Radiation dose evaluation in tomosynthesis and C-arm cone-beam CT examinations with an anthropomorphic phantom

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Purpose: The objective of this study was to evaluate organ dose and the effective dose to patients undergoing tomosynthesis (TS) and C-arm cone-beam computed tomography (CBCT) examinations and to compare the doses to those in multidetector CT (MDCT) scans.
Methods: Patient doses were measured with small sized silicon-photodiode dosimeters, 48 in number, which were implanted at various tissue and organ positions within an anthropomorphic phantom. Output signals from photodiode dosimeters were read out on a personal computer, from which organ and effective doses were computed. The doses in head, chest, abdomen, and hip-joint TS, and in head and abdomen C-arm CBCT were evaluated for routine protocols on Shimadzu TS and C-arm CBCT systems, and the doses in MDCT with the same scan regions as in TS and CBCT were on Toshiba 64-detector-row CT scanners.
Results: In TS examination of the head, chest, abdomen, and hip-joint, organ doses for organs within scan ranges were 1–4 mGy, and effective doses were 0.07 mSv for the head scan and around 1 mSv for other scans. In C-arm CBCT examinations of the head and abdomen, organ doses within scan range were 2–37 mGy, and effective doses were 1.2 mSv for the head scan and 4–5 mSv for abdominal scans. Effective doses in TS examinations were approximately a factor of 10 lower, while the doses in CBCT examinations were nearly the same level, compared to the doses in the corresponding MDCT examinations.
Conclusions: TS examinations with low doses and excellent resolutions in coronal images compared to recent MDCT would widely be used in tomographic examinations of the chest, abdomen, pelvis, skeletal-joints, and knee instead of MDCT examinations with significantly high doses. Since patient dose in C-arm CBCT was nearly the same level as that in recent MDCT, the same consideration for high radiation dose would be required for the use of CBCT. © *2010 American Association of Physicists in Medicine*. [DOI: 10.1118/1.3465045]

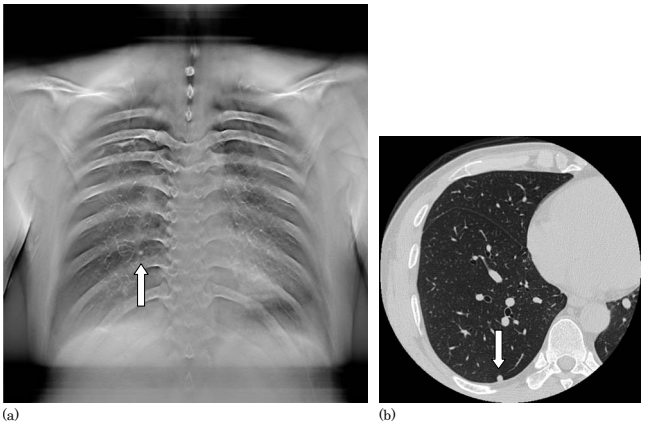
Key words: organ dose, C-arm cone-beam CT, tomosynthesis, effective dose, dosimetry

I. INTRODUCTION

Tomographic technique, in particular, x-ray computed tomography (CT), has been preferentially used in clinical x-ray imaging because of its high diagnostic image quality compared to simple radiography. CT scanners have made remarkable progress over the past few years, contributing to the improvement of diagnostic image quality and the reduction in examination time. The increase in CT examination frequency and higher radiation doses in CT examinations compared to the doses in other x-ray diagnosis have raised concerns about patient doses and patient safety.

Quite recently, with the practical use of a large size of flat-panel detector (FPD), a new version of old radiographic tomography, named tomosynthesis (TS), was realized, where it could make multiple tomographic images with a single linear scan. The system is a general radiographic system with a tilt table, and it provides coronal images alone. The system has been used in the examinations of chest, abdomen, pelvis, skeletal-joints, and knee,[1,2] and excellent resolution could be obtained in coronal images compared to the interpolated coronal multiplane images obtained with the recent multidetector CT (MDCT) scanners.[1] Dobbins and McAdams[2] described TS application for screening and detection of lung nodule and four strategies to replace chest radiography or chest CT with TS in clinical use. An example TS image of a pulmonary nodule is shown in Fig. 1 with a corresponding MDCT axial image. Although radiation dose to the patients undergoing TS examination was considered to be low[3] compared to that from MDCT examination, the dose has not been investigated experimentally and therefore exactly.

Practical use of a large size of FPD stimulated the devel-



(a) (b)

FIG. 1. An example TS image of a pulmonary nodule (a) and a corresponding MDCT axial image (b), where the nodule is indicated by arrow in each of the images. The TS image was obtained with Shimadzu SONIALVISION safire with a FPD of 17×17 in.^{2} (Shimadzu Corporation, Kyoto, Japan).

opment of another type of CT for a C-arm system, "C-arm cone-beam CT (CBCT)," to be used for the three-dimensional vascular imaging of the brain and other organs in interventional procedures.[4] CBCT is similar to conventional CT, but with a larger beam width, and this configuration provides projection radiography, fluoroscopy, digital subtraction angiography, and volumetric CT capabilities in a single patient setup within the interventional suite. Hence, an interventionalist may perform CT scans without patient transportation from interventional suite. Although C-arm CBCT was conveniently used, radiation doses to patients could be as high as those from MDCT examinations.

