Estimation of effective doses in pediatric X-ray computed tomography examination

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Received May 19, 2016; Accepted March 23, 2017

DOI: 10.3892/etm.2017.5102

Abstract. X-ray computed tomography (CT) images are used for diagnostic and therapeutic purposes in various medical disciplines. In Japan, the number of facilities that own diagnostic CT equipment, the number of CT examinations and the number of CT scanners increased by ~1.4-fold between 2005 and 2011. CT operators (medical radiological technologists, medical physicists and physicians) must understand the effective doses for examinations at their own institutions and carefully approach each examination. In addition, the patients undergoing the examination (as well as his/her family) must understand the effective dose of each examination in the context of the cumulative dose. In the present study, the numbers of pediatric patients (aged 0-5 years) and total patients who underwent CT at Hirosaki University Hospital (Hirosaki, Japan) between January 2011 and December 2013 were surveyed, and effective doses administered to children aged 0, 1 and 5 years were evaluated. Age- and region-specific conversion factors and dose-length products obtained from the CT scanner were used to estimate the effective doses. The numbers of CT examinations performed in 2011, 2012 and 2013 were 16,662, 17,491 and 17,649, respectively, of which 613 (1.2%) of the overall total involved children aged 0-5 years. The estimated effective doses per examination to children aged 0, 1 and 5 years were 6.3±4.8, 4.9±3.8 and 2.7±3.0 mSv, respectively. This large variation was attributed to several factors associated with scan methods and ranges in actual setting. In conclusion, the requirement for individual patient prospective exposure management systems and estimations of low-dose radiation exposure should be considered in light of the harmful effects of exposure.

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Key words: computed tomography, effective dose, dose-length product conversion factors

Introduction

X-ray computed tomography (CT) is a medical imaging technique in which computer-processed X-ray projections are used to produce tomographic images or slices of specific areas of the body. Since 2000, the importance of multi-detector CT, which permits faster scanning and a wider range of clinical applications, has been recognized (1). According to a report from the Ministry of Health, Labour and Welfare of Japan, the number of facilities that owned diagnostic CT equipment, the number of CT examinations and the number of CT scanners in 2005 were 8,149 [1-month (September) total], 1,634,056 [1-month (September) total] and 8,903 (as of October 1st), respectively (2). By 2011, these numbers had increased to 11,415 [1-month (September) total], 2,357,580 [1-month (September) total] and 12,482 (as of October 1st), respectively (3), demonstrating a ~1.4-fold increase relative to 2005.

A study by Tsushima *et al* (4) indicated that CT is accountable for more than half of the radiation exposure incurred from diagnostic imaging. The authors noted that unfortunately no reliable data regarding radiation exposure from radiological imaging are available; it is expected that the situation in Japan is similar. The International Commission on Radiological Protection (ICRP) developed the 'as low as reasonably achievable' concept to minimize exposure (5). Although the effects of low-dose exposure have not been clarified, various reports have suggested that exposure is carcinogenic (6-8). As pediatric patients are generally highly radiation-sensitive and have a long life expectancy, it is necessary to pay particular attention to their medical exposure. In 2005, the Japan Radiological Society, Japanese Society of Radiological Technology and Japanese Society of Pediatric Radiology published CT guidelines with the intent to reduce CT exposure dose (9). Therefore, the actual pediatric medical exposure derived from CT scans should be estimated.

The present study aimed to clarify the actual radiation exposure incurred by children during CT examinations and the effective doses in various regions, particularly in

children aged 0, 1 and 5 years, using data collected at Hirosaki University Hospital (Hirosaki, Japan) during a 3-year period from January 2011 to December 2013.

