Pediatric computed tomography scan parameters and radiation dose revisited for pediatric imaging team

Sayed E. Abdou[a], Dina H. Salama[b], Khaled A. Ahmad[c], Abdelsattar M. Sallam[d], El-Sayed M. El-Sayed[d], M.S Talaat[d]

[a]Department of Radiology, Ain Shams University Hospitals, Cairo, Egypt, [b]Department of Radiology and Medical Imaging Technology, Misr University for Science and Technology and Egyptian Atomic Energy Authority, Cairo, Egypt, [c]Department of Pediatric Imaging, Ain Shams University, Cairo, Egypt, [d]Department of Physics, Faculty of Science, Ain Shams University, Cairo, Egypt

Correspondence to Sayed E. Abdou, Department of Radiology, Ain Shams University Hospitals, Radiology Department, Cairo, Post Code 11591 Egypt.
E-mail: Phy.sayedabdou@gmail.com

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Given the substantial evidence and growing concern for the potential carcinogenic effects of children's exposure to ionizing radiation during computed tomography (CT) examinations, appropriate use of acquisition parameters is essential to attain diagnostic image quality at the lowest possible radiation dose. The objective of this article is to provide a systematic review to the pediatric imaging team members on how to manage pediatric CT doses and control the essential scanning parameters. The article also highlights other key factors that can be easily used to ensure safe imaging. Some practical tips and technical considerations are provided to be simply incorporated into clinical practice. Optimization of CT imaging is a dynamic process and needs understanding and engagement of all pediatric imaging team members, as keeping our children safe should be the ultimate goal in CT imaging.

Keywords:
automated tube current modulation, low kVp, pitch, radiation dose

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Introduction

Over the past several years, there has been increasing recognition of the importance of reducing radiation dose in pediatric computed tomography (CT) scan, particularly regarding multidetector CT. The growth in the volume of multidetector CT studies, the increasing use of CT in vulnerable populations (including children), and the growing concerns of the general public regarding radiation exposure have provided an impetus for performing these studies with the least possible radiation dose. It is now believed that as many as 0.4% of all malignancies can be traced back to radiation from CT studies and that radiation from pediatric CT studies may ultimately account for 1.5–2% of all cancers in the future [1].

One of the basic tools representing the standard to optimize the patient dose for each CT examination is diagnostic reference levels (DRLs) recommended by International Commission on Radiological Protections. DRLs are important dose databases that help optimize the radiation exposure of pediatric patients in radiological examinations performed for similar purposes in different radiology centers. These databases that can represent local DRL are based on the third quartile (the 75th percentile) value of the distribution of patient doses obtained from radiology departments in a single large health care facility. The national DRL is based on the third quartile (the 75th percentile) value of the median (the 50th percentile) values of the distributions of patient doses obtained from a representative sample of radiology departments in the country, and a European DRL is based on the median (the 50th percentile) value of the distribution of the national DRLs for a defined clinical imaging task (i.e. common indication-based protocol) surveyed for standardized patient groupings. Primarily PiDRLs carried out by the UK 2011, USA 2018, and other European countries, establishment of PiDRLs is now a worldwide practice, which is recommended to be updated in every 5 years at most [2].

Unfortunately, despite this growing awareness, the introduction of each new generation of CT scanners has resulted in scanning protocols that are increasingly complex and difficult to manipulate. When facing increasing criticism regarding CT dose even with the new intelligent doze equipment, the best way to tackle the issue is that the pediatric radiology imaging team including radiologists, medical physicists, and technologists should understand all factors and parameters that can affect radiation dose and image quality. They should also agree on how they can be optimized to reduce doses in different pediatric age groups while maintaining an acceptable level of diagnostic image quality. Controlling these parameters is a practical no-cost solution for any

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pediatric imaging center especially in middle and low-income countries with no access to sophisticated new software for radiation protection [3].

A significant dose reduction of CT examinations performed in emergency patients was achievable via strategies that targeted simple adjustments (e.g. reduction of scan coverage and number of acquisition), technical optimization [e.g. mAs, kVp reduction, and Automatic Tube Current Modulation (ATCM)], and the use of indication-specific protocols while maintaining an acceptable level of diagnostic image quality. There are broad international efforts in improving informed use of radiation in pediatric CT such as the International Atomic Energy Agency's technical cooperation projects on radiation safety and Image Gently's CT campaigns. These initiatives were effective to some extent in lowering tube mAs and peak kilovoltage, being the most commonly employed techniques effective at reducing pediatric CT dose [4].

