Contents lists available at ScienceDirect

European Journal of Radiology

Breast exposure reduction using organ-effective modulation on chest CT in Asian women

Joji Ota[a,b,*], Hajime Yokota[c], Hazuki Takishima[a], Akiyo Takada[a], Ryosuke Irie[a], Yuka Suzuki[a], Takeshi Nagashima[d], Takuro Horikoshi[a], Koichi Chida[b], Yoshitada Masuda[a], Takashi Uno[c]

[a] Department of Radiology, Chiba University Hospital, 1-8-1, Inohana, Chuo-ku, Chiba City, Chiba 260-8677, Japan
[b] Course of Radiological Technology, Health Sciences, Graduate School of Medicine, Tohoku University, 2-1 Seiryo, Aoba, Sendai, Miyagi, Japan
[c] Diagnostic Radiology and Radiation Oncology, Graduate School of Medicine, Chiba University, 1-8-1, Inohana, Chuo-ku, Chiba City, Chiba 260-8670, Japan
[d] Department of General Surgery, Chiba University Graduate School of Medicine, Chiba University, 1-8-1, Inohana, Chuo-ku, Chiba City, Chiba 260-8670, Japan

ARTICLE INFO

ABSTRACT

Purpose: Organ-effective modulation (OEM) is a mechanism to reduce radiation dose to selected organs on computed tomography (CT). The purpose of this study was to measure radiation dose to the breast in Asian patients undergoing chest CT and to clarify the degree of exposure reduction.
Method: We randomly selected 60 female patients undergoing non-contrast chest CT after breast cancer surgery. To measure radiation dose, an optically stimulated luminescence dosimeter had been attached directly to the gown over the nonoperated breast in 30 patients. Radiologists evaluated the image quality with and without OEM. In order to clarify the characteristics of OEM, the effects of angle and object size were measured using a phantom and an ionization chamber dosimeter.
Results: The OEM group received 9.1 ± 1.9 mGy and the non-OEM group received 10.7 ± 2.4 mGy. OEM reduced the exposure by 12.2% ($P < 0.01$). OEM caused no reduction in diagnostic quality. In the phantom study, the results of the angle effect were 3.2%, 11.2%, 28.7%, 31.3, 25.9%, 14.9% and 6.0% dose reductions at -90, -60, -30, 0, 30, 60 and 90°, respectively. The effect of the subject thickness was 3.7%, 17.5%, 30.2%, 31.7%, and 34.1% at 16, 20, 24, 28 and 32 cm diameters, respectively.
Conclusions: OEM is a useful mechanism for reducing radiation exposure to the breast without affecting diagnostic imaging quality. The reduction rate correlated negatively with body habitus.

1. Introduction

Medical radiation exposure in the United States has increased about sixfold in 30 years, mostly attributable to computed tomography (CT) [1]. The increase in radiation exposure has elicited concern about increasing radiation-induced cancer [2–4]. The tissue weighting factor of the breast was revised from 0.05 to 0.12 by the International Commission on Radiological Protection (ICRP) 2007 recommendation, indicating the higher radiosensitivity of breast tissue. In chest CT, suppression of breast exposure is a topic of discussion [5,6]. For example, the breast cancer patients regularly undergo CT during and after therapies such as surgery. Frequent radiation exposure should increase the risk of breast cancer in the contralateral breast.

To reduce exposure to anterior organs, organ-based tube current modulation (OBTCM) is used as a breast exposure reduction technique in chest CT examinations [5–9]. There are two types of OBTCM available; one (X-CARE, Siemens Healthcare, Forchheim, Germany) is a mechanism that decreases the tube current when scanning the anterior body and increases the tube current on the posterior aspect, whereas organ-effective modulation (OEM, Toshiba Medical Systems, Tochigi, Japan) is a mechanism that decreases the tube current when scanning the anterior body and does not increase the tube current when scanning posteriorly, which is seen as advantageous [7–20].

Previous studies using OEM retrospectively analysed the chest and abdominal CTs of patients. In a previous report, OEM reduced exposure by 8.3%. Deterioration of image quality accompanying exposure reduction did not become a problem in diagnosis. However, radiation dose assessment in the study was done by CT dose index (CTDI) and

---

Clinical study

Post-operative follow-up CT of 60 patients with breast cancer
- OEM group of 30 patients between Nov. 2015 to Jan. 2016
- Non-OEM group of 30 patients between Apr. 2016 to Jun. 2016

2.3 Breast dosimetry

12 OSL dosimeters (Nanodot)

Cross calibration

Ionization chamber dosimeter (90M10)

Breast dose (mGy)

