European Journal of Radiology 130 (2020) 109138

Contents lists available at ScienceDirect

European Journal of Radiology

journal homepage: www.elsevier.com/locate/ejrad

Relation between age and CT radiation doses: Dose trends in 705 pediatric head CT

Mohammad Hassan Kharita[a], Huda Al-Naemi[a], Chiara Arru[b,*], Ahmed Jenaid Omar[a], Antar Aly[a], Ioannis Tsalafoutas[a], Shady Alkhazzam[a], Ramandeep Singh[b], Mannudeep K. Kalra[b]

[a] *Hamad Medical Corporation, Doha, Qatar*
[b] *Massachusetts General Hospital and Harvard Medical School, Boston, MA, USA*

ARTICLE INFO

Keywords:
CT head
Children
Radiation dose
Age
Diagnostic reference levels (DRL)

ABSTRACT

Purpose: To evaluate the relationship between patient age and radiation doses associated with routine pediatric head CT performed with automatic tube potential selection and tube current modulation techniques.
Methods: We obtained patient demographics, scan parameters, and radiation dose descriptors (CT dose index volume -CTDIvol and dose length product -DLP) associated with consecutive routine head CT in 705 children (mean age 6.9 ± 5 years). Children were scanned on one of the three multidetector-row CTs (64–128 slices, Siemens) over 6 months period in a tertiary hospital. All head CT exams were performed in helical scan mode using automatic tube potential selection (Care kV) and automatic tube current modulation (Care Dose 4D) techniques. The information was obtained from a radiation dose monitoring software. Data were analyzed using linear correlation and analysis of variance.
Results: Most age-wise median CTDIvol (9 – 27 mGy; 703/705 pediatric head CT, > 99 %) from our institution were lower than the European Diagnostic Reference Levels (EDRL, CTDIvol 24 – 50 mGy) but median DLP (151 – 586 mGy cm) from 201/705 children (28 %) was higher than the EDRL (DLP 300 – 650 mGy cm). Unlike the age-stratified EDRL, a combination of automatic tube potential selection and tube current modulation for pediatric head results in a significant linear correlation between radiation doses and patient age (r2 = 0.66, $p < 0.001$).
Conclusions: Radiation doses for head CT change linearly with children's age. Despite lower CTDIvol and DLP for most children, longer scan length resulted in higher DLP for some pediatric head CT compared to the corresponding EDRL; this result underscores the need to promote clear guidelines for technologists operating CT.

1. Introduction

Computed tomography (CT) of the head continues to be one of the most frequently performed CT examinations [1–4]. Although in our practice, MRI has replaced CT for evaluation of many known or suspected intracranial findings, particularly in children, availability, speed, and ease of interpretation of CT are reasons for its popularity and widespread use. CT is frequently used for evaluating suspected head trauma, paranasal sinuses, and patency of ventricular shunts. Given the concerns over radiation risks associated with CT, users must ensure justification and carefully select scan parameters to ensure that as low as reasonably achievable (ALARA) radiation doses are used for all patients [3,4].

To enable dose reduction while maintaining diagnostic information, CT vendors have introduced technologies such as automatic tube potential selection, automatic tube current modulation, iterative reconstruction techniques, as well as dose efficient scanners [1–3]. With the automatic tube potential selection technique, the scanner selects a tube potential (in kilovoltage or kV) based on the specified reference kV and the type of examination to reduce radiation dose while maintaining the contrast-to-noise ratio. The automatic tube current modulation techniques adapt tube current to maintain consistent image quality over the region of interest based on a reference image quality metric (such as quality reference mAs or noise index). These techniques can enable substantial dose reduction in both adult and pediatric patients [1,2].

