Pediatric organ dose measurements in axial and helical multislice CT

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An anthropomorphic pediatric phantom (5-yr-old equivalent) was used to determine organ doses at specific surface and internal locations resulting from computed tomography (CT) scans. This phantom contains four different tissue-equivalent materials: Soft tissue, bone, brain, and lung. It was imaged on a 64-channel CT scanner with three head protocols (one contiguous axial scan and two helical scans [pitch=0.516 and 0.984]) and four chest protocols (one contiguous axial scan and three helical scans [pitch=0.516, 0.984, and 1.375]). Effective mAs $[(\text{tube current} \times \text{rotation time})/\text{pitch}]$ was kept nearly constant at 200 effective mAs for head and 290 effective mAs for chest protocols. Dose measurements were acquired using thermoluminescent dosimeter powder in capsules placed at locations internal to the phantom and on the phantom surface. The organs of interest were the brain, both eyes, thyroid, sternum, both breasts, and both lungs. The organ dose measurements from helical scans were lower than for contiguous axial scans by 0% to 25% even after adjusting for equivalent effective mAs. There was no significant difference ($p > 0.05$) in organ dose values between the 0.516 and 0.984 pitch values for both head and chest scans. The chest organ dose measurements obtained at a pitch of 1.375 were significantly higher than the dose values obtained at the other helical pitches used for chest scans ($p < 0.05$). This difference was attributed to the automatic selection of the large focal spot due to a higher tube current value. These findings suggest that there may be a previously unsuspected radiation dose benefit associated with the use of helical scan mode during computed tomography scanning. © 2009 American Association of Physicists in Medicine. [DOI: [10.1118/1.3101817](https://doi.org/10.1118/1.3101817)]

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I. INTRODUCTION

A small but increasing proportion of all computed tomography (CT) examinations done annually are performed in pediatric patients. In 1989, about 4% of all CT scans were performed on children, in 1993 about 6%, and in 1999 about 11%.¹ In 2000, approximately 2.7 million CT examinations were performed on pediatric patients under the age of 15 yr, and about one-third of children who undergo CT will have three or more examinations.² Multiple CT examinations expose patients to increased radiation dose, which is a concern to the medical community.³

Pediatric patients are more radiosensitive than adults. They experience greater tissue damage than adults with the same absolute level of radiation dose, and they have a longer postirradiation life expectancy, which equates to an increased lifetime risk of radiation-induced cancer per unit dose.^{4,5}

Another factor to consider when determining radiation dose for pediatric patients is the patients' size. Radiation beams have less tissue to pass through in children than in adults, so using adult scan parameters for children results in less beam attenuation and exposure of tissue to higher beam intensities. Thus, the CT scan parameters chosen should reflect child's size, the reason for the scan, and the area of the body being scanned.⁶

Methods to accomplish this include decreasing mAs (tube current $\times$ rotation time), increasing pitch (in helical scanning), and reducing kilovolts peak (kVp).⁷ Tube current modulation can also be used to reduce the radiation dose to pediatric patients. Minimizing the need for multiphase pediatric studies as well as multiple CT examinations will help reduce accumulated dose in pediatric patients.^{8,9} CT scans

should be avoided unless it is clearly indicated that the scans will aide in the diagnosis of a medical problem.

There is little information available regarding measured pediatric organ dose from 64-channel CT scanners. Pediatric organ dose has been examined using the Monte Carlo method and voxelized phantoms.^{10,11} However, because Monte Carlo only produces results from simulated scans, this approach should be validated with physical dose measurements. Also, there is little information available regarding measured organ doses for axial and helical scan modes in pediatric patients.

The purpose of this study was to investigate the dose to specific organs within a pediatric anthropomorphic phantom when both axial and helical scan modes were used on a 64-channel CT scanner in which the effective mAs (tube current $\times$ rotation time/pitch) was approximately the same across protocols. These results are expected to be useful for validating computer models that predict point or organ dose values and for improving the general understanding of organ dose ranges in small children undergoing CT examinations.