2.4 Image quality evaluation

5 point scaling by radiologists
- Artefact
- Noise
- Overall image quality

Phantom study

2.5 Characterization of OEM using AEC phantom
- Angle effects
- Influence of subject thickness

Ionization chamber dosimeter $(10 \times 6 - 0.6$ CT)

Reduction Ratio (%)

2.6 Measurement of image noise level by human phantom

ROI (1 cm diameter circle)
- Chest section
- Abdomen slice
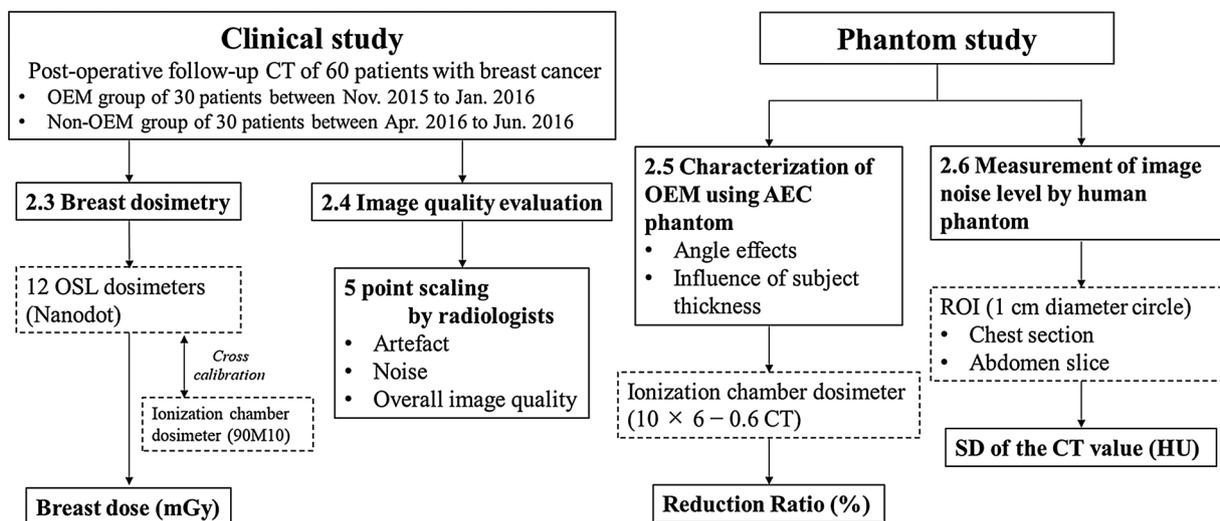
SD of the CT value (HU)

Fig. 1. Study design.
The phantom study of this study and the prospective clinical study are shown in the flowchart. OEM = organ-effective modulation, OSL = optically stimulated luminescence, AEC = automatic exposure control, ROI = region of interest, SD = standard deviation.
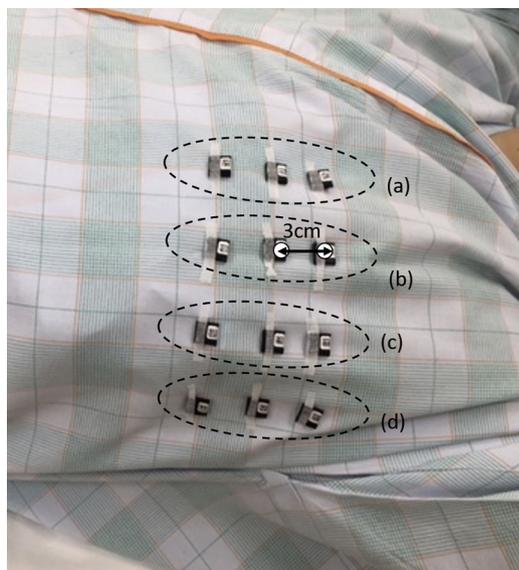

Fig. 2. Positions of dosimeters.
(a) Parasternal line: The line between the centre of the breastbone and the nipple. (b) Nipple line: A centred on the nipple. (c) Anterior axillary line: anterior side of the axilla. (d) Lateral axillary line: the centre of the axilla. In the body axis direction, three OSL dosimeters were attached at intervals of 3 cm around the nipple.

dose length product (DLP). Since CTDI and DLP are dose indices of the entire scan, they did not correctly evaluate the exposure to the breast [7]. The only way to accurately measure each patient's breast dose is to actually measure it. Therefore, the effect of OEM on breast dose has not been clarified.

As OEM is affected by body habitus, there is a possibility that the effect of radiation reduction differs between Asians and Westerners. The purpose of this study was to measure breast dose in phantoms and in Asian patients and to clarify the effect of OEM's breast exposure reduction, with image quality evaluation by radiologists.