The grasp of patient doses requires the evaluation of organ and effective doses for patients undergoing TS and C-arm CBCT examinations. One common method of evaluating organ and effective doses is based on the dose measurement using thermoluminescence dosimeters (TLD) implanted in various organ positions within an anthropomorphic phantom.[5–9] Though TLD dosimetry has been considered to be the standard method for measuring absorbed doses in a phantom, the dose measurement is laborious and time-consuming. Hence, we devised in-phantom dosimetry system using silicon-photodiode dosimeters implanted in various organ positions,[10] where absorbed dose at each position could be read out electronically. In the present study, we evaluated organ and effective doses in TS and C-arm CBCT examinations with scan protocols clinically used for adult patients undergoing head, chest, abdomen, and hip-joint examinations. We compared the doses in TS and C-arm CBCT scans to those in digital radiography (DR) and MDCT scans for TS and in MDCT scans for CBCT.

II. MATERIALS AND METHODS

II.A. In-phantom dosimetry system

An adult anthropomorphic phantom, in which small sized silicon-photodiode dosimeters were implanted, was used for dose measurements in TS and C-arm CBCT examinations. Planar silicon *p-i-n*-photodiodes, Hamamatsu S8385-04 (Hamamatsu Photonics, Hamamatsu, Japan), with a sensitive area of 2.0×2.0 mm^2, were used as the dosimeters for dose measurement of tissues and organs within the head region. Since the sensitivity of the photodiode to diagnostic x rays differed with the incident direction of x rays between front and back, two photodiodes were glued together back to back with epoxy cement, and they were used as a single dosimeter with a parallel connection to reduce angular dependence of dosimeter sensitivity to incident x rays.[10] Using this construction of the dosimeter, dose error due to the angular dependence of dosimeter sensitivity was estimated to be negligibly small—from zero to a few percent—even for the worst case of CT examinations.[10] These photodiode dosimeters were implanted in 14 sites of the head and neck region of the phantom. Dose measurement for the trunk region was carried out using 32 photodiode dosimeters composed of Hamamatsu S2506-04 photodiodes (Hamamatsu Photonics, Hamamatsu, Japan), which were the same type as those used for the head region but had a larger sensitive area of 2.8×2.8 mm^2. The construction detail and characteristics of the dosimeters were fully described in our previous paper.[10]

The anthropomorphic phantom used for the dosimetry is Kyoto Kagaku THRA1 (Kyoto Kagaku, Kyoto, Japan), which imitated the standard Japanese adult male, 60 kg in weight and 170 cm tall. The phantom composed of three types of tissue substitutes, corresponding to soft tissue, cortical bone, and lung, respectively, was used as both male and female with the left breast attached externally, where the phantom with implanted dosimeters are shown in Fig. 2. Forty-eight dosimeters were installed at the positions of tissues and organs assigned in the definition of the effective dose by ICRP Publication 103.[11] The number of photodiode dosimeters implanted in each tissue or organ is indicated in Table I.

II.B. Evaluation of organ and the effective doses

Output voltage signals generated from 48 photodiode dosimeters were read on a personal computer through analog-to-digital converters and were converted to absorbed doses for soft tissue, where the conversion factor was estimated for each dosimeter separately at the half-value layer or the effective energy of x rays used.

Dose calibration of the dosimeters for various x-ray energies was performed against Radcal 1015 and 9015 ion-chamber dosimeters (Radcal Corporation, Monrovia, CA), which were placed free-in-air adjacent to the dosimeters, a few centimeters apart, at the same distance from the x-ray tube of a radiography unit. The ion-chamber dosimeters used were a tertiary standard, calibrated at the laboratory of the Japan Quality Assurance Organization. The values of exposure in roentgen or C/kg obtained with the ion-chamber dosimeters were converted to the values of absorbed dose for soft tissue by using the ratio of mass energy–absorption coefficient of "tissue, soft (ICRU-44)"[12] to that of "air, dry (near sea level)."[12] X-ray energy dependence of dosimeter sensitivity[10] could be utilized to derive conversion factors to convert output voltage from photodiode dosimeters to ab-

