The readout thickness versus the measured thickness for a range of SFM and FFDM units

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Purpose: To establish a simple method to determine breast readout accuracy on mammography units.
Methods: A thickness measuring device (TMD) was used in conjunction with a breast phantom. This phantom had compression characteristics similar to human female breast tissue. The phantom was compressed, and the thickness was measured using TMD and mammography unit readout. Measurements were performed on a range of screen film mammography (SFM) and full-field digital mammography (FFDM) units (8 units in total; 6 different models/manufacturers) for two different sized paddles and two different compression forces (60 and 100 N).
Results: The difference between machine readout and TMD for the breast area, when applying 100 N compression force, for nonflexible paddles was largest for GE Senographe DMR+ (24 cm × 30 cm paddle: +14.3%). For flexible paddles the largest difference occurred for Hologic Lorad Selenia (18 cm × 24 cm paddle: +26.0%).
Conclusions: None of the units assessed were found to have perfect correlation between measured and readout thickness. TMD measures and thickness readouts were different for the duplicate units from two different models/manufacturers.
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Key words: mammography, breast thickness, breast compression

I. INTRODUCTION

Accurate breast thickness estimation is required in order to calculate the mean glandular dose (MGD).[1–3] Accuracy is also required for density measurements (which can be used for predicting breast cancer risk)[4] and for estimation of breast tissue volume.[5,6] Compression paddles may deform/tilt during mammography and this can lead to differences between the actual and readout (displayed by the mammography machine) thickness of the compressed breast. Under realistic clinical imaging conditions (phantom-simulated) this study aimed to conduct a comparative analysis of readout versus measured thicknesses over a range of mammography units.

Previous studies have highlighted inaccuracies with thickness readouts of mammography machines; some of these studies have also proposed methods which may provide a better estimate of the compressed breast thickness.[3,7–9] Diffey *et al.*[10] found a maximum variation of 21.1 mm in the chest wall to nipple direction, while the paddle deformation in the lateral direction was found to be insignificant in comparison to the chest wall to nipple direction. Tyson *et al.*[9] described a technique for measuring breast thickness by using optical stereoscopic photogrammetry. This method had a precision of >1 mm, and a measurement accuracy of >0.2 mm. The readout thickness for a number of different mammography systems was found to vary by as much as 15 mm when compressing the same breast or phantom.[9] The value of the method developed by Tyson *et al.*[9] was its accuracy; system use however is labor intensive, being highly dependent on room lighting and also on image quality. Mawdsley *et al.*[7] developed functions that can estimate the compressed breast thickness based upon the machine readout thickness and compression force reported by the machine.

This study aimed to develop a simple, clinically adaptable and accurate method to measure the difference between the readout and measured thickness. Building on previous research there was particular interest in, the creation and documentation of the physical breast phantom characteristics, particularly in relation to in-vivo female human breast tissue. In order to investigate how the thickness readout and the thickness across the breast correlated, a breast thickness measuring device (TMD) was constructed.

II. METHODS AND MATERIALS

The method comprised of three stages. First, a clinically realistic breast phantom and backing plate with the creation of a rigid torso was tested. Second, the TMD was designed and tested. Finally, using the TMD, the breast phantom with its backing plate was used to assess several mammography units/paddle combinations.

II.A. Design, creation, and validation of breast phantom

Three breast prostheses (small (220 cm^3), medium (360 cm^3), and large (700 cm^3), Trulife, Sheffield, United Kingdom) were assessed for their compression characteristics. Each of the breast prostheses were adhered onto a semiflexible backing plate. The backing plate was mounted onto a rigid torso (Fig. 1) in order to simulate how a real breast will behave when it is compressed. The resistance to compression incurred by the torso changed the compressibility of the phantom to better simulate a real breast.

Six rubber balloons were glued onto the flexible backing plate. The balloons gave minor mobility similar to pectoral muscle and fascia. The phantom was glued onto the balloons and covered with layers of latex. The latex was painted across the surface of the phantom and along the edges, with fewer layers across the surface than around the edges. The backing plate was mounted onto a rigid torso (CIRS, Norfolk) using two ratchet straps, one above and one below the breast phantom. Before compressing the breast phantom, a lubricant was applied to the phantom. This allowed the compression paddle to slide smoothly over the breast surface when pressure was applied.

Using the three breast phantoms, mounted as described, compression (N)/thickness (mm) graphs were generated from 40 to 100 N stepping through 10 N values. For each phantom, the compressed breast thickness data were averaged and normalized (the data were normalized to 1 for 40 N compression force). For comparison the normalized average of 29 female human datasets were acquired (Fig. 2).

Fig. 1. Breast mounted to semiflexible background plate and rigid torso.

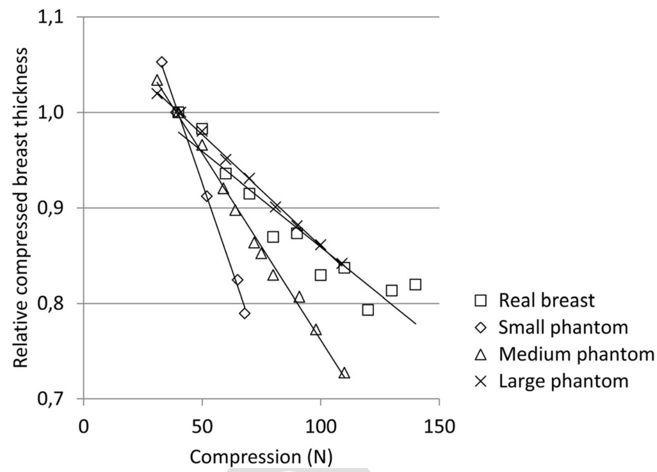

Fig. 2. Compressed breast thickness (mm) as a function of compression force (N) for real breasts and the three breast phantoms.

