

# 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. © 2012 American Association of Physicists in Medicine. [DOI: 10.1118/1.3663579]

Key words: mammography, breast thickness, breast compression

## I. INTRODUCTION

Accurate breast thickness estimation is required in order to calculate the mean glandular dose (MGD).<sup>1-3</sup> Accuracy is also required for density measurements (which can be used for predicting breast cancer risk)<sup>4</sup> and for estimation of breast tissue volume.<sup>5,6</sup> 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.<sup>3,7-9</sup> Diffey *et al.*<sup>10</sup> 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.*<sup>9</sup> 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.<sup>9</sup> The value of the method developed by Tyson *et al.*<sup>9</sup> was its accuracy; system use however is labor intensive, being highly dependent on room lighting and also on image quality. Mawdsley *et al.*<sup>7</sup> 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

69 documentation of the physical breast phantom characteristics,  
 70 particularly in relation to in-vivo female human breast  
 71 tissue. In order to investigate how the thickness readout and  
 72 the thickness across the breast correlated, a breast thickness  
 73 measuring device (TMD) was constructed.

74 **II. METHODS AND MATERIALS**

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

81 **II.A. Design, creation, and validation of breast  
 82 phantom**

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

91 Six rubber balloons were glued onto the flexible backing  
 92 plate. The balloons gave minor mobility similar to pectoral  
 93 muscle and fascia. The phantom was glued onto the balloons  
 94 and covered with layers of latex. The latex was painted  
 95 across the surface of the phantom and along the edges, with  
 96 fewer layers across the surface than around the edges. The  
 97 backing plate was mounted onto a rigid torso (CIRS, Nor-  
 98 folk) using two ratchet straps, one above and one below the  
 99 breast phantom. Before compressing the breast phantom, a  
 100 lubricant was applied to the phantom. This allowed the com-  
 101 pression paddle to slide smoothly over the breast surface  
 102 when pressure was applied.

103 Using the three breast phantoms, mounted as described,  
 104 compression (N)/thickness (mm) graphs were generated  
 105 from 40 to 100 N stepping through 10 N values. For each  
 106 phantom, the compressed breast thickness data were aver-  
 107 aged and normalized (the data were normalized to 1 for 40 N



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

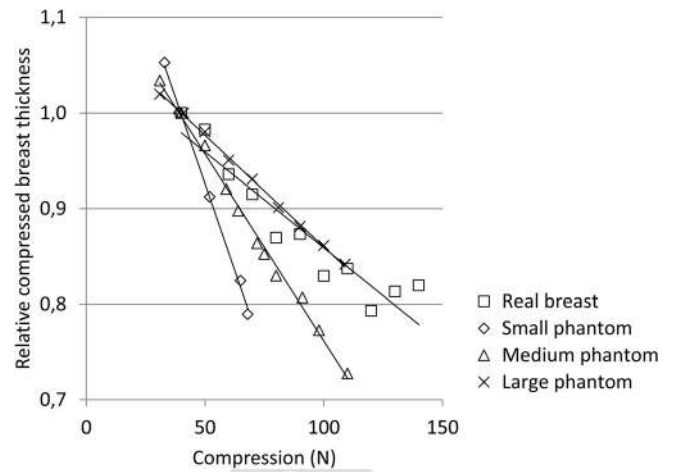


FIG. 2. Compressed breast thickness (mm) as a function of compression force (N) for real breasts and the three breast phantoms.

compression force). For comparison the normalized average  
 of 29 female human datasets were acquired (Fig. 2).

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 cor-  
 relation curve of the real breast, and it was found that the  
 compression characteristics correlated well, with a correla-  
 tion coefficient of 0.95. On this basis the large phantom  
 (700 cm<sup>3</sup>) 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 ma-  
 trix 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 mam-  
 mography units from three different manufacturers [General



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

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 <sup>b</sup>	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 <sup>a</sup>	−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 <sup>d</sup>	Nonflexible	Nontilting
			±10 mm		19 cm × 23 cm <sup>d</sup>	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 <sup>d</sup>	Flexible	Tilting
			±0.5 cm		24 cm × 29 cm <sup>d</sup>	Flexible	Tilting
			±0.5 cm		24 cm × 30 cm	Flexible	Tilting
E	Hologic Lorad Selenia	FFDM	±0.5 cm	−0.4 cm <sup>c</sup>	18 cm × 24 cm	Flexible	Tilting
			±0.5 cm		24 cm × 30 cm	Flexible	Tilting

<sup>a</sup>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.

