Radiation dose evaluation in multidetector-row CT imaging for acute stroke with an anthropomorphic phantom

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ABSTRACT. This study evaluated radiation dose and dose reduction in CT imaging for acute stroke. Radiation doses in three types of CT imaging (*i.e.* non-contrast-enhanced CT, CT perfusion (CTP) and CT angiography (CTA)) were measured with an in-phantom dosimetry system for 4-, 16- and 64-detector CT scanners in 5 hospitals. To examine the relationship between image quality and radiation dose in CTA, image contrast-to-noise ratio was evaluated. Doses to the brain, lens, salivary glands and local skin obtained with scan protocols in routine use were: 42–71 mGy, 30–88 mGy, 3.9–7.3 mGy and 40–97 mGy in non-contrast-enhanced CT; 41–75 mGy, 9.9–10 mGy, 1.5–2.1 mGy and 107–143 mGy in CTP; and 8.2–55 mGy, 26–69 mGy, 2.0–73 mGy and 32–72 mGy in CTA. For the combination of these CT examinations, on average a patient would receive 236 mGy for the maximum local skin dose and 4.2 mSv for the effective dose evaluated by the International Commission on Radiological Protection (ICRP) 103. Effective doses in CTP in this study were less than those obtained with representative protocols of Western countries. Average effective doses in each CT examination were not more than 1.5 mSv. The use of reduced kV and a narrow scan range would be effective in dose reduction of CTA and CTP, and intermittent scanning would be essential in CTP. Although lens and maximum local skin doses were far less than the thresholds for deterministic effects, since radiation risks would be increased in repeated CT examinations, efforts should be devoted to dose reduction in stroke CT examinations.

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Most patients with suspected stroke undergo either CT or MRI as the initial diagnostic examination [1, 2]. MRI has some advantages over CT in depicting stroke lesions; however, the provision of MR scanners in general hospitals is still low, an examination takes more time and patients with pacemakers cannot undergo MRI examinations. While CT techniques carry the risk of radiation exposure, CT scanners are nearly always available [3] and scans can be done quickly. Schramm *et al* [4] have reported that CT images obtained by the combination of various CT examinations allow diagnostic assessment of acute stroke with a quality comparable with that of stroke MRI. So CT examination has some advantages for the diagnosis of acute stroke patients who have no time to lose.

The diagnostic CT examination for acute stroke generally requires three imaging techniques: non-contrast-enhanced CT of the head; CT perfusion (CTP); and CT angiography (CTA) of intracranial vessels. In these CT examinations the local skin dose in CTP might be considerably high. In a previous study we reported that the maximum skin dose was as high as 712 mGy, 13 times higher than that in non-contrast-enhanced CT of the head [5]. Although the latest multidetector-row CT (MDCT) scanners have a dose reduction function of

intermittent scanning or shuttle scanning, detailed patient doses using the function have not been reported.

The CTA technique has been developing with great potential owing to high scan speed and thin-slice image reconstruction, made possible by MDCT technology. It is predicted that CTA scan ranges will vary depending on diagnostic policy, so, while patient doses will vary among hospitals, the degree of variation is not yet clear. Since there is a trade-off between patient dose and image quality, technical protocols should be optimised. However, there has been little research evaluating the effect of each dose reduction method in detail.

It is known that the patient dose in a CT examination ranges from several tens to a hundred times higher than that in conventional radiography [5, 6], while radiation risks for tissues and organs included in the head region were underestimated in the International Commission on Radiological Protection (ICRP) 60 [7]. The ICRP's 2007 recommendations (ICRP 103) [8] allocated new tissue weighting factors to brain and salivary glands within the head region, so the large difference between evaluated dose values would be predicted in stroke CT examinations because of the high radiation dose in the head region. In comparison with other literature evaluated by ICRP 60 [7], we need to understand the difference in effective dose evaluation between the old and new ICRP recommendations.

The purpose of this study was primarily to produce the latest dose information for acute stroke patients undergoing MDCT examinations. Also investigated was

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dose reduction in MDCT examinations for acute stroke from the relation between image quality and radiation doses, particularly focusing on the possibility of dose reduction in CTA examinations.

