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Investigation of Radiation Quality and Doses in Japanese Routine Mammography

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マンモグラフィにおけるX線線質と被曝線量の検討

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目　的：マンモグラフィでの放射線質，平均乳腺線量および乳腺含有率を推定し，圧迫乳房厚や年齢との相互関係を分析する．臨床データは，1,266名の女性を対象にした5,064マンモグラムである．
方　法：放射線質は，スペクトルプロセッサを使用して入射X線の半価層，あるいは実効エネルギーを計算した．画像の質に影響する透過X線の半価層あるいは実効エネルギーは，乳房組成を計算後，重回帰分析により推定した．平均乳腺線量は，スペクトルプロセッサで得られた出力値と臨床データから得られたmAs値から入射空気カーマを求め，SobolやBooneにより報告された変換係数の修正値を乗じて推定した．放射線質と平均乳腺線量の推定に必要な乳腺含有率は，乳腺含有率と乳房厚が既知のファントムを使用して，ターゲット/フィルタおよび管電圧毎の乳腺含有率，乳房厚およびmAs値の関係を測定後，重回帰分析により臨床データから得られる圧迫乳房厚とmAs値から乳腺含有率を推定した．
結　果：透過X線の半価層，平均乳腺線量および乳腺含有率の平均は，おのおの0.58 mmAl，1.97 mGyおよび38.0%であった．放射線質はターゲット/フィルタの組み合わせにより，平均乳腺線量は圧迫乳房厚およびターゲット/フィルタの組み合わせにより，乳腺含有率は圧迫乳房厚により主に変化した．放射線質と平均乳腺線量は年齢によりほとんど変化せず，乳房含有率の年齢依存性が影響していると考えられた．
結　論：日本の臨床施設における乳房撮影での放射線質，平均乳腺線量および乳腺含有率が示され，圧迫乳房厚や年齢との関係が分析された．本報告において，50%の乳腺含有率を有する標準ファントムの修正を提案するとともに，日本人にフィットした乳房撮影システムの構築や，乳房撮影を最適化するための資料の一部を示した．

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Introduction

Morbidity and mortality of breast cancer in Japan have recently shown increasing trends[1)]. Mammography is employed for mass screening of breast cancer due to its excellent diagnostic performance in the early detection of this disease[2)].

The purpose of mammography is to visualize lesions within the breast, preferably using a minimal radiation dose. However, breast tissues display an extremely small difference in X-ray absorption, and the glandular tissues within the breast are quite sensitive to radiation-induced carcinogenesis. The use of lower X-ray tube voltage to improve contrast generally leads to a higher radiation dose to the patient. An actual survey is needed to assess the mammography procedure.

Previous investigations into image quality and exposure dose conducted according to American College of Radiology (ACR) accreditation phantoms[3)-5)] do not represent the actual clinical scenario. Studies of compressed breast thickness have revealed substantial differences from overseas data[6), 7)]. There have been practically no investigations based on the copious data produced by mammography procedures in Japanese women. Breast composition and exposure conditions exert substantial effects on image quality and exposure dose[8)]. Ascertaining the relationships between these important factors is fundamental to optimizing mammography procedures.

We have provided estimates of radiation quality [half-value layer (HVL) or effective energy], exposure dose (mean glandular dose), and breast glandular fraction (glandularity) for routine mammography in the clinical situation. In addition, we have analyzed the relationships between three factors and both compressed breast thickness and age.

Methods

(1) Principles

Radiation quality

Radiation quality determined by the X-ray spectrum significantly affects image quality. The Institute of Physics and Engineering in Medicine (IPEM) has recently released a Spectrum Processor that facilitates theoretical calculation of X-ray spectra, X-ray output, and aluminum-equivalent HVL[9]. The Spectrum Processor uses the following equation to calculate X-ray output (air kerma, K_{air}) from the photon fluence of energy E, $\Phi(E)$,

$$K_{air} = \int_{E_{min}}^{E_{max}} \Phi(E) \cdot E \cdot \frac{\mu_{tr}(E)}{\rho} dE \quad \cdots\cdots (1)$$

where $\mu_{tr}(E)/\rho$ is the mass energy transfer coefficient of air for photon energy E. HVL calculated by the Spectrum Processor is converted to the effective energy value by power approximation in the X-ray energy range 10-30 keV. HVL or effective energy values are convenient and quantitative expressions of radiation quality. Furthermore, X-ray spectra in diagnostics and mammography can be computed using radiation data and the material of filters (absorbers) used[10].

