Evaluation of patient dose and operator dose in swallowing CT studies performed with a 320-detector-row multislice CT scanner

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Evaluation of Patient Dose and Operator Dose in Swallowing CT Studies Performed with a 320-Detector-Row Multislice CT Scanner

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Abstract

Recently, attempts to develop new types of swallowing function analysis with 320-detector-row multislice CT (320-MDCT) have been reported. The present report addresses (1) patient exposure, (2) operator exposure, and (3) spatial dose distribution. For dose measurement, a human-body phantom in which 303 thermoluminescent dosimeter elements were inserted and a survey meter was used. The patient position was confirmed with a single-volume scan at a tube voltage of 120 kV, a tube current of 10 mA, a rotation speed of 0.35 s/rot., a slice thickness of 0.5 mm, coverage of 160 mm, a scan field of view of 240 mm, a small focal spot size, and a gantry tilt angle of 22° (volume CT dose index;$CTDI_{vol}$ displayed on the console: 0.8 mGy, dose-length product;DLP: 12.1 mGy·cm). The effective dose for the patient in swallowing CT was 3.9 mSv. The conversion factor for obtaining the effective dose was 0.0066 mSv/mGy·cm. The effective dose for the operator was 0.002 mSv. In the operator exposure measurement, the ambient dose equivalent H*(10), that would be produced by an expanded and aligned radiation field at a depth 10 mm in the International Commission on Radiation Units and Measurements (ICRU) sphere, was 0.012 mSv. In this report, the safety of swallowing CT, which has become possible with the introduction of 320-MDCT, was evaluated by measurement of the exposure to the patient and operator.

Keywords

CT;CT dose index, effective dose; radiation protection

1.Introduction

Videofluoroscopy (VF) and videoendoscopy (VE) have typically been employed for the functional evaluation of swallowing. In particular, VF is less invasive than VE and has the advantage that the dynamics of swallowing can be observed in X-ray images. VF has therefore served as the basis for the establishment of functional analysis. Recently, attempts to develop new types of swallowing function analysis with use of 320-detector-row multislice CT have been reported [1,2]. The main advantages of swallowing CT (SCT) are that images can be observed in the axial direction and other directions that cannot be acquired by VF, morphologic evaluation is possible on 3D images, and dynamic analysis can be performed with use of 4D images. It is also anticipated that the data obtained by SCT will prove useful for the evaluation of swallowing disorders and lead to the development of new rehabilitation techniques. When standard examination protocols have been established and the software programs required for functional analysis have been developed, it is expected that SCT will become a practical CT examination.

However, the radiation dose is an important consideration in all examinations employing ionizing radiation. Proper risk-benefit analysis of this imaging technique requires accurate estimates of the patient and operator doses. Dose control for both patients and operators is essential in SCT if this new technology is to gain widespread acceptance. Simple analyses of exposure in VF and SCT have been presented in previous reports [1,2]. The results of these reports suggest that deterministic effects are unlikely in SCT, as in many other diagnostic examinations involving X-rays. However, the evaluation of SCT with regard to the assessment of swallowing function in certain clinical cases has just begun. It is expected that SCT will be employed for research and for diagnosis in various cases, and examination techniques and methods will undergo

further development accordingly. Dynamic CT often involves rather high doses, and careful dose control is therefore required. Conducting detailed dose control in a new type of examination from its early stages provides useful information for future studies on the examination method.

The present report addresses the following points: (1) The exposure in SCT was reevaluated in detail for various tissues and organs. (2) In SCT, it is necessary to match the swallowing timing with the scan timing, and the operator remains in the scan room during the examination to give the patient instructions related to swallowing. It is therefore necessary also to control the exposure to the operator. The exposure to the operator due to scattered radiation was evaluated. (3) A reclining chair made of the same carbon material as the bed is used to support the patient in SCT examinations, and the gantry is tilted to the maximum tilt angle of 22°. The spatial dose distribution in the scan room under these specific conditions has never been measured. For investigation of methods for reducing the exposure to the operator, measurements were obtained, and evaluation of the spatial dose distribution, was evaluated.