2. Material and methods

2.1. Research design: subjects

This study was a prospective study and approved by the ethics committee of our institute, and an informed consent was provided to all patients. Fig. 1 shows the study design. In Nov. 2015 to Jan. 2016 and Apr. 2016 to Jun. 2016, We selected patients who met the inclusion criteria by continuous follow-up CT of 30 cases of breast cancer after surgery.

Patients with bilateral mastectomy and patients weighing ≥ 100 kg were excluded. Patients under chemotherapy or radiation therapy, and patients with lung comorbidities that change the volume of the thorax were also excluded. The present study required 60 patients for the examination of 20% dose reduction. With a one-sided α of .05 and use of a Wilcoxon-signed-rank test, 30 patients per group provided an 80% power [5,7,8]. Sample size was calculated by G*power [21]. Finally, 60 patients were included in this study.

2.2. Scanning parameters of CT

All patients underwent non-contrast CT (Aquilion ONE VISION ver. 7.0, Canon Medical, Tokyo, Japan). OEM is installed as organ-based automatic exposure control (AEC) in this scanner. The acquisition conditions were: tube voltage, 120 kV; gantry rotation speed, 0.5 s/rot; beam width, 0.5×80 mm; setting standard deviation of tube current AEC, 9.0 in 5 mm image of standard function. The pitch factor was 0.813 (helical pitch = 63).

2.3. Breast dosimetry

An optically stimulated luminescence (OSL) dosimeter (Nanodot Nagase Landauer Ltd., Ibaraki, Japan) was used in this study. The patients wore hospital gowns. The OSL dosimeter was placed after obtaining the positioning image. Positions of the 12 dosimeters are shown in Fig. 2. The dose along each line was defined as the mean of the values registered by the 3-point OSL dosimeters after multiplying by the calibration constant of each dosimeter. The mean of all 12 values was defined as the dose to the whole breast.

The OSL dosimeters were cross-calibrated with an ionization chamber dosimeter (ACCU-PRO90M10, Radcal, Monrovia CA, USA) calibrated by the Japan Quality Assurance Organization in 2015, whose chamber used 90 M 10 (6 mL). This was not performed with patients.

The geometrical arrangement was as follows: distance between the irradiation focus and dosimeter, 100 cm; irradiation field at the dosimeter, 10×10 cm^2. The ionization chamber dosimeter and OSL dosimeter were placed along the irradiation beam axis, and the calibration constant of each OSL dosimeter was calculated. Scanning parameters were: tube voltage, 120 kV; tube current, 200 mA, irradiation time 0.025 s, irradiation number, 10 times.

2.4. Image quality evaluation: subjective image quality analysis with clinical images

CT images of 60 clinical images with and without OEM were randomly displayed and evaluated by two board-certified radiologists (16 and 13 years' experience). Artefact, noise, and overall image quality were scored using a five-point scale. Subjective image quality was assessed in terms of image artefact, noise and overall image quality at the thoracic level. The settings of window width (WW) and window level (WL) were for the mediastinum condition (WL 30, WW 300) and lung windows (WL-600, WW 1500). The two observers independently evaluated images and finally decided final results with consensus.

2.5. Characterization of OEM using AEC phantom

To investigate the influence of the angle of the OEM, an AEC cone phantom (Kyoto Kagaku, Kyoto, Japan) was placed at the isocentre, and the front of the phantom was defined as 0°direction (12 o'clock position) at the position where the beam centre diameter was 32 cm. An ionization chamber dosimeter (10×6–0.6 CT, Radcal) was placed at $-90°$, $-60°$, $-30°$, 0°, 30°, 60°, and 90° with the angle changed by 30° in the X-ray tube rotation direction and the dose was measured (Fig. 3a). The effect of body habitus was investigated. The ionization chamber dosimeter was placed in the 0° direction, which is expected to maximize the dose reduction effect of OEM. The dose was measured at the positions of AEC phantom diameters of 16 cm, 20 cm, 24 cm, 28 cm, and 32 cm (Fig. 3b).

Since scattered radiation could not be removed, an accurate output dose could not be measured. Therefore, in this study, we assumed scatter rays was the same on each scan. The dose was measured at each angle with and without OEM and the dose reduction rate at the time of using OEM was recorded. We used non-helical scanning and modulation in the X–Y direction was off. To reduce the influence of the position of the X-ray tube at the start of scanning, the scan was performed five

times with the interval between scan start times being 10.1 s.