Materials and methods

Analysis of CT examination. Data of CT examinations performed at Hirosaki University Hospital from January 2011 to December 2013 were extracted from the hospital's radiology information system (RISE-1 Version 1.1.6.0, PSP Corporation, Tokyo, Japan) and analyzed using a Digital Imaging and Communication in Medicine image viewer (EV Insite Version 2.10.6.45, PSP Corporation). The extracted data included the patient's age, examination region, scan protocols, volume CT dose index ($CTDI_{vol}$) and dose-length product (DLP). Other specific information about each patient was not extracted to avoid a loss of confidentiality. In addition, the original study files were subjected to high security. The files were password-protected for both reading and editing, and only the first author managed the data. Regions on which CT examinations were performed were classified as the head, neck, chest, abdomen, pelvis, coronary and extremity. For example, if one patient had undergone head, abdominal, and pelvic scans, the numbers of patients and regions would be 1 and 3, respectively. Hirosaki University Hospital used the following CT devices for diagnostic radiation: LightSpeed QX/i (GE Healthcare, Waukesha, WI, USA), Discovery CT 750HD (GE Healthcare), SOMATOM Definition (Siemens AG, Erlangen, Germany), SOMATOM Definition AS (Siemens AG) and Aquilion PREMIUM (Toshiba Medical Systems Corp., Otawara, Japan). The present study was approved by the Committee of Medical Ethics of Hirosaki University Graduate School of Medicine (Hirosaki, Japan).

Evaluation of effective doses. Effective doses were calculated using the age-specific and region-specific conversion factors provided in the ICRP Publication 102 (Table I) (10). The effective dose in mSv was calculated by multiplying the conversion factors by the DLP. Although the present study focused on children aged 0-5 years, Publication 102 only provided conversion factors for children aged 0, 1 and 5 years. Therefore, the effective dose evaluation only included children of the following ages: 0 years (up to 11 months after birth), 1 year (up to 1 year and 11 months after birth) and 5 years (up to 5 years and 11 months after birth). The evaluated regions were the head, neck, chest, abdomen and pelvis. Coronary and extremity CT scans were excluded from the evaluation due to a lack of available conversion factors in Publication 102 (10). The clinical scan protocols obtained from the Discovery CT 750HD device, including region, scan type, tube voltage, tube current, noise index, rotation time and pitch are summarized in Table II. The console-displayed $CTDI_{vol}$ was calculated from the mean tube current when the automatic exposure control (AEC) setting on the Discovery CT 750HD was used. Discovery CT 750HD equipment was used for effective dose estimation in the present study. All displayed DLP data were obtained from the Discovery CT 750HD in accordance with the International Electrotechnical Commission 60601-2-44 Ed.3 (11). At that time, patients without displayed DLP data were excluded from the evaluation, as the effective dose could not be calculated. Exposure doses incurred from positioning images (i.e., scout view) were not evaluated in the present study as they differed in terms of concepts of $CTDI_{vol}$ and DLP.

Table I. Age-specific and region-specific conversion factors derived from the International Commission on Radiological Protection Publication 102.

	Patient age, years		
Region	0	1	5
Head	0.0110	0.0067	0.0040
Neck	0.0170	0.0120	0.0110
Chest	0.0390	0.0260	0.0180
Abdomen	0.0490	0.0300	0.0200
Pelvis	0.0490	0.0300	0.0200

To confirm the accuracies of the displayed $CTDI_{vol}$ and DLP, it was necessary to compare the measured $CTDI_{vol}$ and DLP. The measured $CTDI_{vol}$ value of each protocol was measured using a 9015 dosimeter and 10X5-3CT chamber (Radcal Corp., Monrovia, CA, USA). A CTDI phantom (16-cm diameter, IBA Dosimetry GmbH, Schwarzenbruck, Germany) was placed on urethane foam at the CT gantry opening to eliminate an influence of the couch. Each measurement was repeated three times per measurement position (center and four peripheral points) on the Discovery CT 750HD, using scan parameters similar to the clinical protocols (Table II). The $CTDI_{vol}$ was calculated using corrected temperature and pressure values, a calibration constant, W-value, beam width, gantry rotation number and pitch. The DLP (mGy x cm) was calculated by multiplying the measured $CTDI_{vol}$ (mGy) by the scan range (cm). These calculations were based on Publication 102 (10). The scan protocols in the present study were subjected to the 16-cm phantom. As ~50% of the pediatric radiological examination data were obtained with 750HD and the differences between the measured $CTDI_{vol}$ and DLP and console-displayed $CTDI_{vol}$ and DLP had a minimum value of <2.4%, the following analysis only used examination data obtained with the 750HD.