2. Materials and Methods

2.1 Evaluation of patient exposure

A multi-detector row CT scanner with 320 rows of detector elements (320-MDCT; Aquilion ONE, Toshiba Medical Systems, Otawara, Japan), which is capable of data acquisition at a slice thickness 0.5 mm with a coverage of 160 mm, was used in this study. The patient position was confirmed with a single-volume scan at a tube voltage of 120 kV, a tube current of 10 mA, a rotation speed of 0.35 s/rot., a slice thickness of 0.5 mm, coverage of 160 mm, a scan field of view of 240 mm, a small focal spot size, and a gantry tilt angle of 22° (volume CT dose index ($CTDI_{vol}$) displayed on

the console: 0.8 mGy, dose-length product (DLP): 12.1 mGy·cm). For SCT, a dynamic scan was performed with scan conditions of 60 mA and 0.35 s/rot. × 9 rotations, 3.15 seconds total scan time (cumulative $CTDI_{vol}$: 36.4 mGy, cumulative DLP: 581.7 mGy·cm). These parameters are summarized in Table 1.

A human-body phantom (Alderson Rando phantom) in which 303 thermoluminescent dosemeter (TLD) elements (MSO-S, Kyokko, Japan) were inserted was placed on a reclining chair that was tilted to 45°, and its position was adjusted so that the chin was pointing in the Z direction and the pharynx was at the same level as the center in the X direction (Fig.1a). The directions were defined as follows: X direction (lateral: left-right), Y direction (dorsoventral: anterior-posterior), and Z direction (craniocaudal: cranial-caudal). Figure 2 shows the placement of the TLD elements. After X-ray exposure, the amount of fluorescence (M) was measured for the TLD elements by use of a TLD reader (model 3000, Kyokko, Japan). For each TLD element, the dose in air (D_{air}) was calculated with use of a correction factor, f, obtained by calibration of the reading of a 6-cm^3 thimble ionization chamber (10X5-6, Radcal Corporation, Monrovia, CA, USA) in free air and the reading of an ionization chamber dosimeter (9015, Radcal Corporation) in free air. The organ dose, D(Gy), was then calculated by multiplying of the air absorbed dose (Gy) by the ratio of the mass energy-absorption coefficient of air and that of each organ [3]. The equivalent dose, H_T(Sv), was then calculated by multiplication of the organ dose by the radiation weighting factor (1.0) specified in the International Commission on Radiological Protection (ICRP) publication 103 [4]. The effective dose, E(Sv), was calculated by multiplying of the equivalent dose by the weighting factor for each tissue or organ, W_T [4].

With regard to the remaining tissues and organs, evaluation was performed for the adrenal gland, gallbladder, heart, kidney, pancreas, prostate gland (for males), small intestine, spleen, and uterus (for females). The conversion factor (mSv/mGy·cm) to be used for conversion of the DLP to the effective dose was estimated based on the DLP displayed on the console and the measured effective dose.

$$D_{air} = M \times f \text{ [Gy]} \quad (1)$$

$$D = D_{air} \times (\mu_{en}/\rho)_{\text{soft tissue etc.}}/(\mu_{en}/\rho)_{air} \text{ [Gy]} \quad (2)$$

$$H_T = D \times 1.0 \text{ [Sv]} \quad (3)$$

$$E = \Sigma W_T \times H_T \text{ [Sv]} \quad (4)$$

where D_{air} is the air absorbed dose, M is the fluorescence, f is a correction factor obtained by calibration, D is the organ dose, (μ_{en}/ρ) is the ratio of the mass energy-absorption coefficient, H_T is the equivalent dose, W_T is the weighting factor for each tissue or organ, and E is the effective dose.

2.2 Evaluation of operator exposure

For representing the CT operator, another human-body phantom in which the TLD elements were inserted was covered with a lead-free X-ray apron (Dream light, Leaktech, Japan; 0.25 mm Pb equivalent) and placed at a position 1.25 m away from the rotation center of the CT gantry in the Z direction and 0.75 m away in the X direction (Fig.3). Another human-body phantom (Alderson Rando phantom) was placed on the reclining chair as a scatterer (Fig.1b).A measurement was then performed at the position where the operator usually stands to give the patient instructions related to swallowing. The phantom height was set to 1.6 m, which is the height of the SCT operator at our facility (Fig.1c). We performed X-ray generation with the SCT scan protocol 30 times in order to measure scattered radiation. The operator dose was

evaluated in terms of the entrance surface dose, organ doses, and effective dose for a single X-ray exposure with the SCT scan protocol.

