Cost-effective pediatric head and body phantoms for computed tomography dosimetry and its evaluation using pencil ion chamber and CT dose profiler

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ABSTRACT

In the present work, a pediatric head and body phantom was fabricated using polymethyl methacrylate (PMMA) at a low cost when compared to commercially available phantoms for the purpose of computed tomography (CT) dosimetry. The dimensions of head and body phantoms were 10 cm diameter, 15 cm length and 16 cm diameter, 15 cm length, respectively. The dose from a 128-slice CT machine received by the head and body phantom at the center and periphery were measured using a 100 mm pencil ion chamber and 150 mm CT dose profiler (CTDP). Using these values, the weighted computed tomography dose index ($CTDI_w$) and in turn the volumetric CTDI ($CTDI_v$) were calculated for various combinations of tube voltage and current-time product. A similar study was carried out using standard calibrated phantom and the results have been compared with the fabricated ones to ascertain that the performance of the latter is equivalent to that of the former. Finally, $CTDI_v$ measured using fabricated and standard phantoms were compared with respective values displayed on the console. The difference between the values was well within the limits specified by Atomic Energy Regulatory Board (AERB), India. These results indicate that the cost-effective pediatric phantom can be employed for CT dosimetry.

Key words: CTDI phantom, CT dose profiler, Pediatric CT, pencil ion chamber, pediatric radiation dose

Introduction

The utilization of computed tomography (CT) in diagnosing pediatric patients has increased considerably due to increase in the number of medical applications pertaining to pediatric CT.[1-8] Despite the obvious benefit that pediatric patients and their families derive from the diagnostic information that CT provides, the radiation dose used in CT for pediatric patients has recently come under scrutiny,[9] and the radiobiological consequences[10-12] appear to be nontrivial. It is well-known that CT delivers radiation dose that is typically at the high end of the diagnostic dose range, and although CT examinations represent only a few percent of the total number of X-ray examinations, they are already the largest contributor to the collective effective dose from medical exposures. Though the recent technical developments in CT, that is, the advent of multislice CT (MSCT) which has extended the range of its applications in diagnosing a pediatric patient, risk factors leading to radiobiological effects is also involved if nonoptimized technical scan parameters are used.[9] In pediatric patients, all the organs are located closer to the scan field and are susceptible to radiation when compared with adults. Hence,

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irrespective of the age, based on the size of pediatric patients the scan parameter needs to be optimized to minimize the radiation risk which can be realized by quality assurance (QA) of machines and selection of optimized scan parameters by technicians. In this regard, the dose distribution in pediatric patients for the selected scan parameters can be studied and optimized using pediatric CT dose index (CTDI) phantom. Number of factors prevents the hospitals from performing the QA and optimization studies. One such factor is the cost of pediatric CTDI phantom. As the commercially available pediatric CTDI phantom is expensive, most of the hospitals in the developing countries do not show interest in such studies. Considering this issue, the aim of the current study is to fabricate a low cost pediatric CTDI head and body phantom and use it to evaluate CTDI to optimize scan parameters and eventually carry forward the study for setting national dose reference levels (DRLs).

Materials and Methods

The study was carried out using Siemens 128-slice Somatom Definition Edge CT scanner installed in PSG Hospitals, Coimbatore, India. The routine scan parameters for average pediatric patients used in this particular hospital was selected for CT procedures (head, chest, and abdomen) are summarized in the Table 1, and the scan parameters selected for CT dosimetry studies are given in Table 2.

Detector and reader system

Usually CTDI is measured by integrating the dose from a single CT using a 100 mm long pencil ionization chamber and can also be obtained by making many point dose measurements along the z-axis to determine the dose profile D(z) and then obtain the integrated dose.[13] In this study, in-site CT dose measurements were carried out using a standard calibrated 100 mm pencil ionization chamber (DCT10 RS, S/N 1636) with Solidose electrometer 400 (S/N 4253) and CT dose profiler (RTI Electronics make) [Figure 1].