Despite technologic developments in radiation dose optimization, there are substantial variations in radiation doses with CT [3]. To aid in dose optimization, national and international diagnostic reference levels (DRL) have been introduced for common radiation-based examinations, including CT [4]. Initially proposed by the International

---

[*] Corresponding author at: 75 Blossom Court, Boston, MA, 02114, USA.
E-mail address: carru@mgh.harvard.edu (C. Arru).

https://doi.org/10.1016/j.ejrad.2020.109138
Received 8 January 2020; Received in revised form 18 May 2020; Accepted 12 June 2020

Commission for Radiation Protection, modality-specific DRLs help set benchmark radiation doses for different body regions, including head, chest, and abdomen-pelvis CT. The DRL is typically set at radiation doses within the 75th percentile of median values observed in the institutions participating in relevant surveys. To account for the influence of patient age and size on the radiation dose, separate DRLs are available for children and adults as well as for children of different ages or sizes. Age- and weight-specific DRL are available from both the United States and the European Commission. The European Guidelines on Diagnostic Reference Levels for Pediatric Imaging provides age-based DRLs for head CT for 0–3 months (CTDIvol 24 mGy; DLP 300 mGy cm), > 3–12 months (28 mGy; 385 mGy cm), 1– < 6 years (40 mGy; 505 mGy cm), and > 6-year-old (50 mGy; 650 mGy cm) children [4].

At the time of writing this manuscript, Qatar did not have national DRLs. Therefore, we used the pediatric head CT DRLs proposed by the European Guidelines on Diagnostic Reference Levels for Pediatric Imaging in our study. The purpose of our study was to evaluate the relationship between patient age and radiation doses associated with routine pediatric head CT performed with automatic tube potential selection and automatic tube current modulation techniques. The secondary objective of our study was to understand differences between our local doses and the European DRLs (EDRLs).

2. Materials and methods

2.1. Approvals and disclosures

The de-identified data for the study were collected as part of the quality and safety initiatives for radiation dose monitoring. The local ethical committee of the Hamad Medical Corporation approved the study for retrospective analysis of pediatric head CT data. The need for informed consent was waived. One study co-author received research grants from Siemens Healthineers and Riverain Inc. for unrelated research projects. Other co-authors have no financial disclosures. The study data were collected from Hamad General Hospital (HGH) in Doha, Qatar.

2.2. Patients and scanners

The study included 705 children (age range 0–15 years; 438 males, 267 females) who underwent routine head CT in a tertiary healthcare center on one of the three multidetector-row CT scanners. These included a single-source 32-detector-row CT (SOMATOM Sensation 64, Siemens Healthineers, Forchheim, Germany; n = 335 children), a single-source 128-detector-row CT (Siemens Definition Edge; n = 340 children), and a second-generation, dual-source, 128-detector-row CT (Siemens Definition Flash; n = 30 children). Children were scanned on either of the three scanners based on their availability.

All children were scanned over a 6-month duration in 2015 and 2016 for clinically indicated reasons including head trauma, headache, and seizures. The date of birth and the scan date were recorded for all children to estimate the patient's age on the day of CT examination. Patients were classified into four age groups to compare their CTDIvol and DLP with those specified in the European Guidelines on Diagnostic Reference Levels for Pediatric Imaging [4]. Age and gender distribution in different age groups are summarized in Table 1.

2.3. Scan parameters

As per HGH clinical imaging department policy, regardless of the scanner type, CT technologists positioned the head in the headrest of the scanner for all routine head CT examinations. Before scanning, they centered the head in the gantry isocenter. On all the three CT scanners included in our study, all patients were scanned with automatic tube potential selection (ATPS, Care KV, Siemens), and combined angular and longitudinal automatic tube current modulation (ATCM; Care Dose 4D, Siemens) in helical scan mode. These techniques select the most appropriate tube potential (kV) and tube current (mA) based on the attenuation profile obtained from the scout views or CT tomograms which is a reflection of patient size. Table 2 summarizes the scan factors for each CT scanner included in our study. Per department protocol, all children underwent a single-phase head CT exam either with or without intravenous iodinated contrast.

