Development of an imaging-planning program for screen/film and computed radiography mammography for breasts with short chest wall to nipple distance

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Objective: Imaging breasts with a short chest wall to nipple distance (CWND) using a traditional mammographic X-ray unit is a technical challenge for mammographers. The purpose of this study is the development of an imaging-planning program to assist in determination of imaging parameters of screen/film (SF) and computed radiography (CR) mammography for short CWND breasts.

Methods: A traditional mammographic X-ray unit (Mammomat 3000, Siemens, Munich, Germany) was employed. The imaging-planning program was developed by combining the compressed breast thickness correction, the equivalent polymethylmethacrylate thickness assessment for breasts and the tube loading (mAs) measurement. Both phantom exposures and a total of 597 exposures were used for examining the imaging-planning program.

Results: Results of the phantom study show that the tube loading rapidly decreased with the CWND when the automatic exposure control (AEC) detector was not fully covered by the phantom. For patient exposures with the AEC fully covered by breast tissue, the average fractional tube loadings, defined as the ratio of the predicted mAs using the imaging-planning program and mAs of the mammogram, were 1.10 and 1.07 for SF and CR mammograms, respectively. The predicted mAs values were comparable to the mAs values, as determined by the AEC.

Conclusion: By applying the imaging-planning program in clinical practice, the experiential dependence of the mammographer for determination of the imaging parameters for short CWND breasts is minimised.

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The automatic exposure control (AEC) system of a mammographic X-ray unit plays an important role in acquiring a mammogram with sufficient image quality and acceptable radiation dose to the patient. By implementing appropriate quality control procedures [1, 2] for a traditional mammographic X-ray unit, both screen/film (SF) and computed radiography (CR) mammograms can provide sufficient image quality for clinical diagnosis. At present, SF mammography still plays an important role in the screening and diagnosis of breast cancer in many countries. Many acceptable limits for digital mammography have been developed based on a series of assessments of SF mammographic units [2].

For traditional mammographic X-ray units, the AEC system keeps the dose to the AEC detector constant over the whole range of breast thickness. However, for a breast with short chest wall to nipple distance (CWND), the AEC detector may not be entirely covered by the compressed breast, even if the AEC detector is moved to the nearest chest wall position. Under such circumstances, the AEC

detector may receive some X-rays that are not attenuated by breast tissue, as shown in Figure 1. Consequently, the mammogram is underexposed because of the AEC prematurely terminating the exposure. In some instances, the SF mammogram of a short CWND breast is unacceptable for clinical diagnosis.

To acquire sufficient image quality in clinical practice, the exposure parameters of short CWND breasts are frequently determined by mammographers depending on their experience. Since compressed breast thicknesses (CBTs) and breast content varies with each patient, the determination of exposure parameters for short CWND breasts is a technical challenge for the mammographer. In our clinical practice, the image quality of these mammograms varied significantly depending on the exposure parameters selected. The repeat rate of SF mammograms at our institution for short CWND breasts is 11%, compared with 3% for all patients. This implies that mistakes in exposure settings may occur and may lead to either under- or overexposure, resulting in insufficient image quality and unnecessary patient radiation exposure.

At present, very few attempts [3] have been made to develop an imaging technique for the short CWND breasts. The suitable exposure parameters of a short CWND breast may be acquired by the modification of

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Figure 1. Illustration of the underexposure effect for a breast with short chest wall to nipple distance when imaging with a traditional mammographic X-ray unit. AEC, automatic exposure control.

imaging settings of a phantom exposure. The purpose of this study is the development of an imaging-planning program to assist in determination of imaging parameters of SF and CR mammography for short CWND breasts.

Methods and materials

Instruments

A traditional mammographic X-ray unit (Mammomat 3000, Siemens, Munich, Germany) and a full field digital (FFD) mammography system (Selenia, Lorad Bedford, MA) were employed. For the Mammomat 3000 mammographic X-ray unit, a set of Fuji screen/film cassettes (ADM film, AD Mammo screen-Fine and UM-Mammo cassettes) and FCR Profect CS (Fuji, Japan) combined with mammographic imaging plates (HR-BD, Fuji Tokyo, Japan) were used to develop SF and CR mammograms, respectively. The unit is equipped with a rigid compression paddle. The AEC was set up for use in the SF, and the optical density (OD) setting of the film was 1.6 under typical clinical conditions.