The 29 female datasets were acquired on a Hologic Lorad Selenia, while the phantom data were collected from a GE Senographe 800 T. The normalized compression curve of the large prosthesis was compared with the normalized correlation curve of the real breast, and it was found that the compression characteristics correlated well, with a correlation coefficient of 0.95. On this basis the large phantom (700 cm^3) was chosen as our breast phantom.

II.B. Compression paddle bend and distortion measuring device

The TMD was constructed of poly methyl methacrylate (PMMA) (Fig. 3). TMD dimensions (depth: 17.1 cm, width: 36.0 cm, and height: 21.8 cm) were such that they would fit the mammography machines/paddles that were to be included in the study. Wooden rods, diameter approximately 5 mm, and of different lengths (10–25 cm) were used (Fig. 3) to measure thickness. The top of the TMD had a matrix of 5 mm diameter holes drilled through it; the centers were 20 mm apart.

II.C. How the study was conducted

The measurements were performed on different mammography units from three different manufacturers [General

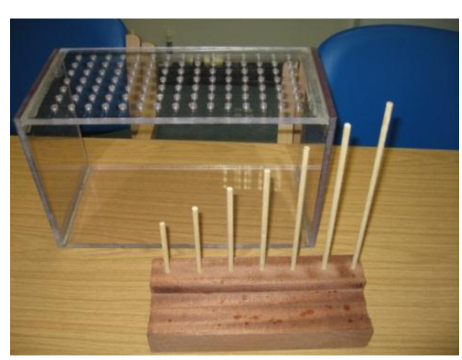

Fig. 3. Thickness measuring device (TMD) and rods.

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TABLE I. Mammographic units included in this study.

Location	Manufacturer/Model	SFM/FFDM	Compressed breast thickness accuracy (specified by manufacturer)	QC: maximum difference in measured and readout thickness[b]	Paddle size	Flexible/Nonflexible paddle	Tilting/Nontilting
A	GE Senographe 800T	SFM	±10 mm	±0.4 cm	18 cm × 24 cm	Nonflexible	Nontilting
			±10 mm		24 cm × 30 cm	Nonflexible	Nontilting
A	GE Senographe DMR+	SFM	±10 mm	+0.5 cm	18 cm × 24 cm	Nonflexible	Nontilting
			±10 mm		24 cm × 30 cm	Nonflexible	Nontilting
B	GE Senographe DMR+	SFM	±10 mm	+0.5 cm	18 cm × 24 cm	Nonflexible	Nontilting
			±10 mm		24 cm × 30 cm	Nonflexible	Nontilting
C	Siemens Mammomat Inspiration	FFDM	39–45 mm[a]	−0.1 cm	18 cm × 24 cm	Nonflexible	Nontilting
					24 cm × 30 cm	Nonflexible	Nontilting
B	GE Senographe Essential	FFDM	±10 mm	−0.3 cm	19 cm × 23 cm[d]	Nonflexible	Nontilting
			±10 mm		19 cm × 23 cm[d]	Flexible	Tilting
			±10 mm		24 cm × 31 cm	Flexible	Tilting
D	Hologic Lorad Selenia	FFDM	±0.5 cm	−0.1 cm	18 cm × 24 cm	Flexible	Tilting
			±0.5 cm		24 cm × 30 cm	Flexible	Tilting
D	Hologic Selenia Dimensions	FFDM	±0.5 cm	−0.1 cm	18 cm × 24 cm[d]	Flexible	Tilting
			±0.5 cm		24 cm × 29 cm[d]	Flexible	Tilting
E	Hologic Lorad Selenia	FFDM	±0.5 cm	−0.4 cm[c]	18 cm × 24 cm	Flexible	Tilting
			±0.5 cm		24 cm × 30 cm	Flexible	Tilting

[a]The thickness of a compressible phantom should be between 39 and 45 mm. The thickness of the compressible phantom (RMI 156, Gammex RMI, Middleton, WI) is 42 mm.
[b]In the UK the compressed breast thickness accuracy is measured during quality control (QC) which is conducted every six months. This consists of measuring the compressed thickness for a PMMA phantom of known thickness. Difference in compressed breast thickness = Thickness of Perspex—Readout thickness. An under- and/or underestimation is considered equally faulty.
[c]All quality control measurements were conducted with a nonflexible paddle.
[d]Even if Hologic Selenia Dimensions and GE Senographe Essential were a bit different in size than the others, they are referred to as 18 cm × 24 cm (18 × 24) and 24 cm × 30 cm (24 × 30) in the figures.