<sup>b</sup>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.

<sup>c</sup>All quality control measurements were conducted with a nonflexible paddle.

<sup>d</sup>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.

132 Electric (GE Medical Systems, Buc, France), Hologic Inc.  
 133 (Bedford, MA) and Siemens (Siemens Healthcare, Erlangen,  
 134 Germany)]. Both screen film mammography (SFM) and full-  
 135 field digital mammography systems (FFDM) were included  
 136 (Table I). This selection is representative of machines that  
 137 were in clinical use at the time of the study. Two different  
 138 paddle sizes, standard [approximately 18 cm × 24 cm  
 139 (18 × 24)] and large [approximately 24 cm × 30 cm  
 140 (24 × 30)] were used (Table I).

141 The TMD was placed on top of the table, with the long  
 142 side (36.0 cm) parallel and along the edge of the chest side  
 143 of the table top and centered left to right. The compression  
 144 paddle was fastened such that it was located between the top  
 145 and bottom plate of the TMD (Fig. 4), with the breast pros-

thesis resting on the bottom plate of the TMD. Two different  
 146 compression forces were applied when compressing the  
 147 breast prosthesis (60 and 100 N).  
 148

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

166 Mawdsley *et al.*<sup>7</sup> defined a reference point along the mid-  
 167 line in the chest wall to nipple direction, 20 mm in from the  
 168 chest wall side. They found that for most images the maximum  
 169 height occurred at this reference point. We defined the same  
 170 reference point in our study—hole in row 1, column 8  
 171 (located 2.5 cm from the breast chest wall side of the imaging  
 172 table, and 18.0 cm from the short edge side).

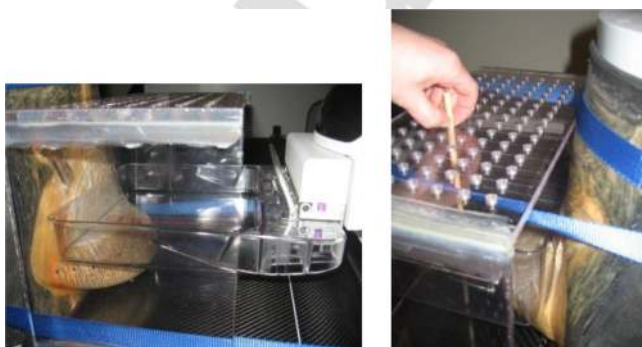


FIG. 4. How the measurements were conducted.



173 **II.D. Calculation of breast thickness**

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

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

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

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

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

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

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

204 **II.E. TMD - precision and observer variability**

205 Prior to commencing the study a precision and operator  
206 variability study was conducted. A wooden block (depth: 96  
207 mm, width: 253 mm, and height: 55 mm) was placed inside  
208 the TMD device, centered in the middle and parallel to the  
209 long side of the TMD device. The thickness was measured  
210 three times by the person who would perform the thickness  
211 measurements. Average measured thickness was 55.5 mm,  
212 with a standard deviation of 0.4 mm across the whole area  
213 measured by the reader for all three measurements. The

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 Inspira-  
tion 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 meas-  
ured (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-

deviation in the measured thickness varied between  $-1$  and  
2 mm (only one measurement varied with 2 mm) with an av-  
erage of  $-0.04 \pm 0.12$  mm (95% confidence interval). Con-  
cluding 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 ba-  
sis to minimize random error. The average difference  
between the first measurement and the second measurement  
(blind testing) was  $-0.17 \pm 0.07$  mm (95% confidence inter-  
val). 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 mammo-  
graphy units in this study) the allowed difference between  
readout and measured thickness is  $\pm 5$  mm.<sup>11</sup> Each machine  
was tested every six months (Table I); all units were operat-  
ing within manufacturer specification.

