Pediatric Computed Tomography Dose Optimization Strategies: A Literature Review

Abstract

Introduction

Computed tomography (CT) dose optimization is an important issue in radiography as CT is the largest contributor to medical radiation dose and its use is increasing. However, CT dose optimization for pediatric patients could be more challenging than the adult counterpart. The purpose of this literature review was to identify and discuss the current pediatric CT dose saving techniques. Optimized pediatric protocols were also proposed.

Methods

A comprehensive literature search was conducted using the Medline, ProQuest Health and Medical Complete, PubMed, ScienceDirect, Scopus, Springer Link and Web of Science databases, and by using the keywords: CT, pediatric, optimization, protocol and radiation dose to identify articles focusing on pediatric CT dose optimization strategies published between 2004 and 2014.

Results and Summary

Seventy-seven articles were identified in the literature search. Strategies for optimizing a range of scan parameters and technical considerations including tube voltage and current, iterative reconstruction, diagnostic reference levels, bowtie filters, scout view, pitch, scan

collimation and time, overscanning and overbeaming for pediatric patients with different ages and body sizes and compositions were discussed. An example of optimized pediatric protocols specific to age and body size for the 64-slice CT scanners was devised. It is expected this example could provide more ideas to medical radiation technologists, radiologists and medical physicists on the way to optimize their pediatric protocols.

Introduction

Computed tomography (CT) dose optimization is an important issue in radiography as CT is the largest contributor to medical radiation dose and its use is increasing [1,2]. However, CT dose optimization for pediatric patients could be more challenging than the adult counterpart because: 1. children are more radiosensitive to radiation [3]; 2. they have longer lifetime allowing potential radiation effects to manifest [4]; and 3. there are large variations of body size and composition (percentages of fat, muscle and bone) within each age group and across different groups [5-7]. Some clinical centers have implemented age and child-size specific CT scan protocols, and its effect on dose reduction has been recognized [5,8,9]. However, variations of these age and child-size specific protocols exist which makes other departments difficult to follow [5-12]. Also, there is a lack of standardization with respect to the definition of pediatric patients. One of the common definitions is those aged 0-15 years are considered as pediatric patients [13-15]. Such definition is used in this paper.

The purpose of this literature review was to identify and discuss the current pediatric CT dose saving techniques. Optimized pediatric protocols and further study directions were also proposed. It is expected this review could potentially increase the awareness of medical radiation technologists on the range of dose saving techniques available in the literature and encourage them to optimize their protocols reducing the risk of pediatric CT examinations.

Methods

A comprehensive literature search was conducted using the Medline, ProQuest Health and Medical Complete, PubMed, ScienceDirect, Scopus, Springer Link and Web of Science databases, and by using the keywords: CT, pediatric, optimization, protocol and radiation dose to identify articles focusing on pediatric CT dose optimization strategies. The article inclusion criteria were: 1. published between 2004 and 2014; 2. original research paper; 3. peer-reviewed; and 4. written in English. Articles were excluded if they belong to conference abstract and commentary. Figure 1 illustrates the literature search process.

'Insert Figure 1 about here'

Results and Discussion

Seventy-seven articles were identified in the literature search and covered a range of areas including pediatric CT protocols specific to age, body size and composition, scan parameters that influence radiation dose and image quality, and other technical considerations (Figure 1). They were discussed in the following sections.

Protocols Specific to Age, Body Size and Composition

According to the International Atomic Energy Agency (IAEA) survey of pediatric CT practices in 40 countries published in 2013 [13], more than half of the clinical centers relied on pre-programmed scan protocols provided by manufacturers. In most of these scan protocols, specific techniques are suggested for each patient age group because it is assumed that body sizes and compositions (percentages of fat, muscle and bone) of patients within the same age group should be similar. However, recent studies indicated even in the same age group, there are great variations of body size and composition due to factors such as obesity [5-21].