II. MATERIALS AND METHODS

II.A. CT scanner

A 64-channel MDCT scanner (VCT, GE Healthcare, Milwaukee, WI) was used for this study. The GE VCT has four operating peak voltages (80, 100, 120, and 140 kVp) and can adjust mA in multiples of 5. In addition, the scanner has fixed helical pitch values that include 0.516, 0.984, and 1.375 and can also perform contiguous axial scans. The scan field of view (SFOV) is selected for the patient size and body region to be examined and also selects one of the three bowtie filters; for all measurements collected during the course of this study, the small bowtie filter was used (both pediatric head and pediatric body SFOVs).

II.B. Anthropomorphic phantom

An ATOM family anthropomorphic phantom (CIRS, Norfolk, Virginia) representative of a 5-yr-old child was used to determine organ dose values. The pediatric anthropomorphic phantom consists of 26 numbered transverse sections; each section is 2.54 cm thick and has a predrilled 3×3 cm² grid pattern into which thermoluminescent dosimeters (TLDs) can be inserted. This phantom contains four different tissue-equivalent materials: Soft tissue, bone, brain, and lung. The sections of the phantom were secured together using plastic straps with Velcro fasteners. The TLDs were placed in the appropriate section of the phantom (Table I), and phantom plugs were inserted to prevent movement of the TLD capsules and air pockets in the phantom.

II.C. Organs and regions scanned

The organs sampled for dose evaluation were brain, left eye, right eye, thyroid, sternum, left breast, right breast, left lung, and right lung. These organs were selected because they are included in the common scan regions and because of our radiological and biological interests in dose to these or-

TABLE I. Indicates the depth of each organ TLD as well as the phantom section in which the TLD was positioned. The phantom section numbers start at top of the head of the phantom and increase toward the feet.

Organ	Depth (cm)	Phantom section number
Brain	9	3
Eyes	Surface	4
Thyroid	4	8
Left and right lung	6	12
Sternum	1	13
Left and right breast	1	13

gans for pediatric patients. The eye lens, the developing brain, and the thyroid are all radiosensitive organs in the head area in children. The lungs and the areas where breast tissue will develop are potentially radiosensitive tissues in the chest area in female children. Dose to bone at the sternum was also evaluated. Because the thyroid was included in both the head scan and the chest scan, the dose values to the thyroid from the head scan were differentiated from the dose values to the thyroid from the chest scan. The protocol parameters used for these scans are shown in Table II. The pitch values of 0.984 and 1.375 are most frequently used in our clinic on this scanner. The pitch value of 0.516 allowed us to examine the effects of using a very low pitch value. A pitch greater than 1 was not tested for the helical head protocol because head scans on this scanner cannot be obtained using a pitch greater than 1.

The axial and helical scan protocols were designed to have approximately the same effective mAs. The effective mAs settings used for the pediatric head protocol are close to those that would be used for a clinical scan. The effective mAs settings used in this study for the pediatric chest protocol are much higher than would be used for a clinical pediatric scan so that the dosimeters would more precisely measure the dose. Because dose varies linearly with effective mAs, the results from any of these protocols can easily be scaled so that they apply to standard clinical pediatric scan settings. The kVp settings used for the head and chest scans are representative of typical pediatric scan protocols.

The scout views (Fig. 1) were used to define the scan extent for the head and chest scans and to ensure that the phantom was properly positioned and centered within the gantry bore. The dose from the scout view was not evaluated and not included in any TLD measurements. The head scans extended from the top of the head to the collarbone (scan extent of about 20 cm). The chest scan extended from the chin to the bottom of the lungs (scan extent of about 20 cm). Chest scans often use the chin as the superior landmark position. If the helical images start at the base of the throat, overscan will nearly always expose the neck and thyroid region of small children.¹² For these reasons, the helical chest scan was explicitly set up to directly expose the neck (and thyroid). Five exposures (scans) were performed for each protocol to assess measurement reproducibility (each exposure was measured with a new set of TLDs). After the initial

TABLE II. Scan protocol parameters. The effective mA s column values indicate that each set of protocol parameter combinations produced nearly equivalent exposures (within 3%).