Table 1
Summary of age and gender distribution in children (# represents number of children in each age-group) included in our study.

Gender	# < 3 months	# 3 – 12 months	# 1 – 6 years	# > 6 years	Total	Median age
Male	7	44	156	231	438	6.2 years
Female	9	28	101	129	267	5.4 years
Total	16	72	257	360	705	5.9 years

Table 2
Summary of scan parameters used for pediatric head CT. Since ATPS is not available on Siemens 64, we used manual tube potential (80-120 kV) for scanning pediatric head. (Key: QRM Quality Reference mAs, FBP filtered back projection, ATCM automatic tube current modulation, ATPS automatic tube potential selection).

Parameters	Sensation 64	Definition Edge	Definition Flash
ATPS (Ref kV)	100	100	100
ATCM (QRM)	260 mAs	360 mAs	360 mAs
Pitch	0.8:1	0.8:1	0.8:1
Detector configuration	64 × 0.6 mm	128 × 0.6 mm	128 × 0.6 mm
Rotation time	1 s	1 s	1 s
Reconstruction technique	FBP	Safire (S3)	Safire (S3)
Section thickness	5 mm	5 mm	5 mm

2.4. Radiation dose information

From the CT radiation dose monitoring software (Radiation Dose Monitor (RDM), MedSquare, Paris, France), we obtained the radiation dose descriptors, namely the volume CT dose index (CTDIvol) and dose length product (DLP) calibrated for the 16 cm polymethacrylate phantom. The software provided additional information including the tube potential and the type of beam shaping filter used for head CT performed in all patients. The data were exported from the dose monitoring program into Microsoft Excel (Office 365, Microsoft Inc., Redmond, Washington, USA) for further analyses. All CT scanners in HGH undergo daily calibration for CT number accuracy. In addition, dose verification of all CT scanners at HGH is done on a semiannual basis.

2.5. Statistical analysis

Data were analyzed within the Microsoft EXCEL. Power Pivot tables (Microsoft Excel) were generated to assess radiation doses and scan parameters for different age groups (according to the EDRL categorization) and scanner types. The scan length was calculated as the ratio of the DLP and CTDIvol. We determined linear correlation coefficients between patient age and radiation dose descriptors. Median dose descriptors (CTDIvol and DLP) were calculated for each age group to enable comparison with the age-specific head CT DRLs described in the European Guidelines on Diagnostic Reference Levels for Pediatric Imaging [4]. One-way analysis of variance (ANOVA) enabled a comparison of radiation doses for different age groups. A p-value of less than 0.05 was considered statistically significant.

Table 3
Median and ranges of age-based CTDI_{vol} and DLP in our study as compared to the corresponding EDRLs for pediatric head CT.

Age group	# Children	Median (range) CTDI_{vol} - mGy	EDRL CTDIvol mGy	Median (range) DLP - mGy cm	EDRL DLP - (mGy cm)
< 3 months	16	9 (7–30)	24	151 (103 – 624)	300
3 – 12 months	72	11 (3.1–37)	28	200 (61 – 677)	385
1 – 6 years	257	13 (7–40)	40	287 (143 – 1111)	505
> 6 years	360	27 (7 – 47)	50	586 (164 – 1192)	650

3. Results

3.1. Patients' age and radiation dose

Age-based distribution of median and range of CTDIvol and DLP is summarized in Table 3. With increasing age, there was a significant increase in both CTDIvol and DLP ($p < 0.0001$). Both CTDIvol and DLP had significant correlations with the patient's age (both $r2 = 0.66$). There were significant differences between age (7.1 vs. 6.5 years, $p < 0.0001$), CTDIvol (17 vs. 16 mGy, $p = 0.04$) and DLP (394 vs 331 mGy cm, $p = 0.003$) for both male and female children.

