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ALARA-CT

Advances in CT technology and application to pediatric imaging

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Abstract The use of imaging in both hospital and non-hospital settings has expanded to more than 70 million CT procedures in the United States per year, with nearly 10% of procedures performed on children. The availability of multiple-row detector CT (MDCT) systems has played a large part in the wider usage of CT. This rapid increase in CT utilization combined with an increasing concern with regard to radiation exposure and associated risk demands the need for optimization of MDCT protocols. This manuscript will briefly discuss how technology has changed in regard to MDCT protocols, helping to reduce radiation dose in CT, especially in pediatric imaging.

Keywords CT · MDCT · Radiation dose · Strategies to reduce radiation dose · Automatic tube current modulation (ATCM) · Radiation dose reports

Introduction

The number of CT procedures has been growing in the United States in both hospital and non-hospital settings during the last decade at an annual rate of nearly 10%, especially since the arrival of multiple-row detector CT (MDCT) scanners. The growth of CT procedures has occurred in all age groups, with pediatric CT accounting for nearly 10% of the total. Nearly 70 million CT procedures were performed in U.S. in 2007, with as many as 7 million in the pediatric populations. The radiation dose associated with CT has drawn considerable scrutiny in the last few years, including the publication of the National Council on Radiation Protection and Measurements (NCRP) Report 160 [1]. That report indicated that the radiation exposure to the United States population from medical sources alone accounts for nearly 50% of all the radiation exposure the U.S. population receives. Also, publications estimating increased cancer risks resulting from increased use of CT [2] as well as studies highlighting the variability in radiation doses among CT protocols [3] have drawn considerable scrutiny and thereby enhanced efforts to reduce dose and modify protocols. In looking at areas to modify, one can find that head, chest, abdomen and pelvis CTs account for nearly 80% of all CT procedures [1].

Optimization of MDCT requires thorough understanding of all technical aspects of CT, including relevant scan parameters [4], available radiation dose reduction techniques, and technological advances. In addition, one needs to tailor the scan and technical parameters according to child size, body regions and, most important, clinical questions. With all the efforts to reduce radiation dose in CT imaging one underlying principle should be that considerable attention is required to maintain image quality. Any efforts to reduce radiation dose that jeopardize image quality are made in vain.

The estimation of cancer risks from medical X-ray imaging including CT is often difficult due to the model utilized in estimating such risks. Most risk estimations are derived from the studies of survivors of atomic bombs in Hiroshima and Nagasaki [5], wherein biological risks are substantiated at radiation dose levels far higher (>250 mSv) than those observed in medical X-ray imaging (typical CT doses range from <1 mSv to 20 mSv) (Table 1) [6, 7]. Irrespective of controversies regarding radiation dose and associated cancer risks [8, 9], most parties agree

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Table 1 Representative effective dose (mSv) and ranges reported in literature for various adult and pediatric CT procedures [6, 7]

Examination	Effective dose (mSv)	Range in literature (mSv)
For adult CT procedures [6]		
CT head	2	0.9–4.0
CT chest	7	4.0–18.0
CT abdomen	8	3.5–25
CT pelvis	6	3.3–10
CT coronary angiogram	16	5.0–32
CT calcium scoring	3	1.0–12
CT virtual colonoscopy	10	4.0–13.2
For pediatric CT procedures [7]		
Pediatric head CT	3	1.9–3.7
Pediatric chest CT	~ 3	1.8–5.5
Pediatric abdomen CT	~ 5	5.0–15.0

that changes need to be made regarding variability in CT protocols, multiple CT scan series within a single CT exam, radiation doses per CT scan, repeat CT scans and overutilization.

A number of technological advances are being made to reduce CT dose, including improved tube current modulation techniques, improved detector efficiency, wide-detector CT scanners (256–320 row MDCT), dual-source CT scanners, dynamic collimation, iterative reconstruction and lower tube voltage techniques.

Automatic tube current modulation techniques (ATCM)

The basic principle behind the ATCM techniques is to vary the tube current based on the patient thickness, e.g., tube current can be lowered when the X-ray tube traverses the anterior-posterior (AP) direction compared to lateral direction. This results in reduced radiation dose compared to a single tube current for the entire gantry rotation [10]. ATCM techniques are available on most MDCT scanners from major vendors (Table 2). To apply these techniques, users specify a desired image quality in terms of image noise (noise index—auto mA from GE Healthcare; standard deviation—sure exposure from Toshiba Medical Systems) or in terms of tube current time product value for a reference adult or pediatric patient (reference mAs—CARE dose 4D from Siemens Medical Solutions; mAs/slice—Z-DOM from Philips Healthcare) (Table 3).