Challenges in pediatric imaging

Radiation protection and safeguarding are paramount concerns for pediatric patients. The risk for cancer induction in children is about 10 times higher than in adults. Moreover, children have longer life expectancy; therefore, they have a greater potential for manifestation of possible harmful effects of radiation.

ALARA principles were used for reviewing CT requests as shown later. Regarding the justification of pediatric medical exposures, all medical imaging exposures must show a sufficient net benefit when balanced against possible detriment that the examination might cause. Optimization is based on the standard pediatric CT protocol. It is a process of evaluation of image quality against patient dose and opting for possible alternatives to maintain necessary image quality while minimizing patient absorbed doses, or selection of better imaging protocols under the given circumstances, and implementation of the selected option and regular review of image quality and patient dose to evaluate if either requires further action.

Appropriate imaging modality should be used depending on the clinical indication [e.g. using ultrasound (USG) instead of CT in a suspected case of appendicitis]. MRI is preferred over CT for most of the cross-sectional imaging workup in children, except for trauma evaluation.

Pediatric USG is relatively safe with no risks of radiation, is cheap, and is readily available. USG may be repeated over and over again for follow-up studies, without any significant risks.

The major challenge in MRI is the need for sedation or general anesthesia in younger children. Second, the relatively smaller anatomic structures in children create a challenge in terms of available signal and image resolution. So, higher signal-to-noise ratio is needed, which can be achieved using pediatric-specific coils, high field strengths, and by optimizing the field of view and slice thickness [5].

Managing pediatric computed tomography doses and controlling the essential scanning parameters

In the last decade, manufacturers and clinical diagnostic centers have started to develop pediatric scanning protocols specific to age, body size, and composition for better dose optimization. However, a recent International Atomic Energy Agency survey suggested that many radiology departments are still using default adult protocols provided by the manufacturers without customized optimization to children.

The danger for the radiation exposure is about two to three times higher than that for adults because pediatric patients have a longer life expectancy and their organs are more sensitive to radiation damage. To maximize the benefit of CT imaging in children and avoid risks, it is important to cleverly utilize different scanning parameters and simple technical solutions that can support the optimization of imaging in children having different ages and sizes.

Tube current (mA) modulation

Pediatric radiation dose is directly proportional to the effective tube current time product. Lowering the mAs is the most direct way to reduce the radiation dose. The increase in tube current or the product of tube current and scan time (mAs) results in improved image quality, decreased image noise, and increased pediatric patient dose [6].

In general, the relationship between tube current and pediatric patient dose was essentially linear; increasing mAs will result in a comparable percentage increase in the patient dose. Although tube current can be manually controlled, it is recommended that most operators use automated tube current modulation (also known as automated exposure control) for most applications.

The specific tube current modulation techniques vary by manufacturer, but all major vendors have this function. The commercial names of tube current modulation software include Auto mA/Smart mA – ASiR (GE Healthcare), Care Dose 4D-SAFIRE (Siemens Healthcare), and Sure Exposure – AIDR (Toshiba Medical Systems), among others. In spite of this, it has been reported that radiation technologists in different sites around the world are still ignoring this function, being unaware of its value.

Modulating tube current has been reported to provide up to 40% dose reduction per examination and should be used in most pediatric CT protocols. The major value of tube current modulation was that it provides proper tube current technique settings for variable patient sizes and examination indications. Thus, its primary use is for consistency of image quality [7].

ATCM is an essential tool to ensure proper patient exposure with CT examinations. It allows the tube current to be actively modulated during the scan to apply radiation to the pediatric patient appropriately [8].

ATCM works on different principles depending on the specific vendor, although a combination of four different strategies is generally used: (a) patient size modulation changes the mAs on the basis of a global evaluation of the overall size of the patient as seen on the scout radiograph.

(b) *Z*-axis modulation changes the mAs constantly along the *z*-axis of the patient depending on the patient attenuation at each point as determined using the scout image.

(c) Angular (*x*, *y*) modulation changes the mAs as the radiograph tube rotates 360° around the patient to account for different attenuations in different projections of the radiograph beam. (d) Combined *x*, *y*, and *z* modulation adjusts the mAs in all three axes on the basis of the patient's attenuation [9].