Image quality assessment for various tube loadings

To evaluate the CWND-related changes in tube loading, a 3 cm BR-12 phantom (Nuclear Associates, Carle Place, NY) was exposed using the Mammomat 3000 and the Selenia FFD mammographic X-ray units with a tube potential of 26 kV. The phantom is 10 × 12.5 cm in size (rigid) and equivalent to 47% glandular content. Since the CWND of the minimal breast outline (the AEC nearest the chest wall position) printed on the compression paddle of the Mammomat 3000 unit is 5 cm, the CWND of the BR-12 phantom was varied from 3 to 6 cm in 1 cm increments. The tube loadings were recorded and analysed.

To evaluate tube loading-related changes in image quality, a contrast detail (CD) mammography phantom (CDMAM, v.3.4, UMC St. Radboud, Nijmegen University, Nijmegen, the Netherlands) was used to evaluate image quality of SF and CR mammograms. A CDMAM

with 3 cm of polymethylmethacrylate (PMMA) slabs was used to simulate the average equivalent PMMA thickness (4 cm) of breasts of Taiwanese women. The CDMAM phantom was imaged with a tube potential of 26 kV and a target/filter combination of molybdenum/molybdenum (Mo/Mo). The tube loadings were determined both manually and by AEC. For manual exposures, tube loadings used were 18, 32, 40, 50, 80, 100, 160 and 200 mAs for the SF mammogram, and 20, 40, 50, 63, 90, 125, 160 and 250 mAs for the CR mammogram. For each tube loading, four CD images were acquired and were analysed by three observers [2]. The CD images of the SF mammogram were displayed on a viewbox for further CD assessment. For CR mammography, all CD images were displayed on a 5 megapixel LCD monitor (MFGD 5421, Barco, Kortrijk, Belgium) and an image presentation tool (SmartRIS, v.1.1.6.52) was used when required, including window level, width and magnification [2].

The results of CD assessments were compared with the manufacturer's correction scheme to determine threshold thickness (C_i), *i.e.* the minimum visible thickness, for each detail diameter (D_i). The inverse image quality factor (IQF_{inv}) for each CD image was determined using the minimum visible thickness for each detail diameter, defined as

$$IQF_{inv} = \frac{100}{\sum_{i=1}^n C_i \times D_i} \quad (1)$$

For further comparison, the relative tube loading and IQF_{inv} of each exposure were calculated. The relative tube loading and IQF_{inv} ($X_{relative}$) are defined as:

$$X_{relative} = \frac{X_{exp}}{X_{AEC}} \quad (2)$$

where X corresponds to tube loading and IQF_{inv} , X_{exp} is the value of tube loading and IQF_{inv} for each exposure and X_{AEC} is the value of tube loading and IQF_{inv} for the exposure using the AEC mode.

Development of the imaging-planning program

In clinical practice, CBT is the only index of breast dimensionality that can be acquired from the imaging system before exposure. The exposure parameters of a breast with short CWND may be estimated by using an adequate thickness of the PMMA phantom in the tube loading measurement. Therefore, the exposure parameters of the mammogram of short CWND breasts were estimated on the basis of the displayed CBT from the imaging system. Three steps were used for development of the imaging-planning program.

