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Radiation dose evaluation in 64-slice CT examinations with adult and paediatric anthropomorphic phantoms

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ABSTRACT. The objective of this study was to evaluate the organ dose and effective dose to patients undergoing routine adult and paediatric CT examinations with 64-slice CT scanners and to compare the doses with those from 4-, 8- and 16-multislice CT scanners. Patient doses were measured with small (<7 mm wide) silicon photodiode dosemeters (34 in total), which were implanted at various tissue and organ positions within adult and 6-year-old child anthropomorphic phantoms. Output signals from photodiode dosemeters were read on a personal computer, from which organ and effective doses were computed. For the adult phantom, organ doses (for organs within the scan range) and effective doses were 8–35 mGy and 7–18 mSv, respectively, for chest CT, and 12–33 mGy and 10–21 mSv, respectively, for abdominopelvic CT. For the paediatric phantom, organ and effective doses were 4–17 mGy and 3–7 mSv, respectively, for chest CT, and 5–14 mGy and 3–9 mSv, respectively, for abdominopelvic CT. Doses to organs at the boundaries of the scan length were higher for 64-slice CT scanners using large beam widths and/or a large pitch because of the larger extent of over-ranging. The CT dose index ($CTDI_{vol}$), dose–length product (DLP) and the effective dose values using 64-slice CT for the adult and paediatric phantoms were the same as those obtained using 4-, 8- and 16-slice CT. Conversion factors of DLP to the effective dose by International Commission on Radiological Protection 103 were 0.024 $mSv \cdot mGy^{-1} \cdot cm^{-1}$ and 0.019 $mSv \cdot mGy^{-1} \cdot cm^{-1}$ for adult chest and abdominopelvic CT scans, respectively.

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X-ray CT scanners have made remarkable advances over the past few years, contributing to the improvement of diagnostic image quality and the reduction of examination time. CT scanners with 64 slices, the clinical use of which started quite recently in many medical facilities, has enabled a large number of thin slices to be acquired in a single rotation. 64-slice CT technology accelerated the practical use of three-dimensional body imaging techniques such as coronary CT angiography and CT colonography with an increasing number of CT examinations. The increase in CT examination frequency not only for adults but also for children and the higher doses in CT examinations compared with other X-ray diagnostic procedures have raised concerns about patient doses and safety. An understanding of patient doses requires the evaluation of organ and effective doses for patients undergoing CT examinations, although these dose values in 64-slice CT scans have seldom been reported.

One common method for estimating organ and effective doses is dose calculation from the CT dose index (CTDI) or dose–length product (DLP), which are both used as readily available indicators of radiation dose in CT examinations. Organ and effective doses can be estimated from the CTDI or DLP, and conversion factors derived from Monte Carlo simulation of photon interactions within a simplified mathematical model of the human body [1]. Another method is based on measurement using thermoluminescence dosemeters (TLDs) implanted in various organ positions within an anthropomorphic phantom [2–6]. Although TLD dosimetry is considered to be the standard method for measuring absorbed doses in a phantom, the dose measurement is laborious and time consuming. Hence, we devised an in-phantom dosimetry system using silicon photodiode dosemeters implanted in various organ positions, where absorbed dose at each position could be read electronically. In the present study, we evaluated organ and effective doses with 64-slice CT scan protocols used clinically for adult and paediatric patients undergoing chest and abdominopelvic CT examinations. We compared the doses with published dose values for 4-, 8- and 16-slice CT, and indicated the conversion factor of DLP to the effective dose in each examination of the chest and abdomen–pelvis for 64-slice CT scanners.

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Methods and materials

Adult and paediatric phantom dosimetry systems

Adult and paediatric anthropomorphic phantoms, in which small silicon photodiode dosemeters were

implanted, were used for dose measurements in CT examinations. The photodiodes used were planar silicon pin-photodiodes: Hamamatsu S2506-04 (Hamamatsu Photonics, Hamamatsu, Japan) with a sensitive area of 2.8×2.8 mm^2 for the adult phantom, and Hamamatsu S8385-04 with an area of 2.0×2.0 mm^2 for the paediatric phantom. Construction detail and the characteristics of the dosemeters were fully described by Aoyama et al [7]. For the paediatric phantom, dosemeters made of a silicon spherical photodiode with a diameter of 2.4 mm (Kyosemi KSPD1840C2; Kyosemi Corporation, Kyoto, Japan) were also used [8], but were replaced by the former dosemeters made of planar silicon pin-photodiodes (Hamamatsu S8385-04) after the first CT dose measurements for the Siemens CT scanner because of the improvement in minimum detectable dose.