In pediatric patients, practice automated tube current modulation should be enabled and used by all users, although some significant caveats and exceptions must be kept in mind:

(1) Small or pediatric patients when incorrectly positioned or improperly centered within the CT gantry can result in excessively noisy images with artificially low mAs.
(2) Many institutions do not use automated tube current modulation when performing scans of the head particularly in pediatric patients because of the difficulty in correctly placing the head in the isocenter of the gantry. A small deviation of the head from the isocenter can result in a significant increase in image noise.
(3) Patients' arms should be out of the field of view for both scout image and axial image acquisition. Any discrepancy in the position of the arms between the scout and axial images can adversely affect the algorithm's function and theoretically increase dose. If neck and chest CT studies are to be performed at the same time, either two separate acquisitions should be performed (with the arms out of the field of view for each) or a single acquisition with the arms up by the neck should be used.
(4) It is important to note that adult modulation settings should not be used for pediatric patients because some scanner software packages use separate modulation curves for children. This information is not well known by many end users and such use may increase doses for children [10].

Tube voltage (kVp)

Reducing kVp can be an effective means of reducing radiation dose for pediatric patients imparted during an examination. As a general rule of thumb, the radiation dose changes with the square of kVp and a reduction in kVp from 120 to 100 reduces radiation dose by around 33%, whereas a further reduction to 80 kVp can reduce dose by 65% (Table 1) [11].

As a further advantage particularly in angiographic studies in which vascular contrast is critical, reductions in kVp result in an increased attenuation of iodine (even with a constant dose of contrast) as a result of the photoelectric effect and approaching the k-edge of iodine, potentially improving contrast-to-noise ratios in pediatric as well as adult patients. Nevertheless, unlike reductions in mAs which have a linear and relatively predictable effect on image noise and contrast-to-noise ratios, a decrease in kVp can result in nonlinear exponential increases in image noise often necessitating a concomitant increase in mAs to preserve image quality [12].

Decreasing kVp in children can reduce the radiation dose and may improve soft tissue contrast. However, there are several factors that should be taken into account when lower kVp techniques are considered. First, the mAs will likely have to be increased to keep noise levels constant; second, a weight-based or size-based kVp/mAs/dose technique chart should be used to determine when a lower kVp is appropriate; third, a

Table 1 Computed tomography protocol parameters (kVp and mAs) for the pediatric head, chest, and abdomen-pelvis computed tomography examinations