Methods and materials

In-phantom dosimetry system

For dose measurements in MDCT imaging, an adult anthropomorphic phantom was used, in which small-sized silicon-photodiode dosimeters were implanted. Planar silicon pin-photodiodes, Hamamatsu S8385-04 (Hamamatsu Photonics, Hamamatsu, Japan), with a sensitive area of $2.0 \times 2.0 \text{ mm}^2$, 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. This was used as a single dosimeter with a parallel connection to obtain isotropic sensitivity to incident X-rays [9]. These photodiode dosimeters were implanted in 16 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), the same type used for the head region but with a larger sensitive area of $2.8 \times 2.8 \text{ mm}^2$. The construction detail and characteristics of

the dosimeters were fully described in our previous paper [9].

The anthropomorphic phantom used for the dosimetry is the Kyoto Kagaku THRA1 (Kyoto Kagaku, Kyoto, Japan), which imitated the standard Japanese adult male, 60 kg in weight and 170 cm tall. Three-dimensional (3D) CT images of the phantom with implanted dosimeters are shown in Figure 1. A total of 48 dosimeters were installed at the positions of tissues and organs assigned in the definition of the effective dose by ICRP 103 [8]. The number of photodiode dosimeters implanted in each tissue or organ is indicated in Table 1.

Evaluation of organ and effective doses

Output voltage signals generated from 48 photodiode dosimeters were read on a computer through analogue-to-digital converters and were converted to absorbed doses for soft tissue. The conversion factor was estimated for each dosimeter separately at the effective energy of X-rays used [10]. X-ray energy dependence of dosimeter sensitivity (*i.e.* reciprocal of the conversion factor) and its derivation is described in our previous papers [6, 9].

The minimum detectable dose was estimated to be 0.02 mGy with 25% uncertainty [9]. Overall uncertainty, including both random and systematic errors that arose in the conversion from measured output voltage of the photodiode dosimeter to the absorbed dose, was estimated to be 7% at 95% confidence level.

Organ dose is used to refer to the mean absorbed dose for a specific organ. Absorbed dose for soft tissue was

Figure 1. Three-dimensional CT images of the dosimetric phantom indicating the location of 48 photodiode dosimeters (red short bars) distributing in the phantom.

Table 1. Number of photodiode dosimeters implanted in each tissue or organ required for the effective dose evaluation by ICRP 103 [8]

Tissue or organ	Number of dosimeters	Tissue weighting factors
Brain	5	0.01
Lens	2	–
Salivary glands	6	0.01
Thyroid	1	0.04
Lung	2	0.12
Breast	1	0.12
Oesophagus	2	0.04
Liver	2	0.04
Stomach	1	0.12
Bladder	1	0.04
Gonads	–	0.08
(Testis)	1	–
(Ovary)	1	–
Bone surface	21	0.01
Red bone marrow	20	0.12
Skin	2	0.01
Remainder tissues	10*	0.12

*Adrenals/kidneys, extrathoracic (ET) region, gall bladder, heart, oral mucosa, pancreas, small intestine, spleen, thymus, prostate/uterus/cervix.

adopted for all tissues and organs except breast, lens and bone surface, since mass energy-absorption coefficients for these tissues and organs, including red bone marrow, were within 5% for diagnostic X-ray energy of more than 30 keV [11, 12]. 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 of breast tissue to soft tissue and of lens-to-soft tissue, respectively. Organ dose evaluation for red bone marrow and bone surface is the same as that described in previous papers [10, 13], where the doses were evaluated from absorbed dose values measured in various bone tissues and the published data of the weight fractions of red bone marrow and mineralised bone [14].

For small organs, such as the 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 a large volume, such as the brain, lung, liver and oesophagus, 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 the salivary (*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 the colon, five dosimeters were set at each position of ascending, transverse, descending and sigmoid colons and rectum, and the dose was calculated according to the method of ICRP 67 [15].

Absorbed dose for skin was measured using two dosimeters attached to the surface on the anterior and lateral positions of the phantom in a scan region. Organ dose for skin was evaluated by multiplying the average dose of these two dosimeters by the ratio of the irradiated area-to-gross surface area of the phantom. The gross surface area with imaginary arms and legs was estimated to be 1.60 m².

A total of 14 organs and tissues (*i.e.* adrenals, extrathoracic (ET) region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate

(male), small intestine, spleen, thymus and uterus/cervix (female)) were categorised into “the remainder” by ICRP 103 [8] for the evaluation of the effective dose. Doses for lymphatic nodes and muscle distributing in the whole body were excluded because of the difficulty of measuring the dose. Therefore, the average dose for 12 organs was adopted as the dose for the remainder. The effective dose was evaluated according to ICRP 103 [8] and ICRP 60 [7], where the dose was quoted as the average value between male and female results.

