

Thyroid doses and risk to paediatric patients undergoing neck CT examinations

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Abstract

Objective To estimate thyroid doses and cancer risk for paediatric patients undergoing neck computed tomography (CT).

Methods We used average $CTDI_{vol}$ (mGy) values from 75 paediatric neck CT examinations to estimate thyroid dose in a mathematical anthropomorphic phantom (ImPACT Patient CT Dosimetry Calculator). Patient dose was estimated by modelling the neck as mass equivalent water cylinder. A patient size correction factor was obtained using published relative dose data as a function of water cylinder size. Additional correction factors included scan length and radiation intensity variation secondary to tube-current modulation.

Results The mean water cylinder diameter that modelled the neck was 14 ± 3.5 cm. The mathematical anthropomorphic phantom has a 16.5-cm neck, and for a constant CT exposure, would have thyroid doses that are 13–17 % lower than the average paediatric patient. $CTDI_{vol}$ was independent of age and sex. The average thyroid doses were 31 ± 18 mGy (males) and 34 ± 15 mGy (females). Thyroid cancer incidence risk was highest for infant females (0.2 %), lowest for teenage males (0.01 %).

Conclusions Estimated absorbed thyroid doses in paediatric neck CT did not significantly vary with age and gender. However, the corresponding thyroid cancer risk is determined by gender and age.

Key Points

- Thyroid doses can be estimated from the $CTDI_{vol}$ in paediatric neck CT.
- Scan length, neck size, and radiation intensity variation should be accounted for.
- Estimated absorbed thyroid doses did not significantly vary with age and gender.
- Thyroid cancer incidence risk is primarily determined by gender and age.

Keywords Tomography · Spiral Computed · Radiation Dosage · Pediatrics · Neck · Thyroid Gland

Abbreviations

$CTDI_{vol}$	Volume CT dose index
DLP	Dose length product
AEC	Automatic exposure control

Introduction

Paediatric computed tomography (CT) usage has rapidly increased in the United States due to the introduction of helical CT, which allows for fast image acquisition and significantly decreases the need for sedation [1–5]. Due to the smaller size of paediatric patients the effective dose to a child from a given CT study is higher than what is received by an adult for the same technical factors [4, 6]. Furthermore, the greater lifetime risks for a unit dose of radiation in children will likely result in a significantly higher lifetime cancer mortality rate attributable to CT radiation exposure in children than adults [6]. A recent retrospective study of a cohort of paediatric patients examined with CT has shown that cumulative doses of 50 mGy to the brain may triple the risk of leukemia and doses of 60 mGy may triple the risk of brain cancer [7]. Mathews et al.

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compared cancer incidence of 680,000 individuals who underwent CT imaging between ages 0 and 19 with cancer incidence of a cohort of over 10 million unexposed, age-matched controls [8]. In this study, CT scans during childhood and adolescence were found to be associated with an increase in cancer incidence for all cancers combined and for many individual types of cancer.

It has been estimated that paediatric CT accounts for approximately 11 % of all CT examinations, and a significant percentage of all paediatric examinations (ranging from 33 % to 80 %, according to the literature) are conducted in the head and neck region [9, 10]. In neck CT examinations, the most radiosensitive organ directly exposed to the x-ray beam and at risk for radiation-induced carcinogenesis is the thyroid gland [11]. The thyroid gland is known to have a significantly greater sensitivity to radiation exposure in young children than adults [12]. A systematic analysis of the relationship between patient characteristics (size of the cervical region), CT parameters (kVp, mAs), scanner-related factors, and the resulting thyroid dose is necessary to provide an estimate of thyroid cancer risk stratified by patient age and gender from a routine cervical CT. We previously developed a method to calculate the absorbed radiation dose to the thyroid gland in a patient undergoing a CT examination [13].