2.3 Evaluation of spatial dose distribution

We used ion chamber survey meter (ICS-323, Aloka, Japan) to measure the spatial dose distribution. This survey meter was calibrated by a standard dosimetry laboratory. For the energy response test, the sensitivity is 1.0. The scan conditions used for patient position confirmation (120 kV, 10 mA, 0.35 s/rot.) were employed. After the background radiation level was measured, the survey meter was positioned with its face perpendicular to the rotation center, and the ambient dose equivalent H*(10), which is defined in International Commission on Radiation Units and Measurements (ICRU) Report 51 [5] as the dose equivalent that would be produced by an expanded and aligned radiation field at a depth of 10 mm in the ICRU sphere, was measured. A total of 118 measurement points were set at 50-cm intervals, with the reference position set to the CT gantry rotation center. At each measurement point, the H*(10) was measured at heights of 0 cm, +50 cm, and -50 cm, with the reference height (0 cm) set to the height of the CT gantry rotation center. A simplified diagram showing the scan room and the measurement points is shown in Figure 3. The spatial dose distribution in SCT was generated based on the measured values, and methods for reducing the operator exposure were investigated.

3. Results

3.1 Patient exposure

Table 2 shows the organ doses and effective dose in SCT. The highest relative absorbed dose levels were measured for the thyroid gland (35.69 mGy), salivary gland

(34.91 mGy), and esophagus (27.62 mGy). Table 3 shows the absorbed dose to the lens of the eye in SCT as measured in the present study, as well as the absorbed dose to the lens of the eye in various types of CT examinations as reported in previous studies [6-10]. Compared with head and neck CT, the absorbed dose to the lens of the eye is lower in SCT. Table 4 shows the effective dose in SCT and the effective doses for neck CT and VF reported in numerous publications [1,11-18]. The effective dose in SCT is 3.9 mSv, which is 1.0 mSv higher than that in typical neck CT and 3.5 mSv higher than that in VF. The conversion factor for obtaining the effective dose was calculated based on the DLP value displayed on the console (593.7 mGy·cm), and the result was 0.0066 mSv/mGy·cm.

3.2 Operator exposure

Tables 5 and 6 show the organ doses and the effective dose to the operator in SCT. The highest relative absorbed dose levels were measured for the thyroid gland (0.016 mGy), esophagus (0.010 mGy), salivary gland (0.008 mGy), and lens of the eye (0.009 mGy), and the effective dose was 0.002 mSv. The absorbed dose to the skin on the chest was 0.002 mGy with the 2.5-mm Pb-equivalent lead-free X-ray apron and 0.012 mGy without the apron. The absorbed dose to the gonads was 0.001 mGy with the lead-free X-ray apron and 0.010 mGy without the apron. These results confirmed the effectiveness of the X-ray protection provided by the lead-free X-ray apron.

3.3 Spatial dose distribution

Figure 4 shows the spatial dose distribution in SCT. At position A (in front of the patient's head on the rear side of the gantry), H*(10) was high at a height +50 cm from the gantry rotation center and low at a height -50 cm from the gantry rotation

center. At position B (45° with respect to the Z axis), H*(10) was low at +50 cm and high at -50 cm. At position C (couch end on the front side of the gantry), H*(10) was high at +50 cm and low at -50 cm. At position D (diagonally opposite position B), H*(10) was also high at +50 cm and low at -50 cm, but the spread of scattered radiation was broader as compared with position C. At the operator exposure measurement position, H*(10) at a height of 0 cm was 1.7 mSv/h. When this value was converted from the total mAs in SCT (245 mAs), the result was 0.012 mSv, which matches the operator exposure at the chest measured without the 2.5-mm Pb-equivalent lead-free X-ray apron.