Table 1: Routine scan parameters for pediatric patients

Procedure	*Tube voltage (kV)*	*Tube current-time product (mAs)**	*Pitch*	*Slice thickness (mm)*	*Scan length (mm)*	*Scan time (s)*
Head	100	100	0.9	2.0	76	7.0
Chest	80	40	1.1	5.0	90	2.49
Abdomen	100	55	1.4	5.0	110	2.51

*Tube current-time product will vary depending on the patient anatomy

Table 2: Scan parameters for computed tomography (CT) dosimetry

Procedure	*Tube voltage (kV)*	*Tube current-time product (mAs)*	*Pitch*	*Slice thickness (mm)*
Head	70	100	0.9	5.0
	80			
	100			
	120			
Body	70	100	1.4	5.0
	80			
	100			
	120			

The CT dose profiler (CTDP) has one solid-state detector (marked SENSOR in Figure 1) placed 3 cm from the end of the probe. The CTDP probe has a greater length of 15 cm to suite 15 cm length of CTDI phantoms. The detector in the profiler is very thin (250 μm) in comparison to the beam width, and is therefore well-suited for point-by-point scanning of the beam. The detector is used to collect the dose profile and it can also be used as a trigger. As radiation hits the detector in either direction, the detector registers the dose value at that point and sends the information to the software. The electrometer can collect 2,000 such dose values per second. When the radiation goes below the trigger level, the software is designed to present all the collected data points in the form of a graph. CTDP is used as a general dose detector which can handle very small field sizes. Since the detector is rotational symmetric, the CTDP can measure dose when the tube is rotating.[13] The advantage of the CTDP over pencil chamber is that it can give integrated dose beyond 10 cm length of the CTDI phantom as well as for maximum beam width of the scanners.[14] Also CTDP can provide the actual dose profile curve after exposure, but the ion chamber cannot. The CTDP replaces the conventional thermoluminescent dosimeter (TLD) and optically stimulated luminescence (OSL) methods or film for dose profile measurements. CTDP is connected to Piranha 557 [Figure 2] via wire and Piranha is connected to CTDP analyzer software via Bluetooth.

Dose measurements

The measurement is conducted during a helical (spiral) scan so the table must move during the measurement to allow the probe to scan the entire beam width. Traditionally, CTDI measurements with an ion chamber must be made with axial scans.

The CT dose indices were measured based on the five-point method proposed by European guidelines[15] by using pencil ion chamber and CTDP for standard and fabricated phantoms.

The CTDI defined in the following equation:

$$\mathrm{CTDI} = [1/nT] \int D(z)\,dz \quad \text{(integration limits from } -50 \text{ mm to } +50 \text{ mm)} \qquad (1)$$

was measured directly by the pencil ion chamber-electrometer system and displayed on the dosimeter unit.