Since the last decade, some manufacturers and clinical centers have started to optimize their protocols based on not only patient age but also their body size in terms of weight. This is known as the color-coded system [9]. The scan settings such as tube potential and current and exposure time are tailored to specific patient conditions leading to lower dose and better image outcome. However, this approach requires medical physicists possessing sound knowledge of scanner specifications with support from radiologists and medical radiation technologists to develop these optimized protocols which is not feasible in many health institutions [13,22].

Patient size parameters such as weight and body mass index (BMI) are commonly used for developing size specific protocols for pediatric and adult patients. Recently, effective diameter and cross-sectional dimension have been considered as more accurate indicators of body size and habitus [5-7]. Also, awareness on variation of organ radiosensitivity across the children age range as well as between genders has been increased [2,4,23-26]. The following sections discuss individual scan parameters and other technical considerations for developing protocols specific to age, body size and composition.

Tube Voltage

Both phantom and clinical studies showed a lower tube voltage (with other settings such as tube current unchanged) could reduce radiation dose and improve image contrast for small-sized patients [27-30]. For example, a tube voltage as low as 60 kV could be used in pediatric CT examinations for structures with high subject contrast such as chest and bone [31]. Also, in (iodinated) contrast studies, a low tube voltage closer to the k-absorption edge of iodine, 33 keV would increase the probability of photoelectric interaction improving the conspicuity of hyper- or hypo- vascular structures [29-35]. The amount of contrast medium could also be reduced in this case minimizing the chance of contrast-induced nephropathy [30,34-37]. However, an inappropriate, low tube voltage could cause the beam hardening artefact and decrease the image contrast due to the increase of image noise (Figure 2) [29,31]. If the image noise is excessive when using a lower tube voltage, adjustment of other parameters such as tube current will become essential [7,27]. The impact of image contrast reduction on pediatric abdominal examinations tends to be more significant when comparing with those for adults because less fatty tissue would normally be present between visceral organs of children representing a lower subject contrast [21,38,39]. In contrast enhanced soft tissue procedures, for example, to assess the small lesions in abdomen, the use of higher tube voltage would be necessary [27,40]. Although patient weight, BMI, effective diameter or cross-sectional dimension of body part can be used to indicate the body size for optimizing tube voltage in pediatric examinations, this information may not always be available [8,9,11-15,27].

'Insert Figure 2 about here'

Automatic tube potential selection with tube current modulation (APSCM) is a relatively new function available in some latest CT scanners. It can assess the attenuation property of body part (i.e. body composition) which is difficult to measure in traditional settings and select the optimal tube voltage (in the range of 70-140 kV) for achieving a balance between radiation dose and image quality automatically [27, 36-41]. Although its dose reduction capability was demonstrated in studies focusing on adult patients [37-44], its potential for pediatric CT dose optimization still needs to be confirmed. In a recent study of APSCM in pediatric imaging, 94% of the chest and abdomen examinations of this study had the tube voltage reduced to 70, 80 or 100 kV resulting in dose decrease up to 27% when comparing with the situation of the standard setting at 120 kV [27].

Tube Current

Similar to tube voltage, a decrease in tube current with other parameters unchanged reduces radiation dose but it could potentially increase image noise. Phantom studies showed that the tube current could be halved for every 3.5-4 cm reduction of diameter of body part, and if image noise is a concern, the mA could be decreased by 50% when there is a 4-6 cm reduction in diameter [31]. However, this rule of thumb does not apply to pediatric head CT because the tube current selection mainly depends on the skull bone composition (amount of calcium content) rather than the diameter of body part. The skull bone composition is more related to age [45].

Tube-current modulation (TCM) is again a recent CT system development. It only requires medical radiation technologists to provide image quality reference inputs. Automatic tube current adjustment takes place subsequently based on the size and attenuation property of body part (i.e. body composition) in the x-y plane (angular modulation), along the z-axis (z-axis modulation) or combined modulation. Studies reported the extent of dose reduction would be in the range of 26-50%. They highly recommended medical radiation technologists to apply TCM to their clinical practices for dose reduction while maintaining the image quality [9,26,46]. When it is used with a low tube voltage, the dose reduction effect will become more prominent [7].