Dose calibration of these dosemeters for various effective X-ray energies was performed against Radcal 1015 and 9015 ion chamber dosemeters (Radcal Corporation, Monrovia, CA) which were traceable to a national standard. The values of exposure in Roentgen or Coulomb per kilogram obtained with the ion chamber dosemeter were converted to the values of absorbed dose for soft tissue by using the ratio of mass energy absorption coefficient of ''tissue, soft'' (International Commission on Radiation Units and Measurements (ICRU) 44) [9] to that of ''air, dry (near sea level)'' [9] at the effective energy of X-rays used. The X-ray energy dependence of dosemeter sensitivity was measured with aluminium filters attached to the window of the X-ray tube at a tube voltage of 120 kV used in our CT scans. This energy response could be utilised to derive conversion factors to convert output voltage from photodiode dosemeters to absorbed dose for soft tissue at the effective energy of X-rays used, where the conversion factors are the reciprocal of dosemeter sensitivity.

The adult and paediatric anthropomorphic phantoms used are shown in Figure 1; the phantoms were manufactured by Kyoto Kagaku (Kyoto, Japan). The adult phantom, which is a human torso phantom, represented a standard Japanese adult male 60 kg in weight and 170 cm tall. The paediatric phantom modelled a standard Japanese 6-year-old child, 20 kg in weight and 115 cm tall; the weight and height were one-third and two-thirds, respectively, of the adult phantom. These phantoms — consisting of three types of tissue substitute corresponding to soft tissue, cortical bone and lung — were used to represent a male and a female; for the latter, the adult phantom had a left breast attached externally. 32 dosemeters were installed at the positions of various tissues and organs assigned in the definition of the effective dose by International Commission on Radiological Protection (ICRP) 103 [10]; these positions are given in Table 1. Two extra dosemeters were attached to the front and the side of the phantoms in the CT scan area to estimate the skin dose.

Evaluation of organ and effective doses

Output voltage signals generated from 32 (and an extra 2) photodiode dosemeters were read on a personal computer through analogue-to-digital converters and

Figure 1. Adult phantom (left) and paediatric phantom (right) dosimetry systems. Seen with the phantoms are twisted carbon-fibre cables derived from photodiode dosemeters embedded within the phantoms.

were then converted to absorbed doses for soft tissue; the conversion factor was estimated for each dosemeter separately at the effective energy of X-rays used.

Minimum detectable dose was estimated to be 0.02 mGy and 0.1 mGy for the planar and spherical photodiode dosemeters, respectively [7, 8]. Overall

Table 1. Number of photodiode dosemeters implanted in each position of tissues and organs required for the effective dose evaluation according to ICRP 103

Tissue or organ	Number of dosemeters	
	Adult	Child
Bone marrow	8	13
Colon	5	4
Lung	2	2
Stomach	1	1
Breast	1	1
Remainder tissues	11[a]	11[a]
Gonads		
Testes	1	1
Ovaries	1	1
Bladder	1	1
Oesophagus	2	2
Liver	2	2
Thyroid	1	1
Bone surface	10	13
Brain	0	2
Salivary glands	0	1
Skin	2[b]	2[b]

ICRP, International Commission on Radiological Protection.
[a]Dosemeters implanted in each position of the adrenals, extrathoracic region, gallbladder, heart, kidneys, pancreas, prostate, small intestine, spleen, thymus and uterus/cervix.
[b]Extra dosemeters externally attached to the surface of the phantom.

uncertainty, including both random and systematic errors that arose in the conversion from measured output voltage of the photodiode dosemeters to absorbed dose, was estimated to be 7% at the 95% confidence level.

Absorbed dose for soft tissue was adopted for all tissues and organs except for the breast and bone surface, as mass energy absorption coefficients for these tissues and organs, including red bone marrow, were within 5% at a diagnostic X-ray energy of >30 keV [9, 11]. The dose for breast tissue was evaluated to be the dose for soft tissue at the position of the breast multiplied by the ratio of the mass energy absorption coefficient of breast tissue to soft tissue; dose evaluation for the bone surface was described by Fujii et al [8]. Doses for the brain and salivary glands, and also for oral mucosa in adult CT scans, which could not be measured because of the headless phantom used, were assumed to be zero, as the minimum distances from the primary X-ray beam to the brain, salivary gland and oral mucosa were 18–22 cm, 8–10 cm and 8 cm, respectively, on adult chest CT. Organ doses are referred to the mean absorbed dose for a specific organ, the evaluation of which is fully described by Seguchi et al [12] and Fujii et al [8].

The effective dose was evaluated according to ICRP 103, where the dose was given as an average value between male and female. The effective dose by ICRP 60 [13] was also evaluated to compare the present dose levels with those in the literature, where ''the remainder'' were those categorised by ICRP 60 in this case.

