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Radiation dose and cancer risk from pediatric CT examinations on 64-slice CT: A phantom study

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ABSTRACT

Objective: To measure the radiation dose from CT scans in an anthropomorphic phantom using a 64-slice MDCT, and to estimate the associated cancer risk.
Materials and methods: Organ doses were measured with a 5-year-old phantom and thermoluminescent dosimeters. Four protocols; head CT, thorax CT, abdomen CT and pelvis CT were studied. Cancer risks, in the form of lifetime attributable risk (LAR) of cancer incidence, were estimated by linear extrapolation using the organ radiation doses and the LAR data.
Results: The effective doses for head, thorax, abdomen and pelvis CT, were 0.7 mSv, 3.5 mSv, 3.0 mSv, 1.3 mSv respectively. The organs with the highest dose were; for head CT, salivary gland (22.33 mGy); for thorax CT, breast (7.89 mGy); for abdomen CT, colon (6.62 mGy); for pelvis CT, bladder (4.28 mGy). The corresponding LARs for boys and girls were 0.015–0.053% and 0.034–0.155% respectively. The organs with highest LARs were; for head CT, thyroid gland (0.003% for boys, 0.015% for girls); for thorax CT, lung for boys (0.014%) and breast for girls (0.069%); for abdomen CT, colon for boys (0.017%) and lung for girls (0.016%); for pelvis CT, bladder for both boys and girls (0.008%).
Conclusion: The effective doses from these common pediatric CT examinations ranged from 0.7 mSv to 3.5 mSv and the associated lifetime cancer risks were found to be up to 0.16%, with some organs of higher radiosensitivity including breast, thyroid gland, colon and lungs.

1. Introduction

The introduction of multidetector row computed tomography (MDCT) has provided shortened scanning duration and improved spatial and temporal resolution [1–3]. These benefits reduce the need for sedation and allow the imaging of younger, sicker and less cooperative children [4–7] making the application of CT in children more feasible and is now commonly practiced for the evaluation of wide ranging pathologies in the brain, thorax, abdomen and pelvis. Moreover, with the development of techniques such as virtual endoscopy and three-dimensional reconstruction, the role of CT in patient management is expanding.

The main concern of CT application, especially in children is the radiation burden [8–10]. Children suffer larger radiation dose compared to adults using the same CT protocol [11]. Thus the increasing application of CT in children has raised concerns about the possible detriment of radiation to the health of children, in particular the risk of cancer. This risk is especially relevant to children because children have a longer life expectancy to develop complications and children are more susceptible to the effects of radiation than adults [12,13]. Hence, it is necessary to study the radiation doses of children undergoing CT examinations, and estimate the cancer risk attributable to the radiation doses.

State-of the-art MDCT scanners, including the 64-slice even the 320-slice MDCT scanners are increasing installed in institutions. There have been some studies evaluating radiation dose from body CT using a 64-slice MDCT scanner [14–16], and from CT coronary angiography [17–19] in pediatric patients. A comprehensive assessment of radiation dose from various types of pediatric CT examinations on the 64-slice MDCT scanner has not to our best knowledge, been published, in particular with regards to organ-specific dose, and the associated cancer risks. Hence, we report the radiation dose measured in a 5-year-old pediatric phantom of common CT scans performed in children using a 64-slice MDCT, and estimate the cancer risk associated with these scans. Four CT protocols, head, thorax, abdomen and pelvic CT were studied. We also

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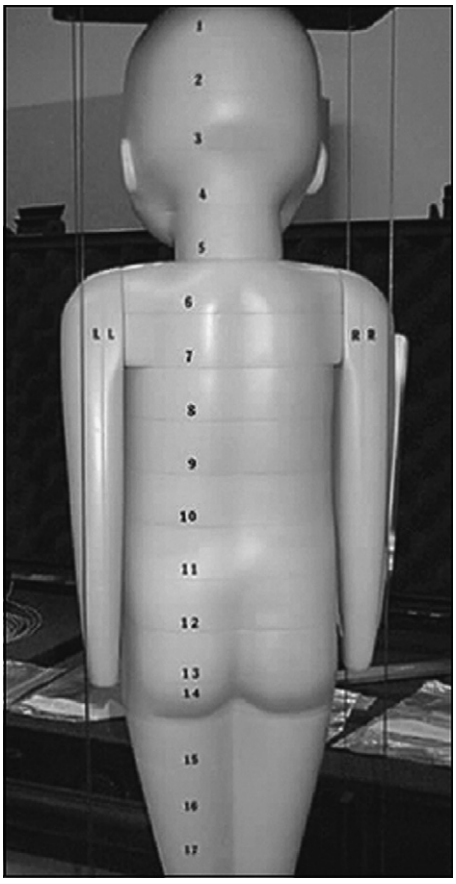