2.6. Measurement of image noise level by human phantom: objective image quality analysis with phantom images

A chest phantom used for lung cancer screening CT (LSCT phantom, Kyoto Science, Kyoto, Japan) was used. Since this phantom has no breast, 500 ml packs of physiological saline were arranged on the left and right on the front of the chest. The phantom was scanned with and without OEM using helical technique with modulation in the X–Y direction turned on. To reduce the influence of the position of the X-ray tube at the start of scanning, the scan was performed five times with the interval between scan start times being 10.1 s. Image noise was evaluated using the standard deviation (SD) of the CT value in the region of interest (ROI) of a 1 cm diameter circle set on the image. One Section 1 cm below the lower edge of the scapula and one Section 2 cm below the lower edge of the sternum were used, and the SD value of each ROI was measured as shown in Fig. 4. The mean value of the SDs of each image taken five times was defined as the measured value.

2.7. Statistics

For comparison of clinical findings between the non-OEM and OEM groups, Mann-Whitney and Fisher's exact tests were applied for continuous and category data, respectively. The differences in dose were evaluated with the Mann-Whitney test. The significance level was $P < 0.05$ (Table 1).

3. Results

3.1. Dose measurement

The characteristics of the 60 cases are summarized in Table 2. All variables are expressed as mean ± standard deviation. There was no significant difference between the groups with and without OEM in age, weight, height, body mass index (BMI) and surgical method. Table 3 shows the results of CTDI, DLP and breast dose of 60 patients. All variables are expressed as mean ± standard deviation. There was no significant difference between the non-OEM and OEM groups in CTDI and DLP. Significant differences were revealed on the whole breast ($P < 0.0001$), parasternal line ($P = 0.0023$), and nipple line ($P = 0.0034$) between the non-OEM and OEM groups. There was no

Fig. 3. Organ-effective modulation output evaluation by phantom analysis (a) Influence of angle (b) Influence of subject thickness.
(a) Measurement points on the influence of angle. We measured the seven points every 30° in the X-ray tube rotation direction with the front position as 0°.
(b) Thickness measurement point: Measurement was done at the five points of the slice position at which the diameter of the cross section of the AEC phantom was 16 cm, 20 cm, 24 cm, 28 cm, 32 cm.
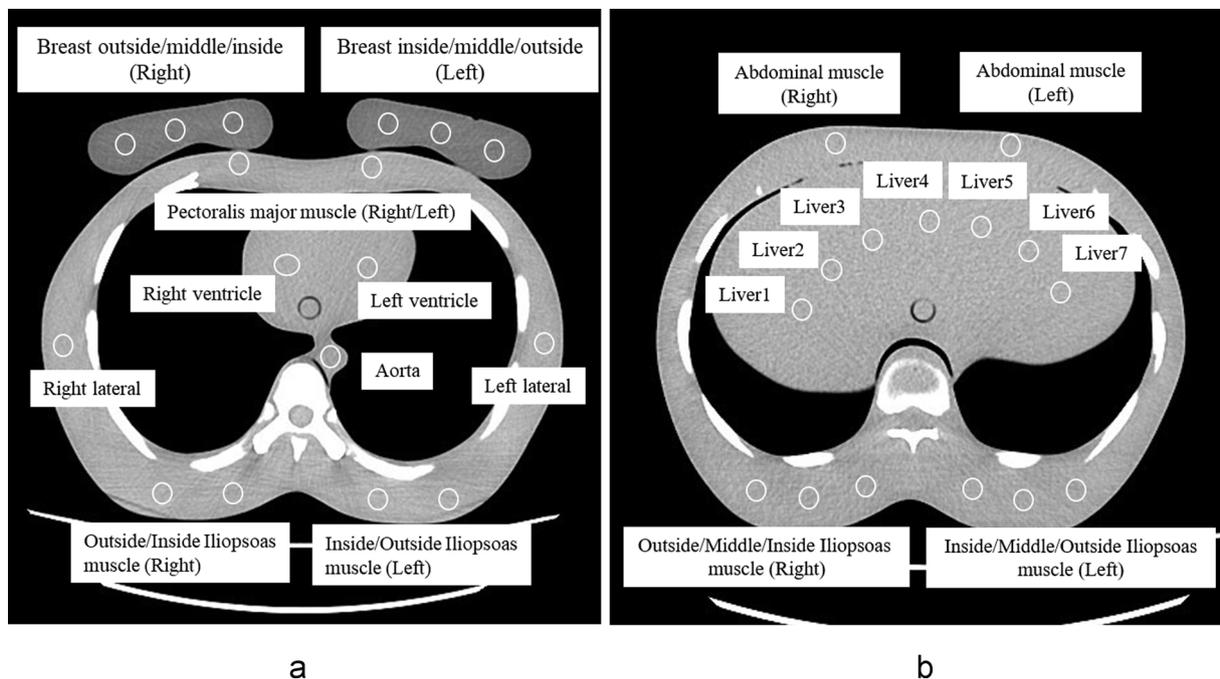
Fig. 4. ROIs used for phantom analyses of image quality.
(a) The level of the lung (b) The level of the abdomen. 1 cm circular ROIs were used to measure the standard deviation of CT values.

significant difference in doses along the anterior axillary line ($P = 0.09$) and lateral axillary line ($P = 0.07$) between the non-OEM and OEM cases.