However, the challenge associated with this function in pediatric imaging is the lack of established guidelines of image quality reference values as they vary across manufacturers. The reference values depend on specific detector configuration, scanning geometry and beam filtration of different scanner models and manufacturers [47]. Table 1 shows the latest modulation software details of various manufacturers [31,47-51]. Although TCM is developed for dose reduction, in some situations such as the use of thin slice, low pitch and short scan time, the dose might increase unexpectedly for maintaining the target image quality (offsetting the negative effect on quality induced by these settings) [21,31,37,45,52].

'Insert Table 1 about here'

Iterative Reconstruction (IR)

Filtered back projection (FBP) is the standard image processing method for CT image formation. Recently, some CT manufacturers have provided the option to use iterative algorithms to reconstruct images and it is known as IR. This technique could reduce image noise and hence address the potential problems of tube voltage and current reduction for dose optimization [53,54]. The details of the latest IR products of different manufacturers are provided in Table 2 [53-57].

'Insert Table 2 about here'

Recently, successful use of IR has been reported in pediatric CT studies such as cardiac, chest and abdomen with possible dose reduction up to 50% depending on diagnostic requirement and patient condition [55-58]. Further reduction up to 90% could be achieved in CT follow-up procedures [56]. Nevertheless, IR in pediatric routine CT examinations is a controversial area because various factors such as detector efficiency and TCM can affect the reconstruction performance [55-61]. Also, the individual preferences of practicing radiologists should be considered as some described IR images as “plastic” or “fogy” in appearance [53-61]. A standard protocol for the appropriate use of IR should be established based on specific pathology, body size and selection of reconstruction kernel [58].

Diagnostic Reference Levels (DRLs)

DRLs are percentile points (commonly 75^{th} percentile) of radiological examination dose distributions [62,63]. It provides clinical centers references of examination doses for protocol optimization [18-22,64-68]. However, the majority of published DRLs for pediatric CT imaging are just age specific and its inadequacy was noted [63-66]. Also, accurate CT dose measurements are not always readily available which makes it difficult to compare the examination doses with the DRLs [8,22]. The established CT DRLs are normally expressed in the quantities of volume CT dose index (CTDIvol), dose-length product (DLP) and effective dose (E) [67]. Although readings of CTDIvol and DLP are provided by modern scanners, their accuracies are questionable. For example, they determine the CTDIvol and DLP just based on 16 and / or 32 cm phantom(s) rather than specific to individual patient sizes. If 32 cm phantom is used, the dose reading provided would underestimate the actual dose received [8,68-69]. Further inaccuracies would be introduced if the effective dose is obtained through converting the DLP to E based on age and region specific conversion coefficients [22].

Bowtie Filters

CT scanners are normally equipped with bowtie filters to shape the X-ray beam for uniform photon distribution leading to optimal radiation dose and image quality [67]. However, cautions should be taken for pediatric cases because of their smaller body sizes. If patients are not placed to the gantry center, increases of dose to the peripheral and noise to the center will be expected [37,52,70-72]. The situation may be even worse when low dose or TCM technique is used inappropriately because it could be another potential source of noise as discussed previously [52].

Optimized Scanogarm or Scout View

The optimization of scanogram or scout view is commonly neglected by medical radiation technologists. However, studies reported the arrangement of placing the X-ray tube under the table for scout view could reduce the dose to one third of the original [21,73]. Although this arrangement is only available in newer scanners, the length of the scout view should always be optimized to just cover the region of interest in any case. This is especially important when considering the smaller body sizes of pediatric patients.

Optimized Pitch and Scan Collimation

Higher pitch or thinner collimation is important in pediatric cases for obtaining adequate image spatial resolution along the z-axis. However, this would increase the image noise and hence decrease contrast-to-noise ratio [45,53]. This is a potential problem in pediatric imaging due to their lower subject contrast. In order to address this issue, some CT scanners would increase the tube current automatically to compensate for the loss in image quality which may go against the concept of dose optimization [45]. A better approach could be to use special post-processing reconstruction software such as algorithm filters and IR to optimize the image outcome [39,74].