CT dose descriptors for children included in our study were compared with the corresponding EDRLs (which represent the doses at 75th percentile as well) (Tables 3–5) [4]. CTDIvol for most head CT exams (703/705 children; 99 %) included in our study were less than the corresponding EDRLs (Table 4) [4]. The 2/705 patients scanned at higher CTDIvol than the corresponding EDRLs were less than 12 months old and had DLP higher than the corresponding EDRL (Table 5). However, 201/705 examinations (28 %) had DLP higher than the corresponding age-based EDRLs, most frequently in children older than six years (155/201, 77 %) followed by those between 1 – 6 years of age (38/201, 19 %).

3.2. Scanners and scan factors

Median CTDIvol and DLP for head CT examinations performed on the three different CT scanners in our study are summarized in Figs. 1 and 2. The ANOVA test demonstrated a significant difference in CTDIvol and DLP of patients scanned on the three scanners ($p < 0.0001$).

Most head CTs were performed at 100 kV (377/705 patients, 53 %) and 120 kV (318/705 patients, 45 %) as opposed to 80 kV (10/705 patients, 2%). Patients' age and radiation doses associated with head CT exams performed at the three kV settings were significantly different ($p < 0.0001$) (Fig. 3).

Median CTDIvol associated with different beam shaping filters is summarized in Fig. 4. The scanner selected less aggressive beam shaping filters (flat filter: median age 13 years, median CTDIvol 37 mGy; wedge 3 filter: median age 10 years, median CTDIvol 38 mGy) for older children to enable greater CTDIvol as compared to the more aggressive filters in younger children (wedge filter: median age 5 years, median CTDIvol 16 mGy; wedge 2 filter: median age 4 years, median CTDIvol 13 mGy) ($p < 0.0001$).

Table 4
Distribution of pediatric head CT performed with CTDI_{vol} and DLP greater and lower than the EDRL for pediatric head CT in the corresponding age groups.

CTDI_{vol}	# Children	Average age (years)	Median CTDIvol (mGy)	Median DLP (mGy cm)
CTDI_{vol} ≤ EDRL				
DLP ≤ EDRL	504	5	13	290
DLP > EDRL	199	12	37	780
CTDI_{vol} > EDRL				
DLP > EDRL	2	1	34	651

Table 5
Distribution of pediatric head CT performed with DLP greater and lower than the EDRL for pediatric head CT in the corresponding age groups.

DLP	# Children	Median CTDI_{vol} (mGy)	Median DLP (mGy cm)	Median scan length (cm)
DLP < EDRL DLP				
< 3 months	14	9	136	16
3 to 12 months	66	10	197	19
1 to 6 years	219	13	270	21
> 6 years	205	17	405	21
DLP > EDRL DLP				
< 3 months	2	25	473	18
3 to 12 months	6	24	511	22
1 to 6 years	38	32	743	23
> 6 years	155	37	796	24

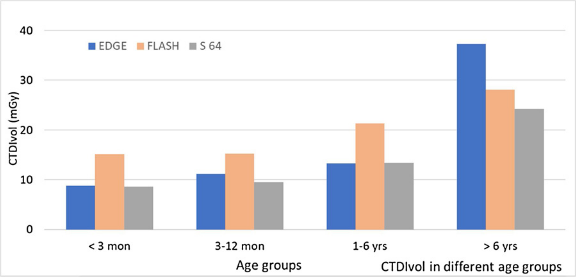

Fig. 1. Bar diagram summarizes CTDI_{vol} associated with the three scanners in different age groups of patients.

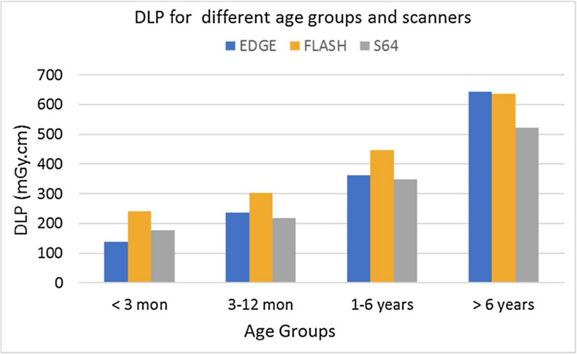

Fig. 2. Bar diagram summarizes DLP associated with the three scanners in different age groups of patients.