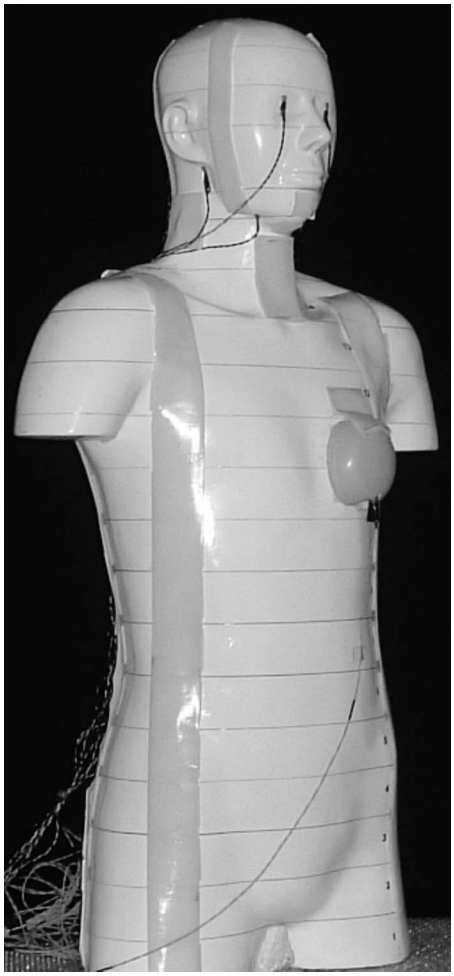


FIG. 2. An anthropomorphic phantom dosimetry system. Seen with the phantom are twisted carbon-fiber cables derived from photodiode dosimeters embedded within the phantom.

TABLE I. Number of photodiode dosimeters implanted in each tissue or organ required for the effective dose evaluation by ICRP Publication 103.

Tissue or organ	No. of dosimeters	Tissue weighting factors
Brain	5	0.01
Lens	2	–
Salivary glands	6	0.01
Thyroid	1	0.04
Lung	4	0.12
Breast	1	0.12
Esophagus	2	0.04
Liver	2	0.04
Stomach	1	0.12
Colon	5	0.12
Bladder	1	0.04
Gonads		0.08
(Ovaries)	1	
(Testes)	1	
Bone surface	22	0.01
Red bone marrow	20	0.12
Skin	2[a]	0.01
Remainder tissues	12[b]	0.12

[a]Extra dosimeters externally attached to the surface of the phantom.
[b]Adrenals, kidneys, extrathoracic region, gall bladder, heart, oral mucosa, pancreas, small intestine, spleen, thymus, prostate (♂), and uterus/cervix (♀).

sorbed dose for soft tissue at the half-value layer or the effective energy of x rays used, where the conversion factors are the reciprocal of dosimeter sensitivity.

Minimum detectable dose was estimated to be 0.01 mGy with 50% uncertainty.[10] Overall uncertainty including both random and systematic errors, which arose in the conversion from the measured output voltage of the photodiode dosimeter 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 excepting breast, lens, and bone surface since mass energy–absorption coefficients for these tissues and organs including red bone marrow were within 5% (Refs. 12 and 13) for diagnostic x-ray energy of more than 30 keV. Doses for breast tissue and lens were evaluated to be the doses for soft tissue at the position of the breast and the lens multiplied by the ratio of mass energy–absorption coefficient[12] of breast tissue to soft tissue and of lens to soft tissue, respectively. Dose evaluation for bone surface was described by Fujii *et al.*[14]

Organ dose is used to refer to the mean absorbed dose for a specific organ. For small organs such as thyroid and gonads, the absorbed dose value obtained from a dosimeter implanted in the centroid of an organ was adopted as the organ dose. For organs with large volume such as brain, lung, esophagus, and liver, between two and five dosimeters were set at each centroid of the organ subdivided equally, and the mean dose value was regarded as the organ dose. For paired glands including in the salivary glands, i.e., parotid, sublingual, and submaxillary glands, one dosimeter was placed in each of the left and right glands. One dosimeter was also placed on each eye lens. For colon, five dosimeters were set at each position of ascending, transverse, descending, and sigmoid colons and rectum, where organ dose for colon was calculated according to the method of ICRP Publication 67.[15] Organ dose evaluation for red bone marrow and bone surface is the same as that described in our previous paper,[14,16] where the doses were evaluated from absorbed dose values measured in various bone tissues and the published data[17] of the weight fractions of red bone marrow and mineralized bone.

Absorbed dose for skin was measured using two dosimeters attached to the surface of the phantom in a direct x-ray beam. Organ dose for skin was evaluated by multiplying the average dose of these two dosimeters by the ratio of the irradiated area to the gross surface area of the phantom. The gross surface area with imaginary arms and legs was estimated to be 1.60 m^2.

Fourteen organs and tissues, i.e., adrenals, extrathoracic region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate (♂), small intestine, spleen, thymus, and uterus/cervix (♀), were categorized into "remainder tissue." Doses for lymphatic nodes and muscle dis-

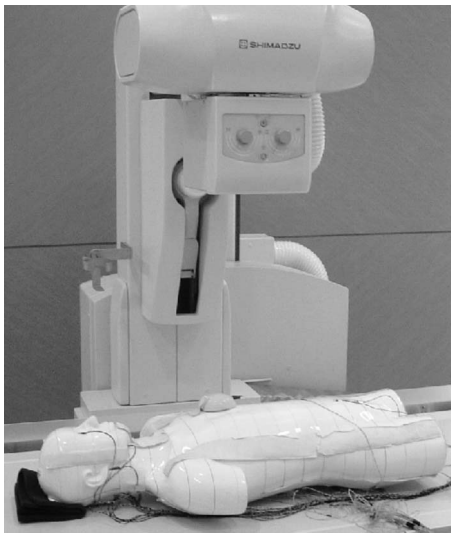


FIG. 3. Dose measurement in TS examination.

tributing in the whole body, however, were excluded for dose evaluation of the remainder tissue because of the difficulty of dose measurement for these tissues. Average dose for 11 organs for each of male and female was adopted as the dose for the remainder tissue. The effective dose was evaluated according to ICRP Publication 103,[11] where the dose was given in average between male and female.

