between the patient groups. The Spearman's rank correlation coefficient was used for correlation of ordinal variables.

Results: The scan time was significantly lower for HPCT compared to MDCT (0.72 ± 0.13 s vs. 3.65 ± 0.81s; p < 0.0001). In 28 of 35 (80 %) HPCT examinations no artifacts were visible, whereas in MDCT artifacts occurred in all examinations. The frequency of pulsation artifacts and breathing artifacts was higher in MDCT compared to HPCT (100 % vs. 17 % and 31 % vs. 6 %). The total artifact score significantly correlated with the patient's age in MDCT (r = –0.42; p = 0.01), but not in HPCT (r = –0.32; p = 0.07). The estimated E_{eff} was significantly lower in HPCT than in MDCT (1.29 ± 0.31 vs. 1.47 ± 0.37 mSv; p < 0.0001).

Conclusion: Our study indicates that the use of HPCT has advantages for pediatric lung imaging with a reduction of breathing and pulsation artifacts. Moreover, the estimated E_{eff} was lower. In

die HPCT ($1,29 \pm 0,31$ mSv vs. $1,47 \pm 0,37$ mS für die MDCT; $p < 0,0001$).

Schlussfolgerung: Die HPCT führt zu einer relevanten Reduktion der typischen Bildartefakte in der Lungenbildgebung bei Kindern. Hierbei ist die berechnete effektive Dosis geringer. Darüber hinaus können die Untersuchungen ohne Sedierung und unter freier Atmung ohne Verlust an Bildqualität durchgeführt werden.

Kernaussagen:
▶ HPCT führt zu einer Reduzierung von Artefakten in der Lungenbildgebung bei Kindern
▶ Reduzierte D_{eff} für die HPCT
▶ HPCT unter freier Atmung und ohne Sedierung ohne Verlust an Bildqualität

addition, examinations can be performed without sedation or breath-hold without losing image quality.

Key points:
▶ Fewer artifacts in pediatric lung imaging with HPCT
▶ Reduced E_{eff} in HPCT
▶ HPCT without sedation or breath-hold without loss of image quality

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Introduction
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Multidetector computed tomography (MDCT) has been established as a standard method for evaluating pathological changes of lung parenchyma in children. The most common indications for chest scanning are tumor staging, detection of bronchial anomalies, recurrent infections, diffuse lung diseases and chest trauma [1]. However, strict guidelines for the application of radiation are indispensable and the optimization of examination requirements is essential for radiation protection. Low-dose protocols have been implemented in pediatric CT of the lung since the late 1990s [2, 3]. Additionally, achieving sufficient image quality also in non-compliant patients is imperative. Insufficient results because of motion or repeating scans should clearly be avoided. Hence, there is a need for sedation or controlled ventilation in infants and younger children. The risks and costs of these procedures are definitely not negligible [4].

One approach to eliminate motion and breathing artifacts is accelerating image acquisition by increasing detector width or increasing the pitch. However, using single-source CT, the pitch value is limited to 1.5 for the prevention of sampling gaps.

A second-generation dual-source scanner (SOMATOM Definition Flash, Siemens Healthcare, Forchheim, Germany) allows fast volume scanning with pitch values up to 3.2 [5]. In this high-pitch scanning mode on dual-source CT (DSCT), sampling gaps of the first tube can be filled with data from the second tube.

Previous studies have reported clinical benefits of high-pitch DSCT (HPCT) in cardiac [6 – 8] and thoracic imaging [9, 10]. In pe-

diatric CT, the high-pitch technique might obviate sedation due to the short acquisition time.

The aim of this study was to evaluate the image quality of HPCT in low-dose pediatric lung examinations in an intraindividual approach compared to standard single-source MDCT.

Materials and methods
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35 patients (17 boys, 18 girls; mean age 112 ± 69 months) were included in the analysis. All patients underwent MDCT and a follow-up scan by HPCT or vice versa in the period from November 2009 to April 2012. Institutional review board approval for this retrospective study was obtained. All CT studies were clinically indicated and written informed consent was obtained from the parents. The underlying diseases and indications for performing CT are listed in ○ **Table 1**. The mean interval between HPCT and MDCT was 87 ± 77 days. In 28 patients, MDCT was performed as the initial scan and HPCT as the follow-up scan, in 7 patients vice versa. None of the children received sedation. Children below the age of 6 years were examined breathing freely, whereas children older than 6 years received a breathing command. Infants were secured in a commercially available support cushion (○ **Fig. 1**).