Electric (GE Medical Systems, Buc, France), Hologic Inc. (Bedford, MA) and Siemens (Siemens Healthcare, Erlangen, Germany)]. Both screen film mammography (SFM) and full-field digital mammography systems (FFDM) were included (Table I). This selection is representative of machines that were in clinical use at the time of the study. Two different paddle sizes, standard [approximately 18 cm × 24 cm (18 × 24)] and large [approximately 24 cm × 30 cm (24 × 30)] were used (Table I).

The TMD was placed on top of the table, with the long side (36.0 cm) parallel and along the edge of the chest side of the table top and centered left to right. The compression paddle was fastened such that it was located between the top and bottom plate of the TMD (Fig. 4), with the breast prosthesis resting on the bottom plate of the TMD. Two different compression forces were applied when compressing the breast prosthesis (60 and 100 N).

FIG. 4. How the measurements were conducted.

In order to estimate the compressed breast thickness, the distance from the top of the TMD to the top of the compression paddle was measured across the whole area (Fig. 4). The distance was measured by using a rod that was dropped into the hole at the top of the TMD. A fingernail was used to mark where the rod touched the top plate, the rod was then removed and the length of the rod from the bottom (where it touched the top of the compression paddle) up to the fingernail was measured using a ruler. This was repeated until the height of the rod for all the holes that covered the compression paddle in question had been measured. Row 1 was defined as the row parallel to the breast chest wall and closest to the breast chest wall. Column 1 was defined as the column perpendicular to the breast chest wall and out to the left side. Column 15 was then the last column on the right. A full set of thickness measurements (105) took approximately 20 min to conduct.

Mawdsley *et al.*[7] defined a reference point along the midline in the chest wall to nipple direction, 20 mm in from the chest wall side. They found that for most images the maximum height occurred at this reference point. We defined the same reference point in our study—hole in row 1, column 8 (located 2.5 cm from the breast chest wall side of the imaging table, and 18.0 cm from the short edge side).

II.D. Calculation of breast thickness

The measurements performed to find the readout and measured thickness of the phantom is illustrated in Fig. 5.

The readout thickness (d) is given by the following equation:

$$d = D - t \tag{1}$$

where D is the system readout thickness including the thickness of the bottom plate. The thickness of the bottom plate (t) had to be subtracted from the total readout thickness (D) in order to obtain the readout thickness for the phantom (d). The measured thickness (M) of the object was calculated as follows:

$$M = H - t - p - 1 \tag{2}$$

where H is the total height of the TMD, p is the thickness of the compression paddle, and l is the distance from the top of the compression paddle to the top of the TMD. Using a vernier caliper, the thickness of the compression paddles (p) was measured to be 1.00 mm for Siemens Mammomat Inspiration and 2.75 mm for all the other paddles in this study. The area covering the compressed phantom (row 1 columns 3–13, row 2 columns 4–12, row 3 columns 6–10, and row 4 column 8) was defined as the breast area. The thickness for the area covering the compressed breast phantom was measured (breast area), and the minimum, maximum and average measured breast thickness for this area was compared to the readout thickness, and the difference between them were found, as follows-

$$\text{Percentage} = \frac{(\text{Average/min/max measured breast area}) - \text{Readout thickness}}{\text{Readout thickness}} \tag{3}$$

A positive value implies that the measured thickness is larger than the readout thickness which suggests the machine underestimates thickness. A negative value implies that the measured thickness is smaller than the readout thickness, which suggests the machine overestimates the thickness. An over- or underestimation is considered equally faulty, and a difference close to zero is preferred.

II.E. TMD - precision and observer variability

Prior to commencing the study a precision and operator variability study was conducted. A wooden block (depth: 96 mm, width: 253 mm, and height: 55 mm) was placed inside the TMD device, centered in the middle and parallel to the long side of the TMD device. The thickness was measured three times by the person who would perform the thickness measurements. Average measured thickness was 55.5 mm, with a standard deviation of 0.4 mm across the whole area measured by the reader for all three measurements. The deviation in the measured thickness varied between −1 and 2 mm (only one measurement varied with 2 mm) with an average of -0.04 ± 0.12 mm (95% confidence interval). Concluding from this, this person would conduct the study with good precision. However, in the study itself 15% of the actual measurements were repeated on a blind sampling basis to minimize random error. The average difference between the first measurement and the second measurement (blind testing) was -0.17 ± 0.07 mm (95% confidence interval). Concluding from this their precision and repeatability was more than adequate for this study.

II.F. Quality control: checking the readout thickness

In the United Kingdom (the location for all the mammography units in this study) the allowed difference between readout and measured thickness is ±5 mm.[11] Each machine was tested every six months (Table I); all units were operating within manufacturer specification.