	A <1 year		B >1–5 years		C >5–10 years		D >10–15 years	
	Median kVp (minimum–maximum)	Median mAs (minimum–maximum)	Median kVp (minimum–maximum)	Median mAs (minimum–maximum)	Median kVp (minimum–maximum)	Median mAs (minimum–maximum)	Median kVp (minimum–maximum)	Median mAs (minimum–maximum)
Head								
H1	108 (100–120)	150 (140–160)	115 (100–120)	200 (180–220)	118 (100–120)	240 (220–260)	120 (120–120)	270 (250–300)
H2	108 (100–120)	150 (140–160)	117 (100–120)	200 (180–220)	115 (100–120)	240 (220–260)	120 (120–120)	270 (250–300)
H3	105 (100–120)	150 (140–160)	115 (100–120)	200 (180–220)	117 (100–120)	240 (220–260)	120 (120–120)	270 (250–300)
H4	107 (100–120)	150 (140–160)	117 (100–120)	200 (180–220)	118 (100–120)	240 (220–260)	120 (120–120)	270 (250–300)
H5	110 (100–120)	150 (140–160)	118 (110–120)	200 (180–220)	116 (100–120)	240 (220–260)	120 (120–120)	270 (250–300)
H6	108 (100–120)	150 (140–160)	117 (100–120)	200 (180–220)	115 (100–120)	240 (220–260)	120 (120–120)	270 (250–300)
H7	107 (100–120)	150 (140–160)	115 (100–120)	200 (180–220)	118 (100–120)	240 (220–260)	120 (120–120)	270 (250–300)
Chest								
H1	90 (80–100)	60 (50–70)	117 (100–120)	70 (65–80)	116 (100–120)	85 (80–90)	120 (120–120)	100 (90–110)
H2	90 (80–100)	65 (50–70)	117 (100–120)	70 (65–80)	115 (100–120)	85 (80–90)	120 (120–120)	100 (90–110)
H3	90 (80–100)	66 (50–70)	115 (100–120)	70 (65–80)	117 (100–120)	85 (80–90)	120 (120–120)	100 (90–110)
H4	90 (80–100)	60 (50–70)	117 (100–120)	70 (65–80)	118 (100–120)	85 (80–90)	120 (120–120)	100 (90–110)
H5	90 (80–100)	65 (50–70)	118 (110–120)	70 (65–80)	116 (100–120)	85 (80–90)	120 (120–120)	100 (90–110)
H6	90 (80–100)	60 (50–70)	117 (100–120)	70 (65–80)	115 (100–120)	85 (80–90)	120 (120–120)	100 (90–110)
H7	90 (80–100)	65 (50–70)	115 (100–120)	70 (65–80)	118 (100–120)	85 (80–90)	120 (120–120)	100 (90–110)
Abdomen-pelvis								
H1	80 (80–100)	80 (80–90)	100 (100–120)	80 (80–90)	100 (100–120)	90 (80–100)	120 (120–120)	100 (80–110)
H2	80 (80–100)	80 (80–90)	100 (100–120)	80 (80–90)	100 (100–120)	90 (80–100)	120 (120–120)	100 (80–110)
H3	80 (80–100)	80 (80–90)	100 (100–120)	80 (80–90)	100 (100–120)	90 (80–100)	120 (120–120)	100 (80–110)
H4	80 (80–100)	80 (80–90)	100 (100–120)	80 (80–90)	100 (100–120)	90 (80–100)	120 (120–120)	100 (80–110)
H5	80 (80–100)	80 (80–90)	100 (100–120)	80 (80–90)	100 (100–120)	90 (80–100)	120 (120–120)	100 (80–110)
H6	80 (80–100)	80 (80–90)	100 (100–120)	80 (80–90)	100 (100–120)	90 (80–100)	120 (120–120)	100 (80–110)
H7	80 (80–100)	80 (80–90)	100 (100–120)	80 (80–90)	100 (100–120)	90 (80–100)	120 (120–120)	100 (80–110)

Table 2 Scan length (cm) for pediatric head, chest and abdomen-pelvis computed tomography examinations

	A < 1 year Median (cm) (minimum–maximum)	B >1–5 years Median (cm) (minimum–maximum)	C >5–10 years Median (cm) (minimum–maximum)	D >10–15 years Median (cm) (minimum–maximum)
Head				
H1	10 (8–15)	12 (10–16)	14 (11–18)	15 (13–20)
H2	11 (8–14)	14 (10–16)	15 (11–18)	17 (13–20)
H3	10 (8–13)	13 (10–16)	14 (11–18)	15 (13–20)
H4	12 (8–14)	12 (10–16)	16 (11–18)	16 (13–20)
H5	10 (8–15)	14 (10–16)	15 (11–18)	17 (13–20)
H6	11 (8–15)	13 (10–16)	14 (11–18)	17 (13–20)
H7	10 (8–15)	12 (10–16)	16 (11–18)	15 (13–20)
Chest				
H1	10 (7–15)	13 (10–18)	18 (14–25)	22 (19–32)
H2	11 (7–15)	14 (10–18)	18 (14–25)	21 (19–32)
H3	9 (7–15)	12 (10–18)	20 (14–25)	25 (19–32)
H4	12 (7–15)	15 (10–18)	20 (14–25)	22 (19–32)
H5	11 (7–15)	12 (10–18)	18 (14–25)	23 (19–32)
H6	10 (7–15)	13 (10–18)	22 (14–25)	25 (19–32)
H7	11 (7–15)	12 (10–18)	20 (14–25)	24 (19–32)
Abdomen-pelvis				
H1	15 (12–22)	20 (17–28)	33 (31–35)	37 (35–42)
H2	14 (12–22)	22 (17–28)	32 (31–35)	38 (35–42)
H3	13 (12–22)	20 (17–28)	33 (31–35)	37 (35–42)
H4	15 (12–22)	21 (17–28)	32 (31–35)	36 (35–42)
H5	14 (12–22)	19 (17–28)	32 (31–35)	37 (35–42)
H6	15 (12–22)	23 (17–28)	33 (31–35)	38 (35–42)
H7	13 (12–22)	22 (17–28)	32 (31–35)	40 (35–42)

lower KVp may require longer scan times because of mAs limits that can increase motion artifacts; and the fourth consideration is a lower kVp may increase iodine conspicuity but not necessarily improve other soft tissue contrast [13].