Fig. 1. Standard anthropomorphic phantom representing a 5-year-old child.

evaluated organ-specific doses and cancer risks, bearing in mind its implications on radiation protection.

2. Materials and methods

2.1. Dose measurement

CT studies were performed on a 64-slice MDCT scanner (Discovery VCT, GE Healthcare, Milwaukee, WI). The standard anthropomorphic phantom representing a 5-year-old child (CIRS, model 705-C, Norfolk, VA) was used for dose measurement. The phantom was composed of 26 contiguous sections with a section thickness of 25 mm, each of which contains matrix of holes for holding thermoluminescent dosimeters (TLD) (Fig. 1). In our study, LiF TLD chips with dimensions of 3.2 mm × 3.2 mm × 0.6 mm (TLD-100H, Harshaw Chemical Company, Solon, Ohio) were placed into the phantom. The batch of TLDs was calibrated using a 100 kVp X-ray beam from a superficial X-ray machine (Philips, RT100, Germany), and the absolute dose outputs were measured with a Farmer ionization chamber (PTW, model TN30013, Freiberg, Germany). This chamber has an air-kerma calibration traceable to national standards via a therapy-level secondary standard. Prior to being inserted into the phantom, the TLD chips were annealed using an oven (TLD annealing oven, PTW, Freiburg, Germany) to make the TLD chips reusable. Twenty-four hours after being exposed by the CT scan, the TLD chips were processed by a TLD reader (Harshaw, model QS5500). The TLD readings were transferred to organ doses by multiplying the factor acquired from the TLD calibration. A total number of 94 TLD chips were equipped in the organs in the pediatric phantom and 4 TLD chips were used to measure the background radiation (Table 1). At least two TLD chips per organ were used to lower the uncertainty. The TLD readings of a specific organ were averaged to calculate the dose for this organ. The effective dose is calculated by

$$E = \sum_T W_T D_T$$

where E is the effective dose, D_T is organ-specific dose, W_T is the tissue weighting factor for organ or tissue T as listed in ICRP publication 103 [13] (averaged for both genders). Age-dependent CT parameters recommended by the CT scanner vendor for scanning the head, thorax, abdomen and pelvis were used (Table 2). AutomA techniques were applied in our study except in head CT.

Table 1
Thermoluminescent dosimeters (TLD) distribution.

Organ	W_T	Number of TLDs
Ovary (girls)	0.08	2
Testicle (boys)	0.08	4
Breast	0.12	4
Bone marrow	0.12	8
Stomach	0.12	3
Colon	0.12	7
Lung	0.12	11
Thyroid	0.04	2
Esophagus	0.04	2
Liver	0.04	8
Bladder	0.04	3
Skin	0.01	12
Brain	0.01	7
Bone surface	0.01	4
Salivary gland	0.01	2
Remainder	0.12	
Heart	–	3
Pancreas	–	2
Spleen	–	2
Small bowel	–	4
Kidney	–	6
Uterus/prostate	–	2
Background	–	4
Total	–	98

W_T = tissue weighting factor.

2.2. Cancer risk estimation

From the measured organ doses, the risks of common cancer induction were calculated by applying the methods introduced by the National Academies' Biological Effects of Ionizing Radiation (BEIR) VII Report [12], in the form of lifetime attributable risk (LAR) of cancer incidence. LAR is defined as the sum of each year's excessive cancer probability after exposure. The LAR data of each organ are tabulated for 100,000 US people who received a radiation exposure of 100 mGy [12]. In our study the LAR data were updated using the cancer statistics data and life tables in United States (US) [20,21]. The results of this updated LAR table have been reported in our previous publication [22]. The LAR of each organ from a specific radiation exposure was calculated with linear extrapolation. To calculate the risk of "other solid organ" cancer, a composite dose was appointed to the "other solid organ" in the BEIR VII report, weighting related organs by the tissue weighting factors recommended in the ICRP publication 103 [13]. The whole body cancer risk was obtained by summing the cancer risk of each organ.