4.Discussion

The absorbed dose was higher for the thyroid gland, salivary gland, esophagus, and lens of the eye than for other organs. The thyroid gland is known to be more radiosensitive than are other endocrine organs. However, the threshold dose for hyperthyroidism is 25 Gy to 30 Gy, which is 800 times higher than the absorbed dose to the thyroid gland in SCT (35.69 mGy). It has been reported that an absorbed dose of 1 Gy or less does not lead to a reduction in thyroid function. It is therefore unlikely that SCT can directly cause thyroid dysfunction [19]. In addition, because the threshold dose for early transient erythema and temporary epilation is 2 Gy to 3 Gy, deterministic effects are unlikely in SCT, where the maximum doses are approximately 100 times less than deterministic dose thresholds. This is also true for the salivary gland and esophagus. The threshold dose for deterministic effects on the lens of the eye has been estimated to be 0.5 Gy to 2 Gy for lens opacification and 2 Gy to 10 Gy for cataract formation [20]. These values are 25 times to 500 times higher than the absorbed dose to the lens of the eye in SCT (20.76 mGy); it is therefore unlikely that SCT can have

deterministic effects on the lens of the eye. However, ICRP draft ref 4844-6029-7736 [21], entitled "Early and late effects of radiation in normal tissues and organs: threshold doses for tissue reactions and other non-cancer effects of radiation in a radiation protection context" suggests that the threshold doses for deterministic effects on the lens of the eye may be lower than the currently accepted values, and it discusses whether radiation injury to the lens of the eye is due to deterministic or stochastic effects. The exposure of the lens of the eye must be considered more carefully in the future. In SCT, unlike head and neck CT, primary radiation does not enter the lens of the eye, and the absorbed dose remains below the level that may cause radiation injuries. In these results, even if SCT was performed several times, the possibility that the radiation injuries would occur was low. The organ dose and the effective dose in that case will be computed from the relationship between the tube current-time product and the dose. Nevertheless, the exposure must be reduced as much as possible.

The effective dose in SCT was found to be 3.9 mSv, which is higher than that in neck CT and VF. SCT is a detailed examination that combines both morphologic and functional evaluation. For functional evaluation, it is necessary to scan continuously during swallowing, and the effective dose is therefore unavoidably increased. However, the effective dose in SCT is only half that of body CT (chest CT: 5 mSv to 7 mSv, abdominal CT: 5 mSv to 7 mSv) [22], in which a wide anatomic range is scanned and the vital organs are exposed to high levels of primary radiation. It therefore cannot be said that the effective dose in SCT is particularly high.

No dose limits are applied to medical exposure in order to avoid imposing excessively strict restrictions on clinical practice. Nevertheless, SCT should be performed only when it is clinically indicated. In SCT, swallowing function can be evaluated accurately and noninvasively based on axial images, 3D images, and 4D

images. In addition, it is expected that analyzing the SCT examination results obtained for large numbers of patients may lead to the development of new rehabilitation techniques. Although SCT is currently considered to be in the research phase, it has many advantages and is a valid clinical examination technique.

As the next step, it is important to determine the optimal scan conditions for SCT. With regard to technical optimization, the patient should practice swallowing before the examination. This permits the operator to determine the timing of swallowing, making it possible to reduce the scan time. With regard to mechanical optimization, motion artifacts must be reduced. It is expected that the exposure can be reduced by adjustment of the scan conditions once motion artifacts in dynamic scams have been minimized. However, one problem in attempting to determine the optimal scan conditions is that there is no reference level that can serve as a target value for exposure reduction. Until SCT examinations performed at various facilities have been evaluated and dose evaluation results have been collected, we suggest using an effective dose of 3.9 mSv as a provisional target value for dose reduction. We also suggest a conversion factor of 0.0066 (mSv/mGy·cm) for converting the DLP to the effective dose in SCT for adults, referring to ICRP 102 [18]. This value is close to the conversion factor for the adult neck (0.0059) shown in Table A.2 of ICRP 102, which was cited in the report of Bongartz et al.[23]. A conversion factor of 0.0059 was calculated by use of the X-ray CT effective dose estimation software ImPACT provided by United Kingdom's CT scanner evaluation center. This software employs national radiological protection board (NRPB)-SR250 (CT-DOSE) as providing the basic data. NRPB-SR250 incorporates the results of Monte Carlo simulations with use of typical X-ray CT scanners and the MIRD-5 mathematical human phantom. Because SCT is currently available only in 320-MDCT, the factor of 0.0066 mSv/mGy·cm,

which we suggest in the present report can be used for evaluation of the effective dose more accurately than the factor of 0.0059 mSv/mGy·cm which covers various types of CT scanners.