Mean glandular dose

As breast cancer almost always arises in glandular tissue, the average absorbed dose to glandular tissue, the mean glandular dose (MGD, given as D_g in calculations), is the preferred indicator of mammography radiation risk[11), 12)]. The factors influencing MGD are primarily the image receptor, radiation quality, breast thickness, and breast glandular tissue content. Since mammography is typically performed using an automatic exposure control (AEC) system, calculation of MGD is based on the assumption that the optical density of the image obtained is constant for radiation quality, breast thickness, and glandularity[13]. MGD can be determined using *Kair* of incident X-rays and conversion factor D_{gN} according to the following equation:

$$D_g = K_{air} \cdot D_{gN} \quad \cdots\cdots (2)$$

where D_{gN} is calculated by a Monte Carlo simulation using a mathematical phantom, and represents MGD relative to K_{air} of incident X-rays or surface absorbed dose. The mathematical phantom typically consists of mixed layers composed of glandular breast and adipose tissue, surround by a 5 mm skin-adipose layer[14]. The conversion factors are shown for different target/filter combinations, and for discrete value of tube voltage, glandularity in the mixed layer, compressed breast thickness, and HVL of incident X-rays.

Glandularity

The breast content representing glandularity is a factor influencing radiation quality and glandular dose. Glandularity is also important in order to estimate carcinogenic risk. As it cannot be directly measured, mean glandularity within the breast is estimated by multiple regression analysis. When AEC-controlled mammography equipment is used to obtain images with phantoms of known thickness and glandularity for each clinical exposure of phantom thickness, target/filter combinations, tube voltage, and the milliampere-seconds (mAs) required for imaging are recorded. Next, the relationship between mAs, compressed breast thickness, and glandularity for each target/filter combination and tube voltage are required. Presumption of glandularity is performed using multiple regression analysis, with glandularity g designated as the target variable and phantom thickness x_1 and mAs value x_2 as independent variables. The multiple regression model is given by:

$$g = \sum_{j=1}^{2} \alpha_j x_j + \beta \quad \cdots\cdots (3)$$

where α_j represents the partial regression coefficient and β is a constant, with each determined by a least-squares technique.

(2) Experimental methods

The procedure for calculating radiation quality penetrating the breast (*HVLdetector*), MGD, and glandularity g is shown in Fig. 1. We calculated effective energy and K_{air} of incident X-rays to the breast using the Spectrum Processor from the target/filter combination (T/F), compressed breast thickness (t), tube voltage (kV), and mAs values obtained from mammography examination. Here, we used the target angle for the mammography equipment, because the X-ray spectrum changes according to target angle[9]. Calculated K_{air}/mAs was corrected by an inverse square correction of distance in proportion to compressed breast thickness. In addition, the K_{air} of incident X-rays was calculated from clinical mammography data for each mammogram.

Next, *mAs* for each target/filter combination and tube voltage were recorded for phantom thicknesses from 2 cm to 7 cm in 1 cm intervals using a planar phantom (SZ-49, Kyoto Kagaku Co., Kyoto) with glandularity 0%, planar phantoms with glandularity 30% and 70% (12A, Eastek Co., Tokyo), and a planar phantom with 50% glandularity (BR-12, Nuclear Associates, NY). We performed empirical multiple regression analysis using the following equation to calculate g for each target/filter combination and tube voltage:

$$g = a_g \cdot \frac{In(mAs)}{t^2} + b_g \cdot \frac{In(mAs)}{t} + c_g \cdot In(mAs) + \frac{d_g}{t} + \beta \quad \cdots (4)$$

where t is compressed breast thickness, and a_g, b_g, c_g, and d_g represents the partial regression coefficients derived from recorded data. Using this equation, the coefficient of determination and multiple correlation coefficient were ≥30.98. Sobol and Wu approximation for Mo/Mo and Mo/Rh[15] and Boone's reported values for W/Rh[16] were used to calculate the D_{gN} from the g obtained for each mammogram.