The purpose of this study was to retrospectively calculate the organ dose to the thyroid gland and the corresponding attributable lifetime thyroid cancer risk for paediatric patients undergoing multidetector CT examinations of the cervical region, with the hypothesis that thyroid cancer risks vary with age and gender.

Methods

Neck CT examinations

This study was approved by the Medical University of South Carolina Institutional Review Board, exempting the study from requiring individual patient consent (exemption number 19967). We retrospectively reviewed all consecutive paediatric neck CT examinations (age range=0-17) performed at our institution between September 2009 and April 2010. Exclusion criteria were absence of the thyroid gland and sub-optimal study quality due to motion artefact.

At our institution, paediatric neck CT examinations are performed following administration of a non-ionic iodinated contrast agent (2 ml per kg of body weight). Imaging commences after a 90-second delay from the start of the contrast injection. Images were acquired on a GE LightSpeed 16, Siemens Sensation 16, or a Siemens Definition 64 scanner, at a pitch of 1.4, 1.11, and 0.7, respectively. All examinations were helical acquisitions, acquired using the CARE Dose4D tube current modulation system that can be used in one of

three settings (i.e., ‘weak,’ ‘average,’ and ‘strong’). The strengths of the CARE Dose4D vendor settings were ‘weak’ for slim patients and ‘strong’ for obese patients. The x-ray tube voltages used to perform these examinations in paediatric patients ranged from 80 to 120 kV. The neck CT examinations started at the forehead and continue to the thoracic inlet. All images were reconstructed and viewed using approximately 3-mm thick contiguous slices with a display field of view ranging from 13 to 24 cm. Demographic data (date of birth and sex) were obtained for each patient.

A neuroradiologist identified all slices proximal to the distal slices of the thyroid gland on a picture archiving and communication system (Agfa Impax 6.4, Agfa Healthcare Corporation, Mortsels, Belgium). Thyroid length (cm) was calculated on the axial CT images by multiplying the total number of images including the thyroid gland by the slice thickness (taking into account any gap between slices). For the central axial slice through the middle of the thyroid gland, a region of interest encompassing the entire neck was drawn and the corresponding area, A (cm²), and the average Hounsfield unit (HU), were recorded. The patient’s neck was modelled as a mass equivalent water cylinder of diameter d (cm) with the same total mass as the region of the patient containing the central image of the patient’s thyroid. Finally, the diameter d was calculated as follows:

$$d = 2 \times \sqrt{\left[A / (\pi) \times (1000 + HU) / 1000 \right]}$$

The amount of radiation used to perform each scan, namely $CTDI_{vol}$ (mGy) and the corresponding dose length product (DLP; mGy-cm) were recorded. Where patients had more than one neck CT scan, these were treated as separate scans and not combined into a single value. All $CTDI_{vol}$ and DLP data pertain to the 32-cm acrylic dosimetry phantom, since these scans are deemed to be “body scans” rather than “head scans.” The length for each individual scan was obtained by dividing the DLP by the corresponding $CTDI_{vol}$.

Estimation of thyroid dose

The thyroid dose for each subject was estimated using previously described methodology [13, 14]. The average radiation intensity used to perform each patient CT examination is given by the scan $CTDI_{vol}$ (mGy). In order to estimate the thyroid dose, this value needs to be modified for the following factors:

- (1) Scanner-specific normalization factor – This factor, D' , accounts for the differences in the thyroid dose for different scanners:

$$D' = D_{thy} / CTDI_{vol}$$

Where, D_{thy} is the thyroid dose estimated from the ImPACT dosimetry calculator for a 16.5-cm neck phantom, and the $CTDI_{vol}$ is estimated in a 32-cm acrylic phantom for that scanner. Thus, D' represents a scanner-specific normalization factor corresponding to the thyroid dose in an average-sized patient undergoing a whole-body CT scan at constant technique divided by the corresponding $CTDI_{vol}$ (32-cm-diameter phantom);

