Published in final edited form as:

AJR Am J Roentgenol. 2017 November ; 209(5): W322–W332. doi:10.2214/AJR.16.17615.

Can Breast Compression Be Reduced in Digital Mammography and Breast Tomosynthesis?

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Abstract

OBJECTIVE—The objective of this study was to investigate the impact of decreasing breast compression during digital mammography and breast tomosynthesis (DBT) on perceived pain and image quality.

MATERIALS AND METHODS—In this two-part study, two groups of women with prior mammograms were recruited. In part 1, subjects were positioned for craniocaudal (CC) and mediolateral oblique (MLO) views, and four levels of compression force were applied to evaluate changes in breast thickness, perceived pain, and relative tissue coverage. No imaging was performed. In part 2, two MLO DBT images of one breast of each patient were acquired at standard and reduced compression. Blurring artifacts and tissue coverage were judged by three breast imaging radiologists, and compression force, breast thickness, relative tissue coverage, and perceived pain were recorded.

RESULTS—Only the first reduction in force was feasible because further reduction resulted in inadequate breast immobilization. Mean force reductions of 48% and 47% for the CC and MLO views, respectively, resulted in a significantly reduced perceived pain level, whereas the thickness of the compressed breast increased by 0.02 cm (CC view) and 0.09 (MLO view, part 1 of the study) and 0.38 cm (MLO view, part 2 of the study), respectively, with no change in tissue coverage or increase in motion blurring.

CONCLUSION—Mammography and DBT acquisitions may be possible using half of the compression force used currently, with a significant and substantial reduction in perceived pain with no clinically significant change in breast thickness and tissue coverage.

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I. Sechopoulos has a research agreement and a speaking agreement with Siemens Healthcare, has a research agreement with Toshiba Medical Systems, and is on the scientific advisory board of Fischer Medical.

Based on a presentation at the American Association of Physicists in Medicine 2015 annual meeting, Anaheim, CA.

WEB

This is a web exclusive article.

AJR 2017; 209:W322–W332

0361–803X/17/2095–W322

Keywords

breast compression; digital breast tomosynthesis; mammography; pain

Between 2005 and 2010, only 67% of eligible women in the United States underwent screening mammography [1]. Some women refuse mammograms due to the pain associated with breast compression [2]. Previous studies have shown that pain is a significant cause for low compliance with screening mammography guidelines [3–8].

Digital breast tomosynthesis (DBT) is replacing standard 2D mammography for cancer screening in many institutions in the United States and is being studied in Europe for use in the national screening programs of various countries. Studies of DBT and its potential to perform breast imaging with reduced breast compression have shown promising results without implementation of special acquisition techniques or image processing [9–12]. Because DBT reduces the phenomenon of tissue superposition, DBT could be performed with reduced breast compression if the changes in dose and image quality are not clinically significant. Saunders et al. [9] performed a Monte Carlo–based simulation study and showed that for constant glandular dose, the conspicuity of masses and microcalcifications remained approximately constant with decreased compression for DBT images. Using the promising results from simulations, Förnvik et al. [10] showed that with tube voltage and anode and filter combinations determined by the automatic exposure control (AEC) of a mammography system, there was no significant difference in image quality of DBT images with mammography-level compression and 50% of that compression. However, this study was performed on a prototype DBT system. Second, the study did not explain why a 50% reduction in compression was selected or if further reduction in compression was possible and did not study the impact of the reduced compression force on the patients' pain level. Third, the observers in the study were not asked to specifically look at tissue coverage while analyzing the images for diagnostic quality. Finally, the study did not distinguish between findings in the craniocaudal (CC) and mediolateral oblique (MLO) views, although we know that the compression force required for the two views is significantly different [13]. Breast cancer screening using DBT without the vigorous compression used in standard 2D mammography would be welcome by women, especially because time under compression is greater with DBT. This reduction in compression, if it results in a reduction in pain, could increase screening compliance. To address these concerns, we planned a two-part study to objectively determine the limit of compression reduction in mammography and DBT in both CC and MLO views and their impact on perceived pain.

In this study, we investigated the level of pain caused by breast compression during mammography or DBT and the impact of decreased compression on perceived pain, breast thickness, tissue coverage, and image quality.

Materials and Methods

In this two-part institutional review board–approved, HIPAA-compliant study, we observed the relationship between compression force, breast thickness, tissue coverage, image quality, and patient-perceived discomfort or pain during mammography using a DBT system

(Selenia Dimensions, Hologic). In part 1 of the study, the goal was to characterize the change in breast thickness, pain, and tissue coverage at multiple stages of breast compression in both the CC and MLO positions. No images were acquired in part 1.