II.C. TS and C-arm CBCT systems and technical parameters

TS system used in this study was Shimadzu SONIALVISION safire with a FPD of 17×17 in.^{2} (Shimadzu Corporation, Kyoto, Japan). The system, which is shown in Fig. 3, is a general radiographic system with a tilt table. The x-ray tube motion is a linear arc of 12:00 position $\pm40°$, and the arc is always symmetric over the anterior of the patient, where the motion of the x-ray tube is synchronized with that of the detector. Seventy-four images were obtained at 15 frames/s with 2.2–32 ms exposure and 96–400 mA tube current per pulse in a scan time of 5 s. Radiation dose was measured with the in-phantom dosimetry system in the TS examinations of the head, chest, abdomen/lumbar-vertebrae, and hip-joint for an anterior-posterior projection. Field-of-view and scan length were 230 mm (9 in.) and 210 mm for head TS, 430 mm (17 in.) and 400 mm for chest TS and for abdomen/lumber-vertebrae TS, and 380 mm (15 in.) and 320 mm for hip-joint TS. Technical parameters including tube voltage, half-value layer, and mA s/pulse used were those of routine, which are indicated in Table II. Tube voltages of 85, 100, 70, and 80 kV were used for head, chest, abdomen/lumbar-vertebrae, and hip-joint TS examinations, respectively, with filtration of 0.2 mm Cu and 0.9 mm Al. Dual energy of x rays was also used in chest and hip-joint TS examinations with tube voltages of 120 and 60 kV. Technical parameters in dual-energy TS (DET) scans are indicated in Table III, where for hip-joint DET dose measurements were performed with and without additional gadolinium filter, 0.0565 mm in thickness.

The C-arm CBCT system used was Shimadzu BRANSIST safire with FPDs of 9×9 and 17×17 in.^{2} (Shimadzu Corporation, Kyoto, Japan). The system, which is shown in Fig. 4, generates a complete volumetric dataset with the patient stationary via a single 215° (180°+fan angle) rotation of the x-ray source and detector, where the x-ray source motion is a symmetric arc centered at approximately 6:00 position, and x rays are incident mainly from the PA direction. Images of nearly 315 in number were obtained at 30 frames/s with 5.0/5.6 ms exposure and 320/360 mA tube current per pulse in a scan time of 10.5 s. Radiation dose was measured with the in-phantom dosimetry system in the C-arm CBCT examinations of the head and abdomen, where scan lengths were determined by detector sizes used of 150 mm for the 9 in. detector and 240 mm for the 17 in. detector. In abdominal examinations, the cranial side of scan regions was a level of diaphragm for both scan lengths of 240 and 150 mm. For a scan length of 240 mm, the scan region extended over liver and kidneys and over major abdominal arteries, and for a scan length of 150 mm, the scan region included arteries of liver, pancreas, and gall bladder. Technical parameters including tube voltage, filtration, and mA s/pulse used were those of routine, which are indicated in Table IV, where tube voltages were 120 and 100 kV in head and abdominal scans, respectively.

III. RESULTS

Table II shows organ and effective doses obtained in typical TS examinations of the head, chest, abdomen, and hip-joint, where the parameters were those routinely used in many medical facilities. In head TS scan, doses for brain, lens, and salivary glands within scan range were between 1 and 4 mGy, where lens dose was the highest with a value of 3.7 mGy due to the AP direction of x rays and lens position at the surface of the phantom within the x-ray field. Effective dose in the head TS scan was 0.07 mSv. In TS scans of the chest, abdomen, and hip-joint, organ doses for organs within scan ranges were between 1 and 4 mGy, and the effective dose was around 1 mSv. Shown in Table III are effective doses obtained in DET scans for the chest and hip-joint, where organ doses were found to be proportional to the effective doses for each scan without depending on the technical parameters. It is found from Tables II and III that in DET scans effective doses were slightly lower than those in typical TS scans, where in hip-joint DET the dose was lowered by 40% with additional gadolinium filter.

Table IV shows organ and effective doses obtained in typical C-arm CBCT examinations of the head and abdomen, where the parameters were those routinely used in many medical facilities. In head CBCT scan, doses for brain, lens, and salivary glands within scan range were between 12 and 37 mGy, where brain dose was the highest. The effective dose in the head scan was 1.2 mSv. In abdominal CBCT

TABLE II. Technical parameters and organ and effective doses in typical TS examinations of the head, chest, abdomen, and hip-joint.