Scan Time

A short scan time is preferable in pediatric imaging for motion unsharpness reduction and hence the higher temporal resolution. This also minimizes the need of the use of sedation. However, the potential issue associated with its use is the introduction of image noise because the number of profiles for image reconstruction would reduce and an increase of radiation dose might be needed to suppress this [31]. Although modern scanners provide a range of scan time selections from 0.28 to 0.5 s, a rotation time of 0.5 s should be used to achieve a balance between temporal and contrast resolutions and radiation dose [53].

Overscanning (Overranging) and Overbeaming

Overscanning (overranging) refers to scanning body part greater than the one planned for obtaining adequate data for image reconstruction [75]. Its effect is greater in pediatric patients than adults because of smaller body sizes in children [73-78]. Generally, the extent of overranging mainly depends on detector collimation and pitch as they affect the dose profile. When they increase, the dose profile will expand and cover a greater area leading to a higher overrange dose (dose deposited outside the imaged volume) [75,77,78]. However, the modern scanners (64 slices or above) provide adaptive pre-patient collimators to reduce the excessive radiation at the start and end of the scan range [75].

The use of newer systems also brings a positive effect on minimizing overbeaming. Overbeaming refers to radiation dose falling outside the active detector area in a gantry rotation due to the focal spot penumbra. When a scanner (such as 32 slices or above) provides a greater active detector area, the effect of overbeaming reduces. Its effect is inversely proportional to the number of detectors and collimation width. Its impact is not significant for the latest scanners [31,75-78].

Optimized Pediatric Protocols and Further Study Directions

In this literature review, the needs and challenges of optimizing pediatric protocols specific to age, body size and composition were discussed. Through exploring individual scan parameters and technical considerations, basic strategies for pediatric CT dose optimization were identified. However, cautions should be taken when applying these techniques into clinical centers because the specifications of various scanners would be different. Table 3 presents optimized pediatric protocols specific to age and body size for the 64-slice CT systems devised based on phantom and clinical studies included in this review with reference to the scanner user manuals **[8,15,31,53,62,66,75,79-81].** Their effectiveness still needs to be confirmed which can be considered as one of the further study directions. It is expected that this example would provide medical radiation technologists, radiologists and medical physicists more ideas on developing protocols specific to age and body size, and encourage them to review and optimize the pediatric protocols in their departments. Although there is limited discussion on protocols specific to gender due to insufficient information provided by the literature, this could be considered as another future study direction.

‘Insert Table 3 about here’

Summary

Since the last decade, manufacturers and clinical centers have started to develop pediatric scanning protocols specific to age, body size and composition for better dose optimization. However, the recent IAEA survey suggested many departments still rely on default protocols provided by manufacturers without further optimization. This literature review identified a range of scan parameters and technical considerations that should be optimized for pediatric patients with different ages and body sizes including tube voltage and current, IR, DRLs, bowtie filters, scout view, pitch, scan collimation and time, overscanning and overbeaming. Although the discussion is not comprehensive, basic strategies to optimize these factors were suggested. An example of optimized pediatric protocols specific to age and body size for the 64-slice CT scanners was devised. It is expected this example could provide more ideas to medical radiation technologists, radiologists and medical physicists on the way to optimize their pediatric protocols.

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Figure Captions

Figure 1. Flowchart illustrating the article identification and selection process.

Figure 2. Siemens Somatom Flash 128 computed tomography images of a paediatric anthropomorphic phantom using two different tube voltage and current settings. A & C, acceptable image quality was obtained when 100 kV and 120 mAs were selected. The volume computed tomography dose index (CTDIvol) was 11.6 mGy. B & D, images obtained with 80 kV and 100 mAs show excessive image noise and beam hardening artefact (arrows) but more than 50% reduction in dose was achieved (CTDIvol: 5.0 mGy).