Dose measurement in stroke CT diagnosis

The MDCT scanners used in this study are summarised in Table 2. These comprised two 4-slice, two 16-slice and four 64-slice systems: Toshiba Asteion, Toshiba Aquilion (Toshiba Medical Systems, Otawara, Japan), GE Light Speed Plus, GE Light Speed VCT (General Electric Healthcare, Milwaukee) and Philips Brilliance (Philips Electronics, Eindhoven, the Netherlands). Dose measurements were carried out for scan protocols routinely used in each hospital, details of which are given in Tables 3, 4 and 5. In CTP we also evaluated organ and effective doses with scan protocols recommended by Wintermark et al [16] using scanner G given in Table 2. The scan protocols and dose data

Table 2. Multidetector CT scanners used for measurement of patient doses

CT scanner	Data acquisition system (number of slices)
A	TOSHIBA Asteion 4
B	GE Light Speed Plus 4
C	TOSHIBA Aquilion 16
D	TOSHIBA Aquilion 16
E	TOSHIBA Aquilion 64
F	TOSHIBA Aquilion 64
G	GE Light Speed VCT 64
H	Philips Brilliance 64

Table 3. Scan protocols and organ and effective doses in non-contrast-enhanced CT examinations of the head

Scanner		A	B	C	D	E	F	G	H
Tube voltage (kV)		120	120	120	120	120	120	120	120
Gantry tilt (°)		0.0	11.5	0.0	8.5	12.0	6.5	8.5	19.0
Effective mAs (mAs)	Upper	225	240	300	375	300	375	300	400
	Lower	300	360	375	375	300	375	360	400
Rotation time (s/rot)		1.5	2.0	1.5	1.5	1.5	1.5	2.0	1.5
Beam width (mm)	Upper	4 mm × 4	5 mm × 4	4 mm × 4	2 mm × 4	4 mm × 4	2 mm × 4	5 mm × 4	0.625 mm × 16
	Lower	2 mm × 4	2.5 mm × 4	2 mm × 4	1 mm × 4	2 mm × 4	1 mm × 4	5 mm × 4	0.625 mm × 16
Beam pitch		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Scan length (mm)		120	130	118	120	120	120	131	125
Tissue or organ		Organ dose (mGy)							
Brain		43.3	43.8	54.2	71.0	41.7	71.0	49.4	53.3
Lens		68.5	54.3	65.7	88.3	44.5	83.8	55.1	29.5
Salivary glands		4.7	7.3	5.2	7.1	3.9	6.6	5.7	4.8
Thyroid		0.7	1.1	0.9	1.2	0.6	1.2	1.1	1.3
Lung		0.2	0.3	0.3	0.3	0.2	0.4	0.3	0.4
Breast		0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.2
Oesophagus		0.1	0.2	0.2	0.2	0.1	0.2	0.2	0.3
Liver		0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.1
Stomach		0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.1
Kidneys		0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.1
Colon		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ovary		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bladder		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Testis		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bone surface		13.9	13.2	16.3	20.8	12.1	20.7	14.9	13.2
Red bone marrow		3.6	3.7	4.4	5.8	3.4	5.8	4.1	4.4
Skin		2.8	2.0	2.2	3.5	1.9	3.6	3.4	2.8
Maximum local skin		45.9	40.3	52.5	96.5	50.3	96.5	53.8	73.3
Remainder tissues		0.5	0.8	0.6	0.8	0.5	0.8	0.7	0.7
		Effective dose (mSv)							
ICRP 103		1.2	1.3	1.5	1.9	1.1	2.0	1.4	1.5
ICRP 60		1.0	1.0	1.2	1.5	0.9	1.6	1.1	1.2

All scans were performed using conventional mode.

Table 4. Scan protocols and organ and effective doses in CTP examinations of the head