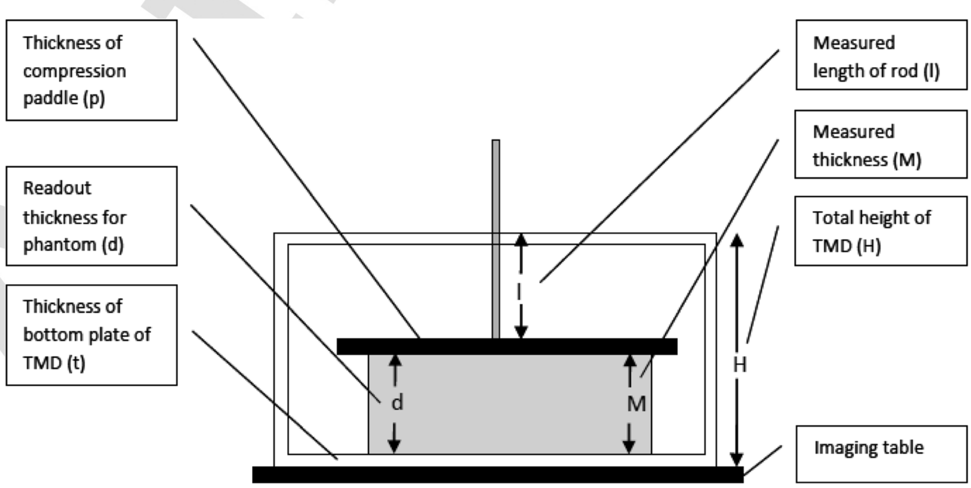

FIG. 5. Diagram to illustrate the measurements performed to calculate readout and measured thickness of the object.

II.G. Quality control: checking the compression force

Accuracy of compression force is assessed on traceably calibrated scales and noted to an accuracy of 5 N every 6 months by a medical physicist and monthly by radiographers. The readout compression force is checked for 40, 80, and 120 N and also at maximum compression force (200 N). The accuracy of the readout compared to the measured compression force was ±10 N (in accordance with IPEM 89 Ref. 11) for all the units.

III. RESULTS

Figures 6 and 7 illustrate a 3D representation of the difference between the measured thickness and the readout thickness for a nonflexible and flexible paddle across the whole measured area. Since the primary interest is the variation across the breast area, and the average percentage difference in compressed breast thickness, the minimum percentage difference in breast thickness and the percentage difference between readout and measured thickness for the reference point are shown in Fig. 8.

III.A. Difference between measured and readout thickness across paddle area

The smallest and largest difference between the measured and readout thickness of the compressed phantom across the whole measured area of the paddle is shown in Fig. 6 for the 18 × 24 flexible paddle (smallest difference: 12 mm and largest difference: 19 mm) and Fig. 7 for the 18 × 24 nonflexible paddle (smallest difference: 3 mm and largest difference: 7 mm). The average difference between the smallest and largest measured thickness across the whole area was smaller for nonflexible paddles compared to flexible paddles (nonflexible/flexible 18 × 24: 5.0/16.0 mm, nonflexible/flexible 24 × 30: 5.3/10.0 mm). Figure 7 illustrates that the compression paddle may be uneven in the left to right direction.

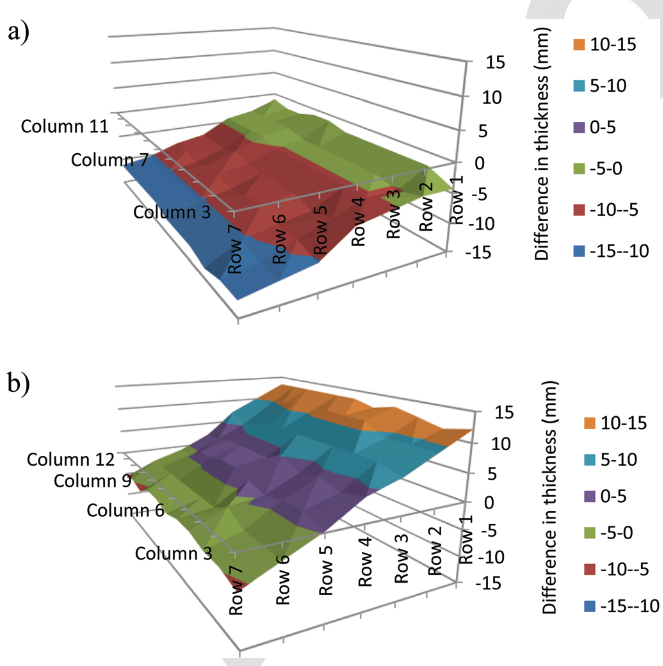

FIG. 6. Map of differences in thickness for the whole area for 18 cm × 24 cm flexible compression paddle for (a) Hologic Selenia Dimensions, which had the smallest (12 mm) difference in thickness across the whole area and (b) Hologic Lorad Selenia, which had the largest (19 mm) difference in thickness across the whole area, when applying 100 N compression force.

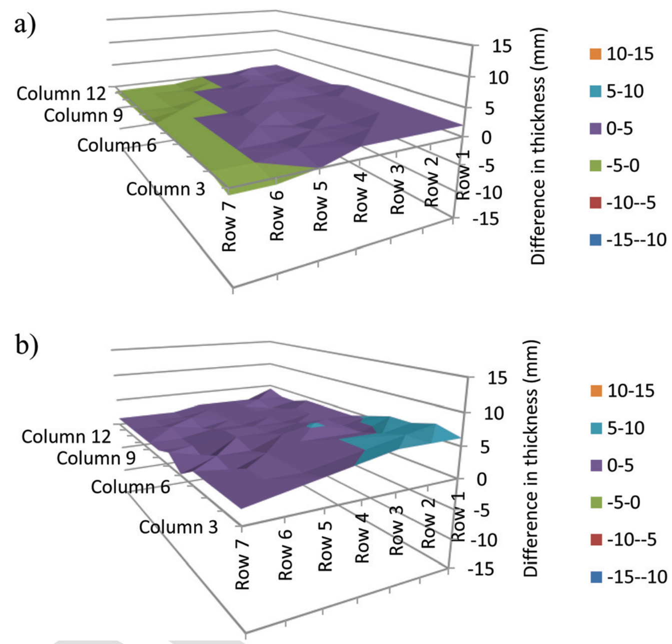

FIG. 7. Map of differences in thickness for the whole area for 18 cm × 24 cm nonflexible compression paddle for (a) Siemens Mammomat Inspiration, which had the smallest (3 mm) difference between measured and readout thickness across the whole area and (b) GE Senographe 800 T, which had the largest (7 mm) difference in measured and readout thickness across the whole area, when applying 100 N compression force.