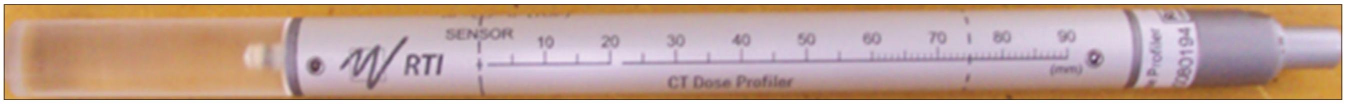

Figure 1: CT dose profiler. CT = Computed tomography

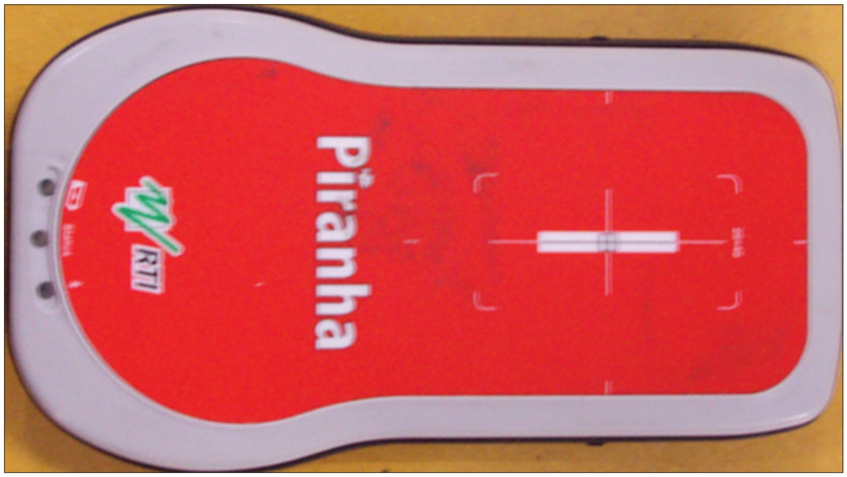

Figure 2: Piranha 557 reader

CTDI is actually defined for a single complete rotation of CT scanner. In the equation above, n is the number of data channels in the multislice CT, T is the slice thickness corresponding to one channel and the integration is carried out over the length of the pencil chamber (100 mm); in our particular case nT = 5 mm (the slice thickness selected). As far as the CTDP is concerned, the doses received by the standard and fabricated phantom at the center ($CTDI_{100,c}$) and periphery ($CTDI_{100,p}$) were measured using CTDP connected to a Piranha 557 dosimeter for the machine operating parameters. The dedicated CTDP software viz., CT Dose Profile Analyzer displays both the graph pertaining to dose/s along the z-axis and the corresponding $CTDI_{100,c}$ and $CTDI_{100,p}$. Using these values, weighted CTDI ($CTDI_w$) and volumetric CTDI (CTDIv) were calculated. The $CTDI_{100,c}$ and $CTDI_{100,p}$ measurements were repeated five times using developed phantoms with both detectors and the mean values with standard deviation (SD) are reported in tables.

Results and Discussion

Fabrication of pediatric CTDI phantom

CT pediatric head and body phantom was fabricated using polymethyl methacrylate (PMMA) of density 1.19 g/cm^3.[16] Two PMMA cylinders of 15 cm length and 10 and 16 cm diameter each were purchased. The cylinder of diameter 10 cm was used to make the head phantom and the one with diameter 16 cm was used to construct body phantom [Figure 3]. In both the phantoms, five holes were machined in our workshop, one exactly at the center and four in the periphery. The peripheral holes were spaced 1 cm from edge and 90° apart from each other. The inner diameter of all the holes was 1.31 cm. All the dimensions have been chosen in compliance with Food and Drug Administration (FDA) norms.[17] Ten PMMA rods of diameter 1.31 cm and 15 cm length were also machined. The holes other than the one that contained CTDP were plugged using these rods when the study was carried out. The cost per fabricated phantom was just 10% of the standard one.

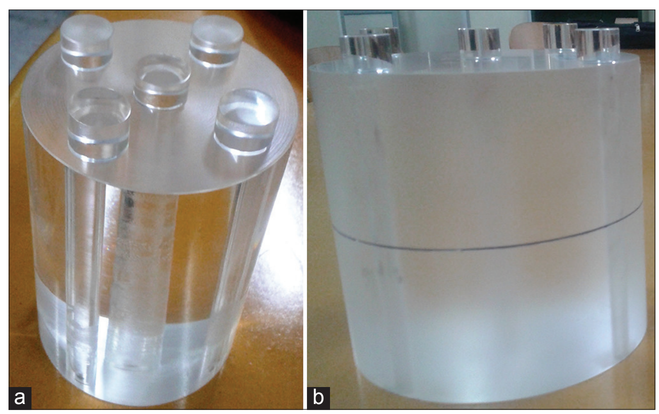

Figure 3: Pediatric CTDI: (a) Head phantom and (b) body phantom. CTDI = Computed tomography dose index

The main objective of the work was to ensure that the characteristics of the fabricated phantom were equivalent to that of the standard imported one. In this line, initially the doses received at the center and periphery of the fabricated and standard phantom was measured using the dosimeters mentioned above. The center and peripheral dose received by the ion chamber were converted into $CTDI_c$ and $CTDI_P$ values and displayed in the Solidose electrometer; whereas a graphical output along with $CTDI_{100}$ values was obtained while using CTDP. The graphical output is given in Figures 4 and 5.