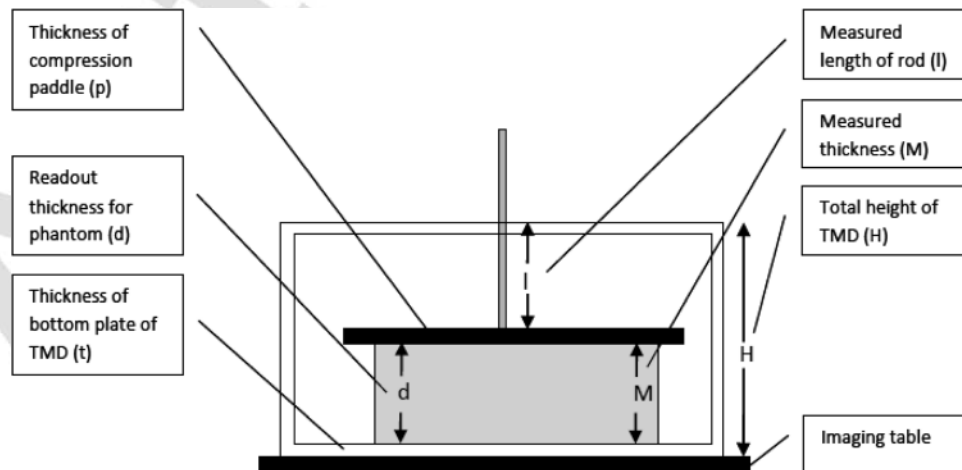


Fig. 5. Diagram to illustrate the measurements performed to calculate readout and measured thickness of the object.

231 **II.G. Quality control: checking the compression force**

232 Accuracy of compression force is assessed on traceably  
 233 calibrated scales and noted to an accuracy of 5 N every 6  
 234 months by a medical physicist and monthly by radiogra-  
 235 phers. The readout compression force is checked for 40, 80,  
 236 and 120 N and also at maximum compression force (200 N).  
 237 The accuracy of the readout compared to the measured com-  
 238 pression force was  $\pm 10$  N (in accordance with IPEM 89 Ref.  
 239 11) for all the units.

240 **III. RESULTS**

241 Figures 6 and 7 illustrate a 3D representation of the dif-  
 242 ference between the measured thickness and the readout  
 243 thickness for a nonflexible and flexible paddle across the  
 244 whole measured area. Since the primary interest is the varia-  
 245 tion across the breast area, and the average percentage dif-  
 246 ference in compressed breast thickness, the minimum  
 247 percentage difference in breast thickness and the percentage  
 248 difference between readout and measured thickness for the  
 249 reference point are shown in Fig. 8.

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

252 The smallest and largest difference between the measured  
 253 and readout thickness of the compressed phantom across the  
 254 whole measured area of the paddle is shown in Fig. 6 for the  
 255  $18 \times 24$  flexible paddle (smallest difference: 12 mm and  
 256 largest difference: 19 mm) and Fig. 7 for the  $18 \times 24$   
 257 nonflexible paddle (smallest difference: 3 mm and largest  
 258 difference: 7 mm). The average difference between the

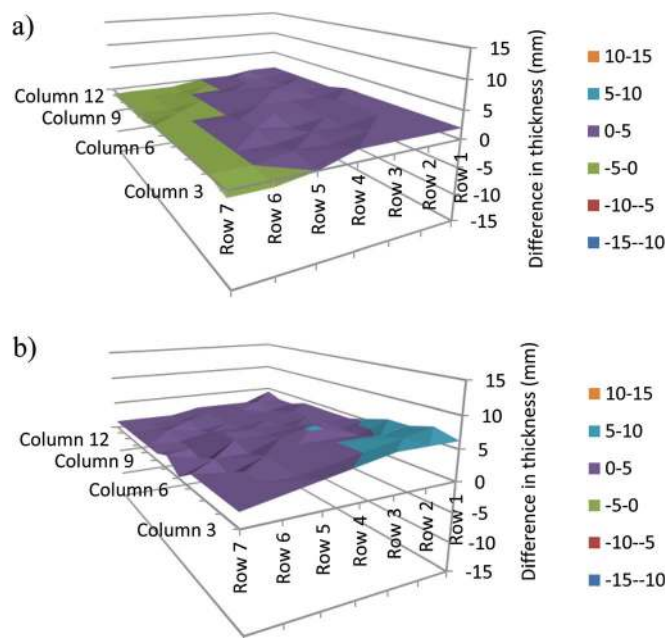


Fig. 7. Map of differences in thickness for the whole area for  $18 \text{ cm} \times 24 \text{ cm}$  nonflexible compression paddle for (a) Siemens Mammomat Inspiration, which had the smallest (3 mm) difference between measured and readout thickness across the whole area and (b) GE Senographe 800 T,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

smallest and largest measured thickness across the whole  
 area was smaller for nonflexible paddles compared to flexi-  
 ble paddles (nonflexible/flexible  $18 \times 24$ : 5.0/16.0 mm,  
 nonflexible/flexible  $24 \times 30$ : 5.3/10.0 mm). Figure 7 illus-  
 trates that the compression paddle may be uneven in the left  
 to right direction.