The average, minimum, maximum percentage, and reference point percentage difference between measured compressed breast thickness and the readout compressed breast thickness for the breast area for the 18 × 24 paddle for 60 and 100 N applied compression force is shown in Fig. 8.

Figure 8 shows that there is a larger spread in the average percentage difference for the flexible than for the nonflexible compression paddle for both 60 N (range: −5.5%–6.8% (nonflexible), −4.5%–9.0% (flexible)) and 100 N (range: −8.0%–11.2% (nonflexible), −6.0%–26.0% (flexible)), and the difference is larger for 100 N than for 60 N applied compression force. For the nonflexible paddles Siemens Mammomat Inspiration (60 N: 1.0%, 100 N: 2.6%) came closest to 0% difference for the average percentage difference, and for the flexible paddle Hologic Selenia Dimensions (60 N: −1.5%) came closest to 0% difference when 60 N compression force was applied and GE Senographe Essential (100 N: −3.1%) came closest to 0% difference when 100 N compression force was applied.

III.B. Variation in thickness across breast area

The average, minimum, and maximum differences (measured in mm) for the compressed breast area is shown in Table II.

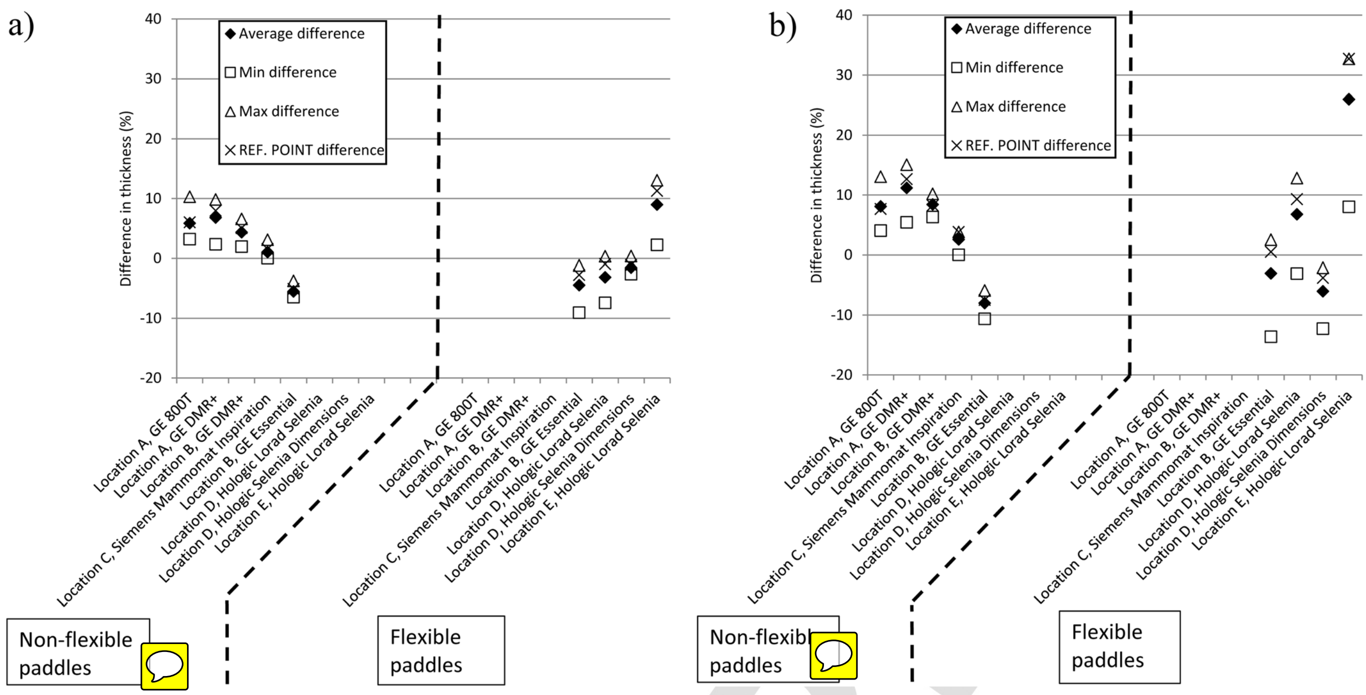

FIG. 8. The percentage difference between measured thickness and readout thickness for the breast area for 18 cm × 24 cm nonflexible and flexible compression paddle for (a) 60 N and (b) 100 N applied compression force.