The effective dose to the operator was found to be 0.002 mSv per examination, which is quite low. The absorbed dose was higher for the thyroid gland, esophagus, salivary gland, and lens of the eye, which were not protected by the lead-free X-ray apron. Thyroid collars and radiation glasses are effective means for protecting these organs. However, the patient may feel uncomfortable if the operator wears too much radiation protection. If the operator does not wear head and neck protection while remaining in the scan room in order to give the patient instructions related to swallowing, the exposure to the head and neck can be reduced by her standing at a position at 45° relative to the gantry rotation center (position B in Fig.3). If the operator stands on an elevated platform, a further reduction in exposure can be expected. The positions at the front of the gantry (C and D in Fig.3) are not suitable, because observing and instructing the patient are difficult and the effects of scattered radiation are greater at these positions.

It has been confirmed in previous studies that 320-detector-row multislice CT is useful in various clinical applications, including whole-brain perfusion CT, coronary CT, and pediatric CT. In this report, SCT, which has become possible due to the introduction of 320-detector-row multislice CT scanners, was evaluated by measuring of the exposure to the patient and operator. It was confirmed that SCT is a dynamic imaging modality in which the risk of radiation injury due to X-ray exposure is negligible.

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Table 1 Scan conditions for SCT

Scan	Positioning CT	Swallowing CT
Scan mode	Volume scan	Dynamic scan
Tube voltage (kV)	120	120
Tube current (mA)	10	60
Rotation time (s/rot.)	0.35	0.35 (3.15 s)
Slice thickness (mm)	0.5	0.5
Beam width (mm)	160	160
Field of view (mm)	240	240
Focal spot size	Small	Small
Tilt angle (°)	22	22
Cumulative $CTDI_{vol}$ (mGy)	0.8	36.4
Cumulative DLP (mGy·cm)	12.1	581.7

Table 2 Organ dose and effective dose in SCT

Organ/tissue	Organ dose (mGy)
Lung	2.61
Stomach	0.30
Colon	0.04
Bone marrow	0.03
Breast	3.95
Gonads	0.01
Thyroid gland	35.69
Esophagus	27.62
Bladder	0.01
Liver	0.24
Bone surface	0.06
Skin	6.07
Brain	10.03
Salivary gland	34.91
Remainder	0.08
Effective dose (mSv)	3.90

Table 3 Comparison of absorbed dose to the lens of the eye between SCT and other types of CT

Examination	Publication	Lens dose (mGy)
Swallowing CT		20.76
Head CT	Abdeen (2010)[6)]	43.5–61.5
	Jaffe (2010)[7)]	25–50
Neck CT	Yamauchi-Kawaura (2009)[8)]	10.6–32.0
Face CT	Zammit-Maempel (2003)[9)]	35.1
Perfusion CT	Hirata (2005)[10)]	5.5–127.2

Table 4 Comparison of effective dose between SCT and other modalities

Examination	Publication	Effective dose (mSv)
Swallowing CT		3.9
Neck CT	Kharuzhyk (2011)[12)]	2.6±1.0
	Hayton (2009)[11)]	2.4–2.8
	Yamauchi-Kawaura (2009)[8)]	1.8–6.6
Videofluoroscopy	Wise (2004)[13)]	6.9
	Iwai (2011)[14)]	0.12
	Fujii (2011)[1)]	1.05
	Chau (2009)[15)]	0.26–0.31
	Zammit-Maempel (2007)[16)]	0.2
	Wright (1998)[17)]	0.40
Barium swallow	ICRP 102 (2007)[18)]	1.5