Examination	Unit	Head	Chest	Abdomen	Hip-joint
Field-of-view	mm	230	430	430	380
Tube voltage	kV	85	100	70	80
Half-value layer	mm Al	6.1	7.2	5.0	5.8
Tube current	mA	200	160	320	400
Pulse width	ms	6.3	3.2	10	6.3
mA s/pulse	mA s	1.3	0.5	3.2	2.5
Frame number		74	74	74	74
Scan length	mm	210	400	400	320
Tissue or organ	Unit	Head	Chest	Abdomen	Hip-joint
Brain	mGy	1.17	0.03	0.01	0.01
Lens	mGy	3.72	0.03	0.02	0.00
Salivary glands	mGy	1.23	0.18	0.01	0.03
Thyroid	mGy	0.09	2.19	0.00	0.00
Lung	mGy	0.01	1.40	0.28	0.00
Breast	mGy	0.01	2.18	0.39	0.01
Esophagus	mGy	0.01	1.17	0.67	0.01
Liver	mGy	0.01	0.89	1.43	0.02
Stomach	mGy	0.00	1.27	3.72	0.04
Colon	mGy	0.01	0.09	2.22	1.33
Uterus	mGy	0.01	0.02	0.39	2.18
Ovary	mGy	0.00	0.02	0.59	3.98
Bladder	mGy	0.00	0.02	0.12	3.55
Testis	mGy	0.00	0.00	0.02	4.12
Bone surface	mGy	0.68	0.73	0.60	2.08
Red bone marrow	mGy	0.13	0.36	0.43	0.80
Skin	mGy	0.07	0.21	0.43	0.42
Remainder tissues	mGy	0.12	0.86	1.23	0.53
Effective dose	mSv	0.07	0.92	1.12	0.82

scans, organ doses for organs within scan ranges were between 2 and 19 mGy, and effective doses were 4–5 mSv.

CBCT examinations can be performed with reduced tube voltage. Table V shows effective doses obtained with a reduced tube voltage of 80 kV, where the original tube voltages were 120 kV for the head scan, and 100 kV for the abdominal scan. Organ doses obtained with different tube voltages

TABLE III. Effective doses obtained with technical parameters in DET of the chest and the hip-joint.

Examination	Unit	Chest	Hip-joint	
Field-of-view	mm	430	380	
Tube voltage	kV	120/60	120/60	120/60
Additional filtration				0.0565 mm Gd
Half-value layer	mm Al	8.4/4.2	8.4/4.2	8.7/4.4
Tube current	mA	96/136	192/170	192/170
Pulse width	ms	2.2/27	2.2/32	2.2/32
mA s/pulse		0.2/3.7	0.4/5.4	0.4/5.4
Frame number		37/37	37/37	37/37
Scan length	mm	400	320	
Effective dose	mSv	0.89	0.65	0.47

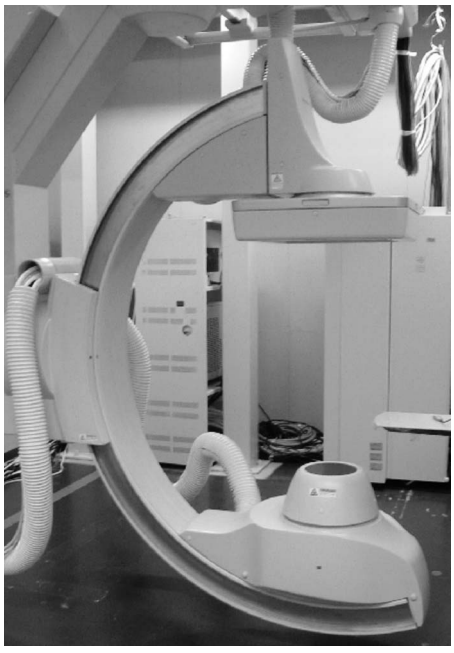


FIG. 4. C-arm CBCT system, Shimadzu BRANSIST safire with a FPD of 17 in. size.

TABLE IV. Technical parameters and organ and effective doses in typical C-arm CBCT examinations of the head and the abdomen.

Examination	Unit	Head	Abdomen	Abdomen
Detector size	in.	9	17	9
Tube voltage	kV	120	100	100
Filtration		0.3 mm Cu	0.6 mm Cu	0.3 mm Cu
Half-value layer	mm Al	9.5	9.4	8.2
Tube current	mA	320	360	360
Pulse width	ms	5.0	5.6	5.6
mA s/pulse	mA s	1.6	2.0	2.0
Frame number		319	315	319
Scan length	mm	150	240	150
Tissue or organ				
Brain	mGy	36.9	0.0	0.0
Lens	mGy	19.6	0.0	0.0
Salivary glands	mGy	11.7	0.1	0.1
Thyroid	mGy	1.0	0.2	0.3
Lung	mGy	0.2	2.4	7.8
Breast	mGy	0.1	1.3	1.7
Esophagus	mGy	0.1	4.6	8.2
Liver	mGy	0.1	9.9	19.1
Stomach	mGy	0.0	8.9	9.7
Colon	mGy	0.0	6.9	3.7
Uterus	mGy	0.0	0.8	0.2
Ovary	mGy	0.0	0.7	0.2
Bladder	mGy	0.0	0.3	0.1
Testis	mGy	0.0	0.1	0.1
Bone surface	mGy	10.7	2.3	3.1
Red bone marrow	mGy	3.2	2.2	1.6
Skin	mGy	1.0	1.3	1.2
Remainder tissues	mGy	0.8	6.1	8.8
Effective dose	mSv	1.2	4.0	5.2

were found to be proportional to the effective doses for each scan. It is found from Tables IV and V that exposure doses were lowered with reduced tube voltage to 40% and 80% for head and abdominal scans, respectively.