3. Results

3.1. Radiation dose

Table 3 tabulates the results of organ dose measurement for different scanning protocols in our institution. The effective doses

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Table 2
Parameters of four CT protocols evaluated in the study.

Parameters Scan-field-of-view	Head CT Head	Thorax CT Large	Abdomen CT Large	Pelvis CT Large
Tube potential (kV)	100	100	100	100
Tube current[a] (lower limit-upper limit)	200	30–300	50–200	50–300
Scan length (mm)	135	210	160	120
Detector configuration (mm)	64 × 0.625	64 × 0.625	64 × 0.625	64 × 0.625
Mode	Axial	Helical	Helical	Helical
Pitch	n/a	0.984	0.984	0.984
Noise level	n/a	7.2	8.4	10
Rotation time (s)	0.8	0.8	0.5	0.4
Scanning time (s)	2.8	2.6	2.1	1.7
Image reconstruction thickness (mm)	5	5	5	5

[a] For thorax CT, abdomen CT and pelvis CT protocols, automA technique was applied, and the lower limit and upper limit were shown in the table.

of head CT, thorax CT, abdomen CT and pelvis CT were 0.7 mSv, 3.5 mSv, 3.0 mSv, 1.3 mSv respectively. As a comparison, we noted that the annual exposure to the human body due to natural background radiation is about 2.4 mSv [23].

For head CT, thyroid, brain and salivary gland received relatively higher organ doses of about 2.52 mGy, 17.91 mGy and 22.33 mGy respectively. However as all these three organs have low tissue weighting factors and are not very sensitive to radiation, the effective dose from head CT is low. The dose to the lens in head CT was 25.88 mGy (not listed in Table 3), much lower than the dose threshold (around 500–2000 mGy) to cause deterministic effect of cataractogenesis [24]. For thorax CT, lung, liver, stomach and breast had a relatively higher radiation dose compared to other organs, of about 5.41 mGy, 5.56 mGy, 5.67 mGy and 7.89 mGy respectively. All these organs have relatively high tissue weighting factors (Table 3). For abdomen CT, the stomach, liver and colon suffered relatively high doses of 4.28 mGy, 5.67 mGy and 6.62 mGy respectively and for pelvis CT, the gonads and bladder suffered relatively high doses of 3.14 mGy and 4.28 mGy respectively (Table 3).

3.2. Cancer risk

LAR of cancer incidence induced by the radiation dose from each CT examination is shown in Fig. 2. The LARs from head CT, thorax CT, abdomen CT and pelvis CT scan for 5-year-old boys were 0.015% (150 cases in 1 million people), 0.044%, 0.053% and 0.031% respectively; for 5-year-old girls were 0.036%, 0.155%, 0.072% and 0.034% respectively. In general, LARs for girls were higher than boys, especially for thorax CT where LAR for girls was 3.5 times than boys due to the high risk to the female breast (Fig. 2).

For specific organs, the typical sites with high (more than 0.003%) lifetime attributable risks of cancer incidence associated with CT examinations are summarized in Table 4. For head CT, the thyroid gland, an organ of very high radiosensitivity for radiation carcinogenesis had the highest LAR of cancer incidence being 0.015% for girls, and 0.003% for boys. For thorax CT, the organ of highest LAR was lung for boys and breast for girls, with a LAR of 0.014% and 0.069% respectively. For abdomen CT, the organ with the highest LAR was colon for boys and lung for girls with a LAR of 0.017% and 0.016% respectively. For pelvis, the organ with the highest LAR was bladder for both males and females with the same LAR of 0.008%.

Table 3
CT doses for 5-year-old pediatric phantom.