The average, minimum, maximum percentage, and refer-  
 ence point percentage difference between measured com-  
 pressed breast thickness and the readout compressed breast  
 thickness for the breast area for the  $18 \times 24$  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 com-  
 pression force. For the nonflexible paddles Siemens Mam-  
 momat 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 compres-  
 sion force was applied and GE Senographe Essential (100 N:  
 $-3.1\%$ ) came closest to 0% difference when 100 N compres-  
 sion 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.

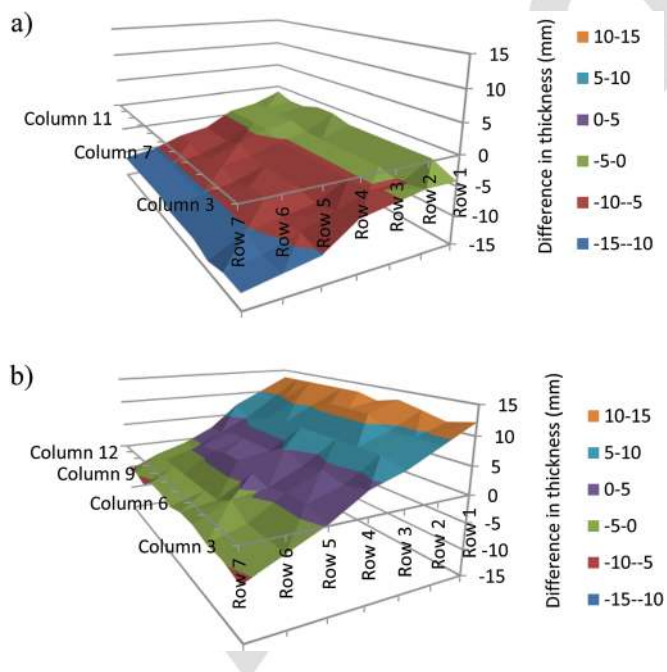


Fig. 6. Map of differences in thickness for the whole area for  $18 \text{ cm} \times 24 \text{ cm}$  flexible compression paddle for (a) Hologic Selenia Dimensions, which had the smallest (12 mm) difference in thickness across the whole area and (b) Hologic Lorad Selenia, which had the largest (19 mm)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