Table 1
Tube-current Modulation Product Details of Different Manufacturers [31,47-51]

Manufacturer	Angular Modulation	Z-axis Modulation	Combined Modulation	Image Quality Reference Parameter
Siemens	CARE Dose	ZEC	CARE Dose 4D	The medical radiation technologist (MRT) is required to select the image quality reference effective mAs (QRM) value and adaptation strength. The tube current is adjusted automatically based on the patient size and body composition.
Philips	D-DOM	Z-DOM	-	A reference image concept is used by the system. The mAs is normalised after the scout view to maintain the image quality close to that of the reference image. The MRT can accept the recommended tube current setting or make any necessary change.
GE	Smart mA	Auto mA	Auto mA 3D	The MRT is required to select the reference noise index and mAs range. The tube current is adjusted automatically to acquire images with noise level matching the selected noise index regardless of the patient size.
Toshiba	-	SURE Exposure	SURE Exposure 3D	The MRT is required to select the reference noise index and mAs range. The tube current is adjusted automatically based on the scout view of the patient, X-ray intensities reaching the detector and reference parameter inputs.

Table 2
Latest Iterative Reconstruction Product Details of Different Manufacturers [53-57]

Manufacturer	Product Name	Product Detail
GE	VEO	VEO implements model-based iterative reconstruction technique based on focal spot and detector sizes to replace adaptive statistical iterative reconstruction (ASIR). Only a single iterative reconstruction strength is available.
Siemens	Sinogram affirmed iterative reconstruction (SAFIR)	SAFIR has succeeded the image reconstruction in space (IRIS). It is designed to work in both projection space and image domains. Five iterative reconstruction strengths are available.
Philips	iDose4	iDose4 is Philips' fourth generation IR product and also one of the components of their DoseRight package. It is designed to work in both projection space and image domains. Seven iterative reconstruction strengths are available.
Toshiba	Adaptive iterative dose reduction (AIDR)	The iterative processing of AIDR 3D is performed in both raw data and reconstruction domains while AIDR only focuses on the reconstruction domain.

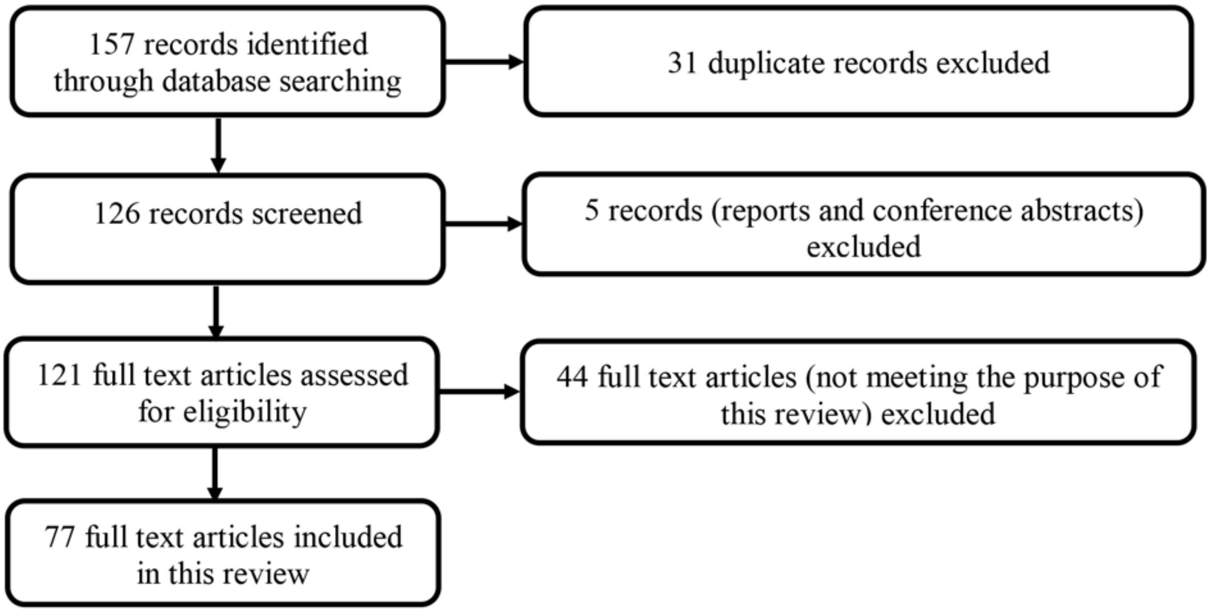
Table 3
Optimized Pediatric Protocols Specific to Age and Body Size for the 64-slice Computed Tomography Systems **[8,15,31,53,62,66, 75,79-81]**