Organs/tissues	Radiation dose (mGy)				
	W_T	Head	Thorax	Abdomen	Pelvis
Gonads (girl)	0.08	0.01	0.20	1.59	3.14
Gonads (boy)	0.08	0.01	0.03	0.06	1.04
Bone marrow	0.12	0.02	0.25	2.55	3.34
Colon	0.12	0.04	0.76	6.62	2.90
Lung	0.12	0.53	5.41	2.46	0.07
Stomach	0.12	0.21	5.67	4.28	0.11
Bladder	0.04	0.01	0.14	0.97	4.28
Breast	0.12	0.26	7.89	0.82	0.05
Liver	0.04	0.13	5.56	5.67	0.41
Esophagus	0.04	0.66	4.16	0.85	0.04
Thyroid	0.04	2.52	3.40	0.16	0.01
Skin	0.01	0.70	4.40	3.32	1.67
Bone surface	0.01	0.13	3.53	3.62	0.75
Brain	0.01	17.91	0.17	0.04	0.01
Salivary gland	0.01	22.33	0.32	0.06	0.01
Remainder	0.12	0.13	3.74	4.39	1.30
Effective dose (mSv)	–	0.7	3.5	3.0	1.3

Table showing the organ doses and effective doses from pediatric CT scans of the head, thorax, abdomen and pelvis. Effective doses were calculated using the tissue weighting factors (W_T) recommended in ICRP publication 103 [13].

4. Discussion

Our results show that effective doses from thorax and abdomen are higher than those from head and pelvis CT examinations, being similar to the annual dose from background radiation, and up to 50 times higher than the dose from a conventional chest X-ray radiography which has an effective dose of 0.06–0.25 mSv depending on the voltage and film-screen system used or the signal to noise ratio in digital systems [25]. However, some specific organ doses were much higher than 3 mGy, up to 22.33 mGy to the salivary grand in head CT. These doses are in the lower range (5–100 mGy) that survivors on the peripheries of Hiroshima and Nagasaki were exposed to. It has been shown that there is a small but statistically significant increase in the risk of cancer in these survivors after being

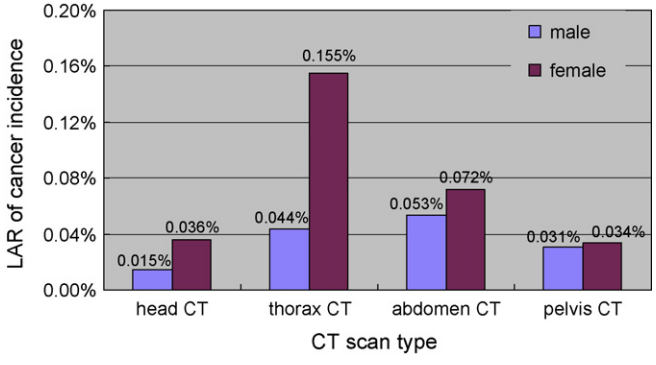

Fig. 2. Lifetime attributable risk of cancer incidence in 5-year-old children induced by CT scan. Note—estimated excess cancer incidence risks attributable to radiation from CT scan on children. Four CT scan types with different scanning parameters were studied. The risks to 5-year-old boys and girls are shown.

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Table 4
Organs with high lifetime attributable risk of cancer incidence (more than 0.003%) associated with each CT examination for 5-year-old boys and girls.

	Boys		Girls	
	Cancer site	LAR	Cancer site	LAR
Head CT	Thyroid	0.003%	Thyroid	0.015%
	Other solid cancer (mainly brain and salivary grand)	0.010%	Other solid (mainly brain and salivary grand)	0.015%
Thorax CT	Lung	0.014%	Breast	0.069%
	Thyroid	0.004%	Lung	0.035%
	Liver or stomach	0.003%	Thyroid	0.021%
Abdomen CT	Colon	0.018%	Lung	0.016%
	Lung	0.006%	Colon	0.012%
	Liver or prostate	0.003%	Breast	0.007%
Pelvis CT	Bladder	0.008%	Bladder	0.008%
	Colon	0.008%	Colon	0.005%

LAR: lifetime attributable risk of cancer incidence.

observed for more than 50 years [26,27]. In addition, this issue is much more critical for children because children are more sensitive to the radiation detriment, and they may undergo more than one scan because of the longer follow up period, thus the accumulated dose can be very high.