Region	Scan	kVp	mA	Time (s)	Effective mA s	Pitch	Beam (mm)	SFOV
Head	Axial	120	200	1	200	NA	40	Pediatric head
Head	Helical	120	100	1	194	0.516	40	Pediatric head
Head	Helical	120	195	1	198	0.984	40	Pediatric head
Chest	Axial	100	290	1	290	NA	40	Small body
Chest	Helical	100	145	1	281	0.516	40	Small body
Chest	Helical	100	285	1	290	0.984	40	Small body
Chest	Helical	100	400	1	291	1.375 ^a	40	Small body

^aNote that for pitch of 1.375, the large focal spot was used due to the higher mA value; all other protocols used the small focal spot.

scout scan was performed (without TLDs present in the phantom), the phantom was carefully disassembled, TLDs were inserted, and the phantom was reassembled without allowing it to slide in the anterior-posterior direction. Temporary positioning aids (such as tape markers on the patient table) were used as a guide for phantom repositioning between TLD replacements.

II.D. TLDs and data analysis

All of the TLD capsules used in this study were produced from the same batch of TLD-100 powder (Radiological Physics Center, Houston, TX). Because of the physical de-

sign constraints of the phantom, TLDs were considered the most appropriate dosimeter for organ dose measurements. The TLD measurements in this project reflect point dose measurements that are assumed to be representative of the dose to the whole organ. All TLDs were processed at the Radiation Physics Center (Houston, TX) using standard handling and processing techniques. Specific corrections or conversions for fading, linearity, energy, and absorbed dose were applied to all TLD data in a consistent manner.

Prior to the statistical analysis of the results, all helical dose values were adjusted (slightly) to account for the small difference in effective mA s relative to axial mode (Table II). Thus, all dose values included in this paper reflect equivalent exposures (axial vs helical scan modes).

TLD-measured organ doses were analyzed with a one-way ANOVA using the SPSS software (SPSS Inc., Chicago, IL). The Tukey method for multiple comparisons was used to correct for repeated measurements.¹³ A corrected *p* value of 0.05 was used to determine the statistical significance. The organ dose measurements were divided into two groups (the head organs and the chest organs) and were compared by scan mode (axial and helical).

III. RESULTS

The range of doses for each of the head organs over the different head scan (performed at 120 kV and scaled for 200 effective mA s) types were as follows: Brain, 32 mGy; eyes, 30–35 mGy; and thyroid, 42–46 mGy. The range of doses for each of the chest organs over the different chest scan types (performed at 100 kV and scaled for 290 effective mA s) were as follows: Thyroid, 40–50 mGy, breasts 39–50 mGy; sternum, 39–52 mGy; and lungs 31–41 mGy (Table III).

For the head scans, when TLD dose values for each organ were averaged for each acquisition type and then compared to contiguous axial scans, the helical dose was found to be significantly lower than the axial acquisition ($p < 0.05$). These differences ranged from 0% for brain to 9% for thyroid and 3%–12% for the eyes. Of the head organs, the thyroid received the highest dose, ranging from 42 to 46 mGy across the different acquisition types.

Similarly for the chest scans, when TLD dose values for each organ were averaged for each acquisition type and then

FIG. 1. Scout view of the anthropomorphic phantom with the approximate positions of the TLDs indicated (small black and white rectangles). Note that the neck region (including the thyroid) was directly exposed in both scans [H=head; F=feet].

TABLE III. Organ dose values by protocol after adjustment to the helical results to reflect the equivalent axial effective mAs including the percent different between doses measured in axial and helical scan acquisition modes.

Region	Organ	Axial		Pitch		%	Pitch		%	Pitch		%
		dose (mGy)	SD (mGy)	0.516 dose (mGy)	SD (mGy)		0.984 dose (mGy)	SD (mGy)		1.375 dose (mGy)	SD (mGy)	
Head	Brain	32	0.2	32	0.4	0	32	0.5	0			
	Left eye	34	0.4	33	2.4	−3	30	2.6	−12			
	Right eye	35	0.2	33	2.2	−6	34	1.0	−3			
	Thyroid H	46	2.9	43	0.9	−7	42	0.5	−9			
	Average % difference					−4			−6			
Chest	Thyroid C	50	0.4	40	0.9	−20	40	0.5	−20	42	0.2	−16
	Left breast	50	0.5	39	1.2	−22	40	0.7	−20	44	6.5	−12
	Right breast	50	0.6	39	1.0	−22	38	1.1	−24	43	6.4	−14
	Sternum	52	0.5	41	0.4	−21	39	1.0	−25	45	7.4	−14
	Left lung	37	1.2	31	0.6	−16	33	1.5	−11	32	1.5	−14
	Right lung	41	0.5	32	0.6	−22	31	0.7	−24	34	1.6	−17
	Average % difference					−21			−21			−15