The advantages of this effective dose estimation method included its user-friendliness and ready availability for estimating pediatric effective CT doses, particularly in diagnostic facilities without specialized equipment, application tools and knowledge. However, the effective doses obtained with this method did not consider each individual patient, and so the effective doses are a reference value (10), that yield normalized effective doses.

Statistical analysis. Normality tests of the data was performed using the χ^2 goodness of fit test to confirm that they were non-parametric data. Significant differences within groups were determined using Kruskal-Wallis tests. The statistical significances of differences among multiple groups were assessed using the Steel-Dwass test for non-parametric multiple comparisons. All statistical analysis were calculated using Excel 2010 Version 14.0.7177.5000 (Microsoft Corp., Redmond, WA, USA) with the Statcel 3 add-on package (OMS

Table II. Discovery Computed Tomography 750HD scan protocol used for effective dose estimation.

			Scan parameter						
Protocol	Region	Scan type	Tube voltage, kV	Tube current, mA	Set min mA[a]	Set max mA[a]	Noise index	Rotation time, sec	Slice thickness, mm	Beam collimation, mm	Pitch
Clinical	Head	Axial	120	AEC	50	400	3.5	0.5	5	20	-
		Helical	120	AEC	50	400	3.5	0.5	5	20	0.969
	Neck, chest	Helical	80, 100	AEC	40	100, 150, 200	10.97, 11.97	0.4	5	20	0.969
	Abdomen, pelvis	Helical	80, 100	AEC	30	80, 100, 120	10.97	0.5	5	20	0.969
Measurement	Head	Axial	120	50, 100, 150	-	-	-	0.5	5	20	-
		Helical	120	50, 100, 150	-	-	-	0.5	5	20	0.969
	Neck, chest, abdomen, pelvis	Helical	80, 100	100, 200	-	-	-	0.4	5	20	0.969

[a]Range setting of the tube current was determined by the minimum and maximum tube currents. Axial, non-helical scan; AEC, automatic exposure control.

Figure 1. Age distribution of computed tomography examinations at Hirosaki University Hospital (Hirosaki, Japan) during a 3-year period from 2011 to 2013. The median age was 65 years.

publishing Inc., Saitama, Japan). Data were presented as the mean ± standard deviation. P<0.05 was considered to indicate a statistically significant difference.

Results

Number of CT examinations. In 2011, 2012 and 2013, 16,662, 17,491 and 17,649 CT examinations were performed, respectively, for a total of 51,802 examinations during the 3-year period. All examinations were classified as follows: Children aged 0-5 years were classified into one group, and all other older subjects were classified into 5-year categories up to >96 years (Fig. 1). The median age was 65 years, and a large proportion of the patients' ages ranged from 61-80 years, with 7,381 and 6,650 cases in the 61-65 and 76-80 year groups, respectively. In total, 613 cases (1.2%) involved children aged 0-5 years. The numbers of CT examinations per region and age group are summarized in Table III.

Estimated effective doses in children. As previously mentioned, although the present study focused on an analysis of children aged 0-5 years (total 613 cases), conversion factors from Publication 102 were only available for ages 0, 1 and 5 years. The present study therefore only evaluated the effective dose for these ages. The effective dose evaluation targeted the 173 cases subjected to diagnostic radiology using the Discovery CT 750HD. The effective doses incurred by children aged 0-5 years are demonstrated in Fig. 2, and the number of examinations are presented in Table IV. The effective dose distribution per examination at each age ranged from 0.66-28.8 mSv, with a mean ± standard deviation of 5.5±4.5 mSv. Patients with 0.66 mSv of exposure underwent only plain imaging from the neck to chest. In contrast, patients who received an estimated exposure of 28.8 mSv underwent both plain and contrast imaging from the head to pelvis. In the present study, the effective doses at each age ranged from 2.7±3.0 mSv (5 years group) to 6.3±4.8 mSv (0 years group). The effective doses received by 5-year-old patients differed significantly from those of the other age groups (P<0.01). Subsequently, the effective doses in each region were

Table III. Number of computed tomography examination regions among children aged 0-5 years.