4. Discussion

The lower age-matched CTDIvol for most pediatric head CT in our study than the EDRL described values may be related to differences in head circumferences in children at HGH versus the European Union or differences in scanners and applied scan parameters. However, the frequency of greater DLP in our patient group compared to EDRL

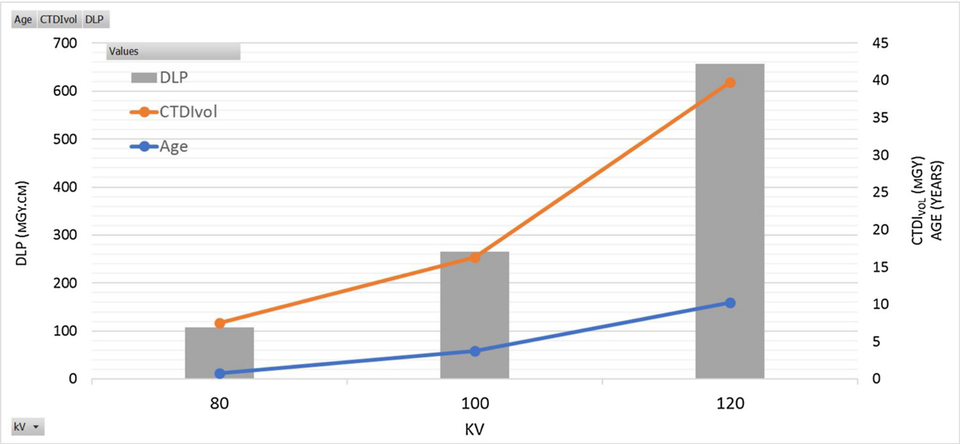

Fig. 3. Bar line graph displays trends of median DLP (y-axis on the left) and CTDI$_{vol}$ (y-axis on the right) at different tube potentials used in our study for head CT examinations. The blue line summarizes average age (in years) of patients scanned at different tube potentials.

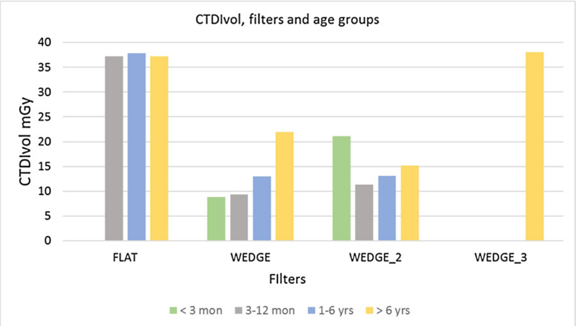

Fig. 4. Bar diagram displays CTDI$_{vol}$ (y-axis in mGy) in different age groups at the various scanner-selected beam shaping filters used for pediatric head CT. Radiation doses for wedge and wedge 2 filters were lower than for the flat and wedge 3 filters.