Table 5 Organ dose and effective dose to the operator in SCT

Organ/tissue	Organ dose (mGy)
Lung	0.002
Stomach	0.002
Colon	0.002
Bone marrow	0.001
Breast	0.002
Gonads	0.001
Thyroid gland	0.016
Esophagus	0.010
Bladder	0.001
Liver	0.002
Bone surface	0.001
Skin	0.004
Brain	0.002
Salivary gland	0.008
Remainder	0.001
Effective dose (mSv)	0.002

Table 6 Effectiveness of the lead-free X-ray apron and dose to the lens of the eye in SCT

Organ/tissue	Organ dose (mGy)
Breast (+2.5 mmPb)	0.002
Breast (–2.5 mmPb)	0.012
Gonads (+2.5 mmPb)	0.001
Gonads (–2.5 mmPb)	0.010
Lens of eye (–2.5 mmPb)	0.009

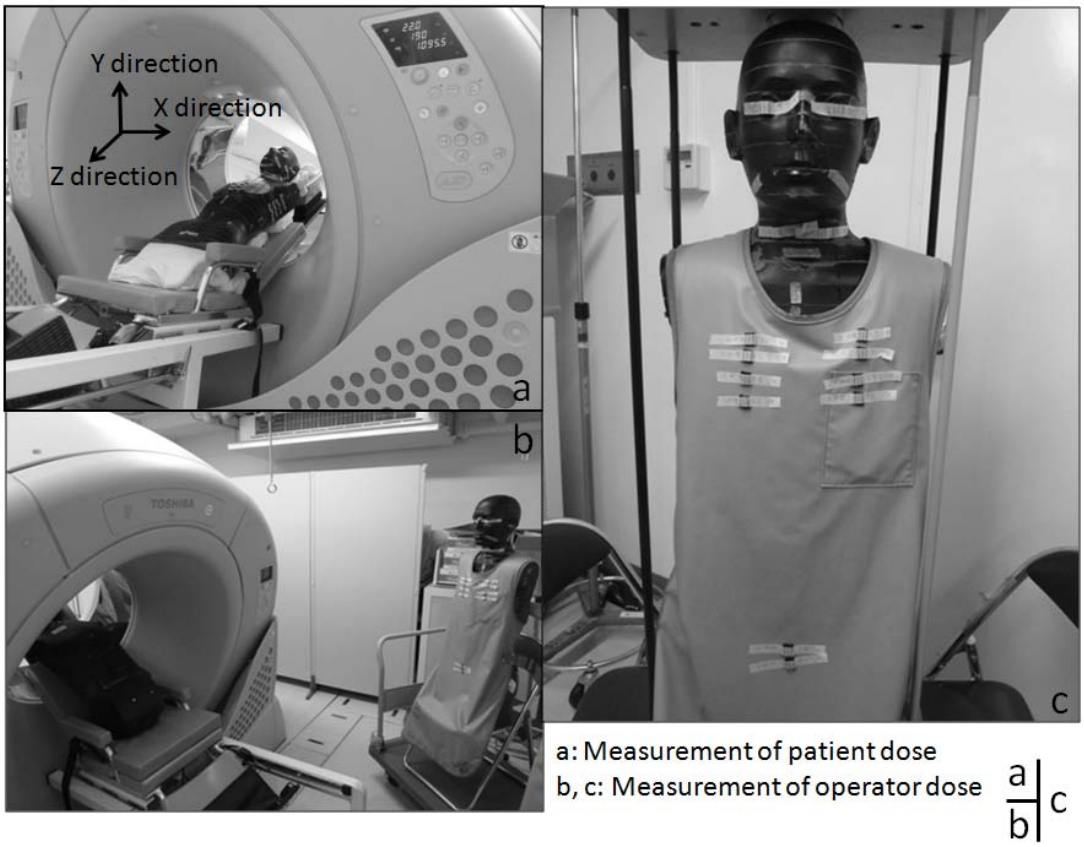

Fig.1 Setup for dose measurement in SCT. a: Measurement of patient dose, b and c: Measurement of operator dose.