Age, years	Number of patients	Region, n							Total regions
		Head	Neck	Chest	Abdomen	Pelvis	Coronary	Extremity	
0	221	110	40	108	103	44	0	1	406
1	104	55	23	40	44	28	0	0	190
2	56	30	8	18	25	15	0	2	98
3	73	27	11	25	37	23	0	1	124
4	78	39	20	32	30	19	0	0	140
5	81	36	24	32	29	17	1	1	140
Total	613	297	126	255	268	146	1	5	1,098

Table IV. Number of computed tomography examination regions for effective dose estimation.

Age, years	Number of patients	Region, n					Total regions
		Head	Neck	Chest	Abdomen	Pelvis	
0	104	69	20	56	58	26	229
1	48	32	8	16	23	17	96
5	21	15	5	6	5	5	36
Total	173	116	33	78	86	48	361

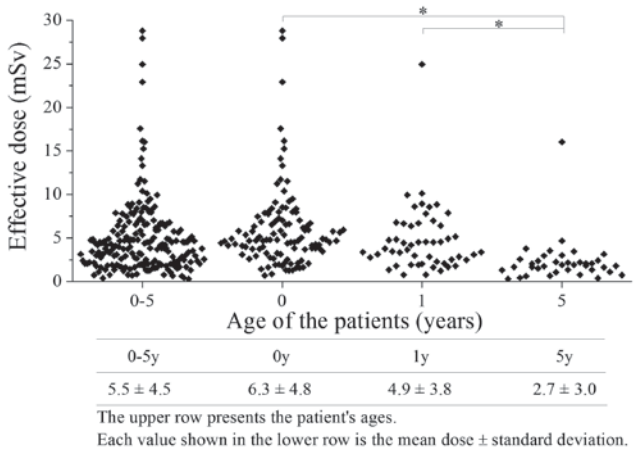


Figure 2. Estimated effective computed tomography examination doses in children aged 0, 1 and 5 years. Black dots represent each effective dose. *P<0.01.

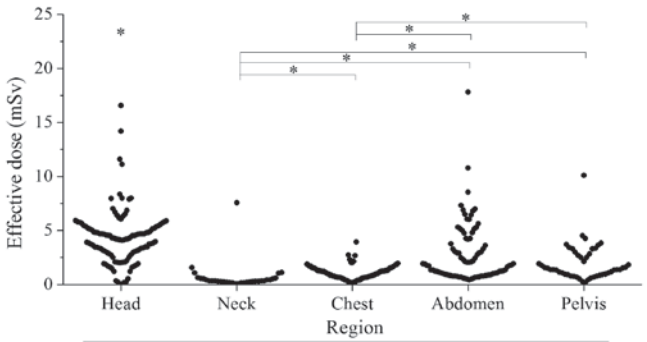
compared in each age group. In Fig. 3, the effective dose to the head (4.3±2.5 mSv) was significantly higher than the doses to the neck (0.60±1.3 mSv), chest (1.1±0.7 mSv), abdomen (2.8±2.7 mSv) and pelvis (2.0±1.6 mSv; P<0.01). Similarly, the effective dose to the abdomen was significantly higher than those to the neck and chest (P<0.01). The effective dose to the neck demonstrated the lowest value of all regions evaluated.