implies use of longer scan lengths in our practice as discussed later in this section. Radiation doses for most pediatric head CT examinations performed at the HGH were within the EDRL recommendations [4]. Our doses are comparable to other pediatric head CT studies [5–8,10–16]. For example, CTDIvol and DLP for pediatric head CT included in our study (9 − 27 mGy and 151 − 586 mGy cm) were lower than both pre- and post-training doses reported by Paolicchi et al. in 215 children between ages of 0–14 years (27 − 51 mGy and mGy cm) [5]. Niiniviita et al. reported mean CTDIvol for 318 children scanned with routine head CT protocol (30 ± 11 mGy) compared to 21 ± 11 mGy in our study [6]. Santos et al. have reported up to 45 % mean reduction in CTDIvol with the use of automatic tube potential selection and automatic tube current modulation techniques for pediatric head CT as compared to fixed tube current [7]. Park et al. reported radiation doses for 30 pediatric head CT performed at 80 kV (24 ± 3 mGy) and 120 kV (25 ± 3 mGy); at corresponding tube potentials, our CTDIvol were lower for 80 kV (6 ± 2 mGy) but higher for 120 kV (30 ± 9 mGy) [8]. Higher CTDIvol in our study for 120 kV head CT can be explained by the fact that children scanned in our study were older than in study from Park et al. (10. 3 years versus 7.9 years) [8].

Although radiation doses for pediatric head CT examinations on the single-source, 32-detector row CT were lowest amongst the three scanners, the difference may be attributed to significantly younger children scanned on the 32-detector row CT (6.1 years) than on the Siemens Flash (7.6 years) and Siemens Edge (6.8 years) (p = 0.0008). The differences in radiation doses based on the scanner types can also be related to over-ranging (radiation dose beyond the planned scan length to reconstruct first and last sections from helical acquisition), which varies based on the scanner type, pitch, as well as the detector configuration [9].

Kilic et al. used adaptive statistical iterative reconstruction (ASIR, GE Healthcare) technique and axial scan mode in 153 low-dose pediatric head CT (CTDIvol 20 ± 4 mGy for the cerebrum and 28 ± 4 mGy for posterior fossa) [10]. Our iterative reconstruction-capable CT scanners (Safire, Siemens) with a single-run helical head CT in 370 children delivered comparable doses (CTDIvol 23 ± 12 mGy) to both Kilic et al. [10] and another study from McKnight et al. (33 children; CTDIvol 22 ± 4 mGy) [11]. Thomas et al. assessed 157 reduced dose pediatric head CT exams performed with iDose (Philips Healthcare, Eindhoven, The Netherlands) and reported radiation doses (CTDIvol 20 − 29 mGy) similar to our study [12]. In a recent 2018 publication on iterative model reconstruction, the mean CTDIvol for pediatric head CT was 24 ± 3.1 mGy compared to 21 ± 11 mGy in our study [13]. In a more recent study from 2020, CTDIvol for pediatric head CT with Admire (iterative reconstruction technique from Siemens) are comparable to our study [14]. However, CTDIvol for pediatric head CT performed with iterative reconstruction technique in our study was higher than those in Mirro et al. (CTDIvol 15 − 18 mGy) with ASIR technique [15] and Kim et al. (CTDIvol 11 − 16 mGy) with ASIRv (GE Healthcare) [16]. These differences may be attributed to differences in patient ages, clinical indications, radiologists' preference, and scanner differences.

The main implication of our study is that CT dose descriptors (CTDIvol and DLP) for pediatric head CT examinations are linearly related to patient age when automatic tube potential selection (on two of the three CT scanners) and automatic tube current modulation techniques are used. Although prior studies have not explicitly reported a linear correlation between patient age, CTDIvol and DLP, these studies report lower doses for younger children and higher doses for older children undergoing head CT examinations [10,12,16]. Automatic tube potential selection and automatic tube current modulation techniques help adapt radiation dose to changing the head size, skull thickness, and/or attenuation with patients' age. Likewise, EDRL for pediatric head CT is available for children in four age groups [4]. Another implication pertains to the importance of paying close attention to DRLs for both CTDIvol and DLP when monitoring radiation doses for CT. Although CTDIvol for most head CT in our study was lower than the corresponding weight group in the EDRL, in more than one-quarter of children, DLP values were higher than the EDRL. Likewise, mean CTDIvol (21 mGy) associated with pediatric head CT included in our study was lower than those reported in a survey study from the United States (mean CTDIvol 27 mGy) but our DLP was higher (459 mGy cm compared with 391 mGy cm in the referenced study [3]). The reason for greater DLP was the use of longer than necessary scan length by the CT technologists in our institution which likely resulted from a lack of guidelines, from variations in the landmarks for the caudal extent of scanning, specific clinical reasons, or radiologists who requested additional scan coverage. It is important to remember that most modern scanners and dose optimization techniques, including iterative reconstruction techniques and efficient scanners (with greater dose efficiency due to pre-patient beam collimation and/or improved detector efficiency), cannot compensate for additional or unnecessary scan length beyond the intent region of scanning.