The first step was the determination of the actual CBT value using the displayed CBT of the imaging system. Since there is ± 0.5 cm tolerance on actual and displayed CBTs, a correction for CBT was required. The CBT correction approach used in this study was similar to that reported by Kruger and Schueler [4]. The CBT correction was measured using the Mammomat 3000 mammographic X-ray unit with a rigid compression paddle. Variations in the flexing of the compression paddle (18 × 24 cm) with various compression forces was measured using a 6 cm thick BR-12 phantom

(Nuclear Associates, Cleveland, OH). Compression forces from 60 to 180 N (in 10 N increments) were applied to compress the BR-12 phantom with a 12.5 cm CWND. The differences between the displayed thicknesses and the phantom thickness were analysed. Additionally, to examine the variation in the CBT correction due to a change in the CWND, the displayed thickness difference between a 12.5 cm and a 5 cm CWND of the BR-12 phantom was analysed.

The second step was the estimation of the equivalent PMMA thickness using the CBT of the patient. Dance et al [5] have reported the complete information for equivalence between PMMA phantoms and breasts for women aged 50–64 years by using a Monte Carlo simulation. However, the development of such information for Taiwanese women of various age groups is needed because many patients with short CWND are younger than 50–64 years. Several previous studies [6, 7] have reported that CBT and glandularity of the breast are affected by age. Therefore, the equivalence of thicknesses of PMMA phantoms and breasts may be affected by the age of the subjects surveyed.

A total of 3910 SF mammograms from Taiwanese women aged 30–69 years were included, with ethics approval obtained. All exposures were imaged using AEC. Subjects with a CWND <5 cm were excluded in this analysis to avoid a potential source of uncertainty because of underexposure.

The approach used in the assessment of equivalent PMMA thickness was similar to that presented by Kruger and Schueler [4]. The PMMA at four thicknesses (2, 4, 6 and 8 cm) was exposed at various target/filter/kV combinations using AEC. The relationship between the equivalent phantom thickness (T) and the exposure parameters can be expressed as:

$$T = C_1 \times \ln(\text{mAs}) + C_2 \times \ln(\text{kV}) + b \quad (3)$$

where C_1 , C_2 and b are fitted coefficients, and mAs and kV are the tube loading and the tube potential, respectively, of each phantom exposure. A least-squares fit was applied to determine the coefficients (C_1 , C_2 and b) for each calibration data set using Equation (1). The fitted functions obtained for calibration data sets were used to calculate the equivalent PMMA thickness of each patient exposure. The conversion equations between CBTs and equivalent PMMA thicknesses (called CBT–PMMA conversion equations) were determined for the age groups 30–49 and 50–69 years.

The third step was the determination of tube loadings for various thicknesses of PMMA phantoms. In our clinical practice, patients with short CWNDs are frequently found to have thin CBTs. To address the clinical conditions, the imaging-planning program must be developed for use in simulating the exposure of thin breasts. A series of PMMA slabs at five thicknesses (1, 2, 3, 4, and 5 cm) were exposed to estimate the tube loadings. These phantoms were exposed from 24 to 26 kV with the target/filter combination of Mo/Mo to simulate the imaging conditions of thin breasts. Tube loadings of each phantom exposure were terminated by the AEC. The relationship between the tube loading and

the thickness of the PMMA phantom was developed for each tube potential.

An imaging-planning program was developed to simplify the calculation processes of tube loadings (from step 1 to step 3). The imaging-planning program was developed using an Excel worksheet by integration of the correction of CBT (step 1), the assessment of the equivalent PMMA thickness for breasts (step 2) and the estimation of tube loadings (step 3).

Verification of the imaging-planning program

To examine the ability of the imaging-planning program developed in this study to correctly predict the tube loadings, both phantom and patient exposure records were used to verify the program. For each exposure, the tube loadings used and those predicted were compared.

For verification of the imaging-planning program using phantom exposure records, various thicknesses (1.5–4.5 cm in 1 cm increments) of standard breast phantoms, which consist of a central region with a mixture of adipose and glandular tissue and a superficial layer of adipose tissue 0.5 cm thick [8], were employed. A series of breast tissue equivalent attenuation slabs (Computerized Imaging Reference Systems, Norfolk, VA) of varying composition (BRFAT, BR-12 and BRGLAND) were exposed using AEC at a target/filter/tube potential combination of Mo/Mo/25 kV. The delivered and predicted tube loadings for each exposure were compared.