Age [year]	Body Size		Acquisition Parameter										DRLs		Reconstruction Parameter	
	Weight [kg]	Effective Diameter [cm]	kV	mAs	Time [s]	Pitch	Beam Collimat-ion [mm]	FOV [mm]	TCM	Scan Length [mm]	Slice Thick-ness [mm]	Scan Mode	CTDIvol [mGy]	DLP [mGy-cm]	Slice Thick-ness [mm]	Algorithm Filter
BRAIN																
0-1	-	-	100	90	0.5	-	1x5.0	Small	Off	Restricted	3-5	Axial	10.0-15.0	100-150	SF 5	SF C30s
			100	100		0.98	64x0.6					Helical	10.0-15.0	100-150	B 3	B B80f
2-5	-	-	100	100	0.5	-	1x5.0	Small	Off	Restricted	3-5	Axial	10.0-15.0	100-180	SF 5	SF C30s
			100	120		0.98	64x0.6					Helical	10.0-15.0	100-180	B 3	B B80f
6-10	-	-	100	110	1	-	1x5.0	Small	Off	Restricted	3-5	Axial	12.0-17.0	120-200	SF 5	SF C30s
			100	150		0.98	64x0.6					Helical	12.0-17.0	120-200	B 3	B B80f
11-15	-	-	120	150	1	-	1x5.0	Medium	Off	Restricted	3-5	Axial	15.0-20.0	150-200	SF 5	SF C30s
			120	200		0.98	64x0.6					Helical	15.0-20.0	150-200	B 3	B B80f
CHEST																
0-1	0-9	<15	90(80[a])	40-45	0.5	0.9	32x1.25	Small	Off	Restricted	3	Helical	1.5-3	25-55	-	B30f/B80f
2-5	10-19	15-19	90(80[a])	40-50	0.5	0.9	32x1.25	Small	Off	Restricted	3	Helical	1.5-3	55-100	-	B30f/B80f
6-10	20-35	20-24	100(80[a])	45-70	0.5	1	32x1.25	Medium	80[b]	Restricted	3	Helical	2-3.5	100-150	-	B30f/B80f
11-15	>35	25-30	100(90[a])	70-85	0.5	1.2	32x1.25	Medium	100[b]	Restricted	3	Helical	2.5-4	>150	-	B30f/B80f
ABDOMEN																
0-1	0-9	<15	70	45-50	0.5	0.9	64x1.25	Small	Off	Restricted	2-5	Helical	1.5-3	25-55	-	B30f/B80f
2-5	10-19	15-19	80	50-60	0.5	0.9	64x1.25	Small	Off	Restricted	2-5	Helical	1.5-3	55-100	-	B30f/B80f
6-10	20-35	20-24	100(80[a])	50-85	0.5	1.3	64x1.25	Medium	125[b]	Restricted	2-5	Helical	2-3.5	100-200	-	B30f/B80f
11-15	>35	25-30	120(80[a])	85-95	0.5	1.3	64x1.25	Medium	125[b]	Restricted	2-5	Helical	2.5-4	>200	-	B30f/B80f

B, bone; CTDIvol, volume computed tomography dose index; DLP, dose-length product; DRLs, dose reference levels; FOV, field of view; kV, kilovoltage; mAs, milliampere seconds; SF, soft tissue; TCM, tube-current modulation.

[a] For contrast studies

[b] Reference mAs for TCM


157 records identified through database searching
31 duplicate records excluded
126 records screened
5 records (reports and conference abstracts) excluded
121 full text articles assessed for eligibility
44 full text articles (not meeting the purpose of this review) excluded
77 full text articles included in this review