Scan protocol	E	G1	G2*	G3	G4†	G5†
Tube voltage (kV)	80	80	80	80	80	80
Effective mAs (mAs)	80	100	100	100	100	100
Rotation time (s/rot)	1.0	1.0	1.0	1.0	1.0	1.0
Beam width (mm)	8 mm × 4	5 mm × 8	5 mm × 8	5 mm × 4	5 mm × 8	5 mm × 8
Beam pitch	0	0	0	0	0	0
Total scan time (s)	50	50	50	50	75	90
Scan length (mm)	32	40	40	20	40	40
Image acquisition rate	1 image/2 s	1 image/2 s	1 image/1 s	1 image/2 s	1 image/1 s: 30 s 1 image/3 s: 45 s	1 image/1 s: 45 s 1 image/3 s: 45 s
Tissue or organ	Organ dose (mGy)					
Brain	41.0	74.6	148.5	39.1	129.4	173.5
Lens	9.9	10.0	19.8	4.6	18.2	24.4
Salivary glands	1.5	2.1	4.1	1.1	4.0	5.9
Thyroid	0.3	0.5	0.9	0.2	1.0	1.4
Lung	0.1	0.1	0.3	0.1	0.2	0.3
Breast	0.1	0.1	0.1	0.1	0.2	0.4
Oesophagus	0.1	0.1	0.1	0.1	0.1	0.2
Liver	0.1	0.0	0.1	0.0	0.1	0.1
Stomach	0.1	0.0	0.1	0.0	0.2	0.3
Kidneys	0.1	0.0	0.0	0.0	0.1	0.3
Colon	0.0	0.0	0.1	0.0	0.1	0.1
Ovary	0.0	0.0	0.1	0.0	0.0	0.0
Bladder	0.0	0.0	0.0	0.0	0.0	0.0
Testis	0.0	0.0	0.1	0.0	0.0	0.0
Bone surface	12.6	22.6	44.9	11.9	39.3	53.0
Red bone marrow	3.3	5.9	11.7	3.1	10.2	13.7
Skin	1.4	1.9	3.8	1.2	3.5	4.6
Maximum local skin	107.4	143.3	285.0	133.2	254.0	338.1
Remainder tissues	0.2	0.3	0.5	0.1	0.6	0.9
Effective dose (mSv)						
ICRP 103	1.0	1.8	3.6	1.0	3.2	4.3
ICRP 60	0.9	1.5	3.0	0.8	2.6	3.6

*Cine mode scan.

†Scan protocols recommended by Wintermark et al [16].

Table 5. Scan protocols and organ and effective doses in CTA examinations of the head

Scanner	A	B	C	D	E	F	G	H
Tube voltage (kV)	120	140	120	120	120	120	120	120
Effective mAs (mAs)	200	136	133	327	234	351	252	300
Rotation time (s/rot)	1.0	0.6	0.5	0.75	0.5	0.75	0.4	0.5
Beam width (mm)	0.5 mm × 4	1.25 mm × 4	0.5 mm × 16	0.5 mm × 16	0.5 mm × 64	0.5 mm × 64	0.625 mm × 32	0.625 mm × 64
Beam pitch	1.5	0.75	0.9375	0.6875	0.641	0.641	0.531	0.391
Scan length (mm)	40	80	40	90	90	171	105	220
Tissue or organ	Organ dose (mGy)							
Brain	9.3	22.6	8.2	22.0	37.3	55.1	32.8	29.7
Lens	33.7	37.5	25.9	69.0	40.0	61.9	39.2	31.0
Salivary glands	2.2	4.9	2.0	37.1	7.6	72.8	18.3	5.0
Thyroid	0.3	0.8	0.3	2.4	0.8	10.7	1.4	1.0
Lung	0.1	0.2	0.1	0.5	0.2	1.0	0.3	0.2
Breast	0.0	0.1	0.0	0.2	0.1	0.4	0.1	0.1
Oesophagus	0.1	0.1	0.1	0.3	0.1	0.7	0.2	0.2
Liver	0.0	0.1	0.0	0.1	0.1	0.2	0.1	0.1
Stomach	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0
Kidneys	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.0
Colon	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ovary	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bladder	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Testis	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bone surface	3.3	6.6	2.8	15.8	11.9	34.3	13.8	7.9
Red bone marrow	0.8	2.0	0.7	2.7	3.1	7.5	3.0	2.5
Skin	0.5	0.2	0.4	1.8	1.0	3.4	1.4	0.6
Maximum local skin	37.8	41.4	31.6	71.5	42.1	69.1	43.2	35.1
Remainder tissues	0.2	0.6	0.2	2.4	0.6	7.8	1.1	0.6
Effective dose (mSv)								
ICRP 103	0.3	0.7	0.3	1.6	1.1	4.1	1.3	0.9
ICRP 60	0.2	0.5	0.2	0.9	0.8	2.4	0.9	0.7

for protocols G4 and G5 are shown in Table 4. The gantry tilt in CTA and CTP was 0.0 because the incident angle of the X-ray was adjusted using a head holder.