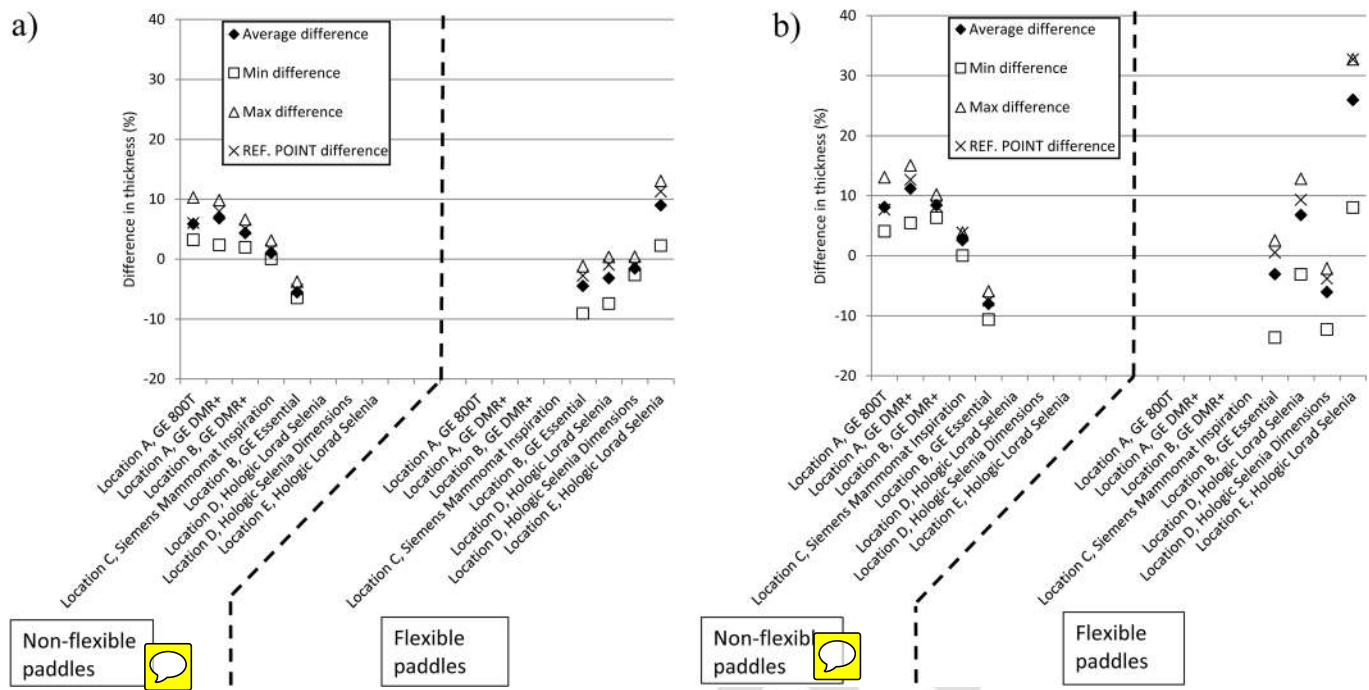


FIG. 8. The percentage difference between measured thickness and readout thickness for the breast area for 18 cm × 24 cm nonflexible and flexible compression paddle for (a) 60 N and (b) 100 N applied compression force.

288 The difference between machine readout and measured  
 289 thickness for nonflexible paddles for the breast area, applying  
 290 100 N compression force was smallest for the Siemens Mammo-  
 291 mat Inspiration (18 × 24 paddle: +2.6% ( $p < 0.01$ ), 24 × 30  
 292 paddle: +0.7% ( $p = 0.05$ )) and largest for GE Senographe  
 293 DMR+ (18 × 24 paddle (location A): +11.2% ( $p < 0.01$ ),  
 294 24 × 30 paddle (location B): +14.3% ( $p < 0.01$ )). For the  
 295 18 × 24 flexible paddle, and with an applied compression force  
 296 of 100 N, the smallest difference between machine readout and  
 297 measured thickness for the breast area occurred for GE Senog-  
 298 raphe Essential [−3.1% ( $p < 0.01$ )], and the largest for a Holo-  
 299 gic Lorad Selenia [26.0% ( $p < 0.01$ )]. For the 24 × 30 flexible  
 300 paddle, and with an applied compression force of 100 N, the  
 301 smallest difference between machine readout and measured  
 302 thickness for the breast area occurred for a Hologic Lorad Sele-  
 303 nia [3.0% ( $p < 0.01$ )] and the largest difference occurred for  
 304 the other Hologic Selenia Dimensions [−8.9% ( $p < 0.01$ )].

305 The average differences for both paddles, both compres-  
 306 sion forces (60 and 100 N) and all modalities in this study  
 307 were +2.6% (60 N: +1.3%, 100 N: +2.8%).

308 In this study, two Hologic Lorad Selenia and two GE  
 309 Essential DMR+ units were included. When comparing the  
 310 results for the two units of equal manufacturer and model, it  
 311 was found that the average difference between the readout  
 312 thickness and the measured thickness for the breast area is  
 313 different for the two units [GE DMR+: 11.2 vs 8.4%  
 314 (18 × 24), 0.7 vs 14.3% (24 × 30), Hologic Lorad Selenia:  
 315 6.8 vs 26.0% (18 × 24), 3.0 vs 8.3% (24 × 30)].

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

318 When increasing the compression force from 60 to 100 N  
 319 an 18% decrease in measured compressed breast thickness

was observed for the breast area (18 × 24:  $17.8 \pm 1.4\%$ ,  
 24 × 30:  $17.7 \pm 5.4\%$ ) when using nonflexible paddles. When  
 using flexible paddles a larger decrease in measured compressed  
 breast thickness can be observed for the 18 × 24 paddles  
 versus the 24 × 30 paddles ( $17.1 \pm 1.9\%$ ).

325 **III.D. Reference point**

326 The average difference for both compression forces, both  
 327 paddles (nonflexible/flexible) and both paddle sizes between  
 328 the measured thickness for the average breast area and the  
 329 measured thickness for the reference point is  $-0.7 \pm 0.2$  mm  
 330 (in percentage:  $-1.4 \pm 0.5\%$ ).