Tube voltage modification (kVp modification): different tube voltages can be chosen for the CT examination depending on the size of the patient or the type of CT examination performed. Generally, reducing tube voltage from 120 kVp to 100 or 80 kVp often permits overall reduced exposure techniques and is advised for pediatric patients. There are some readymade protocols for pediatrics that can suite different scanner models: they are prepared by some international organizations concerned with dose reduction, for example, Image Gently to assist adjusting different scanning parameters to different ages [14].

Scan range

Scan length is the extent of pediatric body length covered in scanning; it does not affect the CTDI (mGy) value but certainly affects DLP (mGy.cm). The scan length for a particular type of CT examination can vary due to the pathology of the patient size. For all these reasons, CT protocols need to be established so as to limit irradiation only to the particular body region of clinical indications. On the contrary, for many pediatric CT applications, significant reductions in scan range may be neither possible nor desirable. The scan range should be reduced to the needed minimum for any examination, particularly when imaging structures such as the heart, for which an increased scan range is unnecessary (Table 2) [15].

Although cardiac studies are certainly the most obvious applications in which a limited scan length can be used, a small scan range may be possible in any traditional body imaging applications as well. It has been found that using a small scan range (from the top of the aortic arch to the bottom of the heart) in pediatric CT pulmonary angiographic studies can allow diagnosis of pulmonary embolism without any loss of sensitivity but with a reduction in radiation dose of 48%. Unfortunately, even if the scan range is kept to the absolute minimum, helical CT requires the acquisition of raw data on either end of the scan length outside of the intended scan range to acquire sufficient projection data. This can particularly be a problem with higher pitches and can result in additional dose as a result of wasted dose at the margins of the scan range. However, this effect can be mitigated with the use of dynamic z-collimation. Unlike a fixed collimator which is fully open throughout the scan range, the dynamic z-collimator opens only that portion of the collimator entering the scan range (while at the beginning of the scan) and closes the proximal edge of the collimator while leaving the scan range, thus minimizing dose outside the intended scan range and resulting in a more rectangular dose profile. Dose savings with the use of dynamic z-collimation can be incremental, although the exact extent of savings will depend on the CT pitch [16].

Pitch

Pitch in the multidetector spiral CT is defined as table travel per rotation divided by beam collimation. To simplify it, pitch less than 1 suggests overlap between adjacent acquisitions, pitch more than 1 implies gaps between adjacent acquisitions, and pitch of 1 suggests that acquisitions are contiguous with neither overlap nor gaps [17].

Simply a smaller pitch with increased overlap of anatomy and increased sampling at each location results in an increased radiation dose. Alternatively, a larger pitch implies gaps in the anatomy and hence lower radiation dose. As a result, if all other parameters are unchanged, increasing pitch reduces radiation dose in a linear fashion. A good balance is required as low pitch technique is associated with less image noise, fewer artifacts, and improved signal-to-noise and contrast-to-noise ratios [18].

For pediatric routine body CT protocols, pitch more than 1 is generally acceptable with no compromise to image quality. However, using higher pitches (pitch >1.5) can result in interpolation artifacts and image noise that is typically unacceptable. For most pediatric cardiac CT applications, pitch values less than 0.5 are routinely used, resulting in higher doses in such studies. These lower pitch values are used to overcome motion artifacts and are also stipulated by the reconstruction algorithms in use.

Diagnostic reference levels

The concept of DRLs should be well understood by the pediatric imaging team as it plays an important role in the optimization of radiation doses in pediatric imaging. DRLs are useful indicators by which the radiologists and radiation technologists can be aware of delivered excess radiation doses to children and take corrective actions if necessary.

A DRL is a specified radiation dose for a given imaging study that is not expected to be exceeded in daily practice. If radiation doses do exceed the DRL for a particular study, this should trigger an investigation of the problem in the radiographic technique or the equipment performance [19].

DRL values may be based on local or national dose data that are estimated according to specific dose surveys. It is very useful to regularly refer the pediatric patient doses in any pediatric imaging center to these local or national reference levels to evaluate the current doses to children in the pediatric imaging facility. They are typically set at the 75th percentile of a distribution of radiation doses collected for a given examination [20].