The settings for tube current and voltage were identical for MDCT and HPCT according to our standard operating procedure (weight-adapted low-dose protocol, 100 – 120 kVp, 30 – 40 mAs). The following specific scanning parameters were used on 64-slice MDCT (Somatom Sensation 64, Siemens Healthcare, Forchheim,

number of patients	underlying disease	indication
17	malignant hematological malignances in aplasia (under HSCT)	exclusion/follow-up of pneumonia
7	malignant neoplasm (6 sarcomas, 1HCC)	exclusion/follow-up of pulmonary metastases
4	blood disorder affecting red blood cells (2 sickle cell anemia, 2 thalassemia)	exclusion/follow-up of pneumonia
2	connective tissue disease	follow-up of pulmonary involvement
1	complex tracheobronchial malformation	initial imaging of anatomy and follow-up in search for foreign bodies
1	VACTERL association	exclusion/follow-up of pneumonia
1	tetralogy of Fallot, ARDS	initial imaging and follow-up of ARDS
1	non-specific hepatopathy, recurrent pneumonia	exclusion/follow-up of pneumonia
1	nephrotic syndrome, recurrent bronchitis	exclusion/follow-up of pneumonia

Table 1 Underlying diseases and indications for scan.

Tab. 1 Zugrunde liegende Erkrankungen und Untersuchungsindikationen.

HSCT: Hematopoietic stem cell transplantation; HCC: Hepatocellular carcinoma; ARDS: Acute Respiratory Distress Syndrome.
HSCT: Hämatopoetische Stammzelltransplantation; HCC: Hepatozelluläres Karzinom; ARDS: Acute Respiratory Distress Syndrome.

Fig. 1 Support cushion to minimize motion artifacts in infants.

Abb. 1 Lagerungshilfe zur Minimierung der Bewegungsartefakte bei Säuglingen.

Germany): 0.33 seconds gantry rotation time, 64 × 0.6 mm slice acquisition using a z-flying focal spot, pitch 1.2. Patients were examined on HPCT using 0.28 seconds gantry rotation time, 128 × 0.6 mm slice acquisition using a z-flying focal spot, pitch 3.0.

Image reconstruction
Axial images were reconstructed from the raw dataset using a standard kernel (B31f) with a slice thickness of 3 mm and an increment of 3 mm as well as in a high-resolution kernel (B60f) with a slice thickness of 1 mm and an increment of 5 mm. Further coronal and sagittal reformations were performed in a standard kernel (B 31f) with a slice thickness of 3 mm and an increment of 2.5 mm and also a sliding thin-slab MIP (maximum intensity projection) (B50f; slice thickness 6 mm, increment 3 mm).

Artifact and image quality evaluation
All images were evaluated in consensus by two senior radiologists on a standard PACS workstation (Centricity RA 1000, GE Healthcare, Waukesha, Wisconsin, USA). Images of both examinations of each patient were evaluated simultaneously with both observers being blinded for all identifying data and technical details. In this intraindividual approach artifacts arising from movement, breathing or pulsation of the heart or pulmonary vessels were classified according to the following ordinal scale: 0 – no artifacts; 1 – moderate artifacts; 2 – severe artifacts. The artifact values were summed up to a total score for each examination ranging from 0 to 8 points. The impression of small normal findings (e. g. sharp visualization of bronchi or septa) was estimated in an intraindividual comparison (0 – equal or 1 – superiority of one CT examination). A third radiologist, who was not blinded for identifying data and technical details, assigned results to the corresponding examination.

Radiation dose
The effective radiation dose (E_{eff}) of CT examinations was estimated according to the European Guidelines on Quality Criteria for Multislice Computed Tomography proposed by the European Study Group of radiologists and physicists [11]. The effective radiation dose was calculated by multiplying the dose-length product (DLP) with a conversion coefficient k that is specific for different body regions and patient ages ($E_{eff} = DLP \times k$). k values for examinations of the thorax are as follows: newborns k = 0.039, 1 year

Table 2 Conversion factors from DLP ($\varnothing$ 32 cm) to DLP ($\varnothing$ 16 cm).