- (2) Scan length – A scan length longer than the length of the thyroid will result in the thyroid getting more scatter radiation than a scan limited to just the length of the thyroid. Correction factors (R_L) for various scan lengths were estimated based on previous work by Huda et al. [13];
- (3) Radiation intensity – Since the CT scans were performed using the automatic exposure control (AEC), it is necessary to take into account the variation of the tube current along the long axis of the patient. The tube current, i.e., (mA) at each slice, was obtained from the DICOM header that permitted quantitative determination of the average tube current value (mA_{ave}) used to perform the CT examination, as well as the specific value that was used at the middle of the thyroid gland (mA_{center}). A ratio of these two values, $R_{mAs} = mA_{center} / mA_{ave}$ yielded an intensity correction factor for each scan.
- (4) Patient size – At a constant X-ray beam intensity, increasing the patient size generally reduces organ doses and vice versa. The normalized thyroid dose was estimated in a mathematical anthropomorphic phantom by Huda et al. [14] using the ImPACT dosimetry calculator, where the thyroid is located in a neck that has a mass equivalence of a 16.5-cm diameter water cylinder. For each patient, the water equivalent diameter served as a surrogate for the patient neck size. For each scan, the thyroid dose was adjusted by utilizing published correction factors (R_d), based on the size of the patient at the location of the middle of the thyroid gland. For patients whose thyroid region is modelled as a cylinder of water with a diameter less than 16.5 cm, R_d will be greater than unity, and vice versa. Thus, although the D' values thus calculated are based on the adult phantom in ImPACT, the correction factor R_d accounts for the difference in the neck size between adult and paediatric patients.

Finally, the thyroid dose was estimated using the following expression:

$$\text{Thyroid dose} = CTDI_{vol} \times D' \times R_L \times R_{mAs} \times R_d$$

Where, the subscripts L, mAs, and d refer to the correction factors for scan length, current modulation, and neck diameter.

Radiation risk

The resultant thyroid doses were used to estimate the sex-specific risk of thyroid cancer incidence using the BEIR VII data [15]. These risk data (R thyroid cancers per 100,000 per 100 mGy) were fitted to a second order polynomial of the form:

$$\log_{10}R = b_0 + b_1Y + b_2Y^2$$

Where Y is the patient age and the coefficients b_0 , b_1 , and b_2 were calculated using a commercial software package (SigmaPlot 10.0). The values of these coefficients can be found in [13].

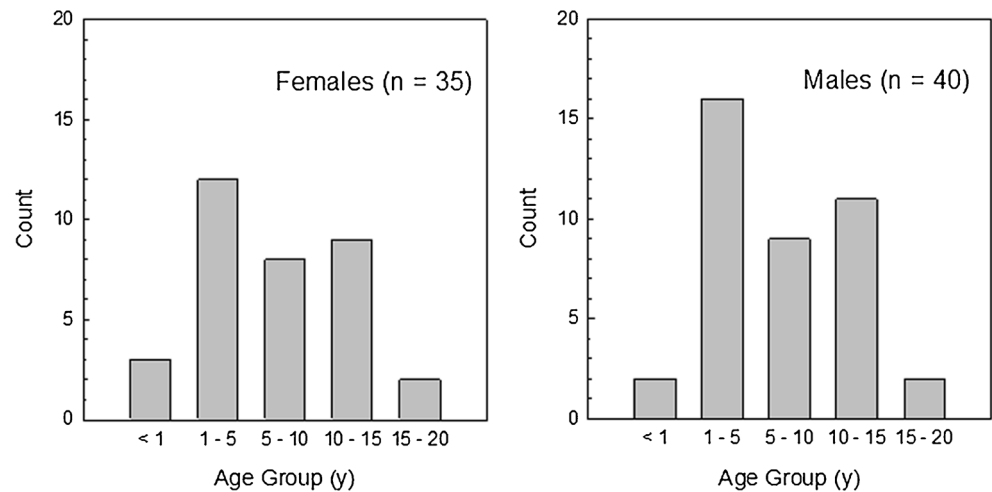
Statistical analysis was conducted using Statistical Product and Service Solutions software (IBM SPSS Statistics 20). A Mann-Whitney test, an independent samples t-test, and a Spearman's rank correlation coefficient were used for statistical analyses.