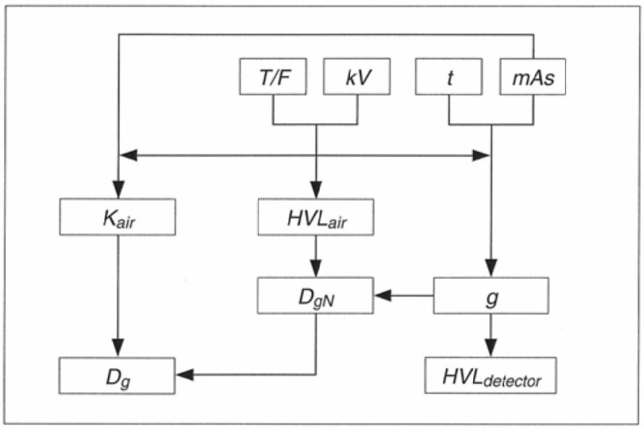

Fig. 1 Illustration of the procedure for calculating radiation quality, mean glandular dose, and glandularity using the target/filter combination (*T/F*), compressed breast thickness (*t*), tube voltage (*kV*), and mAs (*mAs*) values for each mammography.

The effective energy penetrating the breast ($keV_{detector}$) with regard to radiation quality of exit X-rays was calculated using empirical multiple regression analysis and the following equation for each target/filter combination and tube voltage:

$$keV_{detector} = a_{keV} \cdot t^3 + b_{keV} \cdot t^2 + c_{keV} \cdot t + d_{keV} \cdot g + \beta \quad \cdots\cdots(5)$$

where a_{keV}, b_{keV}, c_{keV}, and d_{keV} represent the partial regression coefficients derived from recorded data. Using this equation, coefficient of determination and multiple correlation coefficient were ≥30.98. In addition, MGD was calculated by multiplying K_{air} of incident X-rays with D_{gN} from equation 2 for each mammogram.

The mammography data used were those obtained from Japanese women by the Cancer Institute Hospital in the 3-month period between December 1998 and January 1999. In this report, the ranges adopted were 25 kV to 32 kV for Mo/Mo, 28 kV to 32 kV for Mo/Rh, and 30 kV to 36 kV for W/Rh. Data for 5,064 exposures in a total of 1,266 patients were used. Two projections of craniocaudal (CC) and mediolateral oblique (MLO) were obtained for each breast. The mean age of patients was 51 years, which similar to the mean age considered in other studies[6), 17)]. Details of the mammography data acquired are provided in the paper by Fujisaki et al[7)].

Results and Discussion

Table 1 shows the mean values of compressed breast thickness, tube voltage, mAs, radiation quality of incident and exit X-rays, mean glandularity, and MGD for different target/filter combinations. The target/filter combination selected was Mo/Mo for 83.5% of cases, Mo/Rh for 15.4% of cases, and W/Rh for 1.1% of cases. The mean compressed breast thickness and MGD in Japanese were significantly lower than reported values in predominantly Europeans and Americans[17),18)]. Only 321 (6.3%) of the 5064 cases received MGD >3 mGy/mammogram. The data reveals that increases in MGD were suppressed by radiation technologists who performed mammography procedures selecting higher radiation quality appropriate to breast thickness. It is paradoxical that higher glandularity breasts need higher radiation quality, however, the glandularity is difficult to predict from shape of breast in mammography. In this report we have investigated only one of the many mammography sites in Japan, and therefore the results may not be typical. In the future, estimation of data from a larger number of different sites is desirable.