TABLE V. Effective doses obtained with reduced tube voltage in C-arm CBCT examinations of the head and the abdomen.

Examination	Unit	Head	Abdomen
Detector size	in.	9	17
Tube voltage	kV	80	80
Filtration		0.1 mm Cu	0.1 mm Cu
Half-value layer	mm Al	4.8	4.8
Tube current	mA	320	360
Pulse width	ms	5.0	5.6
mA s/pulse	mA s	1.6	2.0
Frame number		319	315
Scan length	mm	150	240
Effective dose	mSv	0.47	3.3

TABLE VI. Technical parameters and effective doses in DR examinations of the chest, abdomen, and hip-joint.

Examination	Unit	Chest	Abdomen	Hip-joint
Field-of-view	in.	17	15	15
Tube voltage	kV	120	80	70
Half-value layer	mm Al	8.4	5.8	5.0
Tube current	mA	200	250	400
Pulse width	ms	5	75	50
mA s	mA s	1	19	20
Projection length	mm	400	350	320
Effective dose	mSv	0.025	0.103	0.088

IV. DISCUSSION

IV.A. Comparison of doses in TS examinations with those in DR and MDCT examinations

TS has been performed for the same clinical purpose as CT by using the same x-ray unit as DR in spite of subtle difference in image property between TS and CT. To compare the doses in TS to those in DR and in MDCT, organ and effective doses were evaluated by using the in-phantom dosimetry system in each DR examination of the chest, abdomen, and hip-joint for an AP projection, and in each MDCT examination of the head, chest, abdomen, and hip-joint. Shown in Table VI are technical parameters in routine DR of the chest, abdomen, and hip-joint with the Shimadzu SONIALVISION safire TS system. Dose measurements in DR were performed with increased mA s values—several to more than ten times larger than those seen in Table VI—to obtain sufficient precision in the measured doses. Doses obtained were corrected by scaling of mA s ratios. Also shown in Table VII are technical parameters in routine MDCT scans of the head, chest, abdomen, and hip-joint, with a Toshiba Aquilion 64-detector-row CT scanner, where the protocol used for dose comparison with head TS was head plain CT (Ref. 18) with a typical scan length of 120 mm, and for dose comparison with abdominal TS, a scan length of 240 mm was used in the abdominal MDCT scan.

Organ doses obtained in head TS and MDCT examinations, and in TS, DR, and MDCT examinations for the chest, abdomen, and hip-joint are shown in Figs. 5(a)–5(d) for each tissue or organ appearing in Table II, where the scales of organ dose for DR, TS, and MDCT are a factor of 10 different among them. It is seen in Figs. 5(b)–5(d) that dose pattern in DR was similar to that in TS because of the AP direction of incident x rays in both examinations, and that organ doses in TS were factors of 10–40 higher than those in DR. Dose pattern in TS differed from that in MDCT because CT scans using rotating x-ray source resulted in reduced dose difference for tissues and organs in a scan region without depending on their positions in the phantom. As is seen in Fig. 5(b), breast dose in chest CT, however, was lower than other organ doses obtained in the chest scan region. This would be due to lower tube current at the breast position by the use of dose modulation of the CT scanner.

TABLE VII. Technical parameters and effective doses in routine CT examinations of the head, chest, abdomen, and hip-joint with a Toshiba Aquilion 64-detector-row CT scanner.

Examination	Unit	Head plain	Head CTA	Chest	Abdomen	Abdomen	Hip-joint
Scan type		Conventional	Helical	Helical	Helical	Helical	Helical
Tube voltage	kV	120	120	120	120	120	120
Half-value layer	mm Al	7.0	7.0	7.0	7.0	7.0	5.0
Dose modulation		None	None	Volume EC	Volume EC	Volume EC	Volume EC
Tube current	mA	200	300	Max. 450	Max. 421	Max. 421	Max. 400
Rotation time	s/rot	1.5	0.5	0.5	0.5	0.5	0.5
Beam width	mm	4×4, 2×4	0.5×64	0.5×64	1×32	1×32	1×32
Beam pitch		1	0.641	0.828	0.844	0.844	0.844
Gantry tilt	deg	12	12	0	0	0	0
Scan length	mm	120	90	325	240	150	320
Effective dose	mSv	1.1	1.1	15.0	14.9	12.9	10.5

Effective doses in DR and MDCT examinations are shown in Tables VI and VII, respectively. It is found from Tables II and VI that effective doses in TS were factors of 10–40 higher than those in DR. Dose ratios between TS and DR of 37 for chest examinations, 11 for abdomen examinations, and 9.3 for hip-joint examinations were proportional to mA s ratios between TS and DR in spite of the difference in the tube voltages used in TS and DR, though mA s ratio for abdomen examination was 10% larger than the dose ratio. Sabol[3] reported that effective dose in chest TS was calculated to be 0.134 mSv—six or seven times lower than ours—from Monte Carlo estimation. This would mainly be due to a lower mA s value—only ten times larger than that of radiography—compared to our TS examination using mA s value that is 37 times larger.