Results

Seventy-nine consecutive neck CT studies obtained in 75 paediatric patients were included in this study. The mean patient age was 8 ± 5 years (range=0–17 years) (Fig. 1). The length of the thyroid gland varies widely across individuals, with a minimum of 1.2 and a maximum of 6 cm (Fig. 2). As expected, there is a significant correlation between the water equivalent cylinder diameter (d) of the neck and age (correlation coefficient=0.689, $p < 0.001$) (Fig. 3). Table 1 shows the range of correction factors used for calculating thyroid dose. Figure 4 shows the scan $CTDI_{vol}$ [average \pm standard deviation (SD) = 11.6 ± 5.7 mGy] and the tube current modulation correction factor R_{mAs} (average \pm SD = 1.2 ± 0.2) as a function of the estimated water equivalent cylinder. There was a significant positive correlation between R_{mAs} and the water equivalent cylinder (correlation coefficient=0.447, $p < 0.001$) and a mild, but statistically significant, correlation between $CTDI_{vol}$ and the water equivalent cylinder (correlation coefficient=0.228, $p = 0.05$).

The estimated average thyroid dose \pm SD was 31 ± 18 mGy for males and 34 ± 15 mGy for females. Thyroid dose estimates were not significantly different between genders ($p = 0.353$). There was no significant correlation between estimated thyroid dose and age (correlation coefficient=0.155, $p = 0.184$) (Fig. 5), and between estimated thyroid dose and the water equivalent cylinder (correlation coefficient=0.478, $p = 0.83$). There was a significant inverse correlation between age and the corresponding thyroid cancer incidence risk based on BEIR VII in both males (correlation coefficient=-0.620,

Fig. 1 Age distribution of male and female patients



$p < 0.001$) and females (correlation coefficient = -0.580 , $p < 0.001$) (Fig. 6). Thyroid cancer incidence risk was significantly greater in female than male subjects ($p < 0.001$). Table 2 shows the thyroid cancer incidence risk for males and females from age zero to 18, based on the curve fit data in Fig. 6.

Discussion

The paediatric thyroid gland is one of the most radiosensitive organs [16, 17]. In neck CT examinations the thyroid gland is directly exposed to the x-ray beam that has the potential to result in the highest thyroid doses in diagnostic CT imaging. Therefore, it is important to accurately estimate the absorbed thyroid dose and corresponding cancer risk in paediatric patients in order to estimate the risk/benefit ratio of a given study.

Dose calculation in neck CT imaging is complex due to the anatomical variability in neck size and shape between

individuals and to the position of the thyroid at the cervico-thoracic junction. We found that paediatric necks could be modelled as water cylinders with diameters ranging from approximately 9 cm in infants to 24 cm in teenagers (Fig. 3). Furthermore, the thyroid is usually at the interface between the neck and the thoracic inlet, although the precise location of the thyroid gland in the neck is variable among individuals [13]. The thyroid is positioned in a relatively more attenuating anatomical area compared to the rest of the neck. As a result, the amount of radiation used to image the thyroid gland region may differ from the average amount of radiation used in neck CT studies performed with the AEC. Therefore, inter- and intra-individual variability in neck and thyroid anatomy should be taken into consideration in the estimation of thyroid doses.