Radiation quality

Fig. 2 shows the mean effective energy of incident X-rays and mean incident K_{air} for each target/filter combination as a function of compressed breast thickness. The effective energy of incident X-rays and incident K_{air} were classified in 5 mm intervals, and mean values and 95% confidence limits were calculated. Mean incident K_{air} increased with compressed breast thickness, dependent on the target/filter combination. The incident K_{air} necessary for exposing a compressed breast thickness of 60 mm was estimated to be about 90% for Mo/Rh and about 31% for W/Rh, compared to Mo/Mo. Mean effective energy of incident X-rays for exposing a compressed breast thickness of 60 mm was estimated to be 15.5±0.1 keV (mean±SD) for Mo/Mo, 16.3±0.1 keV for Mo/Rh, and 18.3±0.2 keV for W/Rh, and was almost completely independent of compressed breast thickness. The effective energy of incident X-rays demonstrates almost no variation according to compressed breast thickness, suggesting that changes in the incident X-ray spectrum are slight, even when tube voltage is altered. Accordingly, selection of the target/filter combination by the radiation technologist may be more significant than the X-ray tube voltage chosen.

Fig. 3 shows the mean effective energy of exit X-rays for each target/filter combination as a function of compressed breast thickness and age. The effective energy of exit X-rays was classified in each interval, and the mean values and 95 % confidence limits were calculated. Mean effective energy of exit X-rays increased with compressed breast thickness, dependent on the target/filter combination. The effective energy of exit X-rays for exposing a compressed breast thickness of 60 mm was estimated to be 19.4±0.5 keV (mean±SD) for Mo/Mo, 20.1±0.1 keV for Mo/Rh, and 21.7±0.5 keV for W/Rh. The effective energy of exit X-rays varies according to compressed breast thickness suggests that the low-energy component of the X-ray spectrum is absorbed. Mean effective energy of exit X-rays was almost independent of age. Although Matsumoto et al.[6)] and Fujisaki et al.[7)] reported that compressed breast thickness was dependent on age with a minimum around

Table 1 Mean values of data obtained in this research for compressed breast thickness, tube voltage, mAs value, radiation quality of incident X-rays, glandularity, MGD, and radiation quality of penetrating X-rays. Target/filter combinations are represented as parameters. Data were obtained from 5064 exposures.

Factor (unit)	Mo/Mo	Mo/Rh	W/Rh	Total
Compressed breast thickness; t (mm)	41.7	49.5	70.0	43.3
Tube voltage; kV (kV)	28.3	29.5	33.0	28.5
mAs (mAs)	46.4	53.1	88.6	47.9
K_{air} (mGy)	10.9	11.9	9.9	11.0
HVL_{air} (mmAl)	0.33	0.40	0.57	0.34
keV_{air} (keV)	15.1	16.2	18.3	15.3
Glandularity; g (%)	41.1	22.6	13.7	38.0
MGD; D_g (mGy)	1.91	2.30	2.05	1.97
$HVL_{detector}$ (mmAl)	0.56	0.68	0.97	0.58
$keV_{detector}$ (keV)	18.2	19.5	22.2	18.4
Number of exposures /women	4228	780	56	5064