Studies have documented substantial CT radiation dose reduction in head, neck, chest and abdomen with use of automatic exposure control in adult as well as pediatric patients [11]. Singh et al. [12] have reported 50–75% dose reduction with an x-y-z modulation technique stratified for different clinical indications in chest and abdomen CT in children. ATCM techniques work best for adult scans in most 16-slice and 16+ MDCT scanners. For pediatric CT scans, dose modulation techniques require special attention such as positioning of patients in the center of the gantry (iso-center), making sure the user-defined parameters such as reference mAs and noise index are well understood and are kept in the optimal settings. In-correct setting of user-defined parameter can result in excessive radiation dose to the child. Special attention is needed while utilizing ATCM techniques in pediatric CT such as patient centering in the CT gantry, scanning multiple anatomical regions such as neck, chest and abdomen in a single CT series and patients with prostheses.

It is equally critical to ensure that the ATCM techniques work optimally in the user-selected scanner chosen for performing pediatric CT scans. In addition, radiation dose can be effectively reduced by manually lowering the tube current based on patient weight.

Wide-detector CT scanners

The rapid race in CT technology to acquire larger scan volumes with high-resolution capability often dubbed “slice wars” [13] has led to the developed of wide-detector CT scanners. A 320-detector row MDCT scanner has a scan volume of 160 mm defined at scanner iso-center, enabling large-volume scanning in minimal time [14]. These scanners are particularly useful in the pediatric population because a large anatomical area can be covered in less time and larger anatomical regions can be scanned with minimal overlap. When utilizing a wide-detector MDCT scanner, certain pediatric CT protocols can cover the entire scan region (e.g., chest CT in an infant) in a single scan. This means there is only minimal scan overlap and less need for sedation. Wide-detector MDCT scanners can reduce overall exam time and minimize patient motion, which is important in pediatric imaging.

Table 2 Automatic tube current modulation (ATCM) techniques currently available from different vendors

AEC technique	GE Healthcare	Siemens	Philips	Toshiba
x-y axis/angular	Smart mA	CARE Dose	D-DOM	–
z axis/longitudinal	Auto mA	ZEC	Z-DOM	SureExposure
x-y-z/combined	Auto mA 3D	CARE Dose 4D	–	SureExposure3D

Table 3 Different methods chosen by CT manufacturers to optimize the tube current by setting the exposure levels

Technique (Manufacturer)	Specified parameter	Implications
Auto mA 3D (GE)	Noise Index	Implies user-desired noise in entire image
	Min and max mA	Range of allowed mA to achieve desired noise index. Selection of this optional function adds x-y modulation to z-modulation (Auto mA)
	Smart mA	
CARE Dose 4D (Siemens)	Reference mAs	Implies need for image quality equal to that obtained with use of specified reference mAs in a standard adult (70–80 kg) or child (20 kg)
Z-DOM (Philips)	Baseline mAs	"*Baseline mAs*" is used as a reference to obtain constant image noise along the z axis
SureExposure 3D (Toshiba)	Standard Deviation	Implies need for obtaining images at specified image noise (standard deviation)

Dual-source CT scanners

Even though the primary goal for dual-source CT scanners is to achieve higher temporal resolution, which is a key aspect of cardiac imaging, DSCT offers certain advantages for pediatric CT. The second-generation DSCT scanner (FLASH; Siemens Healthcare, Erlangen, Germany), which has a rapid table speed (43 mm/gantry rotation) [15], can accommodate high-pitch scanning, providing a great opportunity for pediatric CT imaging. Protocols with a rapid table speed and thus high pitch values can cover a scan region of up to 120 mm in less than a second. Pediatric CT protocols with DSCT can achieve low doses in minimal amount of scan time. Shorter scan times are important in children because they minimize patient motion, reduce the need for sedation and create opportunities to reduce the amount of contrast agent used for certain CT protocols.

Over-ranging or over-scanning

In the helical mode, the reconstruction algorithms require additional data on both sides of the planned scan volume. These data are acquired by an additional half to full rotation on both sides and outside the planned scan volumes. This leads to radiation exposure of tissue outside the regions of interest, increasing the patient dose. Over-ranging length increases with increased table movement and increased pitch so it is an important factor in pediatric populations [16]. Recent technological advances such as dynamic or adaptive collimation have the potential to eliminate this effect. Dynamic or adaptive collimators automatically move in and out at the beginning and end of the scan length, thereby blocking the extraneous radiation from reaching the patients [17].