3.2. Subjective image quality analysis for clinical images

No significant difference was found between the non-OEM and OEM groups in any of the image quality evaluation factors (Table 4). All values are expressed as mean ± standard deviation.

3.3. Characterization of OEM using the AEC phantom

The results of the angle effect were 3.2%, 11.2%, 28.7%, 31.3, 25.9%, 14.9% and 6.0% reductions at $-90°$, $-60°$, $-30°$, $0°$, $30°$, $60°$, and $90°$, respectively. The effect of the subject thickness was 3.7%, 17.5%, 30.2%, 31.7%, and 34.1% at 16, 20, 24, 28 and 32 cm diameters, respectively. These results are shown in Fig. 5.

3.4. Objective image quality analysis for phantom images

A significant difference was observed between non-OEM and OEM (6.58 vs. 7.16 of SD value on non-OEM and OEM; 9% noise increase; $P = 0.000134$) in image noise measurements with the human body phantom (Table 5). All values are expressed as mean ± standard deviation.

Table 2
Patient characteristics.

	Non-OEM	OEM	P value
Age (y)	61.6 ± 11.0	60.4 ± 12.1	0.34
Weight (kg)	53.9 ± 8.3	53.6 ± 6.1	0.37
Height (cm)	155.2 ± 4.9	155.2 ± 5.75	0.5
BMI (kg/m²)	22.0 ± 3.6	22.3 ± 2.6	0.38
Surgical method			0.95
Total left resection	6	6	
Left partial resection	9	7	
Total right resection	6	7	
Right partial resection	6	10	
Pathology			1
Invasive ductal carcinoma	24	25	
Invasive lobular carcinoma	3	2	
mucinous carcinoma	1	1	
Ductal carcinoma in situ (DCIS)	2	2	

4. Discussion

In this study, we revealed that using OEM for non-contrast chest CT imaging of Asian women reduced the whole breast exposure by 12.2%. The level of deterioration in image quality was insignificant. In the phantom study, dose reduction increased with increasing body habitus. The maximum reduction effect was > 30%. For this reason, the effect of OEM for the breast was relatively low for Asians with small body habitus.

A previous retrospective study of OEM was performed using CTDI and DLP for dose evaluation [7]. It reported that OEM was associated

Table 1
Five-point scale of visual assessment.

Artefact	Noise	Overall image quality
Unacceptable artefact	Unacceptable image noise	Unacceptable
Severe artefact making hard to delineate some structures	Above average image noise	Diagnostic imaging severely limited
Acceptable artefact	Acceptable image noise	Acceptable
Only few artefacts	Below average image noise	Good imaging quality with minimal unsharpness
No or minimal artefact	No or minimal image noise	Structures clearly defined

Table 3
Dose evaluation.

	Non-OEM	OEM	P value	Reduction rate
CTDI (mGy)	11.1 ± 3.0	10.6 ± 2.0	0.78	4.50%
DLP (mGy· cm)	572.0 ± 141.7	567.9 ± 112.3	0.98	0.70%
Parasternal line (mGy)	11.6 ± 3.0	10.3 ± 4.7	0.0023	11.20%
Nipple line (mGy)	10.7 ± 2.4	9.1 ± 1.9	0.0034	15.00%
Anterior axillary line (mGy)	10.3 ± 2.5	9.0 ± 2.1	0.09	12.60%
Lateral axillary line (mGy)	10.3 ± 2.7	9.0 ± 2.5	0.07	12.60%
Total (mGy)	10.7 ± 2.7	9.4 ± 3.0	< 0.0001	12.20%

Table 4
Visual assessment.

	Non-OEM	OEM	P value
Noise(mediastinal window)	4.97 ± 0.18	4.97 ± 0.18	0.98
Artefact(mediastinal window)	4.31 ± 0.47	4.50 ± 0.51	0.23
Noise(lung window)	5.00 ± 0	5.00 ± 0	–
Artefact(lung window)	5.00 ± 0	5.00 ± 0	–
Overall image	4.97 ± 0.18	4.97 ± 0.18	0.98

with an 8.3% decrease in CTDI. However, since CTDI is the dose evaluation of the entire scan, it could not assess regional dose such as that to the breast. Our study directly measured the dose to the surface of the breast and found a reduction rate of 12.2%.