CT scanners

Doses for adult and paediatric patients were measured with different types of 64-slice CT scanners from worldwide manufactures, *i.e.* Toshiba (Toshiba Medical Systems, Otawara, Japan), GE (GE Medical Systems, Milwaukee, WI), Siemens (Siemens AG, Erlangen, Germany) and Philips (Philips Medical Systems, Eindhoven, the Netherlands). The identification letters A to D were in turn assigned to these CT scanners, which were used in different medical facilities. All of these were equipped with automatic tube current modulation (ATCM) systems. The systems named ''Volume EC'' (Toshiba), ''Smart mA'' (GE Medical Systems) and ''Care Dose 4D'' (Siemens) for each scanner of A, B and C utilised combined longitudinal and angular tube current modulation mechanisms [14–16]. These systems vary tube current along the longitudinal direction (z-axis) of the CT scanner and at each projection angle of X-ray tube rotation according to the X-ray attenuation in the patient. The scanner D was equipped with another angular tube current modulation system named ''D-DOM'' (Philips); this system continuously varied the tube current at each projection angle after determination of the maximum tube current from a single localiser radiograph [15–17].

Organ and effective doses for chest CT and abdominopelvic CT examinations were evaluated using the adult and the paediatric phantom dosimetry systems and routinely used scan parameters in each medical facility; scan parameters are shown in Tables 2 and 3. For scanners A, B and C, tube current modulation systems were used in chest CT and abdominopelvic CT examinations. For scanner D, although adult CT scans were performed with the ATCM system, paediatric CT scans were carried out with constant tube current, whereby the tube current was selected manually by a radiological technologist according to the bodily habitus of the patient.

The scan range in chest CT scans was from the upper end of the lung apex to the lower region of the diaphragm, and that in abdominopelvic CT scans was from the upper region of the diaphragm to the pubic symphysis. Scan lengths in each CT scan were nearly constant among medical facilities.

Effective dose estimation from displayed $CTDI_{vol}$ and DLP

Dose indicator $CTDI_{vol}$ was recorded directly from the console display at the time of CT scan with modern CT scanners, and the value was referenced to polymethyl methacrylate cylindrical phantoms, which were 16 cm or 32 cm in diameter. In trunk CT examinations, $CTDI_{vol}$ values for a 32 cm diameter phantom should be displayed in adult CT scans, and a 16 cm diameter phantom in paediatric CT scans. However, all $CTDI_{vol}$ values displayed in our dose measurements using the paediatric phantom corresponded to those for the 32 cm phantom owing to the large field of view used. CT scanners B, C and D reported the mean $CTDI_{vol}$ values for adult and paediatric CT examinations with ATCM, and scanner A reported the maximum values. Hence, the mean $CTDI_{vol}$ for scanner A was estimated from the ratio of tube current between the maximum and the mean value.

DLPs were also displayed for scanners A, B and D. For scanner C, DLPs were estimated from the product of the displayed $CTDI_{vol}$ and exposed scan length, as DLPs were not displayed. The exposed scan length (L) is given by the equation:

$$L = \frac{T}{t_{\mathrm{rot}}} \times p \times \mathrm{BW} \qquad (1)$$

where T is the total scan time, t_{rot} the rotation time, p the pitch factor and BW the nominal value of the beam width. The estimated DLP values for CT scanners coincided with the displayed values to within 6%. We investigated the relationship between the DLP and the effective dose.

Results

Tables 2 and 3 show the organ and effective doses for adult and paediatric patients in routine chest CT and abdominopelvic CT examinations performed with 64-slice CT scanners where the effective doses were evaluated according to ICRP 103 and ICRP 60. CT scan parameters shown in Tables 2 and 3 were those routinely used in each medical facility, and which are widely used in Japan. In chest CT scans, organ doses for organs within the scan range were 4–17 mGy for the paediatric phantom and 8–35 mGy for the adult phantom. In abdominopelvic CT scans, organ doses for organs within

Table 2. Organ dose (mGy) and effective dose (mSv) obtained in routine adult and paediatric chest CT examinations with 64-slice CT scanners