Compared to other studies of the similar scanning types in children in the literatures, average effective doses from chest CT and head CT were reported to be 7.42 mSv and 2.6 mSv respectively in Japan for 6-year-old children [28] and in another study, effective doses of about 1.3 mSv from head CT and 2 mSv from thorax CT for 5-year-old children [29]. Both were studied on 4- or 16-slice CT scanners, and are generally higher than our results (except for thorax CT by Huda et al.). Arthurs et al. compared effective dose of thorax CT between 64-slice MDCT scanner and 16-slice scanner and found an effective dose of 1.9 mSv on 64-slice MDCT and 2.1 mSv on 16-slice CT [14], while Fuji et al. reported an effective dose of 3–7 mSv for chest CT and 3–9 mSv for abdominopelvic CT [16]. In the study by Arthurs et al. they concluded that the 64-slice MDCT examinations do not impart a higher effective dose than 16-slice CT examinations, while Fuji et al. declaimed that doses for organs positioned at the boundaries of the scan length were higher with 64-slice MDCT. Generally, the dose depends more on scanning parameters than CT detector array number.

The LAR calculated in our study is in the similar order of magnitude with that reported for pediatric CT examinations in the literatures. The cancer risks from a low-dose chest examination on 16-slice CT for 5-year-old children were about 0.06% [30]. It was reported that the risks from an abdominal CT and a head CT of 1-year-old children performed on single-slice CT scanner was 0.18% and 0.07% respectively; age may have been an important factor causing the risks to be higher in this cohort [31]. Our estimated cancer risks are much lower than the cancer risks associated with cardiac CT examinations, which impart a higher radiation dose. According to our recently published study, LAR of 0.14–0.20% and 0.43–0.60% were associated with coronary CT angiography in 5-year-old boys and girls respectively, and this varied with heart rate [32].

There are some radio-sensitive organs which are not in the field of direct exposure and receiving a lower radiation dose from scatter radiation, but are associated with relatively high LAR. For example, the high thyroid cancer incidence associated with head CT and thorax CT, and relatively high lung and breast cancer incidence caused by abdomen CT (Table 4). In abdomen CT, although only the lung base is exposed directly to radiation, the risk to the lung is high due to the higher baseline cancer incidence compared to the colon [21] and the lung being more sensitive to radiation than the colon according to the cancer risk models in BEIR VII report [12]. It has been suggested that some specific measures should be taken to protect these organs from radiation exposure and it has been reported in the literature that such radiation protection leads to a great reduction in dose. Ngaile et al. reported that lead shields of 0.25 mm thickness reduce the doses to the lens of the eyes and thyroid by 44% and 51% respectively without comprising the image quality in head CT [33].

Our study of dose measurement and cancer risk estimation has some limitations. Firstly, the limitations of dose measurement comes from the inherent variation of TLD-100H dosimeters, TLD chips positioning and the directionality error associated with the edge and surface of TLD (±2%) [34]. Secondly, uncertainties also arise from the method of calculating the effective doses and LAR [21,35]. Our study may underestimate the effective doses, given that the radiosensitivity of pediatric organs and tissues are higher compared to adults. However, reference factors for children of various ages are yet to be developed for use in the determination of separate weighting factors for pediatric individuals [13]. Thirdly, our study was performed using a phantom and a CT scanner from specific vendors, and there may be some variation in the results, albeit probably small, if different vendor equipment were used. Finally, our results are obtained from a 5-year-old phantom only; a complete study of radiation dose in children should include dose measurements for pediatric phantoms of different ages.

In conclusion, our results show that the doses from common pediatric CT examinations using a 64-slice MDCT ranged from 0.7 mSv to 3.5 mSv and the associated lifetime cancer risks were found to be up to 0.16%. This is a potential public health problem if multiplied by the large pediatric population who undergo CT scans. With the proliferation of 64-slice MDCT scanners in hospitals and institutions, pediatricians should be aware of these doses and cancer risks, and benefit-risk should be carefully considered before referring children for CT imaging. Protocols should be tailored to reduce the dose, and protection devices may be considered to prevent unnecessary radiation to some organs.

Conflict of interest

All the authors of the manuscript entitled 'Radiation Dose and Cancer Risk from Pediatric CT Examinations using 64-Slice MDCT: A Phantom Study' declare that there is no conflict of interest with regard to equipment, contrast, drug or other materials described in the study.

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