Image quality

In the first place, it is important for the pediatric imaging team to agree on that the pediatric patients' risks from radiation doses associated with CT could be small compared with the benefits that accurate diagnosis and treatment can provide but only if the examination is optimized and ended up with adequate image quality. The relationship between radiation dose and image quality indicates that image noise increases as tube voltage decreases. When tube voltage is decreased, radiation dose decreases in phantoms of all sizes. It is very possible to use a tube voltage as low as 80 kVp and maintain image contrast in pediatric phantoms as the increase in image noise is more obvious in larger phantoms of adults than in smaller phantoms. There is no appreciable difference in image noise in the infant-sized (8-cm) phantoms at the 80 and 120-kVp settings because there is less radiograph attenuation caused by intervening material.

The differences in image quality may not be as robust in all pediatric patients because of the differences in the administration of contrast medium or in breathing-related artifacts, both of which can affect the visibility of structures. There is a need that the pediatric imaging team develops local clinical protocols for the pediatric population that adjust the use of tube voltage and tube current to reduce radiation dose in contrast-enhanced CT examinations. Although reduction in radiation dose is an important exercise, maintaining appropriate quality of diagnostic imaging studies is also essential to provide an accurate and definitive diagnosis. There is a need to achieve a fine balance between image quality and radiation dose [21].

The general guidelines that should be recommended while using computed tomograph equipment for pediatric imaging

(1) CT dose management system is an important tool for dose reviewing and optimization programs targeting the improvement of patient safety. An ideal dose management solution should include multiple elements such as radiation dose tracking software, clinical protocol mapping, alert notification, and support for dose optimization experts' team. CT dose management for pediatric patients is done through extracting information from Picture Archiving and Communication System or Radiology Information System. The manual method has tendency to typographic errors and inconsistencies in data tracking and requires longer time. Therefore, the digital dose monitoring software is commenced as an automated tool to track and analyze the big data for patient dose management and consequently suggest strategies for reducing excessive radiation exposure for pediatric patients.

(2) Position the pediatric patient carefully; check that at the isocenter of the scanner, the arms are correctly positioned to avoid beam hardening artifacts and dose increase if mA modulation is used. Incorrect positioning may result in significant (up to 25%) dose increase.

(3) Use the smallest possible scan range that is compatible with the scan request. Limit the scanned volume (field of view and number of slices) to what is just necessary to answer the clinical questions justifying the procedure.

(4) Choose the lowest kVp compatible with the necessary image quality according to patient age and weight. For the same field of view, dose to patient increases with tension to the power of 2.5. In practice, the kVp used for pediatric CT is between 80 and 120; 80 kVp being used for less than 30 kg patients, 100 kVp for patients until 60 kg, and 120 kVp being used for adult sized children [22].

(5) Lower the dose by decreasing current mA and/or rotation time within limits that are compatible with the image quality criteria (signal to noise ratio).

(6) Use automatic current modulation systems (mA modulation) as they allow for dose reduction. These techniques must be used in addition to an optimization of the protocols. Quality indices (noise index in the image, reference mAs, or reference image according to different manufacturers) are used to maintain a constant image quality [23].

(7) Be careful when selecting thin slices (<1 mm) because dose is automatically increased when collimation decreases to these levels.

(8) Use the manufacturer's pediatric protocols, age or weight classified; they can help choose the best parameters considering the child's age and weight adapted as a function of the clinical indication.

(9) Shields can be used to protect sensitive organs. Bismuth shields are available commercially: breast shields should be used during the chest examination of young females, as they reduce the absorbed dose by a factor of 2.

(10) Do not use lead shields to protect radiosensitive organs (thyroid and pelvis) because they might negatively interfere with mA modulation and result in a fault sense of protection [24].

Conclusion

Pediatric protocols with scanning parameters specifically designed for children must be well understood and properly used by all pediatric imaging team members. The continuous technical development of radiation-sparing techniques clearly indicates radiation dose awareness among CT scanner manufacturers. Continuous research and innovation will lead to even more and better dose-saving intelligent tools. It is important to keep all the medical imaging staff informed on how to keep current with the newest technology to offer the best available service with the lowest radiation burden to pediatric patients. Scanning protocols based on the clinical question, the anatomic region, and the different pediatric ages and sizes should be always adopted to ensure good image quality and safe children.

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Conflicts of interest

There are no conflicts of interest.

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