We have conveyed these findings to the relevant radiologists and technologists so that they can pay close attention to the scan length when performing pediatric head CT. Proper training to the technologists with guidelines on the importance of limiting scan coverage to well-defined anatomic landmarks (such as from the vertex to the cranio-cervical junction from lateral scout view) is the key first step in mitigating the problem posed by longer than necessary scan length. Some newer scanners with machine learning/artificial intelligence and scanner mounted cameras can automatically select scan landmarks for different CT protocols and thus reduce human variations in selecting proper scan range. Until such features are universally available, CT users must pay close attention to scan protocols and scan range prescriptions for dose optimization purposes.

There are a few limitations to our study. Although we did not perform a power analysis to determine the required number of head CT, we included a large number of consecutive patients scanned on all three of our CT scanners over the study duration. We did not perform a formal evaluation of image quality or diagnostic findings since all CT examinations were performed for clinically indicated reasons. Likewise, we did not assess the justification or appropriateness of the clinical indications in our study since we did not have access to such information. Unfortunately, like most countries, at the time of writing of this manuscript, Qatar does not have guidelines on the clinical justification for ordering CT examinations in children or adults.

Another limitation of our study pertains to the lack of generalizability of our study to other CT vendors since we do not have data from non-Siemens CT scanners. However, both automatic tube potential selection and automatic tube current modulation techniques are available on scanners from other vendors. Thus, the results of our study can be validated at sites with other scanners not included in our study. Also, we did not include non-routine pediatric head CT examinations in our study, such as CT for shunt patency or CT angiography. Since there are no pediatric head CT DRLs available from Qatar or the Middle East, we could not perform a local or region comparison of our doses.

In conclusion, pediatric head CT doses vary linearly with patient age when automatic tube potential selection and automatic tube current modulation techniques are used on the more modern CT scanners included in our study. Although CTDIvol for most pediatric head CT in our study were lower than the EDRLs, DLP for more than a quarter of our exams were higher than the corresponding European DRLs due to longer scan length. Proper training and guidelines on the use of anatomic landmarks from scout views can help CT technologists reduce the frequency of longer than necessary scan length.

CRediT authorship contribution statement

Mohammad Hassan Kharita: Conceptualization, Methodology, Writing - original draft, Visualization, Investigation, Writing - review & editing. **Huda Al-Naemi:** Visualization, Investigation, Writing - review & editing. **Chiara Arru:** Conceptualization, Methodology, Data curation, Writing - original draft, Visualization, Investigation, Software, Validation, Writing - review & editing. **Ahmed Jenaid Omar:** Visualization, Investigation, Writing - review & editing. **Antar Aly:** Visualization, Investigation, Writing - review & editing. **Ioannis Tsalafoutas:** Conceptualization, Methodology, Data curation, Software, Validation, Writing - review & editing. **Shady Alkhazzam:** Data curation, Writing - review & editing. **Ramandeep Singh:** Visualization, Investigation, Writing - review & editing. **Mannudeep K. Kalra:** Conceptualization, Methodology, Writing - original draft, Visualization, Investigation, Supervision, Writing - review & editing.

Declaration of Competing Interest

One study co-author (MKK) received research grants from Siemens Healthineers and Riverain Inc. for unrelated research projects.