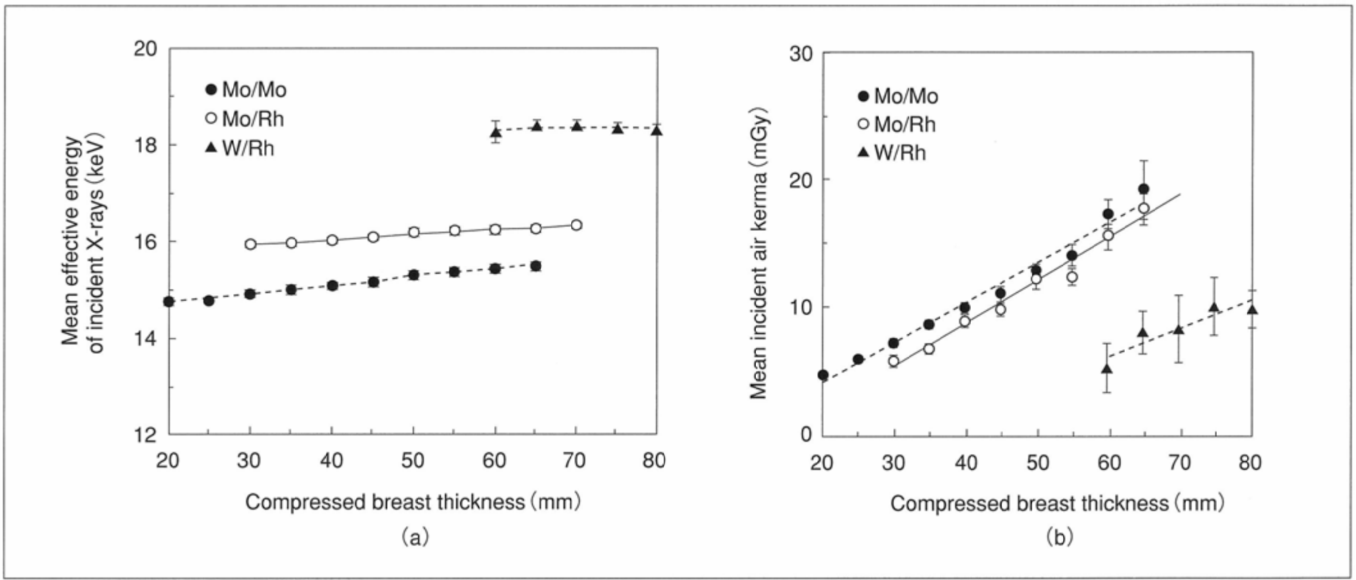

Fig. 2 Mean effective energy (a) of incident X-rays and mean incident air kerma (b) for each target/filter combination as a function of compressed breast thickness. Each axis label represents the mid-point of 5 mm intervals. Error bars indicate 95% confidence limits.

30 years and a maximum at about 60 years, the effective energy of exit X-rays in the present study was maximal in patients about 20 years and displayed little variation with age. Effective energy of exit X-rays was shown to be affected by not only compressed breast thickness, but also breast contents.

Mean glandular dose

Fig. 4 shows mean MGD for each target/filter combination as a function of compressed breast thickness and age. MGD was classified in each interval, and the mean value and 95% confidence limits were calculated. MGD increased with compressed breast thickness, dependent on the target/filter combination. MGD for Mo/Mo and Mo/Rh were almost identical. MGD (mean±SD) for exposing a compressed breast thickness of 60 mm was 2.7±0.5 mGy and 2.7±0.4 mGy for Mo/Mo and Mo/Rh, respectively. MGD was 1.3±0.4 mGy for W/Rh. W/Rh therefore provided about 50% of the MGD of Mo/Mo. The difference to MGD contributed by Mo/Rh is minimal, as shown by the similarity of Mo/Mo and Mo/Rh values. Furthermore, MGD was almost completely independent of age. The tendencies of the MGD curves and effective energies of exit X-rays were basically identical, as shown in Fig. 3. As the MGD and effective energy of exit X-rays were almost independent of age, the effect of breast contents on MGD is illustrated.

Glandularity

Fig. 5 shows mean glandularity as a function of compressed breast thickness and age. Glandularity was classified in each interval, and the mean value and 95% confidence limits were calculated. Glandularity decreased sharply with compressed