Figure 4 shows the distribution of $CTDI_{vol}$ as a function of water equivalent cylinder diameter (a surrogate of patient size) measured in a 32-cm diameter CT dosimetry phantom. The graph shows that, in neck CT imaging, the scanner radiation output increases as a function of the patient size, similar to the trend indicated in the American Association of Physicists in

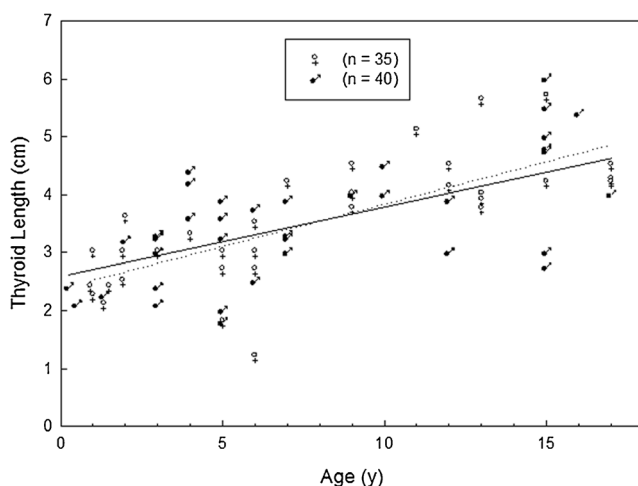


Fig. 2 Thyroid length as a function of age

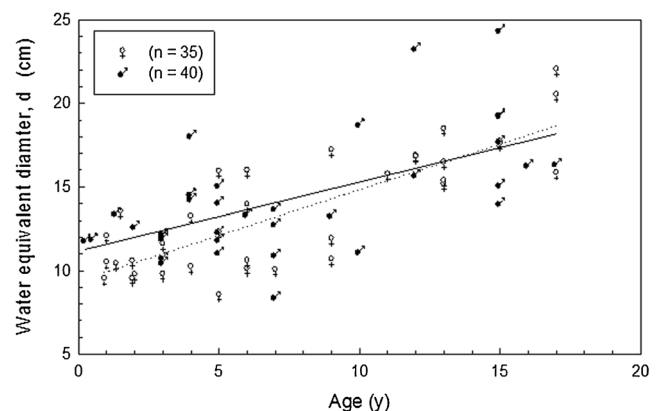


Fig. 3 Water cylinder diameter as a function of age

Table 1 Correction factors for estimating thyroid dose

	R_L	R_d	R_{mAs}
Minimum	0.83	0.62	0.73
10 %ile	0.87	0.91	0.95
25 %ile	0.90	1.02	1.00
Median	0.92	1.18	1.18
75 %ile	0.93	1.29	1.34
90 %ile	0.94	1.37	1.46
Maximum	0.96	1.70	1.76

Medicine (AAPM) report 204 [18]. The average $CTDI_{vol}$ was 12 mGy in paediatric patients, less than half compared to the average $CTDI_{vol}$ previously reported in adult subjects [13]. We also found substantial $CTDI_{vol}$ variability for necks of equivalent size. For example, $CTDI_{vol}$ ranged from 4 to 19 mGy in paediatric necks equivalent to water cylinder diameters from 10 to 12 cm. The variability of $CTDI_{vol}$ for necks of equivalent size in CT studies performed with the AEC is due to variation in the patient’s body habitus and selected scan range [19, 20]. In fact, $CTDI_{vol}$ is expected to differ for patients of the same size if there are differences in neck thickness and density. Furthermore, if the scan range of a neck CT is extended in the cranial or caudal direction,