Tab. 2 Konversionsfaktoren von DLP ($\varnothing$ 32 cm) auf DLP ($\varnothing$ 16 cm).

pediatric body	Siemens Somatom Definition Flash	Siemens Somatom Sensation 64
70 kV	2.4	n. a.
80 kV	2.3	2.2
100 kV	2.2	2.1
120 kV	2.2	2.0
140 kV	2.2	2.0

k = 0.026, 5 years k = 0.018, 10 years k = 0.013 and for adults k = 0.014 [11]. Both DLP and $CTDI_{vol}$ were recorded from electronic patient protocols that summarized the individual radiation exposure parameters of each CT acquisition. Both CT scanners used in this study supply a $CTDI_{vol}$ referring to a 32-cm body phantom. However, for pediatric patients k refers to a 16-cm body phantom so that the volume CT dose index ($CTDI_{vol}$) as well as the DLP had to be converted to a 16-cm phantom using a scanner-specific additional converting factor provided by the manufacturer (○ **Table 2**).

Statistical analysis
Statistical analysis was performed using commercially available software (SAS jmp, release 11.0 for Windows, SAS Institute Inc., Cary, NC, USA). Continuous variables were expressed as mean ± standard deviations, and categorical variables were expressed as frequencies. Additionally, median values were provided where appropriate. The Mann-Whitney U test was used to analyze differences between the study groups. The Spearman's rank correlation coefficient was used for correlation of ordinal variables. P values below 0.05 were considered statistically significant.

Results
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All examinations were performed successfully in both HPCT and MDCT, and no scan had to be repeated. As expected from our experience with conventional X-ray examinations, all children tolerated fixation in the support cushion without significant resistance. In HPCT the mean scanning time was 0.72 ± 0.13 s compared to 3.65 ± 0.81 s in MDCT (p < 0.0001). Thus, the mean time saving in HPCT was 2.93 ± 0.68 s.

The mean scanning range was 29.4 ± 5.5 cm in HPCT and 25.5 ± 5.7 cm in MDCT (p = 0.0035). In all patients except one, the scanning range was larger in HPCT, even in those patients, in whom HPCT was performed as the initial scan. The mean difference between both scanning methods was 3.9 ± 1.9 cm resulting in a relative difference of 17 %. The highest relative difference of 23 % was found in the first third of HPCT examinations.

The overall image quality was excellent for HPCT with no artifacts in 28 examinations (80 %) whereas in MDCT artifacts occurred in all examinations. There was a higher frequency of breathing artifacts in MDCT (11 examinations, 31 %) compared to HPCT (2 examinations, 6 %). Pulsation artifacts next to the heart were found in all MDCT examinations, and in 6 HPCT examinations (17 %). All patients were examined without moving artifacts irrespective of the scan mode. Details are given in ○ **Table 3**. The total artifact score was significantly lower for HPCT 0.26 ± 0.56 (median 0; range 0 – 2) than for MDCT 2.46 ± 1.31 (median 2; range 1 – 6) (p < 0.0001). The patient's age significantly correlated with the

total artifact score in MDCT (r = - 0.42; p = 0.01), but not in HPCT (r = – 0.32; p = 0.07)

The depiction of small objects was rated equal for both scanning modes in 26 examinations (74 %), superior for HPCT in 8 examinations (23 %), and superior for MDCT in 1 examination (3 %).

Examples of differences in image quality are shown in ○ Fig. 2, 3. Mean effective radiation dose E_{eff} was significantly lower in HPCT (1.29 ± 0.31 mSv) compared to MDCT (1.47 ± 0.37 mSv, p < 0.0001) (○ Fig. 4).

Discussion
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Pediatric patients, especially young children and infants, benefit from lower radiation doses, and investigators benefit from better image quality (because of fewer artifacts) in HPCT compared to MDCT.

Our study supports the interindividual comparison of Lell et al. [10] who have shown a lower rate of image artifacts in pediatric chest HPCT compared to 10 or 64-row MDCT. We compared both scanning modes using an intraindividual study design with a mean time interval of 87 days. As shown in the present study, breathing artifacts occurred in only two HPCT examinations, but in 11 children examined with MDCT. The benefit of rapid scan was also clearly shown in the considerably lower rate of pulsation artifacts: in HPCT they occurred in 6 patients next to the mediastinum and in only 1 patient next to the pulmonary vessels. In MDCT they occurred in 35 and 20 patients, respectively. There were no moving artifacts observed in either scanning mode, which can be related to the use of a support cushion assuring secure fixation of small children and infants.