	Adult CT				Paediatric CT			
CT scanner	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
Tube voltage (kV)	120	120	120	120	120	120	120	120
The method of tube current adjustment	Volume EC	Smart mA	Care Dose 4D	D-DOM	Volume EC	Smart mA	Care Dose 4D	Fixed (203 mA)
Effective mAs[a]	186	134	266	112	37	28	116	100
Rotation time (s rotation^{-1})	0.5	0.4	0.5	0.5	0.5	0.4	0.33	0.5
Beam width (mm)	0.5 mm × 64	0.625 mm × 64	0.6 mm × 32	0.625 mm × 64	1.0 mm × 32	0.625 mm × 32	0.6 mm × 32	0.625 mm × 64
Pitch factor	0.828	1.375	1.0	1.015	1.406	1.375	1.0	1.015
Planned scan length (mm)	305	300	300	260	205	200	186	190
Exposed scan length (mm)	360	371	332	325	300	234	218	260
Tissue or organ	**Organ dose (mGy)**				**Organ dose (mGy)**			
Brain[b]	–	–	–	–	0.3	0.1	0.5	0.6
Lens[b]	–	–	–	–	0.1	<0.1	0.3	0.3
Salivary glands[b]	–	–	–	–	4.1	0.5	1.6	3.8
Thyroid	19.9	34.8	26.8	17.2	8.5	6.4	17.0	13.5
Lung	32.4	16.5	31.2	12.1	8.8	4.9	16.1	12.6
Breast	23.6	11.3	18.4	8.2	8.4	4.1	12.5	12.0
Oesophagus	29.1	15.7	28.5	10.8	8.3	3.6	14.3	12.1
Liver	27.7	9.7	19.7	10.7	7.7	4.1	12.3	12.2
Stomach	31.0	11.8	16.6	12.0	7.7	1.6	3.4	6.5
Colon	3.1	1.7	1.7	1.1	0.9	0.3	0.8	1.1
Ovaries	0.2	0.1	0.2	0.1	0.2	0.1	0.3	0.4
Bladder	0.1	0.1	0.1	<0.1	0.1	<0.1	0.2	0.2
Testes	0.1	<0.1	0.1	<0.1	0.1	<0.1	0.2	0.1
Bone surface	17.8	9.5	14.4	5.7	10.0	4.7	12.3	11.4
Red bone marrow	12.0	7.5	12.4	3.9	2.7	1.4	4.5	3.8
Skin	4.8	2.1	3.5	2.0	1.0	0.7	1.8	2.0
ICRP 103								
Remainder tissues	17.6	10.1	14.1	7.7	6.3	3.1	7.5	7.5
Effective dose (mSv)	17.7	9.6	14.5	7.0	5.4	2.5	7.3	6.9
ICRP 60								
Remainder tissues	15.9	7.6	11.8	5.8	5.5	2.3	5.1	5.5
Effective dose (mSv)	15.5	8.6	12.9	6.2	4.5	2.1	6.2	5.8
$CTDI_{vol}$ (mGy)	18.7	11.8	19.2	8.8	3.5	2.5	6.7	5.9
DLP (mGy cm)	672	436	635	286	104	59	146	153

CTDI, CT dose index; DLP, dose–length product; ICRP, International Commission on Radiological Protection.

[a] $\text{Effective mAs} = \dfrac{\text{Average tube current} \times \text{rotation time}}{\text{Pitch factor}}$

[b] Doses not measured for the adult phantom were assumed to be zero.

Table 3. Organ dose (mGy) and effective dose (mSv) obtained in routine adult and paediatric abdominopelvic CT examinations with 64-slice CT scanners