The effective doses per region in each age group are demonstrated in Fig. 4. The dose to each of the 5 regions differed according to the age group. In 0- and 1-year-old children, the effective doses to the head (5.1±2.4 and 3.5±2.6 mSv, respectively) were significantly higher than those to the neck of the 0 year group (0.40±0.26 mSv; P<0.01), chest of the 0- and 1-year old children (1.2±0.71 and 0.94±0.54 mSv, respectively) and pelvis of the 0- and 1-year old children (2.3±2.0 and 1.5±0.88 mSv, respectively; P<0.01). At all ages, the doses to the neck and chest tended to be lower than those of other regions. In the head, chest and pelvis, the conversion factors indicated reduced values with younger ages; a similar trend was observed for the effective doses.

Discussion

The present study aimed to clarify the actual dose of pediatric radiation exposure incurred during CT examinations and the effective doses to various regions, particularly in children aged 0, 1 and 5 years, using data collected at Hirosaki University Hospital during a 3-year period from January 2011 to December 2013. The proportions of children aged 0-5 years among patients aged 0-15 years who were examined by CT at the Nagasaki University Hospital (Nagasaki, Japan) in 2004 were ~9.5, 5.1, 4.9, 2.9, 4.9 and 4.5%, respectively (12). In the present study, the corresponding proportions were 11.1, 5.2, 2.8, 3.7, 3.9 and 4.1%, respectively. Although the target age differed, the proportion of CT examinations in the 0-year group was significantly higher than that in the 1-5 year groups.

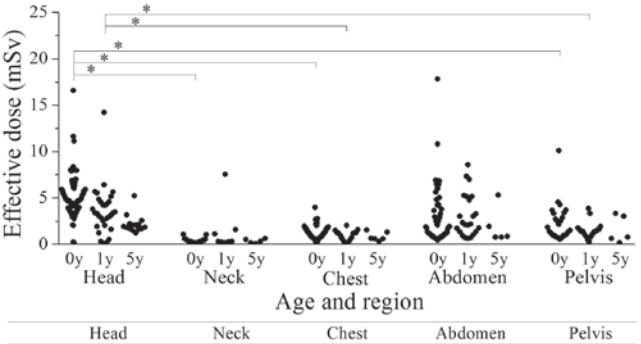
The mean effective dose per examination among children aged 0, 1 and 5 years was 5.5±4.5 mSv. Furthermore, the estimated effective doses to the head, chest and abdomen were 4.3, 1.1 and 2.8 mSv, respectively. A study by Thomas



Head	Neck	Chest	Abdomen	Pelvis
4.3 ± 2.5	0.6 ± 1.3	1.1 ± 0.7	2.8 ± 2.7	2.0 ± 1.6

The upper row presents the CT examination regions.
Each value shown in the lower row is the mean dose ± standard deviation.

Figure 3. Estimated effective doses according to region. Black dots represent each effective dose. *P<0.01; Head vs. all other regions.



	Head	Neck	Chest	Abdomen	Pelvis
0y	5.1 ± 2.4	0.4 ± 0.3	1.2 ± 0.7	2.8 ± 3.0	2.3 ± 2.0
1y	3.5 ± 2.6	1.5 ± 2.4	0.9 ± 0.5	3.1 ± 2.3	1.5 ± 0.9
5y	2.2 ± 0.9	0.3 ± 0.2	0.8 ± 0.4	1.9 ± 1.7	1.6 ± 1.3

The upper row lists the regions, and the left column presents the patient's ages.
Each data value is expressed as a mean dose ± standard deviation.

Figure 4. Estimated effective doses according to each age and region. Black dots represent each effective dose. *P<0.01.

and Wang (12) reported that an 0-year old patient would incur mean effective doses to the head of 4.2 mSv, following a single same-region scan in one examination, and 9.1 mSv following two same-region scans in one examination. According to the Japanese pediatric CT guidelines, the effective doses from the reference CT protocol for infants were 3.4 (male) and 3.9 mSv (female) to the chest, 8.8 (male) and 11.9 mSv (female) to the abdomen (100 kV multiplied by 0.63) (9). In children, the effective doses according to the reference CT protocol were 2.1 (male) and 2.5 mSv (female) to the chest, and 7.0 (male) and 8.7 mSv (female) to the abdomen (100 kV multiplied by 0.63) (9). Previously reported doses incurred by other age and region groups were higher than those observed in the present study (12). Therefore, the mean effective doses to all regions in the present study were similar to or lower than the reference and effective doses described in other reports.