331 **IV. DISCUSSION**

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

345 **IV.A. Quality control and tolerance data supplied by**  
 346 **manufacturers**

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



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 (%) <sup>a</sup>	Min difference mm (%) <sup>b</sup>	Max difference mm (%) <sup>c</sup>	Ref. point difference mm (%) <sup>d</sup>	Average difference mm (%) <sup>a</sup>	Min difference mm (%) <sup>b</sup>	Max difference mm (%) <sup>c</sup>	Ref. point difference mm (%) <sup>d</sup>
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)

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

349 maximum difference in measured thickness (for phantom of  
 350 known thickness) and readout thickness from the annual  
 351 quality control. Only two units (GE Senographe DMR+  
 352 (Location A) and GE Senographe Essential) of the eight  
 353 units (25%) were found to have an average difference  
 354 between measured and readout thickness within the maxi-  
 355 mum difference found at the annual quality control. For the  
 356 Hologic Lorad Selenia at Location D the average difference  
 357 was larger than the difference between measured and readout  
 358 thickness from the quality control for both paddles and both  
 359 compression forces. For the other units (GE Senographe  
 360 800T, GE Senographe DMR+ (Location B), Siemens Mam-  
 361 momat Inspiration, Hologic Selenia Dimensions and Hologic  
 362 Lorad Selenia (Location E)) discrepancies were found for  
 363 18 × 24 and/or 24 × 30 paddle and/or for both compression  
 364 forces (60 and 100 N). The results in this study show that the  
 365 test performed annually by the medical physicist might not  
 366 be adequate to reveal discrepancies between the measured  
 367 and the readout thickness.

368 Our measurements for the compressed breast thickness  
 369 were compared to the tolerance data stated in the operator  
 370 manuals supplied by the different manufacturers. For GE  
 371 Senographe 800T and GE Senographe DMR+ our results  
 372 were within the tolerance limits of ±10 mm stated in the op-  
 373 erator 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 Essen-  
 tial the difference between the measured and readout thick-  
 ness 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 compres-  
 sion 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, Nor-  
 folk, VA). A compression force of 133.5 N is applied, and  
 then the compression thickness is calibrated for the installed  
 paddle/receptor combination.

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

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

#### 413 IV.B. Reference point

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

428 Where Diffey *et al.*<sup>10</sup> found for real breasts an underesti-  
429 mation of thickness of as much as 21.2 mm in the chest to  
430 nipple direction, our results show a maximum underestima-  
431 tion of 13 mm for a Hologic Lorad Selenia mammography  
432 machine, and a maximum overestimation of 8 mm for a  
433 Hologic Selenia Dimensions mammography machine. If one  
434 takes into consideration this under-/overestimation of thick-  
435 ness only (and not the fact that a change in the thickness  
436 might also have implications for the choice of target/filter-  
437 combination and kV), the MGD can be estimated. For a  
438 Hologic Lorad Selenia, for instance, an underestimation of  
439 13 mm would imply a smaller estimated MGD of 17% for a  
440 thin breast (readout thickness 35 mm) and 9% for a thick  
441 breast (readout thickness 80 mm). An underestimation of  
442 thickness will in general imply that the MGD originally esti-  
443 mated is too large, and thus overestimate the MGD and the  
444 risk. For a Hologic Lorad Dimensions an overestimation of 8  
445 mm would imply a larger estimated MGD of 20% for a thin  
446 breast (readout thickness 31 mm) and 6% for a thick breast  
447 (readout thickness 79 mm). An overestimation of thickness  
448 will in general imply that the MGD originally estimated is  
449 too small, and thus underestimate the MGD and the risk.

#### 450 IV.C. Correction factor

451 Varying paddle/machine combinations give different  
452 error levels between readout thickness and measured thick-  
453 ness. 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 pad-  
dle sizes (in this study:  $18 \times 24$  and  $24 \times 30$ ) 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 pro-  
pose 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 con-  
sidered, 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 measure-  
ments were repeated. When compressing the phantom, dif-  
ferent 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 mid-  
dle of the compression paddle (along midline), but the com-  
pressed thickness still altered.

Tyson *et al.*<sup>9</sup> devised a method for determining the com-  
pressed 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.*<sup>9</sup> Tyson *et al.*<sup>9</sup> 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 com-  
pressed breast thickness in this study, it will probably be nec-  
essary 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 prob-  
ably be difficult to accomplish, since it has been shown to be  
difficult to obtain the same thickness applying the same com-  
pression 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



507 between manufacturers. Individual correction factors for  
 508 breast thickness may need to be established for each depend-  
 509 ent on paddle selection and compression force applied. Any  
 510 corrections to compressed breast thickness need therefore to  
 511 be performed for the unit in question, and one cannot assume  
 512 that the correction in compressed breast thickness applies to  
 513 all mammography machines of the same model.

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