	Adult CT				Paediatric CT			
CT scanner	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
Tube voltage (kV)	120	120	120	120	120	120	120	120
The method of tube current adjustment	Volume EC	Smart mA	Care Dose 4D	D-DOM	Volume EC	Smart mA	Care Dose 4D	Fixed (203 mA)
Effective mAs[a]	208	124	251	247	43	28	90	100
Rotation time (s rotation^{-1})	0.5	0.5	0.5	0.5	0.5	0.5	0.33	0.5
Beam width (mm)	1.0 mm × 32	0.625 mm × 64	0.6 mm × 32	0.625 mm × 64	1.0 mm × 32	0.625 mm × 32	0.6 mm × 32	0.625 mm × 64
Pitch factor	0.844	0.984	1.0	0.641	1.406	1.375	1.0	1.015
Planned scan length (mm)	440	420	460	425	260	280	275	260
Exposed scan length (mm)	497	488	492	482	355	314	308	325
Tissue or organ	**Organ dose (mGy)**				**Organ dose (mGy)**			
Brain[b]	–	–	–	–	0.1	<0.1	0.1	0.1
Lens[b]	–	–	–	–	<0.1	<0.1	0.1	0.1
Salivary glands[b]	–	–	–	–	0.1	<0.1	0.1	0.2
Thyroid	0.5	0.3	0.6	0.7	0.6	0.1	0.5	0.5
Lung	12.0	7.4	12.7	12.3	6.5	2.1	6.4	6.8
Breast	17.9	11.3	14.9	16.1	10.0	0.6	3.8	7.3
Oesophagus	13.6	5.9	12.6	13.3	6.1	1.8	6.3	6.4
Liver	27.1	11.5	21.9	24.9	8.5	4.5	12.2	12.2
Stomach	31.0	11.9	22.2	29.6	7.9	4.6	12.3	13.7
Colon	31.3	15.1	23.9	26.6	8.2	5.4	12.2	13.1
Ovaries	31.1	19.6	28.7	22.9	8.1	5.2	12.3	11.2
Bladder	32.6	17.3	27.5	20.1	8.6	5.2	11.3	11.3
Testes	21.0	6.5	7.2	10.3	6.5	3.2	3.7	8.9
Bone surface	29.4	17.8	23.4	21.2	10.1	4.4	9.7	8.2
Red bone marrow	14.4	8.2	12.6	11.8	4.1	1.8	4.8	3.9
Skin	5.8	4.0	5.0	6.1	1.0	1.2	2.0	2.5
ICRP 103								
Remainder tissues	21.3	9.9	16.5	19.1	6.2	3.4	8.7	8.7
Effective dose (mSv)	20.7	10.3	16.6	17.8	6.8	3.0	7.8	8.5
ICRP 60								
Remainder tissues	22.1	9.7	16.8	19.7	6.1	3.4	8.8	8.7
Effective dose (mSv)	21.9	10.7	17.2	18.0	6.8	3.3	8.1	8.9
$CTDI_{vol}$ (mGy)	22.9	10.3	18.1	17.6	4.2	2.2	5.2	5.9
DLP (mGy cm)	1138	503	891	848	148	69	160	192

CTDI, CT dose index; DLP, dose–length product; ICRP, International Commission on Radiological Protection.

[a] $\text{Effective mAs} = \dfrac{\text{Average tube current} \times \text{rotation time}}{\text{Pitch factor}}$

[b] Doses not measured for the adult phantom were assumed to be zero.

the scan range were 5–14 mGy for the paediatric phantom and 12–33 mGy for the adult phantom. In paediatric CT scans, organ doses for organs within the scan range were lower, by factors of 2–5 in chest CT and 2–4 in abdominopelvic CT scans, than those in adult CT scans, except for chest CT with scanner D. For chest CT using scanner D, paediatric doses were the same as adult doses because of the similar effective mAs (tube current–time product divided by pitch factor) used in both paediatric and adult CT scans. Dose variation among CT scanners was thought to be caused by the variation in effective mAs with a constant tube voltage (120 kV in this case). The variation in effective mAs would depend on the difference in acceptable diagnostic image quality required for each CT scanner and at each medical facility.

Discussion

Effect of over-ranging to organ doses

Over-range length was found to increase with beam width and/or pitch factor, where over-range length is taken to be the difference between the exposed scan length and the planned scan length. It can be seen from Tables 2 and 3 that, in adult CT scans with 64-slice CT, over-range lengths were 55–71 mm for beam widths of 32–40 mm and 32 mm for a beam width of 19.2 mm. In paediatric CT scans, the longest over-range length was 95 mm for scanner A with a beam width of 32 mm because of its large pitch factor. Over-ranging contributed to the increase in doses to organs and tissues positioned at the boundaries of the scan length. In paediatric chest CT, doses to the salivary glands and stomach were higher for scanner A with a large pitch factor and longest over-range length of 95 mm and for scanner D of large beam width and the second longest over-range length of 70 mm than those for scanners B and C. In paediatric abdominopelvic CT, relatively high doses to the breast and testes were observed for scanners A and D.

To evaluate the effect of beam width and pitch factor on over-ranging, we compared the doses in adult and paediatric CT protocols with a large beam width and large pitch factor with those with a small beam width and small pitch factor at a constant tube voltage, effective mAs, slice width, reconstruction image thickness and planned scan length. Tables 4 and 5 show doses for organs and tissues positioned within, and at the boundaries of, the scan length in chest CT and abdominopelvic CT examinations obtained with CT scanner A. As seen in Table 4, doses for the salivary glands and stomach in paediatric chest CT with a beam width of 32 mm and a pitch factor of 1.406 were 5.2 mGy and 3.4 mGy, respectively, which were larger than those for CT with a beam width of 16 mm and a pitch factor of 0.9375. In Table 5, it can be seen that doses for the breast and testes in abdominopelvic CT with a large beam width and large pitch factor were higher by 7.3 mGy and 13.0 mGy, respectively, for the adult protocol, and 4.7 mGy and 5.0 mGy, respectively, for the paediatric protocol than those with a small beam width and small pitch factor. Higher doses for these organs with a large beam width and large pitch factor would indicate that they were caused by the larger extent of over-ranging. Although the use of CT protocols with a large beam width and large pitch factor can shorten the total scan time and reduce motion artefact, medical staff should pay attention to the increase in doses to organs and tissues positioned at the boundaries of the scan length. The setting of strict scan lengths would be required for the reduction of unnecessary exposure to patients in CT scans with a large beam width and large pitch factor.