To examine the ability of the imaging-planning program to correctly predict the tube loadings of patient exposures, a total of 597 mammograms, including 468 SF mammograms and 129 CR mammograms, were analysed. The predicted tube loading of each simulated exposure was calculated using the imaging-planning program, depending on the displayed CBT of each patient exposure. For further comparison, the fractional tube loading ($TL_{\text{fractional}}$) of each exposure was calculated. The $TL_{\text{fractional}}$ is defined as

$$TL_{\text{fractional}} = \frac{TL_{\text{predicted}}}{TL_{\text{delivered}}} \quad (4)$$

where $TL_{\text{predicted}}$ corresponds to the predicted tube loading of the simulated exposure, and $TL_{\text{delivered}}$ corresponds to the tube loading of the patient exposure.

Some modern mammographic X-ray units recommend the tube loadings for use in manual exposures. The recommended tube loadings of these systems can be used to examine the imaging-planning program developed in this study. For this purpose, the Selenia FFD unit was used, and the predicted tube loadings of the imaging-planning program were compared with the tube loadings suggested for the unit. To predict the tube loadings of the Selenia FFD unit, some modifications of the imaging-planning program were carried out to comply with the clinical settings of this unit. Since the Selenia FFD unit is equipped with a tilting compression paddle, the CBT correction approach used in this study may not be suitable for this system. Therefore, this examination did not include CBT correction, *i.e.* the CBT correction function (step 1) in the imaging-planning program was disabled.

To measure the tube loadings, step 3 was repeated with the Selenia FFD unit. The PMMA phantoms were compressed (140–155 N) until the displayed CBT was equivalent to the thickness of each phantom. Exposures were made using 25 and 26 kV (Mo/Mo) with the high-contrast mode. The relationship between tube loading and the thickness of the PMMA phantom was developed for each tube potential. The predicted tube loadings of a 3 cm thick breast were compared with the tube loadings suggested for the Selenia FFD unit in high-contrast mode.

Results

Variations in image quality correlated with tube loadings

Figure 2 shows variations in relative tube loading for the 3 cm BR-12 phantom with various CWNDs. The tube loading of each exposure was terminated by the AEC. The relative tube loading was defined as the tube loading of each exposure normalised to the tube loading of the phantom with a 5 cm CWND. For the Mammomat 3000 X-ray unit, the relative tube loadings of both SF and CR mammography rapidly decreased with CWND when the AEC detector was not fully covered. For the Selenia FFD X-ray unit, the relative tube loading was constant for all exposures.

Figure 3 shows variations in relative IQF_{inv} corresponding to relative tube loading. The image quality of a SF mammogram was significantly decreased if substantially under- or overexposed. The relative IQF_{inv} of a SF mammogram increased with increasing the relative tube loading, reached a maximum at a relative tube loading of 1.3 and tended to decrease for a relative tube loading >1.7 . For CR mammography, the relative IQF_{inv} increased with the relative tube loading. The relative IQF_{inv} values of SF and CR mammography were comparable to each other when the relative tube loading was <1.3 . For substantial overexposure, the relative IQF_{inv} of a CR mammogram was significantly greater than that of a SF mammogram.

Figure 2. Variations in relative tube loadings with chest wall to nipple distances (CWNDs) of a 3 cm BR-12 phantom for various mammographic systems. CR, computer radiography; SF, screen/film; FFD, full field digital.

Figure 3. Variations in relative inverse image quality factors (IQF_{inv}) with relative tube loadings for screen/film (SF) and computer radiography (CR) mammography.

Basic data for the imaging-planning program

Table 1 shows the thickness corrections of the displayed CBT for various compression forces. Figure 4 shows variations in equivalent PMMA thickness corresponding to CBT for the age groups 30–49 and 50–69 years. The equivalent PMMA thickness can be expressed as a linear function of CBT. The fitted equations (CBT–PMMA conversion equations) are listed in Table 2. To acquire equivalent PMMA thicknesses for various breast densities, the conversion equations were developed for three breast types, *i.e.* fatty, medium and dense breasts. The CBT–PMMA conversion equations of fatty, medium and dense breasts were obtained from the data sets of the average value minus 1 standard deviation (SD), the average value and the average value plus 1 SD, respectively.