Iterative reconstruction

CT image reconstruction has been achieved mainly by the use of conventionally filtered back-projection. However, the iterative reconstruction method is now becoming the mode of choice for image reconstruction. Iterative reconstruction methods can acquire dose at a much lower tube current, process to lower image noise by performing multiple iterations and yet meet image quality standards [18]. The IR method makes several passes over the raw data (obtained using low-dose techniques) to produce more accurate model of images and reduce the amount of noise. IR techniques have shown to reduce radiation as much as 40–80% while maintaining diagnostic quality. The caveat of using IR techniques is that it requires increasing computer processing speed.

Table 4 Normalized values of effective dose per DLP over various body regions and standard phantom-based ages [7, 19]

Region of body	Effective dose per DLP (mSv mGy^{-1} cm^{-1})				
	Children[a]				Adults[b]
	0 years	1 year	5 years	10 years	
Head	0.011	0.0067	0.0040	0.0032	0.0021
Neck	0.017	0.012	0.011	0.0079	0.0059
Chest	0.039	0.026	0.018	0.013	0.014
Abdomen/pelvis	0.049	0.030	0.020	0.015	0.015

[a] All data normalized to $CTDI_w$ measured in the 16-cm diameter CT dosimetry phantom

[b] Data for the head and neck regions normalized to $CTDI_w$ in the 16-cm diameter CT dosimetry phantom; data for other regions normalized to $CTDI_w$ in the 32-cm diameter CT dosimetry phantom

Multiple CT scans within a CT exam

Multiple scan series within a CT exam are of great concern because each exam yields a radiation dose, especially in pediatric CT imaging. Advances in dual-energy techniques have the potential to lower radiation dose during multiple scan series by reconstructing virtual non-enhancing images at image quality similar to that of true non-enhanced images, therefore avoiding additional scans. Dual-energy techniques have the potential to reduce by nearly one-third the dose from a multiple-series CT exam. Even though dual-energy CT acquisition yields about 30% more than the single-energy CT acquisition, the possibility of reconstructing non-enhanced images can eliminate any additional scans, which is beneficial. These methods are still in evaluation stages and once refined can be considered as dose-reducing strategies.

Radiation dose reports

Most MDCT scanners have the capability to display dose information for each exam. The basic radiation dose descriptors in CT are the CT dose index volume ($CTDI_{vol}$) and the dose length product (DLP). By using these descriptors for each CT scan, one can estimate effective dose based on published conversion factors for standard CT scans such as head, neck, abdomen and pelvic CT scans (Table 4) [7, 19]. Special care has to be taken while assessing effective dose estimations for pediatrics. Since the dose descriptors displayed are based on a standard adult phantom size (a 16-cm diameter head phantom and a 32-cm diameter abdomen phantom), they require appropriate correction for pediatric sizes are needed prior to using conversion factors to estimate effective doses (Table 4) [7]. The radiation dose displays can be saved as an image file. In the future, DICOM structured dose reports will enable clinics to save and record data in patient charts. Structured dose reports will also provide a way to audit CT doses periodically for internal quality-control purposes.

CT dose check (XR 25)

With recent concerns regarding radiation doses in CT and potential skin injuries, CT manufacturers are introducing a feature called CT dose check [20]. The XR 25 dose-check standard will provide an alert to CT machine operators when the recommended radiation levels are exceeded. $CTDI_{vol}$ and DLP values can be set by the user for each scan series so that whenever set values are exceeded, the program will alert the operator. The main purpose is to avoid accidental overdose caused by incorrect scan techniques [21]. If the operator still wishes to use a technique with a dose that exceeds a preset threshold level, he may do so but is required by the program to document the change. The feature will allow each site to perform a periodic audit of the practice as part of quality control. The American Association of Physicists in Medicine (AAPM) has released recommendations regarding notification and alert values for CT scanners [22] for select CT protocols.

In addition to the topics discussed, there are number of other initiatives focused on reducing dose, especially in pediatric CT. Among them the Image Gently campaign [23] has achieved greater success and wider visibility. The Image Gently campaign is a social marketing campaign designed to raise awareness about pediatric radiation and imaging safety. The campaign has achieved success and wide visibility among both pediatric and adult radiology practices. The Image Wisely campaign is a similar effort addressing radiation concerns in adult imaging.

Conclusion

Currently, CT imaging appears to be in the crosshairs of many who have concerns that CT is a high-dose procedure, sometimes performed inappropriately. As long as the CT examination is justified, the benefits far outweigh the associated radiation risks. Technological advances, along with increased scrutiny and review of CT protocols, with optimization as the ultimate goal, are paving the way for better and safer CT imaging. Many of the newer technological advances are specifically aimed at decreasing radiation doses. It is imperative that these methods be rapidly disseminated to users and that the methods be clearly understood and optimally utilized.

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