compared, helical dose was found to be significantly lower than the axial acquisition ($p < 0.05$). These differences ranged from 11% to 16% for the left lung to 17%–24% for the right lung. The average organ dose for the chest scan using helical pitch of 1.375 was also found to be significantly higher (an average of 8%) than for the other two pitch settings ($p < 0.05$). Of the chest organs, the thyroid (40–50 mGy), breasts (38–50 mGy), and sternum (39–52 mGy) received the highest doses. It should be noted that the thyroid dose was one of the highest doses in each scan region and for each protocol tested.

IV. DISCUSSION

The statistically lower organ point dose values for the helical compared to the axial scans were unexpected because the dose values obtained for using helical protocol acquisition parameters had been adjusted for equivalent effective mAs. Several previously published papers also reported a similar axial-helical dose difference using similar methods. One previous study compared axial and helical (single detector-row) CT doses using TLDs placed in a similar but adult-sized anthropomorphic phantom.¹⁴ After the acquisition techniques were normalized, helical CT doses were 13% (thoracic) to 162% (brain) lower than axial doses. Potential causes for this discrepancy were not addressed. A second previous study compared axial and helical (also single detector-row) CT doses using TLDs placed in the pelvic region of a male and a female adult human cadaver, in addition to an adult anthropomorphic phantom.¹⁵ This paper reported that helical scanning produced reduced dose when compared to axial scanning (from 12% to 53% lower dose, on average, 24% less) when used in 1 s per rotation mode. This helical dose reduction was speculated to be due to differences in x-ray tube on-time characteristics between helical and axial mode. A third paper reported the results of using TLDs within standard CTDI phantoms and comparing helical and axial mode dose results, also using a single detector-row CT

scanner.¹⁶ A 3%–14% decrease in helical mode radiation dose compared to axial mode was reported (the magnitude of the difference was dependent on beam width), and this difference was not addressed. We conclude that the dose difference we have detected between axial and helical CT scan mode is real and is not specific to multidetector-row CT scanners. Indeed, it appears to have existed since the introduction of helical CT scanners but has not been fully appreciated.

The combination of point dosimeters and nonuniform dose distribution definitely affected the data presented here. Because the radiation exposure pattern was not perfectly uniform, some sampling error or bias must be included in our results. This is true for some extent even for the axial mode scans; surface dose distributions with substantial irregularities due to beam divergence have been observed in contiguous axial mode scans of similar (although adult-sized) phantoms.^{17,18} The effect of surface dose nonuniformity is even greater when helical scan mode (pitch not equal to one) is used. There is no way, using current methods, to pinpoint if a given point dosimeter happened to fall in a peak region, a trough region, or somewhere between, after the scan is complete. Although it is theoretically possible that most TLDs fell into the trough regions for the helical scans relative to the axial scans, the probability of that happening is very low. It is much more likely that the point dosimeters were distributed fairly randomly related to the surface dose modulations and thus reflect an overall average of dose delivered during the scans. In addition, it should be recognized that five scans were performed for each protocol, with no attempt made to control the angle at which the x-ray tube was turned on (our attempt to determine the beam-on angle after each helical run was not successful). The need to replace the TLDs after each scan also must have caused at least a small amount of change in phantom's location (and thus the TLD positions) relative to the x-ray beam path for each scan. These conditions, taken together, further increase our

confidence that the sampling bias introduced by the combination of point dosimeters and helical scanning (with pitch not equal to 1) are not totally responsible for the unexpectedly significantly lower dose results associated with helical scan mode in this study.