The superiority of HPCT image quality, especially the reduction of pulsation artifacts, possibly results in an improved detection rate of pathological pulmonary findings. In the past, several approaches were described to increase detection rates of pulmonary pathologies by reducing pulsation artifacts, for example with ECG-triggering. Pauls et al. showed the superiority of ECG-triggered MDCT in detecting pulmonary nodules [12]. In their study including 50 patients with malignant tumors, ECG-triggered MDCT detected 38 % more pulmonary nodules (64 % more pulmonary nodules < 5 mm) than non-triggered MDCT. Nevertheless, ECG-triggered MDCT results in an increased radiation dose. This application in pediatric patients is therefore not suitable, except in specially indicated cases. HPCT clearly delineated small pulmonary nodules next to the mediastinal borders potentially being superimposed by pulsation artifacts in MDCT as shown in ○ Fig. 3. We believe that the use of HPCT has a relevant clinical impact in patients with pulmonary metastases. Fuchs et al. observed a lower number of pulmonary metastases in preoperative MDCT in 5 of 16 tumor patients compared to intraoperative status [13]. Grundy et al. have shown that Wilms' tumor patients with metastatic lung disease undergoing therapy with 3 instead of 2 drugs have an improved five-year event-free survival compared to patients with metastases detected by chest radiograph (80 % vs. 56 %) [14]. Furthermore Warmann et al. have shown a poorer outcome in Wilms' tumor patients with persistent metastases after local treatment [15].

Table 3   Rating of artifacts in MDCT and DSCT.

Tab. 3   Bewertung der Artefakte für MDCT und DSCT.

	MDCT			DSCT		
artifacts	**0**	**1**	**2**	**0**	**1**	**2**
movement	35	0	0	35	0	0
breathing	24	5	6	33	2	0
pulsation heart	0	23	12	29	6	0
pulsation vessels	15	18	2	34	1	0

Bold numbers indicate the severity of artifacts: 0 – no artifacts; 1 – moderate artifacts; 2 – severe artifacts. Cursive numbers are frequencies.

Die fett geschriebenen Nummern entsprechen dem Schweregrad der Artefakte: 0 – keine Artefakte; 1 – geringe Artefakte; 2 – deutliche Artefakte. Die kursiv geschriebenen Nummern entsprechen den Häufigkeiten.
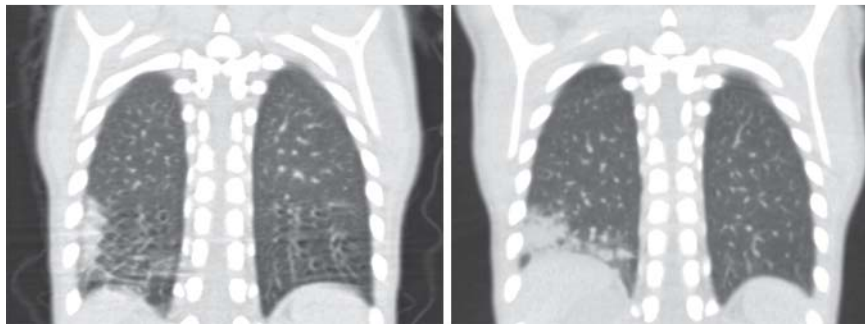

Fig. 2   4-year-old patient, sickle cell anemia, hematopoietic stem cell transplantation, pneumonia, follow-up within 2 weeks, no sedation, no breath-hold; left: MDCT, scanning time 2.75 s, severe breathing artifacts, right: HPCT, scanning time 0.59 s, no artifacts.

Abb. 2   4-jähriger Patient, Sichelzellanämie, Stammzelltransplantation, Follow-up nach 2 Wochen, keine Sedierung, kein Atemkommando; links: MDCT, Scanzeit 2,75 s, deutliche Atmungsartefakte, rechts: HPCT, Scanzeit 0,59 s, keine Artefakte.
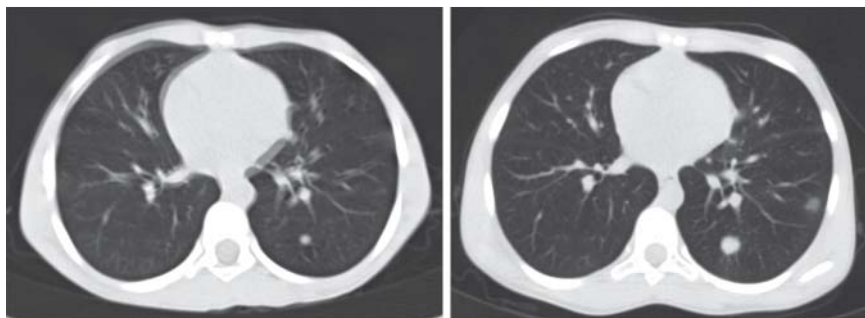

Fig. 3   13-year old boy, osteosarcoma, pulmonary metastasis, follow-up within 79 days, no sedation, breath-hold; left: MDCT, scanning time 4.07 s, severe pulsation artifacts, right: HPCT, scanning time 0.77 s, no artifacts.