It is found from Tables II and VII that effective doses in TS were 13–16 times lower than those in MDCT. CT doses is known to depend largely on the types of CT scanner—e.g., effective doses by ICRP 103 of 7–18 mSv in the chest CT with 64-detector-row CT scanners from different manufacturers.[19] Mettler *et al.*[20] found from their extensive investigation that effective doses in various CT examinations

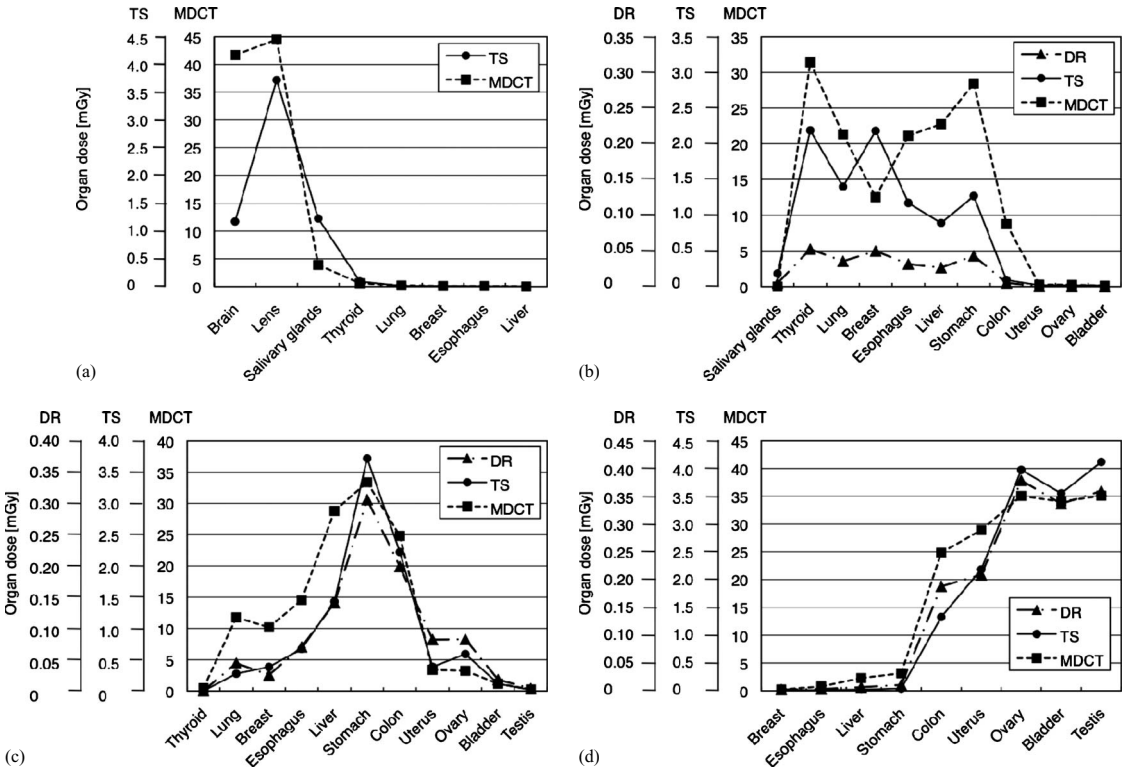


FIG. 5. Organ doses in routine head TS and MDCT examinations (a) and in routine TS, DR, and MDCT examinations for the chest (b), abdomen (c), and hip-joint (d). Technical parameters in each examination are indicated in Tables II, VI, and VII, where the protocol used for the head MDCT was that for head plain, and a scan length of 240 mm was used in the abdominal MDCT.

varied in wide ranges, e.g., 4.0–18.0 mSv (by ICRP 60) in chest CT and 3.5–25 mSv (by ICRP 60) in abdominal CT. Effective doses obtained in our chest and abdominal CT examinations of 13.5 mSv (by ICRP 60) were within their dose ranges. Considering dose variation expected in each CT examination, effective doses in TS would be approximately a factor of 10 lower than those in MDCT.

Although image quality on TS has never been inspected in this study, the quality such as low contrast resolution might be some inferior to that on MDCT. Hence, lower dose on TS than the dose on MDCT should not be the only factor taken into account in the comparison of their usefulness.