Figure 5 shows the relationship between tube loadings and various thicknesses of PMMA phantom for each tube potential. The tube loading exponentially increases with the thickness of the PMMA phantom.

Verifications of the imaging-planning program

Figure 6 shows the delivered and predicted tube loadings for various thicknesses of the standard breast phantom. The predicted tube loadings of each standard breast phantom were calculated using the CBT–PMMA conversion equations determined from women aged 30–49 years. For thicknesses of standard breast phantoms >3.5 cm, the predicted tube loadings of a simulated exposure were within delivered tube loadings determined by the AEC system. For thin standard breast phantoms (≤ 2.5 cm), the predicted tube loadings of a

Table 1. Thickness corrections of the displayed compressed breast thickness (CBT) for various compression forces

Compression force interval (kg)	Corrected thickness	Compression force interval (kg)	Corrected thickness
6–8	Add 0.2 cm	12–14	Add 0.5 cm
8–10	Add 0.3 cm	14–16	Add 0.6 cm
10–12	Add 0.4 cm	16–18	Add 0.7 cm

Figure 4. Variations in equivalent phantom thicknesses with compressed breast thicknesses. PMMA, polymethylmethacrylate.

simulated exposure were greater than the delivered tube loadings of the standard breast phantoms.

The results of verification assessments for patient exposures are summarised in Table 3. The average values of age and CBT for categories A and B were greater than those for the other categories (C–F). For categories A and B, the average fractional tube loadings were comparable to each other. The average fractional tube loadings of categories C and D were greater than those of categories E and F.

Figure 7 shows the distribution of ratios of equivalent PMMA thickness for SF mammograms with CWND ≥ 5 cm (category A). The equivalent PMMA thickness ratio is defined as the ratio between the equivalent PMMA thickness predicted from the CBT–PMMA conversion equations for medium breasts and the equivalent PMMA thickness that is calculated from the tube loading of a SF mammogram. The average equivalent PMMA thickness ratio for all subjects was 1.02 ± 0.10 .

Figure 8 shows the distributions of delivered and predicted tube loadings of the SF mammograms for breasts with CWND ≥ 5 cm. All exposures were imaged using 25 kV. The age of the women ranged from 30 to 49 years and a total of 118 breasts were included. The predicted tube loadings of each exposure were obtained by applying the CBT–PMMA conversion equations to various breast density types (fatty, medium and dense). In general, the distributions of predicted tube loadings

were in agreement with tube loadings determined by the AEC mode.

For the Selenia FFD unit, the recommended tube loadings for use in the manual exposure of a 3 cm thick breast were 60 (25 kV), 75 (25 kV) and 75 (26 kV) mAs for fatty, normal and dense breasts, respectively. The predicted tube loadings calculated from the imaging-planning program for fatty, medium and dense breasts were 66, 75 and 76 mAs, respectively, in the age group 30–49 years, and 60, 69 and 70 mAs, respectively, in the age group 50–69 years. The predicted tube loadings were in agreement with the recommended tube loadings.

Discussion

Uncertainty analysis

The imaging-planning program was developed on the basis of experimental measurements. Some experimental conditions may not fully mimic the imaging conditions of breasts with short CWND in clinical practice. Therefore, uncertainties developed from the factors used in this study are discussed.

The CWND of the BR-12 phantom slightly affects the results of CBT correction (step 1). The difference in corrected CBTs between a CWND of 12.5 and that of 5 cm does not exceed 0.2 cm for compression forces of 60–180 N. For an extremely small breast, this effect may be important, and therefore a special CBT correction approach may be needed. The uncertainty in assessment of equivalent PMMA thickness (step 2) using curve-fitting algorithms was assessed to be within 0.1 cm for 2–6 cm PMMA phantoms. The uncertainty in tube loading assessment (step 3) using curve-fitting algorithms was assessed to be $<2\%$ for 1–5 cm PMMA phantoms.