References

[1] M. Kalra, A. Sodickson, W. Mayo-Smith, CT radiation: key concepts for gentle and wise use, RadioGraphics 35 (2015) 1706–1721.
[2] R. Gottumukkala, M.K. Kalra, A. Tabari, A. Otrakji, M. Gee, Advanced CT techniques for decreasing radiation dose, reducing sedation requirements, and optimizing image quality in children, Radiographics 39 (2019) 709–726.
[3] K.M. Kanal, J.M. Graves, M.S. Vavilala, K.E. Applegate, J.G. Jarvik, F.P. Rivara, Variation in CT pediatric head examination radiation dose: results from a national survey, AJR 204 (2015) W293–W301.
[4] European Guidelines on Diagnostic Reference Levels for Paediatric Imaging; n.185; http://www.eurosafeimaging.org/wp/wp-content/uploads/2018/09/rp_185.pdf last (Accessed on December 2nd 2019).
[5] F. Paolicchi, L. Faggioni, L. Bastiani, et al., Optimizing the balance between radiation dose and image quality in pediatric head CT: findings before and after intensive radiologic staff training, AJR 202 (2014) 1309–1315.
[6] H. Niiniviita, T. Kiljunen, M. Huuskonen, S. Teperi, J. Kulmala, Dose monitoring in pediatric and young adult head and cervical spine CT studies at two emergency duty departments, Emerg. Radiol. 25 (2018) 153–159.
[7] J. Santos, S. Foley, G. Pulo, M. McEntee, L. Rainford, The impact of pediatric-specificc dose modulation curves on radiation dose and image quality in head computed tomography, Pediatr. Radiol. 45 (2015) 1814–1822.
[8] J.E. Park, Y.H. Choi, J. Cheon, et al., Image quality and radiation dose of brain computed tomography in children: effects of decreasing tube voltage from 120 kVp to 80 kVp, Pediatr. Radiol. 47 (2017) 710–717.
[9] A. Schilham, A.J. van der Molen, M. Prokop, H.W. de Jong, Overranging at multisection CT: an underestimated source of excess radiation exposure, Radiographics 30 (2010) 1057–1067.
[10] K. Kilic, G. Erbas, M. Guryildirim, et al., Quantitative and qualitative comparison of standard-dose and low-dose pediatric head computed tomography: a retrospective study assessing the effect of adaptive statistical iterative reconstruction, J. Comput. Assist. Tomogr. 37 (2013) 377–381.
[11] C. McKnight, K. Watcharotone, M. Ibrahim, et al., Adaptive statistical iterative reconstruction: reducing dose while preserving image quality in the pediatric head CT examination, Pediatr. Radiol. 44 (2014) 997–1003.
[12] A.K. Thomas, R. Southard, J. Curran, R. Augustyn, Comparing fourth generation statistical iterative reconstruction technique to standard filtered back projection in pediatric head computed tomography examinations, J. Comput. Assist. Tomogr. 42 (2018) 475–481.
[13] H.H. Cho, Sm Lee, S.K. You, Pediatric head computed tomography with advanced modeled iterative reconstruction: focus on image quality and reduction of radiaton dose, Pediatr. Radiol. 50 (2020) 242–251.
[14] H.G. Kim, H. Lee, S. Lee, H.J. Kim, M. Kim, Head CT: image quality improvement with ASIR-V using a reduced radiation dose protocol for children, Eur. Radiol. 27 (2017) 3609–3617.
[15] A.E. Mirro, S.L. Brady, R.A. Kaufman, Full dose-reduction potential of statistical iterative reconstruction for head CT protocols in a predominantly pediatric population, AJNR Am. J. Neuroradiol. 37 (2016) 1199–1205.
[16] R.N. Southard, D.M.E. Bardo, M.H. Temkit, Comparison of iterative model reconstruction versus filtered back-projection in pediatric emergency head CT: dose, image quality, and image-reconstruction times, AJNR Am. J. Neuroradiol. 40 (5) (2019) 866–871.