Comparison of $CTDI_{vol}$ and DLP with dose reference levels

Dose reference levels have been reported in the literature. Shrimpton et al [18] reported that UK national reference doses of $CTDI_{vol}$ and DLP for multislice CT scanners were 13 mGy and 580 mGy cm, respectively, for adult chest CT and 14 mGy and 560 mGy cm, respectively, for adult abdominopelvic CT scans. $CTDI_{vol}$ and DLP values obtained in adult chest CT scans of 8.8–19.2 mGy and 286–672 mGy cm, respectively, were similar to the UK national reference doses. $CTDI_{vol}$ and DLP values obtained in adult abdominopelvic CT scans of 10.3–22.9 mGy and 503–1138 mGy cm, respectively, were similar or slightly larger than the reference doses. The values of $CTDI_{vol}$ and DLP for a 32 cm diameter phantom in paediatric 64-slice CT scans could not be compared directly with reference doses indicated for a 16 cm diameter phantom.

Effective doses

In chest CT scans, effective doses evaluated by ICRP 103 of 7.0–17.7 mSv for the adult phantom and 2.5–7.3 mSv for the paediatric phantom were higher by 13% for adults and by 19% for children than those evaluated by ICRP 60 because of the high doses to the breast and remainder tissues, for which the tissue-weighting factor increased from 0.05 to 0.12, and low doses to the gonads, for which tissue-weighting factors decreased from 0.20 to 0.08. Conversely, in abdominopelvic CT scans, effective doses evaluated by ICRP 103 of 10.3–20.7 mSv for the adult phantom and 3.0–8.5 mSv for the paediatric phantom differed only slightly — a decrease of 3% for adults and 4% for children — from those evaluated by ICRP 60 because of the relatively high doses to the breast, gonads and remainder tissues.

Effective doses evaluated by ICRP 60 in 64-slice adult chest CT scans of 6.2–15.5 mSv were similar to the values of 8.4–10.9 mSv in 4- and 16-slice CT scans evaluated by Nishizawa et al [5] and of 5.1–11.1 mSv in 8- and 16-slice CT scans reported by Fujii et al [8], although the doses were higher than those of 3.2–4.1 mSv in 16-slice CT scans found by Van der Molen et al [19]. Effective doses in 64-slice adult abdominopelvic CT scans of 10.7–21.9 mSv were also similar to the values of 9.0–18.0 mSv reported by Nishizawa et al [5] and 7.6–18.0 mSv reported by Fujii et al [8], although the doses were higher than those of 6.0–7.8 mSv reported by Van der Molen et al [19]. Effective doses by ICRP 60 in paediatric chest CT and paediatric abdominopelvic CT scans with 64-slice CT scanners were 2.1–6.2 mSv and 3.3–8.9 mSv, respectively, which were similar to the

Table 4. Doses for tissues and organs positioned within and at the boundaries of the scan length in adult and paediatric chest CT examinations with CT scanner A

	Adult CT				Paediatric CT			
Tube voltage (kV)	120	120	120	120	120	120	120	120
Rotation time (s rotation^{-1})	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Beam width (mm)	1.0 mm × 16	1.0 mm × 16	1.0 mm × 32	1.0 mm × 32	1.0 mm × 16	1.0 mm × 16	1.0 mm × 32	1.0 mm × 32
Pitch factor	0.938	1.438	0.844	1.406	0.938	1.438	0.844	1.406
Effective mAs	100	100	100	100	50	50	50	50
Planned scan length (mm)	305	305	305	305	205	205	205	205
Exposed scan length (mm)	340	356	364	400	240	256	264	300
Tissue or organ	**Organ dose (mGy)**				**Organ dose (mGy)**			
Salivary glands	–	–	–	–	1.5	2.2	2.8	6.7
Thyroid	21.9	24.1	21.5	25.1	11.6	11.6	10.8	13.2
Lung	15.4	15.7	14.1	14.2	10.6	11.2	10.6	10.7
Breast	10.5	7.2	9.7	11.1	8.3	7.3	8.4	9.4
Oesophagus	14.5	14.4	13.6	14.3	10.7	10.8	10.2	10.3
Liver	12.5	12.5	12.3	13.2	9.6	10.5	10.0	10.2
Stomach	12.9	15.3	13.2	11.9	5.2	6.6	6.8	8.6
Colon	1.1	1.4	1.4	2.0	0.6	0.8	0.8	2.5