Evaluation of dose reduction techniques for CTA scan protocol

Scan length

CTA scans were performed for the dosimetric phantom using three different scan lengths of 60, 105 and 300 mm to evaluate the effect of scan length on patient dose. GE Light Speed VCT (64-slice, scanner G) was used with 32 sections at 0.625 mm beam collimation, 120 kVp, 252 mAs effective, 0.531 beam pitch, 0.4 s gantry rotation. For 300 mm scan length, the dose reduction effect using automatic tube current modulation (Auto mA) was also investigated.

Tube voltage and effective mAs

The relations among effective mAs, effective dose and image contrast-to-noise ratio (CNR) of contrast-enhanced vessels were assessed at 80, 100 and 120 kV. These relationships were then used to evaluate dose reduction strategies in CTA.

The dosimetric phantom and a head phantom for image analysis were scanned with three different tube voltages of 80, 100 and 120 kV in combination with various tube current settings from 49 to 350 mAs effective. In each scan protocol, radiation doses and CNR were estimated. As a standard protocol, GE Light Speed VCT (64-slice, scanner G) was used with 32 sections at 0.625 mm beam collimation, 0.531 beam pitch, 0.4 s gantry rotation and 105 mm scan length. For the evaluation of CNR we used a CTA head phantom (Kyoto Kagaku, Kyoto, Japan) as shown in Figure 2a. This is because the dosimetric phantom could not be used for this purpose owing to artefacts induced by the 12 photodiode dosimeters embedded within the head region of the phantom. The CTA head phantom consists of mock brain, blood vessel and artificial cranial bone. The brain is made from urethane resin corresponding to soft tissue, while the blood vessels are made with a mixture of barium sulphate and urethane resin (see Figures 2b and c). In this phantom, the mean CT number of brain parenchyma was approximately 33 HU in all images of the cerebrum level at 120 kV. The mean attenuation for brain parenchyma of the patients is reportedly 35 HU in CTA at 120 kV [17]. The mean CT numbers for the internal carotid artery of 20 patients were 340 ± 60.1 HU at 90 kV and 253 ± 46.3 HU at 120 kV in CTA [17]. In the CTA head phantom, the mean CT number of vessels was 406 ± 17.6 HU at 80 kV, 319 ± 27.7 HU at 100 kV and 254 ± 16.5 HU at 120 kV. The CT number of phantom vessels at 90 kV was estimated to be 364 HU from the relationship between tube voltages and CT numbers of vessels. Therefore, CT numbers in HU of brain parenchyma and blood vessels in this phantom were similar to the mean values in the human brain.

To estimate the CNR of the source image (axial image) in CTA, three regions of interest (ROIs) per image were chosen in the internal carotid artery, brain parenchyma and background at the pons level of the CTA head

phantom (Figure 2c). The size of ROI in the brain parenchyma and background was 20×20 pixels (9.0×9.0 mm²), and that in the vessel was 4×4 pixels (1.8×1.8 mm²). The standard deviation (SD) of pixel CT number values within the ROI was calculated in the background. The measurement was performed in 10 consecutive images around the pons level (see Figure 2c), where the image thickness was 0.625 mm.

The CNR was defined as:

$$\text{CNR} = \frac{\left(\begin{array}{l} \text{average CT value of blood vessel ROI} \\ - \text{average CT value of brain ROI} \end{array} \right)}{\text{SD of background ROI}}$$

CNR was evaluated as the average value of the 10 images mentioned above.

Results

Organ and effective doses

Non-contrast-enhanced CT examination

Organ and effective doses obtained in non-contrast-enhanced CT examinations are summarised in Table 3. For brain and lens, which were in the direct path of the X-ray beam, brain doses were relatively high at 41.7–71.0 mGy, with lens doses of 29.5–88.3 mGy. When the scan angle was decided by the gantry tilt of CT scanners, lens doses decreased with increasing tilt. Maximum local skin doses were 40.3–96.5 mGy and largely varied depending on scan protocols and the types of CT scanner used. Doses to thyroid positioned in the proximity of the scan range were 0.6–1.3 mGy. Organ doses from the level of the lung to the testis were low at 0.4 mGy or less. Effective doses, evaluated according to ICRP 103 [8] and ICRP 60 [7], were 1.1–2.0 mSv and 0.9–1.6 mSv, respectively.