Variations in image quality correlated with tube loadings

The tube loading rapidly decreased with CWND of the phantom when the AEC detector was not fully covered by the phantom. The relative tube loadings were 0.97 and 0.70 for phantom exposures of 4.5 cm and 4 cm CWND, respectively. Since the shape of the BR-12 phantom is rectangular whereas the geometry of a compressed breast

Table 2. The fitted coefficients of CBT–PMMA conversion equations in Figure 4. A linear fit was applied to obtain the conversion equation for each data set. The conversion equation was defined as: equivalent PMMA thickness = $(a \times \text{CBT}) + b$

Patient information		Coefficients of CBT–PMMA conversion equations		Coefficients of determination
Age interval	Breast types ^a	<i>a</i>	<i>b</i>	<i>R</i> ²
30–49 years	Fatty	0.6918	0.9156	0.9993
30–49 years	Medium	0.6934	1.1382	0.9982
30–49 years	Dense	0.695	1.3608	0.9916
50–69 years	Fatty	0.6847	0.7713	0.9995
50–69 years	Medium	0.6782	1.0251	0.9992
50–69 years	Dense	0.6718	1.2789	0.9977

CBT, compressed breast thickness; PMMA, polymethylmethacrylate.

^aThe fitted equations for fatty, medium and dense breasts were obtained from the dataset of the average value minus 1 standard deviation (SD), the average value and the average value plus 1 SD, respectively.

Figure 5. Variations in delivered tube loadings with thicknesses of polymethylmethacrylate (PMMA) phantoms for various tube potentials. CR, computer radiography; SF, screen/film.

is semielliptical with a round edge (Figure 1), the AEC detector cannot be fully covered by a compressed breast when the CWND exactly equals 4.5 cm. The result is in agreement with the CWND value (5 cm) of the minimal breast outline printed on the compression paddle of the Mammomat 3000 unit. In clinical practice, the CWND of 5 cm appears to be a reasonable reference value to infer whether the AEC detector can be fully covered by the compressed breast.

The image quality of a mammogram is affected by the tube loading used. For SF mammography, a substantially under- and overexposed mammogram may result in a significant reduction in image quality. In this study, comparable relative IQF_{inv} values were obtained when the relative tube loadings equalled 1 and 2. This implies that doubling the tube loadings for a SF mammogram cannot improve the image quality. However, the image quality can be improved if the relative tube loading is between 1 and 2.

Figure 6. Verification of the imaging-planning program for screen/film (SF) mammography using standard breast (SB) phantoms of various thicknesses. The data sets of SB (BRFAT), SB (BR-12) and SB (GLAND) are delivered tube loadings exposed using SB phantoms with a central layer of BRFAT, BR-12 and BRGLAND materials, respectively. The predicted tube loadings were calculated using the CBT-PMMA conversion equations for the age group of 30–49 years.

Unlike SF mammography, the image quality of an overexposed CR mammogram is increased, and the overexposure results in an unnecessarily increased radiation dose to the patient. For CR mammography, underexposure may result in an increase in image noise and therefore the image quality is decreased. Since the radiologist is allowed to adjust the image display with an image presentation tool, a slight increase in image noise for an underexposed CR mammogram may not be easy to identify.

In clinical practice, an underexposed SF mammogram can be immediately recognised by the mammographer after imaging owing to the change in the OD of the film. For CR mammography, however, it is difficult to recognise the noise of an underexposed CR mammogram by the mammographer in clinical practice. A slight variation in image quality on a CR mammogram may be identified by a well-trained radiologist using an image presentation tool combined with a high-resolution monitor. Therefore, care must be taken when imaging breasts with short CWND using CR mammography.