Table 5. Doses for tissues and organs positioned within and at the boundaries of the scan length in adult and paediatric abdominopelvic CT examinations with CT scanner A

	Adult CT				Paediatric CT			
Tube voltage (kV)	120	120	120	120	120	120	120	120
Rotation time (s rotation^{-1})	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Beam width (mm)	1.0 mm × 16	1.0 mm × 16	1.0 mm × 32	1.0 mm × 32	1.0 mm × 16	1.0 mm × 16	1.0 mm × 32	1.0 mm × 32
Pitch factor	0.938	1.438	0.844	1.406	0.938	1.438	0.844	1.406
Effective mAs	100	100	100	100	50	50	50	50
Planned scan length (mm)	440	440	440	440	260	260	260	260
Exposed scan length (mm)	475	491	499	535	295	311	319	355
Tissue or organ	**Organ dose (mGy)**				**Organ dose (mGy)**			
Lung	5.9	6.7	6.8	7.7	5.4	6.1	5.4	6.3
Breast	3.1	10.1	8.1	10.4	1.9	2.5	5.2	6.6
Oesophagus	7.4	7.6	7.3	7.6	4.6	5.0	4.8	5.4
Liver	13.7	13.4	13.5	12.6	10.7	11.2	9.6	10.8
Stomach	16.0	13.5	14.5	16.9	11.3	11.8	10.3	9.9
Colon	15.5	14.9	14.4	13.8	11.2	11.3	10.5	11.0
Ovaries	15.8	16.1	14.7	12.8	9.1	9.2	8.7	8.9
Bladder	14.9	15.5	15.2	13.4	9.3	8.5	9.3	9.4
Testes	4.1	6.6	8.6	17.1	2.0	2.5	3.4	7.0

values for 4-, 8- and 16-slice CT scanners [5, 8, 20] because of the same level of effective mAs used in paediatric CT scans with these scanners. The variation in effective dose seen in adult and paediatric CT scans with 64-slice CT scanners would depend on the difference in CT scan protocols recommended for adults and children among 64-slice CT scanners and the acceptable diagnostic image quality required at each medical facility.

Conversion factors of DLP to the effective dose

Figure 2 shows the effective dose as a function of DLP in adult CT and paediatric CT examinations, where effective doses were evaluated according to ICRP 103. Two linear regression lines through the origin were calculated by using the method of least squares, where solid and dashed lines corresponded to the doses in chest CT and abdominopelvic CT scans, respectively. As seen in Figure 2, effective doses for adult and paediatric patients were directly proportional to the DLP, without being dependent on the manufacturers of the CT scanner, when the coefficients of determination were more than 0.95. The slopes of the lines for adult chest CT and adult abdominopelvic CT scans were 0.024 mSv mGy^{-1} cm^{-1} and 0.019 mSv mGy^{-1} cm^{-1}, respectively, which were factors of 2–2.5 smaller than those values for paediatric chest CT and paediatric abdominopelvic CT scans of 0.048 mSv mGy^{-1} cm^{-1} and 0.046 mSv mGy^{-1} cm^{-1}, because $CTDI_{vol}$ values for the 32 cm diameter phantom were displayed in paediatric CT scans as well as in adult CT scans.

Huda et al [21] estimated conversion factors of 0.017 mSv mGy^{-1} cm^{-1} for adult chest CT, 0.016 mSv mGy^{-1} cm^{-1} for adult upper abdomen CT and 0.019 mSv mGy^{-1} cm^{-1} for adult pelvic CT from effective doses and DLPs computed with three commercially available dosimetry software. Bongartz et al [22] reported the conversion factors of 0.018 mSv mGy^{-1} cm^{-1} for adult chest CT and 0.017 mSv mGy^{-1} cm^{-1} for adult abdominopelvic CT. We estimated the conversion factors from the linear relationship between DLP and the effective dose (from ICRP 60) to be 0.021 mSv mGy^{-1} cm^{-1} for adult chest CT and 0.020 mSv mGy^{-1} cm^{-1} for adult abdominopelvic CT, which were 17% and 18% higher, respectively, than those reported by Bongartz et al [22]. Groves et al [23] showed that the effective dose measured with TLDs and a Rando phantom was 18% higher than that obtained by using the ImPACT table, showing the same magnitude of difference between conversion factors measured in our study and those reported by Bongartz et al [22]. Huda [24] pointed out that conversion factors would depend on the size of the phantom used and the scan length. In this study, we therefore indicate conversion factors to estimate effective doses for standard Japanese-sized adults and children who undergo typical chest CT and abdominopelvic CT examinations.