CTP examination

Patient doses in CTP were measured in only two hospitals because CTP examination was not performed in acute stroke diagnosis in the other hospitals. Table 4 shows scan protocols and organ and effective doses in CTP of the head, where scan protocols E and G1 were routine in each hospital with scanners E and G, respectively (see Table 2). Both hospitals used intermittent scanning taking a scan cycle of '1 s on, 1 s off' at a tube voltage of 80 kV. Average doses among these two hospitals were 57.8 mGy to the brain, 17.6 mGy to the bone surface and 10.0 mGy to the lens. The maximum local skin dose was 125.4 mGy on average. Mean effective doses were 1.4 mSv by ICRP 103 [8] and 1.2 mSv by ICRP 60 [7], the same level as effective doses in non-contrast-enhanced CT. If a narrow beam width of 20 mm was used (scan protocol G3 in Table 4), doses to the brain, lens and salivary glands decreased by 50%, although the maximum local skin dose was constant. For the use of cine scan without the intermittent scanning mode, organ and effective doses were doubled (scan protocol G2 in Table 4).

Wintermark et al [16] have recommended representative protocols for CTP. These recommendations may well have been the most comprehensive for CTP scan protocols to date. The image acquisition rate was changed in two phases per examination: in the first phase, the image was

Figure 2. The appearance and inner structure of a CTA head phantom produced by Kyoto Kagaku, Japan. (a) A lateral image of the phantom. (b) three-dimensional image of blood vessels and skull in the phantom. (c) Axial image of the pons level in the phantom.

acquired at a rate of one image every second with a duration of 30–45 s, while in the second phase it was acquired at one image every 2–3 s with a duration of 30–45 s [16]. The total scan time was at least 70–90 s [16]. Using scanner G, we simulated two scan protocols among their recommendations — the total scan time was 75–90 s (see G4 and G5 in Table 4). As seen in Table 4, organ doses in the protocols recommended by Wintermark et al [16] were 129.4–173.5 mGy to the brain and 18.2–24.4 mGy to the lens. Maximum local skin doses were 254.0–338.1 mGy. The effective doses were 3.2–4.3 mSv by

ICRP 103 [8] and 2.6–3.6 mSv by ICRP 60 [7]. Our results demonstrated that patient doses for CTP of the head in Japan were half or less of those obtained with the protocols of Wintermark et al [16].

CTA examination

Organ and effective doses in CTA examinations are summarised in Table 5. In CTA examination, brain, lens and salivary glands indicated relatively high doses of 8.2–55.1 mGy, 25.9–69.0 mGy and 2.0–72.8 mGy, respectively. The doses to the salivary glands in CTA

Table 6. Summary of organ and effective doses in stroke CT examinations

	Average doses in each examination			Total doses in combination examinations	
	Non-contrast-enhanced	CTP	CTA	Combination 1†	Combination 2**
Brain (mGy)	53.5	57.8	27.1	138.4	80.6
Lens (mGy)	61.2	10.0	42.3	113.5	103.5
Maximum local skin (mGy)	63.6	125.4	46.5	235.5	110.1
ED* (ICRP 103) (mSv)	1.5	1.4	1.3	4.2	2.8
ED* (ICRP 60) (mSv)	1.2	1.2	0.8	3.2	2.0

*ED: effective dose.

†Total dose for combination of non-contrast-enhanced CT, CTP and CTA.

**Total dose for combination of non-contrast-enhanced CT and CTA.

greatly varied in comparison with those in non-contrast-enhanced CT of 3.9–7.3 mGy. Maximum local skin doses were 31.6–71.5 mGy. Effective doses evaluated according to ICRP 103 [8] were 0.3–4.1 mSv. The average effective dose of 1.3 mSv in CTA evaluated by ICRP 103 [8] was 1.6 times higher than the value of 0.8 mGy in ICRP 60 [7].

Radiation doses for overall CT examinations

Table 6 shows the average organ and effective doses in each of three different stroke CT examinations and the total doses for these examinations combined. If a patient with an acute stroke undergoes a series of MDCT examinations (*i.e.* non-contrast-enhanced CT, CTP and

CTA) in a short period, the patient's brain, lens and maximum local skin doses would amount to 138 mGy, 114 mGy and 236 mGy, respectively. Without CTP, doses would amount to 81 mGy for brain, 104 mGy for lens and 110 mGy for maximum local skin (see Table 6).

Relation between image quality and patient dose in CTA

Scan length

Three different scan ranges, which include the circle of Willis, are shown in Figure 3. The range seen in Figure 3b was the routine protocol in CTA for scanner

Figure 3. Topogram of the dosimetric phantom in CTA examination of the head, where the scan region is shown in each figure. (a) 60 mm scan length. (b) 105 mm scan length. (c) 300 mm scan length.