The difference between machine readout and measured thickness for nonflexible paddles for the breast area, applying 100 N compression force was smallest for the Siemens Mammomat Inspiration (18 × 24 paddle: +2.6% ($p < 0.01$), 24 × 30 paddle: +0.7% ($p = 0.05$)) and largest for GE Senographe DMR+ (18 × 24 paddle (location A): +11.2% ($p < 0.01$), 24 × 30 paddle (location B): +14.3% ($p < 0.01$)). For the 18 × 24 flexible paddle, and with an applied compression force of 100 N, the smallest difference between machine readout and measured thickness for the breast area occurred for GE Senographe Essential [−3.1% ($p < 0.01$)], and the largest for a Hologic Lorad Selenia [26.0% ($p < 0.01$)]. For the 24 × 30 flexible paddle, and with an applied compression force of 100 N, the smallest difference between machine readout and measured thickness for the breast area occurred for a Hologic Lorad Selenia [3.0% ($p < 0.01$)] and the largest difference occurred for the other Hologic Selenia Dimensions [−8.9% ($p < 0.01$)].

The average differences for both paddles, both compression forces (60 and 100 N) and all modalities in this study were +2.6% (60 N: +1.3%, 100 N: +2.8%).

In this study, two Hologic Lorad Selenia and two GE Essential DMR+ units were included. When comparing the results for the two units of equal manufacturer and model, it was found that the average difference between the readout thickness and the measured thickness for the breast area is different for the two units [GE DMR+: 11.2 vs 8.4% (18 × 24), 0.7 vs 14.3% (24 × 30), Hologic Lorad Selenia: 6.8 vs 26.0% (18 × 24), 3.0 vs 8.3% (24 × 30)].

III.C. Change in measured compressed breast thickness when increasing the compression force

When increasing the compression force from 60 to 100 N an 18% decrease in measured compressed breast thickness was observed for the breast area (18 × 24: 17.8 ± 1.4%, 24 × 30: 17.7±5.4%) when using nonflexible paddles. When using flexible paddles a larger decrease in measured compressed breast thickness can be observed for the 18 × 24 paddles (18.6 ± 2.6%) versus the 24 × 30 paddles (17.1 ± 1.9%).

III.D. Reference point

The average difference for both compression forces, both paddles (nonflexible/flexible) and both paddle sizes between the measured thickness for the average breast area and the measured thickness for the reference point is −0.7 ± 0.2 mm (in percentage: −1.4 ± 0.5%).

IV. DISCUSSION

For all machine and paddle combinations the readout breast thickness was different to; reference point thickness, average thickness, minimum thickness, or maximum thickness. This resulted in the measured thickness being over-estimated and also under-estimated. The difference was more marked at 100 N compared with 60 N, suggesting that as force increases the error in thickness readout also increases. At 100 N and 18 × 24 paddle, only 2 (Location B GE Essential/18 × 24 flexible; Location C, Siemens Mammomat Inspiration/18 × 24/24 × 30 nonflexible) out of 9 machines (22%) gave reference point and average values for the breast area that were within ±5% of the readout thickness. Flexible paddles had greater departure from measured thickness when compared with nonflexible paddles.

IV.A. Quality control and tolerance data supplied by manufacturers

The results for the average difference in compressed breast thickness for the breast area was compared to the

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TABLE II. Average, minimum and maximum difference in thickness (mm) for the breast area for the compression forces 60 and 100 N for the different mammography units included in this study.