From the findings of this study it could be argued that scanning in axial mode comes with an unexpected dose penalty. However, since we have always measured CT dose in axial mode using the CTDI approach, this “extra” dose associated with axial mode scanning has always been included in our CT dosimetry estimates. Therefore, it seems more logical to conclude that the difference we have observed in axial and helical scan modes represents an unrecognized dose savings in helical mode compared to the manner in which we routinely assess it (axial mode). This difference between axial and helical scan modes should also be evident when using small point dosimeters and scanning through the phantom in both modes (as in the method suggested by Dixon¹⁹); however, the axial and helical dose difference we observed has not been reported to date as far as we are aware using that method.

It can be speculated that the decrease in organ dose observed with helical scans may be due to one or a combination of several differences in scan mechanics between these two modes, including (a) in contiguous axial scans, the x-ray beam has to ramp up and ramp down for each rotation, causing the beam to produce radiation over slightly more than 360° for each rotation (while a helical scan only has to ramp up and ramp down the beam at the beginning and end of each scan, which are at different locations), or (b) the overlap in the *x-y* plane of the fan angle portion of the x-ray beam during the brief period when the x-ray tube is at the start and stop positions (the same tube angle), or (c) a difference in physical beam collimation between axial and helical scan modes, or (d) a difference in focal spot tracking between axial and helical scans, or (e) inaccurate or imprecise table speed in helical mode.

It is especially interesting (and puzzling) that the differences we observed in axial and helical scans were much more striking for the chest region (and at 100 kVp) than for the head region (and at 120 kVp). Several experiments to confirm the cause of the organ dose difference between axial and helical scan acquisitions are currently underway, but these studies are not within the scope of this work and will be the focus of future work.

The higher mA setting (400 mA) used for the helical scan with pitch of 1.375 caused the CT scanner to switch from the small focal spot to the large focal spot (Table II), which in turn resulted in a higher x-ray tube output even though the mA setting was adjusted to produce the same effective mA s as the other protocols using the small focal spot (the maximum small focal spot current was 320 mA for 100 kVp on this tube/generator combination). We have noted an increase in x-ray tube output during acceptance testing of this scanner model (10%–15% increase in output when switching between the small and large filaments). This likely contributed to the larger organ dose values observed using the largest pitch value for the helical chest scans relative to the lower

pitch helical chest scans. Slight differences in phantom and TLD position relative to the variable exposure pattern in CT imaging may have contributed to the higher standard deviations in organs near the surface in the chest scans when using a pitch value of 1.375.

The chest scan protocol used in this study (100 kVp and 290 effective mA s) is quite different from our previous manual protocol (we currently utilize tube current modulation) for a similar size pediatric patient (100 kVp and 61 effective mA s). To scale the measured dose values for our protocol would require multiplying all data points by the ratio of the effective mA s values (0.21); this would result in chest organ dose values that would range from 6.4 to 10.9 mGy. Thyroid dose in this pediatric protocol scenario would be reduced from a maximum value of 50.2 mGy to a maximum value of 10.5 mGy.

The thyroid TLD location was completely included in both head and chest scan regions. The point dose measured at the thyroid was relatively high for the head scan (42–46 mGy) using approximately 200 effective mA s. This dose is high primarily because the thyroid is located in the thinnest region of the patient (the neck). When manual (constant) tube current methods are implemented, the smaller the diameter of a region, the higher the radiation dose to that region; hence, the thyroid receives the highest dose of any of the organs measured here. If a dual phase head scan (with and without IV contrast enhancement) was completed on an actual pediatric patient of approximately this size using similar technique factors, the total dose to the thyroid could be close to 100 mGy. Special care should be taken when determining scan extents that include the thyroid region of a pediatric patient, especially for relatively higher dose head and neck CT exams. Automatic tube current modulation could be an effective method of reducing thyroid exposure in pediatric patients.

V. CONCLUSIONS

In summary, no difference was expected in axial versus helical organ point dose values after making slight adjustments for techniques between the different scan acquisitions. However, the helical scan organ point dose measurements were found to be an average of 13% (range of 0%–25%) lower than the axial scan acquisitions using TLDs and a pediatric anthropomorphic phantom. Investigation of the underlying cause of this dose discrepancy is a topic of future research. In addition, we have measured organ doses in a pediatric anthropomorphic phantom. These absolute point dose values may be useful for validating Monte Carlo dose models.

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