G (see Table 5). Organ and effective doses, shown in Figure 4, indicate that doses to the salivary glands, thyroid, lung and oesophagus largely increased with scan length. The dose to the salivary glands at a scan length of 60 mm was 4.0 mGy, which was approximately a fifth of the routine dose at a scan length of 105 mm. On the other hand, at a scan length of 300 mm the dose to the salivary glands was three times higher than that of the routine protocol for scanner G. The thyroid dose at a 300 mm scan length was high at 59.8 mGy, which was 43 times higher than that at a 105 mm scan length. When the automatic current modulation system (Auto mA) was used in a 300 mm scan length, organ doses to the brain, lens and salivary glands decreased, while those to the thyroid, lung and oesophagus increased.

The effective dose for a 60 mm scan length was 0.7 mSv, while that for 300 mm with Auto mA was a maximum of 9.6 mSv. The use of a narrow scan range of 60 mm reduced the effective dose by approximately half of that in the routine protocol of 105 mm. The dose for a wider scan range of 300 mm was approximately six times greater than that for 105 mm without Auto mA, and seven times greater with Auto mA.

Tube voltage and effective mAs

The effects of varying tube voltage and effective mAs on radiation dose and image quality were studied using scanner G. Figure 5a,b, shows the lens dose and the effective dose as functions of effective mAs obtained with different tube voltages of 120, 100 and 80 kV. Lens doses and effective doses were seen to be proportional to the effective mAs. The square of CNR as a function of

effective mAs is shown in Figure 5c with tube voltages of 120, 100 and 80 kV. CNR^2 is known to be proportional to the effective mAs [18], and Figure 5c indicates the linear relation between CNR^2 and the effective mAs.

Figure 5c shows that a constant effective mAs of 252 mAs CNR^2 at 100 kV was improved by approximately 25% compared with that at 120 kV, while at 80 kV CNR^2 was the same level as at 120 kV. Figure 5a,b, shows the lens dose and the effective dose of 39.2 mGy and 1.3 mSv at 120 kV were decreased to 27.2 mGy and 0.8 mSv at 100 kV, and 15.3 mGy and 0.4 mSv at 80 kV for the constant effective mAs of 252 mAs.

On the other hand, for a constant CNR^2 corresponding to the value at 120 kV, 252 mAs, effective mAs values required for tube voltages of 100 kV and of 80 kV were estimated to be 200 mAs and 279 mAs, respectively. In each scan condition, lens doses and effective doses were decreased to 21.4 mGy and 0.7 mSv at 100 kV, and to 16.4 mGy and 0.5 mSv at 80 kV.

Discussion

Patient doses in MDCT imaging for acute stroke

The highest dose observed in stroke CT examinations with routine scan protocols was a maximum local skin dose in CTP of 143 mGy (see Table 4). This value, although not over the thresholds for deterministic effects such as hair loss and erythema, indicates considerably higher doses than maximum local skin doses from MDCT examinations in chest and abdominal regions.

The effective dose evaluated according to ICRP 103 [8] in CTA was highest at 4.1 mSv (see Table 5). Effective

Figure 4. Doses of CTA examinations for various scan ranges. (a) Organ doses for scanner G. (b) Effective doses.

Figure 5. The relationship between image quality and organ effective dose for various tube voltage and effective mAs settings in CTA examination (scanner G) as functions of effective mAs. (a) Lens dose. (b) Effective dose. (c) CNR^2 .

doses in stroke CT examinations, especially in CTA, varied among hospitals, presumably due to the difference of CT scanners and diagnostic policy in each hospital. In stroke CT examinations, effective doses evaluated by ICRP 103 [8] were considerably higher than those by ICRP 60 [7]. The reason is that the doses to the brain, salivary glands and oral mucosa included in the head region contributed to the effective dose evaluation by ICRP 103, although these tissues and organs did not, or only slightly, contributed to the effective dose by ICRP 60.

Cohnen et al [19] comprehensively evaluated organ and effective doses of patients with stroke undergoing MDCT examinations for head CT, CTA and CTP using a radiation-dose-measuring system consisting of thermoluminescent dosimeters (TLDs) and an Alderson-Rando phantom. According to their results, brain and lens doses of the overall three examinations were estimated to be 110–350 mGy and 26–56 mGy, respectively. Effective doses for the combination were between 4.7 and 9.5 mSv. Brain dose and effective dose by ICRP 60 [7] in our results were at the

same level as those in Cohnen et al, while lens doses of 114 mGy were higher than their results.