	Compression force 60 N				Compression force 100 N			
	Average difference mm (%)[a]	Min difference mm (%)[b]	Max difference mm (%)[c]	Ref. point difference mm (%)[d]	Average difference mm (%)[a]	Min difference mm (%)[b]	Max difference mm (%)[c]	Ref. point difference mm (%)[d]
Nonflexible paddle, 18 × 24								
Location A, GE 800T	4.1 (5.9)	2.3 (3.2)	7.3 (10.3)	4.3 (6.0)	4.5 (8.1)	2.3 (4.1)	7.3 (10.3)	4.3 (7.7)
Location A, GE DMR+	3.6 (6.8)	1.3 (2.3)	5.3 (9.8)	4.3 (7.9)	4.6 (11.2)	2.3 (5.4)	6.3 (15.1)	5.3 (12.7)
Location B, GE DMR+	2.8 (4.3)	1.3 (1.9)	4.3 (6.6)	3.3 (5.0)	4.3 (8.4)	3.3 (6.3)	5.3 (10.2)	4.3 (8.3)
Location B, GE Essential	−2.8 (−4.5)	−0.8 (−1.2)	−5.8 (−9.1)	−1.8 (−2.8)	−1.5 (−3.1)	1.3 (2.5)	−14.8 (−13.6)	0.3 (0.5)
Location C, Siemens Mammomat Inspiration	0.7 (1.0)	0.0 (0.0)	2.0 (3.1)	1.0 (1.6)	1.3 (2.6)	0.0 (0.0)	2.0 (3.8)	2.0 (3.8)
Nonflexible paddle, 24 × 30								
Location A, GE 800T	2.8 (5.0)	2.3 (4.1)	4.3 (7.7)	3.3 (5.9)	3.4 (7.7)	1.3 (2.8)	4.3 (9.6)	3.3 (7.3)
Location A, GE DMR+	3.9 (7.4)	3.3 (6.1)	5.3 (9.8)	4.3 (7.9)	0.3 (0.7)	−0.8 (−1.8)	1.3 (2.9)	1.3 (2.9)
Location B, GE DMR+	4.6 (9.7)	2.3 (4.7)	7.3 (15.3)	5.3 (11.1)	5.6 (14.3)	3.3 (8.2)	7.3 (18.4)	6.3 (15.7)
Location C, Siemens Mammomat Inspiration	0.1 (0.1)	−1.0 (−1.6)	2.0 (3.3)	0.0 (0.0)	0.3 (0.7)	−1.0 (−1.9)	2.0 (3.8)	1.0 (1.9)
Flexible paddle, 18 × 24								
Location B, GE Essential	−2.8 (−4.5)	−0.8 (−1.2)	−5.8 (−9.1)	−1.8 (−2.8)	−1.5 (−3.1)	1.3 (2.5)	−6.8 (−13.6)	0.3 (0.5)
Location D, Hologic Lorad Selenia	−2.4 (−3.2)	0.3 (0.3)	−5.8 (−7.4)	−0.8 (−1.0)	3.8 (6.8)	−1.8 (−3.1)	7.3 (12.8)	5.3 (9.3)
Location D, Hologic Selenia Dimensions	−1.0 (−1.5)	0.3 (0.4)	−1.8 (−2.6)	−0.8 (−1.1)	−3.6 (−6.0)	−1.3 (−2.1)	−7.3 (−12.3)	−2.3 (−3.8)
Location E, Hologic Lorad Selenia	5.0 (9.0)	1.3 (2.3)	7.3 (13.1)	6.3 (11.3)	10.5 (26.0)	3.3 (8.0)	13.3 (32.7)	13.3 (32.7)
Flexible paddle, 24 × 30								
Location B, GE Essential	−2.9 (−4.4)	−1.8 (−2.7)	−3.8 (−5.8)	−2.8 (−4.2)	−3.8 (−7.0)	−2.8 (−5.1)	−4.8 (−8.7)	−2.8 (−5.1)
Location D, Hologic Lorad Selenia	−4.1 (−4.9)	−2.8 (−3.3)	−5.8 (−6.8)	−3.8 (−4.4)	2.0 (3.0)	−1.8 (−2.6)	4.3 (6.4)	3.3 (4.9)
Location D, Hologic Selenia Dimensions	−4.8 (−8.9)	−1.8 (−2.9)	−2.8 (−4.5)	−1.8 (−2.9)	−4.8 (−8.9)	−2.3 (−4.2)	−8.3 (−15.3)	−2.3 (−4.2)
Location E, Hologic Lorad Selenia	0.2 (0.3)	1.3 (1.9)	−1.8 (−2.6)	1.3 (1.9)	4.5 (8.3)	1.3 (2.3)	7.3 (13.3)	6.3 (11.5)

[a]Average difference: average difference between measured and readout thickness across the area defined as the breast area.
[b]Min difference: minimum difference between measured and readout thickness across the area defined as the breast area.
[c]Max difference: maximum difference between measured and readout thickness across the area defined as the breast area.
[d]Ref. point difference: difference between measured and readout thickness for the hole defined as the reference point (row 1, column 8).

maximum difference in measured thickness (for phantom of known thickness) and readout thickness from the annual quality control. Only two units (GE Senographe DMR+ (Location A) and GE Senographe Essential) of the eight units (25%) were found to have an average difference between measured and readout thickness within the maximum difference found at the annual quality control. For the Hologic Lorad Selenia at Location D the average difference was larger than the difference between measured and readout thickness from the quality control for both paddles and both compression forces. For the other units (GE Senographe 800T, GE Senographe DMR+ (Location B), Siemens Mammomat Inspiration, Hologic Selenia Dimensions and Hologic Lorad Selenia (Location E)) discrepancies were found for 18 × 24 and/or 24 × 30 paddle and/or for both compression forces (60 and 100 N). The results in this study show that the test performed annually by the medical physicist might not be adequate to reveal discrepancies between the measured and the readout thickness.

Our measurements for the compressed breast thickness were compared to the tolerance data stated in the operator manuals supplied by the different manufacturers. For GE Senographe 800T and GE Senographe DMR+ our results were within the tolerance limits of ±10 mm stated in the operator manuals. Hologic Lorad Selenia user manual states that compression thickness accuracy should be ±0.5 cm for thicknesses between 0.5 and 15 cm. This was found to be true for one of the Hologic Lorad Selenia units (difference in measured and readout thickness for average breast area: 3.8 mm), but not for the other unit [difference in measured and readout thickness for average breast area: 10.5 mm (18 × 24)], when the 18 × 24 paddle was used and 100 N compression force was applied. For GE Senographe Essential the difference between the measured and readout thickness for the breast area was within the tolerance limit (±10 mm). Had the tolerance limit been ±5 mm, in other words the same as for Hologic Lorad Selenia/Hologic Selenia Dimensions, the results for the minimum difference between measured and readout thickness for the 18 × 24 paddles (nonflexible and flexible), when 100 N compression force was applied, would have also been within the limits.

To calibrate the readout thickness Siemens uses a 42 mm phantom and compresses the object using a 70 N compression force. The readout thickness should read between 39 and 45 mm. If not a recalibration is performed.

A calibration of the Hologic Lorad Selenia is performed by compressing a 5 cm thick phantom (BR-12, CIRS, Norfolk, VA). A compression force of 133.5 N is applied, and then the compression thickness is calibrated for the installed paddle/receptor combination.