Equivalence between the thickness of the PMMA phantom and CBT

For a given CBT, the equivalent PMMA thickness obtained in the age group 50–69 years is thicker than that obtained in the age group 30–49 years. Results from this study confirmed that the equivalence of thicknesses of PMMA phantoms and breasts is affected by the age of the subjects surveyed. The equivalence between PMMA phantoms and breasts obtained in the age group 50–69 years in this study were in agreement (CBT difference ≤ 0.2 cm) with those reported in a previous study [5] for the thickness of PMMA phantoms ≥ 3 cm.

In general, PMMA phantoms are thinner than the equivalent breasts. For thin PMMA phantoms, however, the PMMA phantoms are thicker than the equivalent breast. Similar results have been reported by Thilander et al [9] for patients aged 44–65 years. Results from the report showed that the CBT of an equivalent breast of the 2 cm PMMA phantom was <1.5 cm. Some previous reports [10, 11] provide circumstantial evidence for this finding. For example, Heggie [10] and Geise and Palchovsky [11] reported average breast glandularities of 82% and 68%, respectively, for thin breasts (CBT <3 cm) using the breast model without a 0.5 cm adipose layer. These values are greater than the equivalent glandularity (55%) of the PMMA phantom [4], and therefore the equivalent PMMA thicknesses of these breasts may be greater than the CBTs. This effect is obvious for the age group 30–49 years.

The imaging-planning program

The imaging-planning program was developed for use in manual exposure of breasts with short CWND. By inputting the displayed CBT and compression force to the program, tube loadings of various tube potential/breast density type combinations (such as 26 kV/fatty breast) can be estimated for both age groups (30–49 and 50–69 years). The mammographer then selects the appropriate parameters (kV and mAs) for use in imaging.

Table 3. The simulated results of verification assessment for collected patient exposures

Categories	CWND	Imaging information		Subjects information			Simulated exposure ^a
	(cm)	Systems	Imaging mode	Number of exposures	Average ($\pm$ SD) age (years)	Average ($\pm$ SD) CBT (cm)	Average ($\pm$ SD) fractional tube loading
A	≥ 5	SF	AEC	365	52 ± 11	4.2 ± 0.8	1.10 ± 0.32
B	≥ 5	CR	AEC	99	53 ± 10	4.4 ± 0.9	1.07 ± 0.31
C	< 5	SF	AEC	44	45 ± 8	3.5 ± 1.1	1.53 ± 0.57
D	< 5	CR	AEC	11	47 ± 10	3.6 ± 1.3	1.55 ± 0.52
E	< 5	SF	Manual	59	45 ± 8	3.3 ± 0.8	1.39 ± 0.54
F	< 5	CR	Manual	19	43 ± 6	3.9 ± 0.4	1.23 ± 0.28

CWND, chest wall to nipple distance; AEC, automatic exposure control; CBT, compressed breast thickness; SD, standard deviation.

^aThe predicted tube loading of each mammogram was calculated using the CBT-PMMA conversion equations for medium breast density.

There are two considerations that should be kept in mind when the imaging-planning program is used. First, the imaging parameters must be determined depending on the clinical conditions. The imaging-planning program was developed on the basis of the CBT-PMMA conversion equations for various breast density types and age groups. The mammographer must select a tube loading depending on age and breast density type.

Second, a dose reduction may be needed for thicker breasts by using a higher tube potential. For the same tube potential, the average glandular dose (AGD) non-linearly increases with CBT [12]. To reduce the patient dose, a higher tube potential is frequently used in imaging thick breasts. When using the imaging-planning program, a mammographer can select an appropriate tube potential for use in imaging, and therefore a saving of AGD may be achieved. Since changing the tube potential influences both AGD and image quality, European guidelines suggest the adequate tube potential for use in SF mammography. For example, 25–26, 25–27 and 26–28 kV are suggested for use with PMMA thicknesses of 2, 3 and 4 cm, respectively.