Because part 1 showed promise and we identified a single feasible reduced compression level, we conducted a second patient study to understand the effect of reduced compression at that level on the possibility of motion blurring. Part 2 of the study involved acquiring DBT MLO view images because of the greater potential for tissue motion in this view. Thus, the relationship between breast thickness, pain, tissue coverage, and presence of motion blurring at two compression levels was studied. The flowcharts of the methods used in part 1 and part 2 are shown in Fig. 1.

Participant Recruitment

Part 1—Women presenting at the breast imaging center of Emory University were recruited if they met the eligibility criteria and provided written informed consent to participate. Flyers were also posted around the center, and volunteers who responded and met the eligibility criteria were included. Part 1 did not involve image acquisition. The only inclusion criterion was to ensure that women had had a prior mammogram so that this experience was not their first with breast compression. Women were ineligible for the study if they had any of the following conditions: confirmed pregnancy, bilateral mastectomy, or breast implants.

Part 2—Women presenting at the breast imaging center of Emory University before or after undergoing diagnostic workup for microcalcifications were recruited if they met the eligibility criteria and provided written informed consent. The inclusion criteria for part 2 were women over 40 years old with prior mammogram experience and presence of microcalcifications. Microcalcification cases were selected for their sensitivity to motion blurring. The same exclusion criteria as part 1 were used.

Measurements

Part 1—The participant's breast was compressed in both the CC and the MLO positions. As a surrogate for tissue coverage, which can only be determined directly by acquisition of a mammographic image, necessitating the use of ionizing radiation at each compression point, the extent of breast skin included in the FOV against the compression paddle was used. Thus, the research technologist placed a custom medical-grade adhesive paperlike ruler on the participant's breast, extending from the nipple to the chest wall skin superiorly in the CC position and from the nipple laterally to the axillary skin in the MLO position (Fig. 2). These ruler positions were selected so that the ruler would be at approximately 90° to the chest wall for CC and to the anterior to mid axillary line for MLO, and therefore at approximately 90° to the edge of the FOV in both cases. The ruler had markings every 2 mm. It was assumed that if the skin and adherent ruler did not move posteriorly during reduction in compression, tissue coverage would not vary.

At each compression level, the research technologist deemed if, on the basis of her experience and opinion, the breast was held stationary enough that the compression level

would be feasible for clinical imaging. These compressions were denoted “adequate compressions” and were used as guidance to decide a priori on the feasible levels of compression that justified further investigation. During the measurement process, the breast was first compressed to a level deemed usual and appropriate for mammographic acquisition by the research technologist. This level is the standard compression routinely used at our institution for mammography. In one case, the compression was stopped when the participant verbally expressed severe pain, as done in general clinical practice. Standard compression force for this patient was measured at the force the patient asked compression to be stopped. Once the standard compression level was reached, the compression force was gradually decreased manually (a quarter counterclockwise turn of the manual control knob) until the breast was no longer stationary or until we measured three levels of compression reduction. At each level of compression, the following measurements were recorded: force, breast thickness, perceived pain as stated by the participant during compression (participants used a 0–11 scale, which was later mapped to an ordinal scale of 0–10, with 0 representing no pain and 10 representing excruciating pain), and change of the first marker on the ruler at the chest wall visible under the compression paddle as determined by the research technologist. We used video recording to document compression thickness and force as displayed by the imaging system, in addition to the research technologist’s and participant’s voices regarding the location of ruler line markers and perceived pain rating, respectively. The display system of the DBT system from which the breast thickness and force were recorded was checked for accuracy during the routine clinical quality control assessments the DBT system underwent.

After measurements were complete and the breast was released, the participant was asked to rate the pain due to standard compression during part 1 compared with her previous clinical mammogram (much less, somewhat less, same, somewhat more, much more). Finally, the participant’s bra cup size, age, race, and BI-RADS breast density score (a–d) from their previous mammogram or mammograms (if done in the same facility) were also recorded.

Part 2—For part 2, the participant’s breast was compressed in the MLO view only. During the measurement process, the breast was first compressed to a standard compression level as previously defined. In one case, the compression was stopped when the participant verbally expressed severe pain. Further measurements were obtained as previously described. Once the standard compression level was achieved, a DBT scan was acquired. Before the second acquisition, the technologist was asked to reduce compression force by manually turning the compression paddle knob to reduce force by approximately 50% (intended reduction and measured reduction will be discussed in the Results section), as determined from part 1. At both levels of compression the following measurements were recorded: force, breast thickness, perceived pain during compression (as described for part 1), and change of the first marker on the tape ruler at the chest wall visible under the compression paddle. An MLO DBT image was also acquired at each of these two compression levels. The adhesive tape ruler was used in part 2 of this study on the first 29 patients to validate its use as a surrogate for tissue coverage change by comparing its results to the observers’ assessment of tissue coverage in the DBT images at the retrospective observer study. The ruler was not

used on all patients to allow observers to study images with and without adhesive tape and to eliminate possible errors due to artifacts introduced by the tape.