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For Hologic Selenia Dimensions most of the calibration is done automatically. A 2 and 8 cm thick phantom (BR-12) is compressed by applying 133.5 N compression force, and the machine will then register the thickness of the phantom. For the "FAST" paddle (the flexible paddle) the same approach is taken, but without any compression. The paddle is just lowered until it touches the phantom, and the machine is told that this is 2 or 8 cm. The fact that a rigid phantom is used for this test is probably not optimal, because a tilt will probably occur. Maybe one needs to rethink how the thickness is measured, or maybe a different approach to how the paddle is constructed needs to be addressed.

GE also has routines for the calibration of the thickness, but the calibration routines are propriety.

IV.B. Reference point

The difference between readout and measured thickness for the reference point and the average breast area values are similar [-0.7 ± 0.2 mm (in percentage: $-1.4 \pm 0.5\%$)], suggesting that a simplistic one-point of sample could be used for accurate estimation of average breast thickness. This approach would involve sampling only at the reference point, which would mean that the measuring time for the thickness would decrease drastically (from a maximum of 105 measurements down to one). We found that there is a large variation in the chest wall to nipple direction, and a smaller lateral variation, in accordance with Diffey *et al.*[10] A better estimate would therefore be to measure the thickness for the points/holes outlining the breast area; in this way, a better average for the compressed breast thickness could be measured.

Where Diffey *et al.*[10] found for real breasts an underestimation of thickness of as much as 21.2 mm in the chest to nipple direction, our results show a maximum underestimation of 13 mm for a Hologic Lorad Selenia mammography machine, and a maximum overestimation of 8 mm for a Hologic Selenia Dimensions mammography machine. If one takes into consideration this under-/overestimation of thickness only (and not the fact that a change in the thickness might also have implications for the choice of target/filter-combination and kV), the MGD can be estimated. For a Hologic Lorad Selenia, for instance, an underestimation of 13 mm would imply a smaller estimated MGD of 17% for a thin breast (readout thickness 35 mm) and 9% for a thick breast (readout thickness 80 mm). An underestimation of thickness will in general imply that the MGD originally estimated is too large, and thus overestimate the MGD and the risk. For a Hologic Lorad Dimensions an overestimation of 8 mm would imply a larger estimated MGD of 20% for a thin breast (readout thickness 31 mm) and 6% for a thick breast (readout thickness 79 mm). An overestimation of thickness will in general imply that the MGD originally estimated is too small, and thus underestimate the MGD and the risk.

IV.C. Correction factor

Varying paddle/machine combinations give different error levels between readout thickness and measured thickness. Correction factors may be applied, in order to obtain higher accuracy clinically. The correction factor can be found by dividing the measured thickness with the readout thickness for different manufacturers/models, different paddle sizes (in this study: 18×24 and 24×30) and different breast compression forces (in this study: 60 and 100 N).

IV.D. Study limitations

Preservation of breast phantom integrity limited our experiment to a maximum pressure force of 100 N. We propose that a more resilient breast phantom should be used across a broader range of clinically representative force values (e.g., 60 N stepping 10 to 150 N). This would provide a better understanding on how bend and distortion may vary across the higher end of the normal clinical pressure range. In this study the effect of different breast volumes or breast densities was not considered; extending these variables might be considered, as bend and distortion may be affected by them.

A further limitation in this study is the fact that a different readout thickness was achieved every time the measurements were repeated. When compressing the phantom, different thicknesses were achieved every time; as such the results are not reproducible. Positioning error was reduced by trying to position the phantom approximately in the middle of the compression paddle (along midline), but the compressed thickness still altered.

Tyson *et al.*[9] devised a method for determining the compressed breast thickness that had a thickness determination accuracy of better than 1 mm, and a measurement accuracy of better than 0.2 mm. The method described here will lead to a larger inaccuracy than the method described by Tyson *et al.*[9] Tyson *et al.*[9] state that a mean accuracy of better than 1 mm is required to make good estimates for the volumetric breast density. It was not possible with the device used in this study to obtain such a precision, but as for use in a busy clinically environment the TMD can be used to determine the difference in measured and readout thickness.

IV.E. Clinically adaptable method

In theory this method can be applied for real breasts in a clinic to measure the real compressed breast thickness for the breast. The breast must be placed inside the TMD, in the same fashion as the phantom, compression must be applied and the compressed breast thickness must be measured. Because of the time span (20 min) for measuring the compressed breast thickness in this study, it will probably be necessary to limit the number of measurements performed to only one point (e.g., the reference point). The breast must then be recompressed (applying the same compression force) in order to obtain the actual image. This last step will probably be difficult to accomplish, since it has been shown to be difficult to obtain the same thickness applying the same compression force when compressing an object similar to a breast.

V. CONCLUSION

The difference in the readout thickness and the measured thickness varies between units for the same model and

ID: varadharajans Time: 11:56 I Path: Q:/3b2/MPH#/Vol00000/110439/APPFile/AI-MPH#110439

between manufacturers. Individual correction factors for breast thickness may need to be established for each dependent on paddle selection and compression force applied. Any corrections to compressed breast thickness need therefore to be performed for the unit in question, and one cannot assume that the correction in compressed breast thickness applies to all mammography machines of the same model.

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