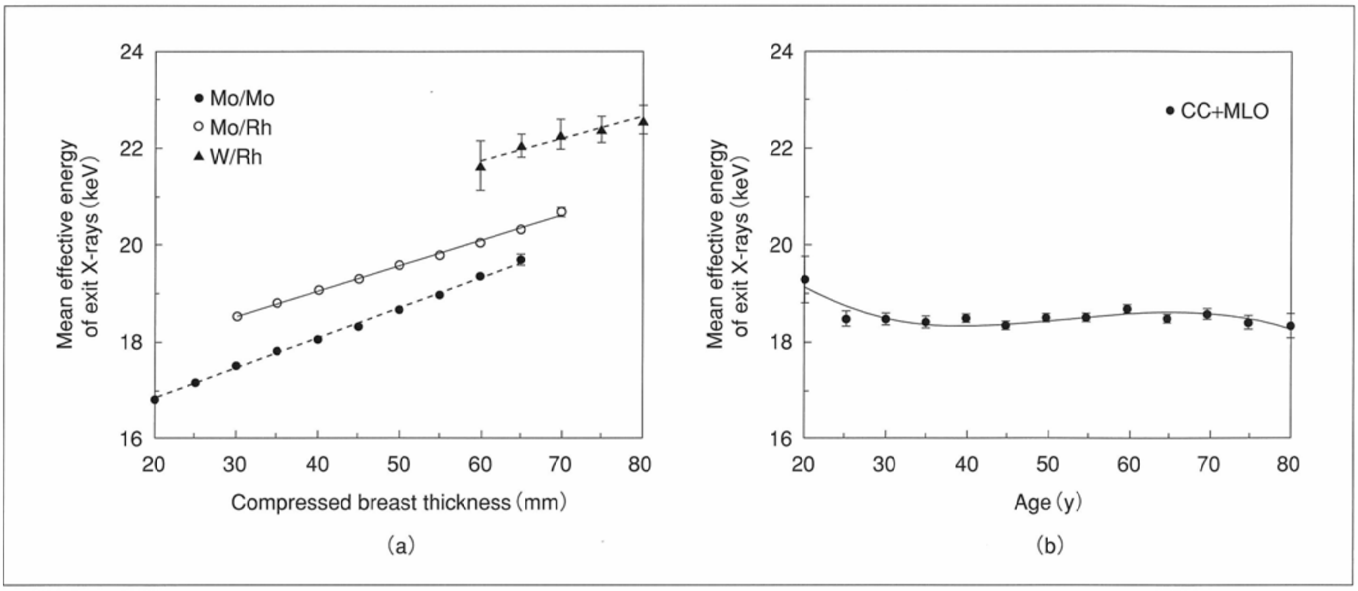

Fig. 3 Mean effective energy of exit X-rays for target/filter combination as a function of compressed breast thickness (a) and age (b). Each axis label represents the mid-point of 5 mm and 5 years intervals, respectively. Error bars indicate 95% confidence limits.

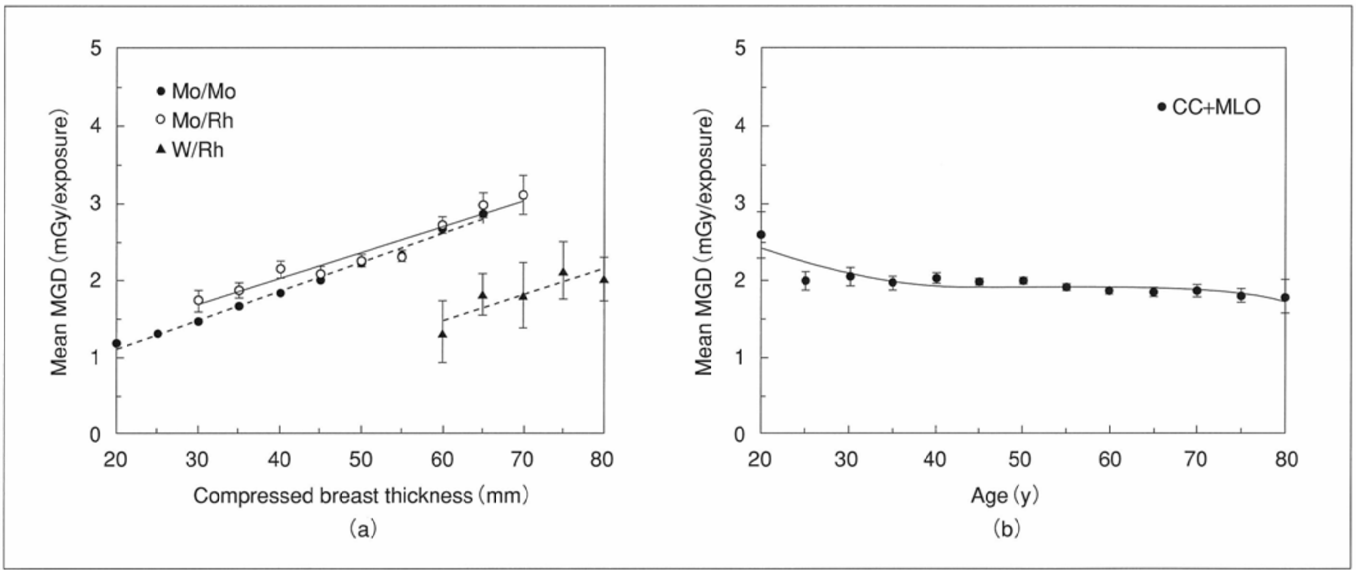

Fig. 4 Mean MGD for target/filter combination as a function of compressed breast thickness (a) and age (b). Each axis label represents the mid-point of 5 mm and 5 years intervals, respectively. Error bars indicate 95% confidence limits.