Previous studies using OBTCM, which increases the dose posteriorly, have found that some breast tissue in included within the increased dose zone of tube current modulation in almost all female breasts. Thus, OBTCM increases the dose to the lateral zone of the breast [20], whereas we found that OEM did not increase the dose to the anterior and lateral breast areas in clinical studies, suggesting that OEM is superior to OBTCM in decreasing breast exposure.
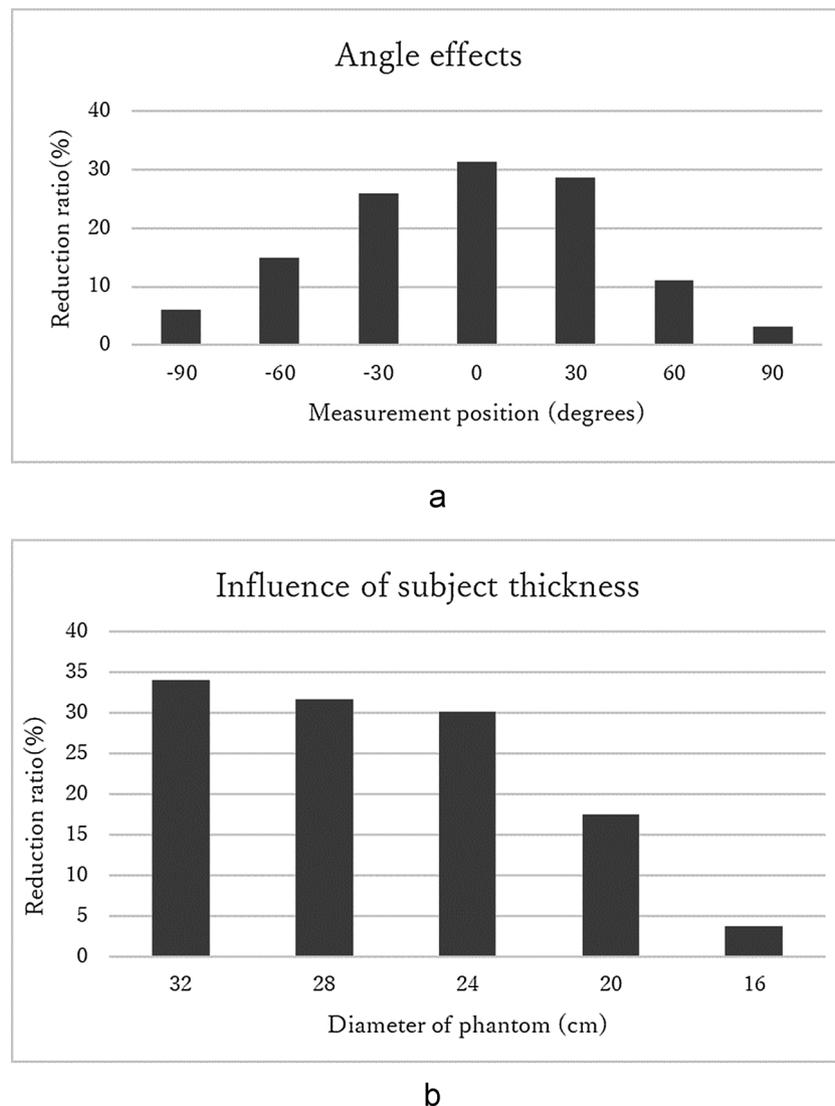

a

b

Fig. 5. (a) Reduction ration of organ effective modulation influenced by angle (b) Reduction ration of organ effective modulation influenced by subject thickness.

Table 5
Image noise (Phantom study).

Chest section: SD Value (HU)

	Breast outside (Right)	Breast middle (Right)	Breast inside (Right)	Breast outside (Left)	Breast middle (Left)
OEM(off)	5.88 ± 0.36	6.09 ± 0.38	5.65 ± 0.70	6.33 ± 0.79	6.40 ± 1.09
OEM(on)	6.84 ± 0.79	6.76 ± 0.65	6.53 ± 0.83	7.17 ± 0.38	7.36 ± 0.97
p value	0.0952	0.151	0.222	0.0952	0.421
	Breast inside (Left)	Right ventricle	Left ventricle	Aorta	Iliopsoas muscle (Right)
OEM(off)	5.47 ± 0.55	6.24 ± 0.37	6.82 ± 0.63	7.22 ± 0.55	7.92 ± 0.50
OEM(on)	6.07 ± 0.30	6.09 ± 0.42	7.64 ± 0.67	7.83 ± 0.89	8.20 ± 0.80
p value	0.0952	0.69	0.1	0.31	0.69
	Iliopsoas muscle (Left)	Major pectoral muscle (Right)	Major pectoral muscle (Left)	Chest Lateral (Right)	Chest Lateral (Left)
OEM(off)	6.60 ± 0.51	6.41 ± 0.44	6.48 ± 0.71	5.91 ± 0.90	5.70 ± 0.65
OEM(on)	7.40 ± 0.77	7.44 ± 0.82	7.32 ± 0.97	7.18 ± 0.43	6.20 ± 0.24
p value	0.15	0.0317	0.173	0.036	0.249
	Wide spine (Right)	Wide spine (Left)	Front organ	Backward organ	Chest slice (Total)
OEM(off)	8.17 ± 1.03	7.07 ± 0.91	6.09 ± 0.71	7.44 ± 0.97	6.58 ± 0.96
OEM(on)	7.66 ± 0.72	7.14 ± 0.54	6.93 ± 0.82	7.56 ± 0.77	7.16 ± 0.88
p value	0.15	0.55	< 0.01	0.62	< 0.01