Figures 4 and 5 show that the actual dose profile generated at the center and periphery point 'A' after exposure to the X-rays produced for a potential of 100 kV, having a current time product of 100 mAs and slice thickness of 5 mm. The observed dose profile depends on a number of factors such as alignment of the beam, unsymmetrical collimators, heel effect of the tube, the design of the table that supports the CT phantom, etc.[13] In the helical scan mode, the rotational X-rays hit the CTDP located at either the center or peripheral hole of the phantom. The X-rays during their travel through the phantom are attenuated due to scattering process, and as they reach the sensor in the CTDP, it starts collecting the data as seen in the above profiles.[13]

This graph has not been filtered, and therefore shows a number of reoccurring dips. A dip occurs each time the tube goes beneath the table and the distance between two dips is the distance the table moves during one rotation. The dips are more pronounced in the profile corresponding to peripheral dose when compared to the center due to continuous change in the distance between X-ray tube and the sensor. While operating the CT in helical scan mode, the X-ray tube does not rotate with an exact number of turns. The CT Dose Profile Analyser software integrates the measured dose rate values between the dotted lines separated by 100 mm to give the respective $CTDI_{100}$ which can be used for further calculations.

Thus, using the $CTDI_c$ and $CTDI_p$ values, weighted and volumetric CTDIs were calculated and the mean values along with SD is given in Tables 3 and 4.

From Tables 3 and 4, it was observed that while measuring the dose at the axial and periphery using both CTDP and ion chamber, for a combination of tube current-time product and voltage, the center of the head and body phantom received less dose when compared to periphery, which is attributed to a constant focus-axial detector and a varying focus-peripheral detector distance during rotations. Also, scatter is constant from other portions of the phantom at the center, while it varies at the periphery.

The second observation is that the dose received by the head phantom is more when compared to the body phantom. This is because; the attenuation is less in the head phantom due to a smaller dimension when compared to body phantom.

Further, an increase in tube voltage leads to an increase in the relative dose level at the respective positions. This is due to increase in X-ray intensity with respect to increase in tube parameters.

Comparing the CTDI values obtained using different types of detectors viz., CTDP and ion chamber, it was found that the values were more while using latter when compared to the former. Solid state detector values were lesser than the ion chamber values by 10% and this decrease may be attributed to energy response of the solid state detector.

Subsequently to assess the performance of the fabricated phantom, a comparison between $CTDI_v$ obtained using the fabricated and standard phantom and also with the ones displayed in the console has been carried out. The measured $CTDI_v$ with respect to the console values and the percentage difference between measured and the console values are presented in Tables 5 and 6. The values in Tables 5 and 6 are also represented graphically in Figures 6 (a) and (b).

It is apparent from Tables 5 and 6 that the difference between the measured $CTDI_v$ corresponding to fabricated