breast thickness, and decreased with advancing age. The tendencies of these decreasing curves were similar to those reported by Beckett and Kotre[8]. Mean glandularity for all exposures was 38%, as shown in Table 1. Mean glandularity has previously been reported as 43%[19] and 36%[20] in Japanese, and as 34%[21], 38%[22], and 43%[23] in predominantly Caucasian populations. Fujisaki et al.[19] and Tanaka et al.[20] estimated mean glandularity using projection images and a computed radiography (CR) system, respectively. Mean glandularity was approximately 40%, as Rosenberg et al. noted[23]. Our results support the need for revision of the generally accepted notion that glandularity of the average breast is 50%.

Conclusions

In this communication we have reported data on radiation quality, MGD, and glandularity in Japanese routine mammography, and analyzed the relationships with compressed breast thickness and age. These data may prove useful in the development of mammography systems suited to Japanese clinical settings, and in the optimization of mammography procedures for Japanese women.

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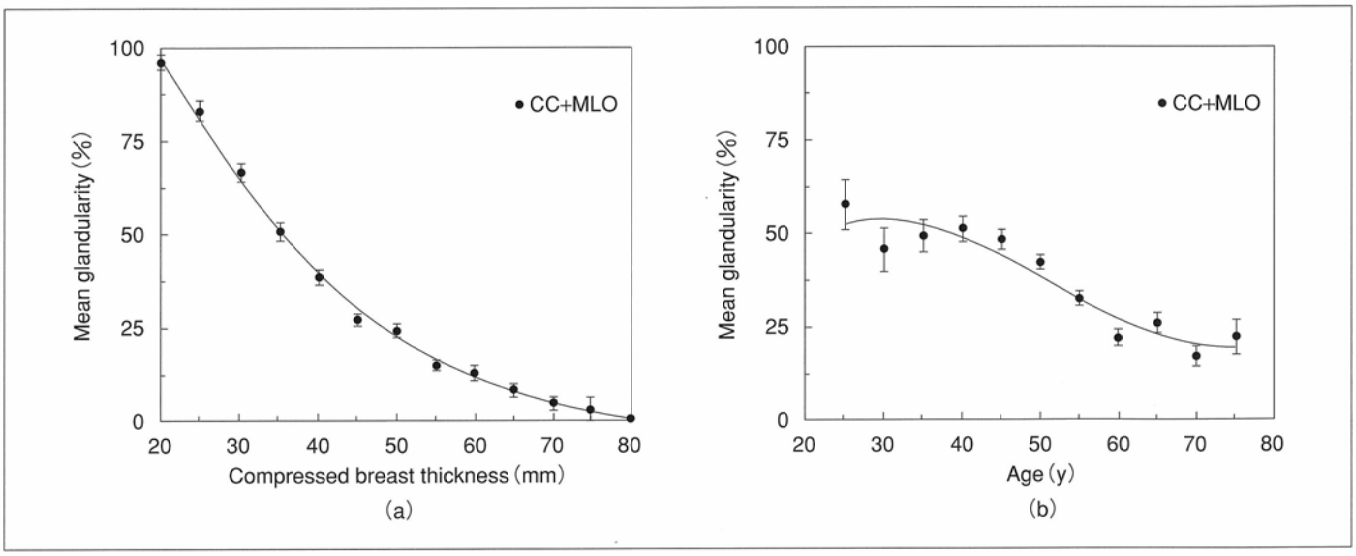

Fig. 5 Mean glandularity as a function of compressed breast thickness (a) and age (b). Each axis label represents the mid-point of 5 mm and 5 years intervals, respectively. Error bars indicate 95% confidence limits.

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