Accordingly, in the present study, the results varied widely across all ages and between some regions. Pediatric CT employs a wide range of effective doses, ranging from specific ultralow-dose protocols (<1 mSv) to the extended-coverage body examinations often used for follow-up imaging in oncology and detailed examinations (>810 mSv) (12). A 44-fold difference in the effective dose was observed in the present study. Within each group, the range of effective doses was larger than we had anticipated. Several factors likely contributed to this discrepancy. The first factor encompasses scan methods and ranges. The variation would therefore result from the use of either plain or contrast imaging alone or together, or multiple-phase imaging. Secondly, single-region examinations affected adjacent regions in the cranio-caudal direction, for example, a chest examination may have also included part of the abdomen (liver, spleen, and kidney); therefore, such cases were also counted as abdominal exposure with respect to effective dose and number. In the present study, even scans with small ranges were classified according to region and were included in the calculations. Some variability in scan length may be expected due to of operator variability, and body examinations vary according to patient height. Such variability was most often encountered in head CT scans, where selected axial images were occasionally repeated if patient motion had significantly degraded the image quality. Also, for head and neck scans, neck images were obtained using the same scan parameters as the head. As a result, large variation occurred in these cases. Furthermore, each age group may include considerable ranges in patient height and weight. Tube current with AEC was determined by calculating the body thickness and size from positioning images. The present study elected to include these patients in the study as the purpose was to reflect actual situations and effective doses.

The displayed DLP conversion factor-based methodology used in the present study demonstrated some limitations and issues. According to a study by Kobayashi *et al* (13), effective doses estimated using conversion factors differed from the measured doses by 20%, even in the simplest scans. Patients who underwent coronary artery and extremity CT evaluations were excluded from the present study as conversion factors have not been reported for these regions (14). Although AEC is applied to optimize the dose to the body size, the displayed $CTDI_{vol}$ would cause uncertainty by averaging the tube current value. Therefore, it is difficult to indicate an assessed dose that is suitable for a particular body size using the effective doses in the present study, as these effective doses are reference value, specifically normalized effective doses (10).

Despite these limitations, the simple approach used in the present study to estimate the radiation exposure from CT examinations is adequate for current data and technology (13,15). The effectiveness of diagnostic imaging is widely and generally known, and the number of CT scanners may be used as an index of hospital quality (1). Compared with other countries, Japanese patients expect higher levels of medical care and seek treatment at hospitals owning CT scanners (1). The strength of the displayed DLP conversion factor-based method is readily available to all radiologists, clinicians and technologists. Furthermore, this method may be used to contribute to pediatric CT examination and diagnostic reference level surveys.

In Japan, no official system is responsible for the quality control of CT examinations and patient radiation exposure (4). In addition, it is difficult to accurately quantify the CT risk level that would require long-term follow-up of a majority of patients (16,17). Reports concerning risks and CT doses have indicated a low level of awareness and knowledge among

medical staff (18,19). The present study may allow medical staff to understand and recognize the significance of a wide effective dose range that encompasses specific low-dose protocols to extended-coverage body scans. In addition, this effective dose estimation method may serve as an important reference value that allows specific values for effective doses to be obtained, and includes the advantage of being a user-friendly and rapidly available method for the estimation of pediatric CT effective doses, particularly in diagnostic facilities without specialized equipment, application tools, and/or knowledge. In conclusion, it is necessary to consider the requirement for a prospective exposure management system in each patient, as well as the estimation of each patient's low-dose radiation exposure (20,21). The introduction of a cancer registration according to medical exposure and a resulting medical exposure dose management system would leave a great legacy for future generations.

Acknowledgements

The present study was supported by Hirosaki University Institutional Research (2012, IK).

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