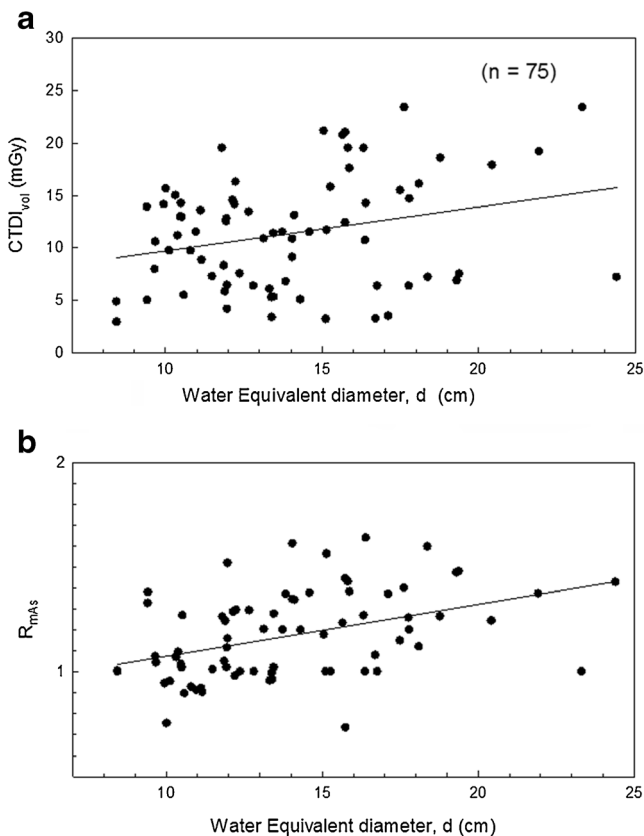


Fig. 4 (A) $CTDI_{vol}$ and (B) the tube current correction factor as a function of water equivalent cylinder diameter. All $CTDI_{vol}$ data pertain to the 32-cm acrylic dosimetry phantom

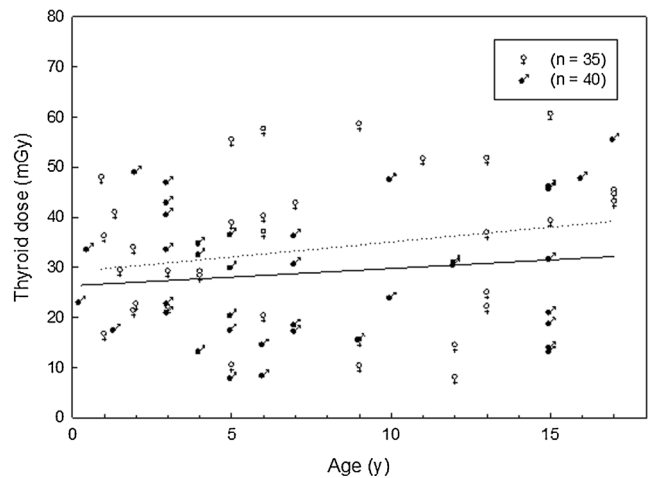


Fig. 5 Thyroid dose as a function of age

anatomical structures such as the skull, shoulders, and lungs will be included in the scan. Including each type of tissue would modify the $CTDI_{vol}$ value of the scan, because the reported $CTDI_{vol}$ is averaged across the entire scan length.

The patient size correction factor (R_d) accounts for differences between the size of the neck at the mid-thyroid location and the size of the mathematical anthropomorphic phantom used in CT dosimetry calculations (Table 1) [14]. The phantom has the thyroid located in a neck that has a mass equivalence of a 16.5-cm diameter water cylinder. For patients whose thyroid region is modelled as a water cylinder with a diameter smaller than 16.5 cm, R_d will be greater than unity, and vice versa. R_d is an important correction factor in the estimation of thyroid dose in paediatric patients. In fact, in our sample, the median R_d correction factor was 1.2, the 10th percentile was 0.9, and the 90th percentile was 1.4. As a result, thyroid doses estimated for the adult anthropomorphic IMPACT phantom were increased by 20 % for an average-sized patient and increased by approximately 40 %