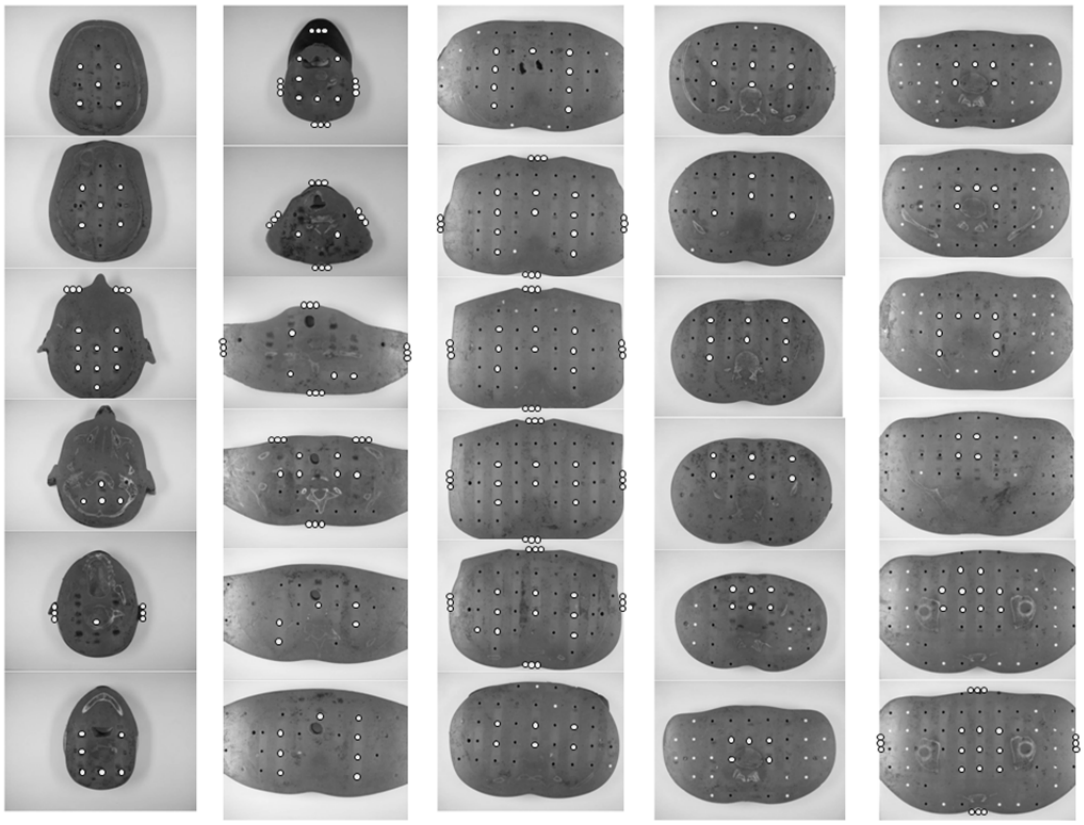

Fig.2 Placement of the TLDs.