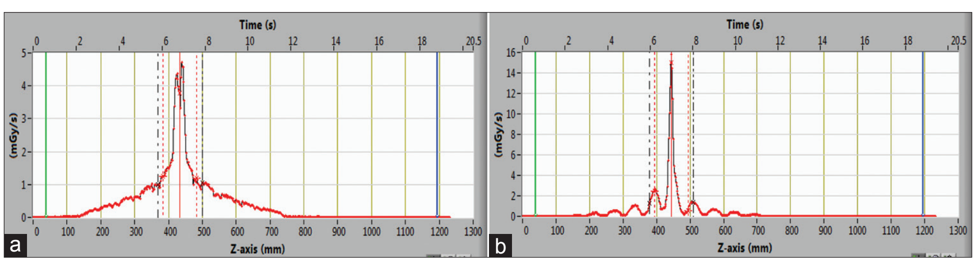

Figure 4: Dose profiles in the standard phantom: (a) Centre (b) periphery

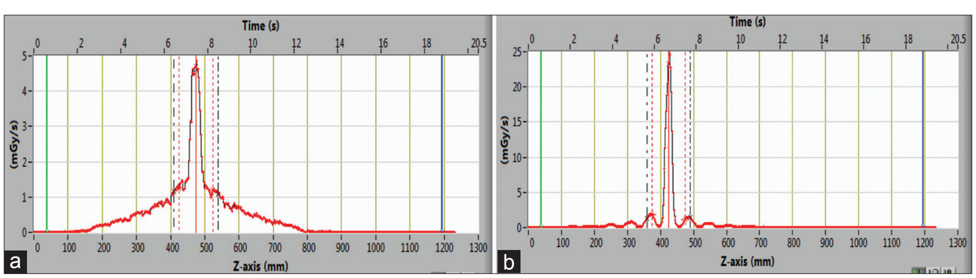

Figure 5: Dose profiles in the fabricated phantom: (a) Centre (b) periphery

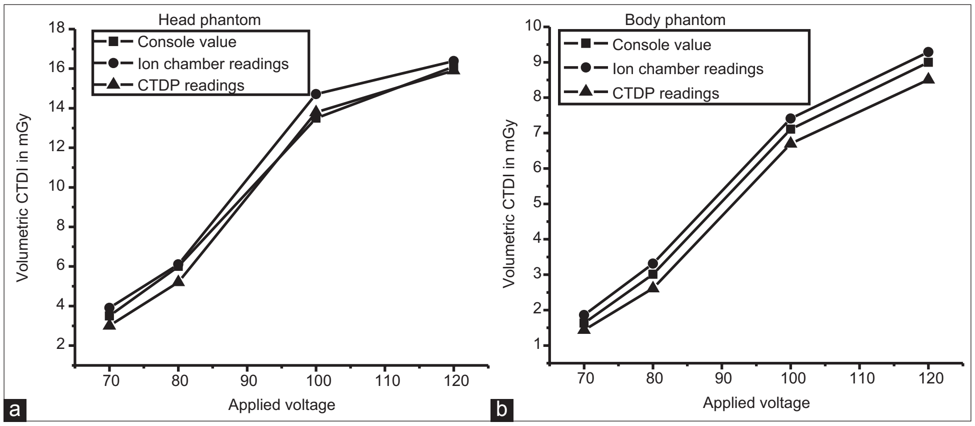

Figure 6: Variations in $CTDI_v$ with tube potential (a) head (b) body. $CTDI_v$ = Volumetric computed tomography dose index, CTDP = CT dose profiler

Table 3: Mean $CTDI_c$, $CTDI_p$, $CTDI_w$, and $CTDI_v$ along with standard deviation using CTDP for fabricated phantoms

Voltage (kV)	Tube current-time product (mAs)	Head (mGy±SD)				Body (mGy±SD)			
		$CTDI_c$	$CTDI_p$	$CTDI_w$	$CTDI_v$	$CTDI_c$	$CTDI_p$	$CTDI_w$	$CTDI_v$
70	100	2.21±0.04	3.01±0.07	2.74±0.03	3.04±0.03	1.97±0.07	2.11±0.03	2.06±0.01	1.47±0.03
80		4.16±0.06	5.07±0.04	4.76±0.06	5.29±0.05	3.06±0.02	4.11±0.04	3.76±0.02	2.68±0.06
100		11.14±0.03	12.78±0.06	12.43±0.02	13.81±0.03	8.61±0.01	9.92±0.03	9.48±0.06	6.77±0.01
120		13.86±0.08	14.62±0.01	14.36±0.01	15.96±0.03	10.88±0.04	12.61±0.06	12.03±0.08	8.59±0.01

$CTDI_c$=Center computed tomography dose index, $CTDI_p$=Periphery CTDI, $CTDI_w$=Weighted CTDI, $CTDI_v$=Volumetric CTDI

Table 4: Mean $CTDI_c$, $CTDI_p$, $CTDI_w$, and $CTDI_v$ along with standard deviation using pencil ion chamber for fabricated phantoms