Abdomen slice: SD Value (HU)

	Abdominal muscle (Right)	Abdominal muscle (Left)	Outside Iliopsoas muscle (Right)	Middle Iliopsoas muscle (Right)	Inside Iliopsoas muscle(Right)
OEM(off)	8.71 ± 0.48	8.03 ± 1.03	7.07 ± 0.50	8.34 ± 1.06	7.45 ± 0.94
OEM(on)	5.84 ± 0.83	7.84 ± 0.64	7.18 ± 0.91	8.36 ± 0.62	8.41 ± 0.65
p value	0.548	1	1	1	0.15
	Outside Iliopsoas muscle (Left)	Middle Iliopsoas muscle (Left)	Inside Iliopsoas muscle (Left)	Liver1	Liver2
OEM(off)	6.51 ± 0.47	7.70 ± 0.53	8.46 ± 0.79	7.79 ± 0.41	8.29 ± 0.94
OEM(on)	7.18 ± 0.42	7.87 ± 0.79	8.63 ± 0.40	7.53 ± 0.76	8.91 ± 0.82
p value	0.1	1	0.75	0.42	0.31
	Liver3	Liver4	Liver5	Liver6	Liver7
OEM(off)	8.02 ± 0.68	7.79 ± 0.58	8.32 ± 0.62	8.57 ± 0.56	8.09 ± 0.95
OEM(on)	8.64 ± 0.75	8.43 ± 0.83	8.55 ± 0.53	8.23 ± 0.46	8.74 ± 0.93
p value	0.22	0.21	0.69	0.31	0.15
	Front organ	Backward organ	Total abdomen slice		
OEM(off)	8.18 ± 0.72	7.58 ± 0.97	7.94 ± 0.88		
OEM(on)	8.38 ± 0.79	7.94 ± 0.84	8.21 ± 0.84		
p value	0.22	0.12	0.07		

The dose reduction depended on the subject thickness and the maximum dose reduction of 34% was observed using the maximum phantom diameter of 32 cm. As the subject thickness became smaller, the dose reduction effect was lower. This should be because tube current control of the device technically becomes difficult as tube current becomes lower. Similar trends have been reported in the previous study as the dose reduction rate decreases in the low BMI group, although only CTDI was measured. Because our clinical studies were for Asian women whose body habitus were smaller than the maximum diameters of the phantom, dose reduction rates were relatively low compared to the phantom studies.

In the use of OEM, an increase in image noise was observed in the phantom study. However, there was no significant difference in visual assessment scores between non-OEM and OEM groups in the clinical study. 9% increase of noise could not be caught by radiologists visually. Image noise due to OEM should not cause clinical problems for diagnosis. Similar to our study, the previous study using OEM also reported that the rise in noise due to its use was not clinically problematic [7]. Therefore, OEM is a feasible method of effective breast radiation reduction in chest CT.

In our clinical study, there were several limitations. First, helical scanning was performed, but when the OSL dosimeter was irradiated with X-rays, it was thought that the dose value was affected by the position of the X-ray tube and overlap of sections. In this study, since three dosimeters were arranged in the body axis direction and the mean of three points was defined as the breast dose, the measurement error seemed to be small. Second, the included patients after breast cancer surgery had deformation of the thorax accompanying by resection may

have affected the characteristics of OEM. However, there was no significant difference in weight, height, BMI and age in patient characteristics between the non-OEM and OEM groups, and the influence on the result might be small. Third, radiologists evaluated the general quality of the image, but did not evaluate actual pulmonary lesions.

5. Conclusion

OEM is a useful mechanism for reducing radiation exposure to the breast and a greater exposure reduction rate of the breast was confirmed than in a previous study using CTDI and DLP. Our exposure assessment method was an accurate method for assessing radiation exposure to the breast and is presumed to be an appropriate method for future radiation reduction technology evaluation. Moreover, there was no change in diagnostic quality of images due to reduced exposure. However, caution is required when targeting Asian women because the dose reduction rate is decreased in patients with small body habitus.

Conflict of interest

None.