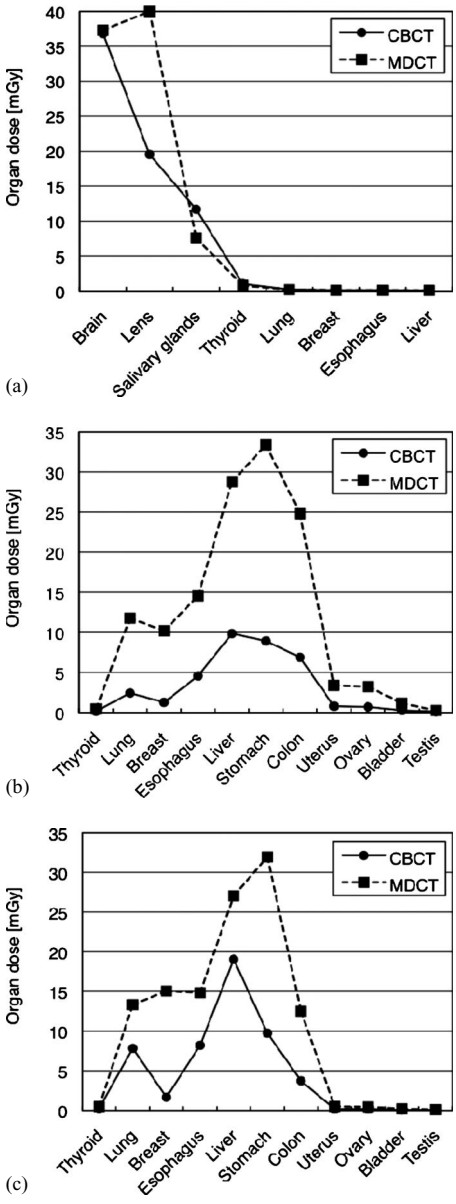


FIG. 6. Organ doses in routine C-arm CBCT and MDCT examinations for the head (a) and for the abdomen with scan lengths of 240 mm (b) and 150 mm (c). Technical parameters in each examination are indicated in Tables IV and VII, where the protocol used for the head MDCT was that for head CTA.

IV.B. Comparison of doses in C-arm CBCT examinations with those in MDCT examinations

To compare the doses in C-arm CBCT to those in MDCT, organ and effective doses were evaluated by using the in-phantom dosimetry system in each MDCT examination of the head and the abdomen. Shown in Table VII are technical parameters in routine MDCT of the head and the abdomen with a Toshiba Aquilion 64-detector-row CT scanner, where scan protocols used in the head CT were those in CT angiography (CTA) because of the same clinical purpose as that in head CBCT examinations. Scan lengths in abdominal CT were the same as those in CBCT, while in head CT a scan length of 90 mm, routinely used in CTA,[18] was adopted to compare the doses in the head CBCT of 150 mm scan length.

Organ doses obtained in C-arm CBCT and MDCT examinations are indicated in Fig. 6, and effective doses are in Tables IV and VII. As seen in Fig. 6, dose pattern for MDCT was not similar to that for C-arm CBCT, where lens dose in the head CBCT and breast and stomach doses in the abdominal CBCT were relatively lower than the doses in each MDCT scan of the head and the abdomen. This is because in CBCT rotation angle per single scan was 215° and most of x-ray beams were incident from the back of the phantom, i.e., PA direction. This resulted in reduced doses for such organs positioned near or at the front surface of the phantom as lens, breast, and stomach. Although in CTA, gantry angle was tilted to avoid direct x-ray incidence into eyes, over-ranging, which is known to be significant for a wide beam width of MDCT scanners,[19] might contributed to high lens dose in the head CT scan. It is found from Fig. 6 and Tables IV and VII that organ and effective doses in C-arm CBCT were factors of 1–3 lower than those in MDCT. Considering dose variation expected in each CT examination, effective doses in CBCT would be nearly the same level as those in MDCT.

V. CONCLUSIONS

Radiation doses for the patients undergoing such new diagnostic x-ray examinations as TS and C-arm CBCT were investigated. In TS examinations of the head, chest, abdomen, and hip-joint, organ doses for organs within scan ranges were 1–4 mGy, and effective doses were 0.07 mSv for the head scan and around 1 mSv for other scans. In C-arm CBCT examinations of the head and abdomen, organ doses within scan ranges were 2–37 mGy, and effective doses were 1.2 mSv for the head scan and 4–5 mSv for abdominal scans. Effective doses in TS examinations were approximately a factor of 10 lower, while the doses in CBCT examinations were nearly the same level, compared to the doses in the corresponding MDCT examinations.

TS examinations with low doses and excellent resolutions in coronal images compared to recent MDCT would widely be used in tomographic examinations of the chest, abdomen, pelvis, skeletal-joints, and knee instead of MDCT examinations with significantly high doses. Since patient dose in C-arm CBCT was nearly the same level as that in recent MDCT, consideration for high radiation dose would be re-

quired for the use of CBCT. The present dose data would be used to estimate radiation risks for patients undergoing TS and C-arm CBCT examinations.

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