Abb. 3   13-jähriger Patient mit Osteosarkom und pulmonalen Metastasen, Verlaufskontrolle nach 79 Tagen, keine Sedierung, Atemkommando; links: MDCT, Scanzeit 4,07 s, deutliche Pulsationsartefakte, rechts: HPCT, Scanzeit 0,77 s, keine Artefakte.
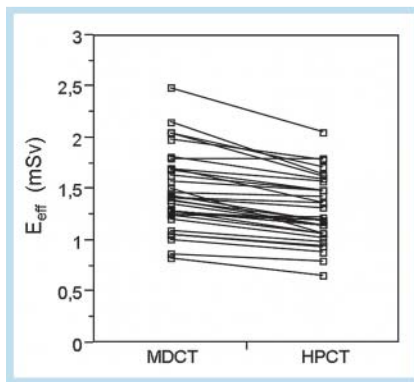
Fig. 4 Intraindividual comparison of effective radiation dose for both scanners.

Abb. 4 Intraindividueller Vergleich der effektiven Dosis zwischen beiden CT-Geräten.

Kroft et al. took a different approach in speeding up imaging acquisition and thereby increasing image quality of thoracic CT in infants [16]. They used a 320-detector-row MDCT that allows axial volumetric scanning of a 16-cm-long range. The performed phantom study has shown that in small children the entire scanning range could be acquired in 0.35 s, leading to a significant reduction of acquisition time compared to conventional helical scanning. However, the shortest HPCT scanning time in our study was comparable (0.47 s, scan range of 19.2 cm). Moreover, HPCT is also a valuable tool for larger scanning ranges in older children with a maximum scanning time of 1 s.

Beyond an increased image quality, HPCT improves the workflow in pediatric CT. Performing all examinations without sedation or even controlled ventilation requires less staff. The presence of an anesthesiologist is unnecessary and there is no need for a rest and surveillance period after examination. Thus, procedural times and costs may be reduced [17]. An even more essential disadvantage of anesthesia is the possible influence on the developing brain. In a recently published study, Ing et al. showed that children below the age of 3 exposed to anesthesia had a higher relative risk of language and abstract reasoning deficits by the age of 10 compared to unexposed children [18]. In a meta-analysis of 12 studies, DiMaggio et al. could also show an association between pediatric anesthetic agents in the setting of surgery and subsequent learning or behavioral problems in children [19]. Anesthesia-related atelectases is another issue, leading to decreased image quality and possibly masking substantial pathological findings. Sargent et al. showed significant atelectases in up to 68 % of children undergoing CT under sedation [20]. Even using optimized ventilation protocols, there still can be atelectases found in up to 29 % of examinations as recently shown by Newmann et al. [21].

Radiation exposure is another important aspect in pediatric CT. Although there was an increase in z-overscanning with higher pitch values, we observed a mean decrease in effective radiation dose of about 12 %. This seems to be related to the bowtie-shaped aluminum filter used in the high-pitch mode. Co et al. showed a 48 % dose reduction in their study using an ultra-high-pitch CT pulmonary angiography protocol with cardiac bowtie-shaped filter [22]. Taking into account that scanning range was longer in HPCT in 34 of 35 patients, the potential dose reduction was underestimated. This overranging seems to be a major limitation of HPCT. However, we found a relationship to the learning curve of the technicians with the highest relative difference in the first third of the examinations.

There are some limitations in our study. First, it was a retrospective single center study in a relatively small pediatric population.

Second, the wide age distribution in our study may underestimate the benefits of high-pitch scanning for infants. Third, an inconsistent time interval between the two CT examinations has to be considered that may have hampered the comparability.

In conclusion, our study indicates that the use of high-pitch DSCT has advantages for pediatric lung imaging by reducing breathing and pulsation artifacts. Moreover, the estimated effective radiation dose was reduced. In addition, examinations can be performed without sedation or breath-hold, even in infants and uncooperative children, without a loss of image quality.

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