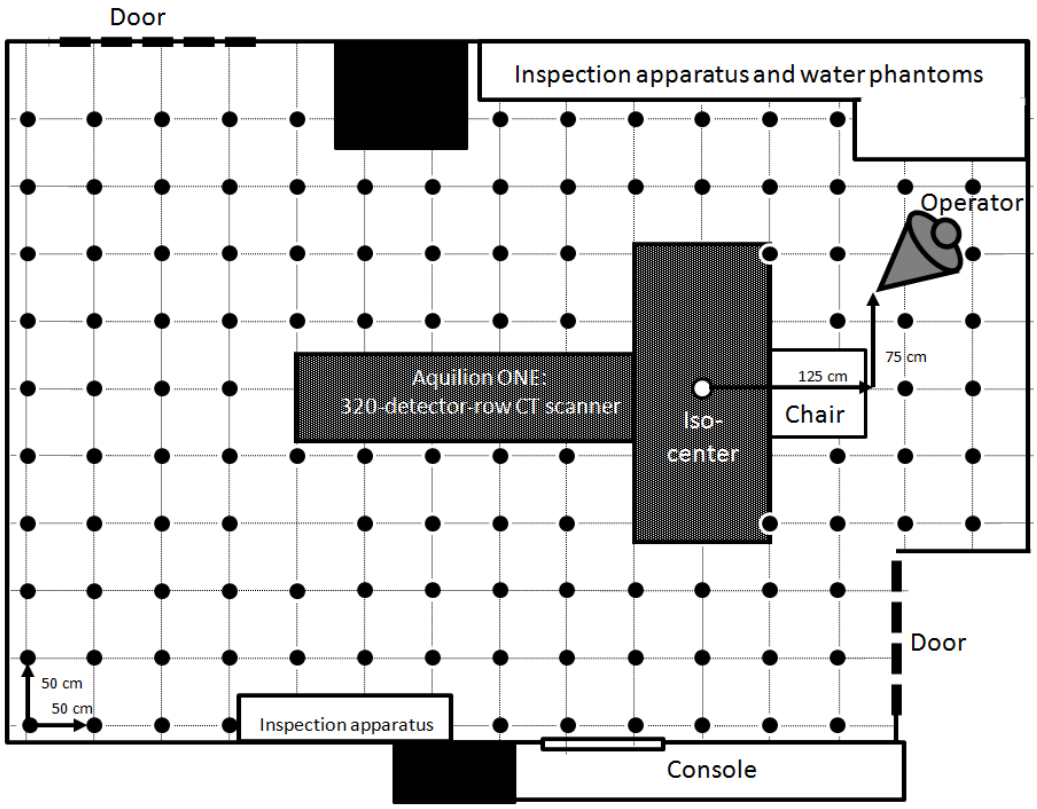

Fig. 3 Layout of the CT room and spatial dose distribution measurement points.

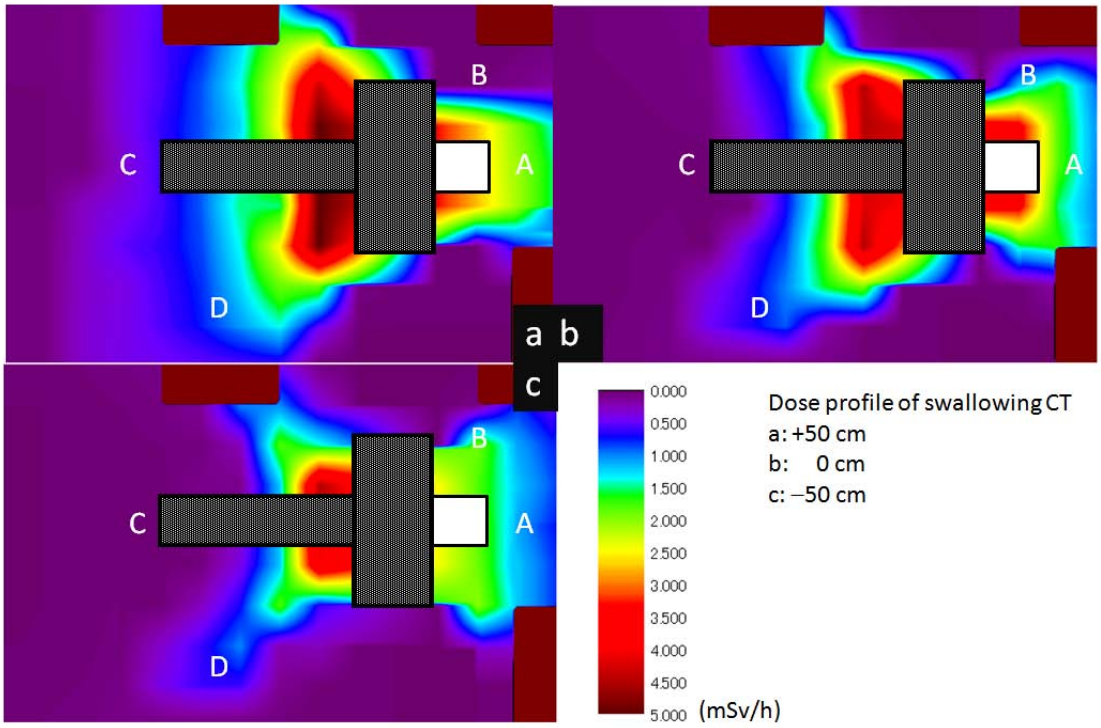

Fig.4 Spatial dose distribution in SCT. a: At height +50 cm from the gantry rotation center, b: At the height of the gantry rotation center, c: At height -50 cm from the gantry rotation center.