Conclusions

Organ and effective doses in chest CT and abdominopelvic CT examinations for adults and children with 64-slice CT scanners were similar to those with 4-, 8- and 16-slice CT scanners. However, doses for organs positioned at the boundaries of the scan length in 64-slice CT with a

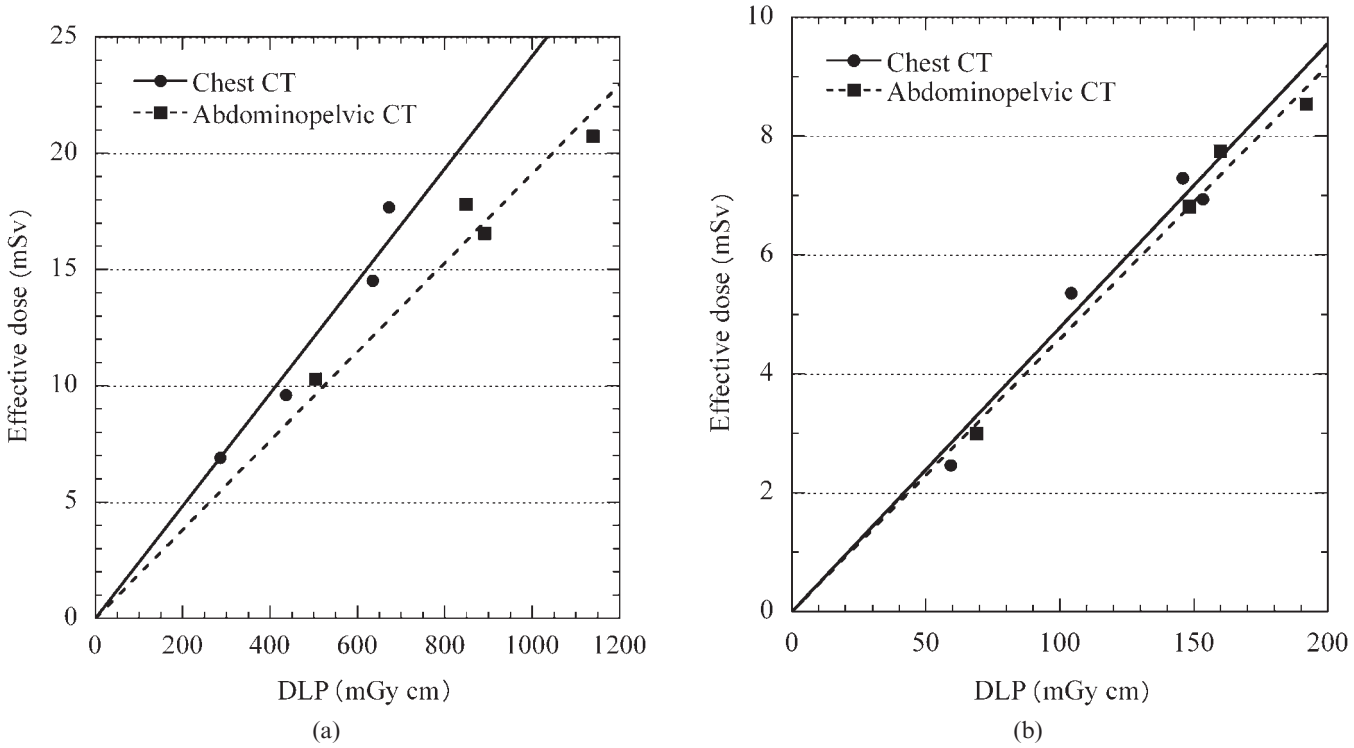

Figure 2. Effective dose as a function of the dose–length product (DLP) in (a) adult CT and (b) paediatric CT examinations, where effective doses were evaluated according to International Commission on Radiological Protection (ICRP) 103. Linear regression lines through the origin were calculated separately from dose values obtained in chest CT (solid line) and abdominopelvic CT (dashed line) examinations.

large beam width and/or large pitch factor, *i.e.* doses to the salivary glands and stomach in paediatric chest CT and doses to the breast and testes in adult and paediatric abdominopelvic CT, were higher than those in 16-slice CT with a narrow beam width and/or small pitch factor because of the larger extent of over-ranging. The effective doses could be estimated from $CTDI_{vol}$ and DLP using evaluated conversion factors, which were applied as a practical tool for optimising scan parameters in CT examinations with 64-slice CT scanners. Feedback of dose data to medical facilities and manufacturers of CT scanners would lead to the review of CT scan protocols and the improvement of CT scanners to reduce the radiation dose to patients.

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