References

[1] F.A. Mettler, B.R. Thomadsen, M. Bhargavan, et al., Medical radiation exposure in the U. S. In 2006: preliminary results, Health Phys. 95 (2008) 502–507.
[2] A. Berrington, S. Darby, Risk of cancer from diagnostic X-rays: estimates for the UK and 14 other countries, Lancet 363 (2004) 345–351.
[3] D.J. Brenner, C.D. Elliston, Estimated radiation risks potentially associated with

full-body screening, Radiology 232 (2004) 735–738.

[4] M.S. Pearce, J.A. Salotti, M.P. Little, et al., Radiation exposure from CT scans in childhood and subsequent risk of leukaemia and brain tumours: a retrospective cohort study, Lancet 380 (2012) 499–505.

[5] J. Wang, X. Duan, J.A. Christner, et al., Radiation dose reduction to the breast in thoracic CT: comparison of bismuth shielding, organ-based tube current modulation, and use of a globally decreased tube current, Med. Phys. 38 (2011) 6084–6092.

[6] B.L. Fricke, L.F. Donnelly, D.P. Frush, et al., In-plane bismuth breast shields for pediatric CT: effects on radiation dose and image quality using experimental and clinical data, AJR Am. J. Roentgenol. 180 (2003) 407–411.

[7] H. Akai, S. Kiryu, E. Shibata, et al., Reducing CT radiation exposure with organ effective modulation: a retrospective clinical study, Eur. J. Radiol. 85 (2016) 1569–1573.

[8] X. Duan, J. Wang, J.A. Christner, et al., Dose reduction to anterior surfaces with organ-based tube-current modulation: evaluation of performance in a phantom study, AJR Am. J. Roentgenol. 197 (2011) 689–695.

[9] Y. Matsunaga, K. Chida, Y. Kondo, et al., Diagnostic reference levels and achievable doses for common computed tomography examinations: results from the Japanese nationwide dose survey, Br. J. Radiol. 92 (2019) 20180290.

[10] A. Euler, Z. Szucs-Farkas, A.L. Falkowski, et al., Organ-based tube current modulation in a clinical context: dose reduction may be largely overestimated in breast tissue, Eur. Radiol. 26 (2016) 2656–2662.

[11] S. Kotiaho, A.L. Manninen, J. Nikkinen, et al., Comparison of organ-based tube current modulation and bismuth shielding in chest CT: effect on the image quality and the patient dose, Radiat. Prot. Dosimet. ncy242 (2018) 1–7.

[12] W. Fu, G.M. Sturgeon, G. Agasthya, et al., Breast dose reduction with organ-based, wide-angle tube current modulated CT, J. Med. Imaging (Bellingham) 4 (2016)

031208.

[13] D. Gandhi, D.J. Crotty, G.M. Stevens, et al., Technical note: phantom study to evaluate the dose and image quality effects of a computed tomography organ-based tube current modulation technique, Med. Phys. 42 (2015) 6572–6578.

[14] S. Haji-Momenian, A. Ellenbogen, N. Khati, et al., Comparing dose-length product-based and Monte Carlo simulation organ-based calculations of effective dose in 16- and 64-MDCT examinations using automatic tube current modulation, AJR Am. J. Roentgenol. 210 (2018) 1–10.

[15] K. Matsubara, M. Sugai, A. Toyoda, et al., Assessment of an organ-based tube current modulation in thoracic computed tomography, J. Appl. Clin. Med. Phys. 13 (2012) 3731.

[16] E.J. Stepusin, D.J. Long, K.R. Ficarrotta, et al., Physical validation of a Monte Carlo-based, phantom-derived approach to computed tomography organ dosimetry under tube current modulation, Med. Phys. 44 (2017) 5423–5432.

[17] X. Tian, X. Li, W.P. Segars, et al., Prospective estimation of organ dose in CT under tube current modulation, Med. Phys. 42 (2015) 1575–1585.

[18] C. Yamauchi-Kawaura, M. Yamauchi, K. Imai, et al., Image quality and age-specific dose estimation in head and chest CT examinations with organ-based tube-current modulation, Radiat. Prot. Dosim. 157 (2013) 193–205.

[19] X. Lopez-Rendon, G. Zhang, W. Coudyzer, et al., Do we need 3D tube current modulation information for accurate organ dosimetry in chest CT? Protocols dose comparisons, Eur. Radiol. 27 (2017) 4490–4497.

[20] S. Taylor, D.E. Litmanovich, M. Shahrzad, et al., Organ-based tube current modulation: are women's breasts positioned in the reduced-dose zone? Radiology 274 (2015) 260–266.

[21] F. Faul, E. Erdfelder, A.-G. Lang, A. Buchner, G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences, Behav. Res. Methods 39 (2007) 175–191.