The threshold for ophthalmologically detectable opacities and visual impairment (e.g. cataract) following a single X-ray exposure has been reported to be 0.5–2.0 and 5.0 Gy [8], respectively. Although our result did not exceed these thresholds, the risk of deterministic effect for eye lens might increase by combining CT with angiography and/or repeating examinations for follow-up after a treatment. Our study indicates that medical workers in Japan should make an effort to reduce lens doses in stroke CT examinations.

Possibility of dose reduction

Among non-contrast-enhanced CT, CTP and CTA, the CTP examination was usually conducted with a high local skin dose and ran the risk of hair loss [20]. Cohnen et al [19] reported that in CTP with continued scan (*i.e.* cine scan), when tube voltage was lowered from 120 kV to 80 kV, the brain dose decreased to a quarter and skin dose to a sixth. In a previous study, we reported that the

maximum local skin dose in CTP was 712 mGy at 120 kV, 100 mAs [5]. In the present study, the dose reduction of CTP was achieved by using a low tube voltage of 80 kV because the maximum local skin dose was 285 mGy in cine scan at 100 mAs (see scan protocol G2 in Table 4). Wintermark et al [21] reported that temporal sampling intervals greater than 1 s could be used without altering the quantitative accuracy of CTP while reducing radiation dose. Table 4 shows that organ and effective doses in cine scan were decreased to half by using intermittent scanning, taking a scan cycle of "1 s on, 1 s off" at a constant tube voltage of 80 kV (see protocols G1 and G2 in Table 4). However, organ and effective doses simulated according to the CTP protocols recommended by Wintermark et al [16] were approximately twice the values for a routine protocol. This is because the protocols in Wintermark et al [16] were those of combined cine scan with intermittent scanning, and the total scan time of 75–90 s was longer than in the present study (50 s).

Furthermore, to reduce brain and lens doses, the selection of a narrow beam width (20 mm) would be effective, though it never reduced the maximum local skin dose (see scan protocol G3 in Table 4). However, Wintermark et al [16] have suggested that double coverage was essential when a minimal coverage of 20 mm slab per contrast bolus injection was used in CT scanners with under 40 mm detector length. Hence, a dose reduction just by using a narrow beam width (20 mm) might not be realised in this day of advanced CT scanners.

We also examined the possibility of dose reduction in CTA using two methods, one using a scan range as narrow as possible to avoid radiosensitive organs (see Figure 4). However, a wide scan range has been required to confirm an access route for the catheter before treating patients with aneurysm. In the case of an operation for stenosis of the internal carotid artery, automatic tube current modulation (ATCM) has been employed with wide scan ranges from supraorbital margin to aortic arch level, as it is known to reduce organ doses and improve image quality of the neck region [22]. However, our experience indicates that the use of ATCM increased doses for radiosensitive organs in the shoulder region, such as thyroid, lung and oesophagus. Since tissue weighting factors of these radiosensitive organs are relatively large (see Table 1), the effective dose obtained at a 300 mm scan length with Auto mA could be high compared with that without Auto mA (Figure 4). Although the ATCM system is effective for maintaining a certain image quality in each slice image, care should be taken to prevent dose increase for stroke patients using this system.

The other approach for dose reduction in CTA is the use of low tube voltages with a higher tube current. Waaijer et al [17] reported that this could produce a superior image quality of the circle of Willis without elevating the patient dose. However, they estimated patient doses by CTDI alone, and the organ doses were never estimated. Figure 5 shows that with a constant CNR^2 at 120 kV, 252 mAs, reduced tube voltage it decreased lens and effective doses by 46% at 100 kV, 200 mAs and by 60% at 80 kV, 279 mAs. So dose reduction would be implemented in CTA without losing

diagnostic confidence by using a reduced tube voltage of 100 or 80 kV with or without increased effective mAs.

Conclusion

Using an in-phantom dosimetry system, organ and effective doses were examined in acute stroke patients undergoing MDCT examinations with routine scan protocols in Japan, and dose reduction was investigated. In CTP and CTA, dose reduction could be successfully implemented by using reduced tube voltage, increased effective mAs and a narrow scan range. When a stroke patient undergoes various head CT examinations repeatedly and/or other radiography examinations with a high radiation dose, such as angiography, monitoring radiation doses would be necessary. Although local skin dose in a single stroke CT examination was approximately 200 mGy at maximum, our study indicated that effective doses evaluated by ICRP 103 were considerably higher than those by ICRP 60. This is because effective dose evaluation by ICRP 103 takes into account the radiation risks to the brain, salivary glands and oral mucosa included in the head region. So dose information evaluated by ICRP 103 should be used in radiation protection and optimisation of stroke CT examinations.

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