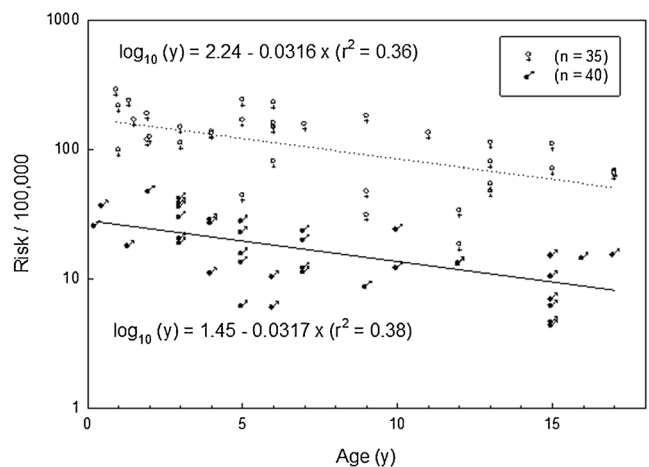


Fig. 6 Thyroid cancer incidence risk based on BEIR VII plotted on a logarithmic scale, as a function of age for males and females

Table 2 Thyroid cancer incidence risk per 100,000 estimated from the curve-fit data in Fig. 6

Age (yrs)	♂	♀
0	28	174
1	26	162
2	24	150
3	23	140
4	21	130
5	20	121
6	18	112
8	16	97
10	14	84
12	12	73
15	9	58
18	8	47

for the smallest patients. In the largest patients, the size correction factor resulted in an approximately 10 % reduction of estimated thyroid dose. For comparison, in a previous study of 11 adults, patient size correction resulted in an average 25 % reduction of the thyroid dose estimated for a 16.5-cm-diameter anthropomorphic mathematical phantom [13].

R_{mAs} is the ratio of the tube current at the centre of the thyroid to the average over the entire length of the scan. Thus, R_{mAs} is an estimate of how much more (or less) radiation was used while scanning the thyroid as compared to the rest of the neck when using the AEC. R_{mAs} was greater than 1.0 in 62 of 75 cases (83 %) (Fig. 4) and varied by a factor of about 3 (range=0.7 - 1.8) (Table 1). For comparison, in adults, R_{mAs} was always greater than 1.0, with an average value of 1.44 [13]. The highest R_{mAs} value, measured in a 15-year old male, indicates an 80 % increase of the tube current at the thyroid mid-point compared to the average tube current. In children from <1 to 3 years of age, the median R_{mAs} was 1.1 (range=0.9 - 1.5), with only one case of $R_{mAs}<1$. Therefore, even in the youngest group, the tube current at the thyroid mid-point was frequently greater than the average tube current. As a result, in most patients a greater amount of radiation was used to image the thyroid compared to the average neck region. This can be explained by the thyroid location at the base of the neck and the use of the AEC. The anatomical area of the neck in which the thyroid is located has a greater diameter than the average diameter of the neck, which results in greater mAs output when the AEC is used [13].

Figure 5 demonstrates the thyroid dose distribution by age and gender. Average estimated thyroid doses in this study were 32 mGy and a wide dose range was observed (10th percentile=14 mGy; 90th percentile=50 mGy). In children from <1 to 3 years of age, the average thyroid dose [SD] was 31.55 mGy [11] (10th percentile=21 mGy; 90th percentile=47 mGy). Figure 5 shows that estimated thyroid doses did not significantly increase with age. Therefore, the

observed increase in $CTDI_{vol}$ with age was likely counterbalanced by increasing neck size and did not lead to increased thyroid doses in older patients. For comparison, average thyroid doses were approximately 40 % higher in adults (average 55 mGy) [13].

Figure 6 shows thyroid cancer risk estimates plotted on a semi-logarithmic scale as a function of patient age. Gender and age are the most important factors in determining thyroid cancer risk in paediatric patients undergoing neck CT imaging. The highest thyroid cancer risk, approximately 0.2 %, was found in females younger than three years of age. The highest individual risk would be to an 11-month old female who received a thyroid dose of 48 mGy and whose thyroid cancer risk would be estimated at nearly 0.3 %. On average, female cancer risk was 6 times higher than male cancer risk. Thyroid cancer risk fell rapidly with age. For example, thyroid cancer risk was 3 times higher in patients under 3 years of age than in patients older than 15 years. In summary, thyroid cancer risk is mainly determined by patient demographics, with the actual organ doses being a secondary factor.