Verification of the imaging-planning program

The predicted tube loadings of the imaging-planning program were in agreement with the tube loadings

Figure 7. Equivalent polymethylmethacrylate (PMMA) thickness ratios for breasts with chest wall to nipple distance > 5 cm (365 subjects).

suggested for manual exposure with the Selenia FFD unit. The results provide straightforward empirical support for the clinical application of the imaging-planning program. For verification using standard breast phantoms, the predicted tube loadings were generally in agreement with the delivered tube loadings of standard breast phantoms, except for thin phantoms. Of note, only ± 1 SD of equivalent PMMA thickness was used in the correction for breast density in the imaging-planning program.

An uncertainty developed when the imaging-planning program was used to image a thin standard breast phantom. The main reason is that the standard breast phantom may not be suitable for simulating thin breasts. Some studies [5, 6] have reported that the standard breast model with a 0.5 cm adipose layer may lead to estimated glandularities of $> 100\%$ for a breast with CBT < 2.5 cm. Therefore, it is understandable that the predicted tube loading of the imaging-planning program is greater than the delivered tube loading of a standard breast phantom for a thickness < 2.5 cm.

For verification using patient exposures with a CWND > 5 cm (categories A and B), the average fractional tube loadings were slightly greater than 1 (1.10 and 1.07). The average predicted tube loading obtained using the imaging-planning program was slightly greater than the average delivered tube loading determined by the AEC. Of note, the predicted tube loading of each

Figure 8. The distribution of delivered and predicted tube loadings for screen/film (SF) mammograms of breasts with a chest wall to nipple distance > 5 cm. All mammograms were imaged with 25 kV. The subjects' ages ranged from 30 to 49 years and a total of 118 mammograms were included, AEC, automatic exposure control.

simulated exposure is calculated by applying the CBT-PMMA conversion equations of medium breast density type, *i.e.* all breasts included here were assumed to be medium density. Therefore, the accuracy in predicting the tube loading using the imaging-planning program is judged to be acceptable.

For verification using patient exposures with a CWND <5 cm (categories C-F), the average fractional tube loadings were significantly greater than 1 (1.23–1.55), *i.e.* the average predicted tube loading was significantly greater than the average delivered tube loading. It is reasonable to suggest that the delivered tube loadings in categories C-F may be increased so that an average fractional tube loading comparable to those obtained in categories A and B can be achieved. Additionally, the average fractional tube loadings determined by mammographers (categories E and F) were improved as compared with those determined by AEC (categories C and D). This implies that the average image quality of the mammograms that were imaged manually was superior to that of the mammograms that were imaged using AEC for breasts with short CWND.

Clinical application and generalisation

The imaging-planning program is easy to use and the mammographer can become familiar with it after several exposures. From our experience, mammographers prefer to use a tube potential of 24 and 25 kV to image a breast with short CWND. The prolonged breast compression did not exceed 10 s. In comparison with the lengthy period of breast positioning, this prolonging of breast compression does not appear to significantly interfere with the imaging procedure.

The basic data sets measured in this study are used for our clinical conditions. The imaging-planning program can be easily generalised to other institutions or mammographic X-ray units by proper modification of some basic datasets, such as CBT correction (step 1) and tube loading estimation (step 3). According to the ACR protocol [1], AEC performance can be tested with PMMA blocks of at least 2, 4, 6 and 8 cm thicknesses. The results of AEC performance testing in quality control may be applied to the tube loading estimations (step 3). Tube loading estimations using higher tube potentials, such as 27 and 28 kV, are available by inputting the measured datasets of tube loadings into the program.

Conclusions

Imaging breasts with a short CWND with a traditional mammographic X-ray unit is a technical challenge for mammographers. The technical demands include proper breast positioning and appropriate exposure parameter determination. Although the challenge of breast positioning remains, the exposure parameters for breasts with a short CWND can be predicted by using the

imaging-planning program. The imaging-planning program developed in this study can be used as a training tool and can be easily applied to clinical practice without modifications to the mammographic equipment. With application of the imaging-planning program in clinical practice, the experiential dependence of the mammographer for determination of the imaging parameters for breasts with a short CWND is minimised. Our future work is to find a more accurate CBT correction approach and to analyse the clinical efficacy of the imaging-planning program.

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