Voltage (kV)	Tube current-time product (mAs)	Head (mGy±SD)				Body (mGy±SD)			
		$CTDI_c$	$CTDI_p$	$CTDI_w$	$CTDI_v$	$CTDI_c$	$CTDI_p$	$CTDI_w$	$CTDI_v$
70	100	3.04±0.03	3.86±0.02	3.58±0.02	3.98±0.03	2.14±0.04	2.92±0.02	2.66±0.02	1.92±0.04
80		4.91±0.04	5.98±0.01	5.62±0.05	6.24±0.04	4.11±0.03	5.06±0.04	4.74±0.03	3.38±0.02
100		12.89±0.04	13.62±0.04	13.37±0.03	14.86±0.05	9.84±0.02	10.63±0.02	10.36±0.04	7.40±0.03
120		14.88±0.06	16.11±0.02	14.84±0.03	16.49±0.04	12.46±0.02	13.48±0.03	13.14±0.06	9.38±0.03

$CTDI_c$=Center computed tomography dose index, $CTDI_p$=Periphery CTDI, $CTDI_w$=Weighted CTDI, $CTDI_v$=Volumetric CTDI

Table 5: Percentage difference between displayed and calculated CTDIv values for CTDP

Voltage (kV)	Tube current-time product (mAs)	$CTDI_v$ for head region (mGy)					$CTDI_v$ for body region (mGy)				
		Standard phantom (A)	Fabricate phantom (B)	Console value (C)	% difference (A and C)	% difference (B and C)	Standard phantom (A)	Fabricated phantom (B)	Console value (C)	% difference (A and C)	% difference (B and C)
70	100	3.01	3.04	3.61	−16.62	−15.78	1.44	1.47	1.63	−11.65	−9.81
80		5.21	5.29	5.81	−10.32	−8.95	2.61	2.68	3.01	−13.28	−10.96
100		13.79	13.81	14.17	−2.68	−2.54	6.70	6.77	7.11	−5.76	−4.78
120		15.91	15.96	16.14	−1.42	−1.11	8.51	8.59	9.00	−5.44	−4.55

CTDP=Computed tomography dose profiler, $CTDI_v$=Volumetric CT dose index

Table 6: Percentage difference between displayed and calculated CTDIv values for pencil ion chamber

Voltage (kV)	Tube current-time product (mAs)	$CTDI_v$ for head region (mGy)					$CTDI_v$ for body region (mGy)				
		Standard phantom (A)	Fabricate phantom (B)	Console value (C)	% difference (A and C)	% difference (B and C)	Standard phantom (A)	Fabricated phantom (B)	Console value (C)	% difference (A and C)	% difference (B and C)
70	100	3.91	3.98	3.61	8.31	10.24	1.86	1.9	1.63	14.11	16.56
80		6.11	6.24	5.81	5.16	7.40	3.31	3.38	3.01	9.96	12.29
100		14.71	14.86	14.17	3.81	4.86	7.41	7.40	7.11	4.21	4.07
120		16.38	16.49	16.14	1.48	2.16	9.29	9.38	9.00	3.22	4.22

$CTDI_v$=Volumetric computed tomography dose index and standard phantom is very small. This is an indication that the quality of the fabricated phantom is on par with the standard one. Also, from Tables 5 and 6 it is found that the percentage difference between the fabricated and console $CTDI_v$ and standard and console $CTDI_v$ are well within the limits recommended by Atomic Energy Regulatory Board (AERB) which is based on International Commission on Radiological Protection (ICRP) standards.[18-20] The large differences for lower kVs may be due to the dose evaluation/calibration method employed by the manufacturer.

Hence, this study confirms that the quality of the pediatric phantom that was fabricated at a lower cost for the purpose of CT dosimetry is on par with the standard one.

Conclusion

Relatively inexpensive pediatric CTDI head and body phantom suiting average Indian infants was developed for measuring CT dose indices to reduce radiation risk to the infants. The radiation output from the Siemens 128-slice Somatom Definition Edge CT scanner was evaluated using the standard pediatric phantom before ascertaining the performance of the developed phantom. After ensuring the proper performance of the CT scanner, the dose received by the developed phantom was measured at the center and periphery using the calibrated pencil ion chamber and CTDP. Using these values, $CTDI_w$ and $CTDI_v$ were then calculated and compared with the console values. The difference between the values was well within the limits specified by AERB, India. These results indicate that the cost effective pediatric phantom can be employed for CT dosimetry applications.

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Conflicts of interest

There is no conflicts of interest.

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