Neck CT scan appropriateness should be considered in paediatric patients on a case-by-case basis [21, 22]. CT examinations should be performed when the patient benefit exceeds any risk, and this requires practitioners to understand the magnitude of radiological risk. Prospective multi-institutional studies are needed to calculate thyroid cancer incidence risk estimates for each gender and age group. This information could be used as a reference to guide practitioners in the assessment of the risk-benefit ratios of neck CT examinations in paediatric patients. In the estimation of risk it should be considered that thyroid cancer mortality rates are low (0.6 per 100,000 in women and 0.3 per 100,000 in men) compared to the reported incidence rates (4.7 per 100,000 in women and 1.5 per 100,000 in men) [17].

Previous studies have reported estimated thyroid doses from head and neck CT studies in paediatric patients. Our estimates of thyroid dose are in line with the dose range described in these studies. Yamauchi-Kawaura et al. conducted an evaluation of radiation doses from head and neck CT examinations using a standard 6-year-old anthropomorphic phantom and found that the average thyroid dose from neck CT exam was 17.2 (SD=11.7) mGy [10]. Al-Senan et al. evaluated paediatric thyroid doses from CT by measuring surface neck doses and found thyroid doses ranging from 20 to 80 mGy in children between 1 and 3 years of age [23]. In a previous study using Monte Carlo simulation, Mazonakis et al. estimated thyroid doses from neck CT examinations to be 15.2 mGy in an infant and 52 mGy in a 15-year-old [24]. For comparison, our average thyroid doses were 28.5 mGy in infants and 37.7 mGy in 15-year-olds.

This study has several limitations. First, this was a retrospective review of CT exams of the cervical region in paediatric patients. The study scans were conducted using 16- and

64-slice multidetector CT systems; therefore, radiation doses may not be representative of doses received with other CT systems. Our dose estimates were not validated by surface dose measurements. To directly quantify the risk of thyroid cancer from CT scans it would require long-term prospective evaluation of a very large cohort of paediatric patients. Our approach was to use thyroid cancer risk estimates from the Biological Effects of Ionizing Radiation (BEIR) VII report (Japanese atomic bomb victims) to predict cancer risk from exposure to CT of the cervical region. It is uncertain and controversial whether patient radiation exposure in diagnostic radiology is associated with corresponding carcinogenic risk. It should be noted that the BEIR VII report data used in this study explicitly provide risk at doses of 100 mGy or greater. The estimated thyroid doses in our study were all less than 100 mGy by an average factor of 3. As a result, it is imperative to acknowledge uncertainties in our computed risk estimate model, but these estimates are the best available given the current state of knowledge. The wide range of dose indices reported for the same CT procedure and age group underscores the extensive efforts still needed to ensure that radiation exposure is optimized for every patient. At our institution, continued efforts are under way to optimize head and neck CT imaging in paediatric patients.

Conclusion

Paediatric thyroid doses in neck CT imaging can be estimated by taking into account the amount of radiation used to perform the CT examination $CTDI_{vol}$, scan length, patient anatomy at the thyroid location, and radiation intensity variation due to the AEC. The use of AEC in CT imaging of the neck is controversial and should be carefully considered. In fact, the benefit of using AEC to reduce the average radiation dose is counterbalanced by the increased radiation delivered to the thyroid gland in most paediatric patients. Thyroid cancer risk should be taken into consideration in the evaluation of the appropriateness of neck CT in children. Age and gender are the most important factors in determining thyroid cancer risk in paediatric neck CT. Finally, since our dose estimates are based on mathematical phantoms, validation of this methodology with paediatric phantoms and the concomitant dosimetry is warranted.

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