As in part 1, we used video recording to record the research technologist's and participant's voices regarding the location of ruler line markers and perceived pain rating, respectively.

We performed an observer study with three radiologists with a wide range (6 months to 35 years) of experience in reading mammographic images. The radiologists were shown all the reconstructed DBT images at the two compression levels in a randomized and blinded fashion. They were asked to rate the images for two conditions: presence of microcalcification blurring and adequate tissue coverage, using the ratings "no," "yes with adequate diagnostic quality," or "yes with poor diagnostic quality." While still blinded, they were then shown images of both compression levels adjacent to each other and were asked to rate the tissue coverage as equal or as one of the images having more or less tissue visualized than the other. The DBT projection images were also similarly evaluated to eliminate the possibility of blur introduced by the reconstruction algorithm.

Mean glandular dose (MGD) and tube voltage at the different compression levels were recorded from the DBT DICOM headers in an effort to determine the effect of compression on dose and contrast.

Analysis

Part 1—The CC- and MLO-positioned data (without imaging) were analyzed independently. The means of measured values at each discrete step of compression—standard compression and three discrete reduced compressions maintaining a stationary breast (RC1, RC2, and RC3)—were compared. Two-sample paired two-tailed *t* tests were used to calculate the *p* values (at 95% confidence level) and hence the statistical significance of the difference between each discrete compression step. For the ordinal scale of pain, the Wilcoxon signed rank test was used to calculate the *p* value.

Part 2—Similar to part 1, the means of the measured values at the two compression levels (standard and reduced compression) were compared. Two-sample paired two-tailed *t* tests were used to calculate the *p* values. For the ordinal scale of pain, the Wilcoxon signed rank test was used to calculate the *p* value. For the observer study, the McNemar test was used to compare the blurring of microcalcifications as well as tissue coverage at the two compression levels. The exact method of sign test was used to test the statistical significance of the observers' comparisons of tissue coverage between standard and reduced compression. Two-sample paired two-tailed *t* tests were also used to calculate *p* values to compare MGD and tube voltage between standard and reduced compression. All *p* values were calculated at a 95% confidence level.

Results

Part 1

Seventy-two women between 41 and 78 years (mean age $\pm$ SD, 58.2 $\pm$ 9.84 years) participated in part 1. Table 1 shows the distribution of participants; of the 72 eligible

participants, we acquired CC and MLO compression information from 62 participants each, including 52 participants for whom we obtained information for both positions. Of the 62 CC breast compressions, 58 were used for the analysis, and of the 62 MLO breast compressions, 53 were used for the analysis. Data from four CC views and nine MLO views were excluded due to video and other technical difficulties. The distributions of breast density (BI-RADS a–d), race, and bra cup size are shown in Fig. 3. Two participants did not report their race.

None of the 58 CC-view participants requested that compression be stopped before standard compression; one MLO-view participant requested that compression be stopped before the technologist reached standard compression. The sample means and SDs of pain (range, 0–10), compression force (in dekanewtons), and breast thickness (in centimeters) are presented in Table 2 for both views. The last column in Table 2 shows if the compression force was adequate to hold the breast stationary for imaging to be possible.

For the CC view, 93.1% (54/58) of participants felt some pain at standard compression; this value decreased to 79.3% (46/58) after RC1. The compression force was high enough to hold the breast in place so as to be deemed adequate for imaging for all cases. However, after RC2, despite the decrease in the number of participants with some pain to 46.6% (27/58), the number of participants who had adequate compression to facilitate imaging decreased to 91.4% (53/58). By RC3, only 15.5% (9/58) of participants had adequate compression to make imaging feasible.

In the MLO view, no participants were pain-free (0/53) at standard compression or RC1. In 98.1% (52/53) of cases, there was adequate compression after RC1. The percentage of cases decreased to 88.7% (47/53) after RC2. Only 15.1% (8/53) of the cases had adequate compression after RC3. Overall, compression for the MLO view was more painful than that for CC view ($p \ll 0.05$). Patients experienced a statistically significant decrease in pain from standard compression to RC1 for both views. In the CC view, the first reduction in compression force resulted in no statistically significant change in breast thickness or change in tissue coverage. In the MLO view, we found a corresponding statistically significant increase in breast thickness. However, this difference was, on average, less than 1 mm, so it is probably not clinically significant. In four of the 53 cases the tissue coverage decreased by 2 mm each at RC1.

The distributions of force, breast thickness, and perceived pain at standard compression and RC1 are shown in Figures 4 and 5 for CC and MLO views, respectively.

The t tests for standard compression to RC2 resulted in $p \ll 0.05$ for pain, compression force, and thickness for both views. The mean statistically significant increases in breast thickness at RC2 were 0.07 cm for the CC view and 0.25 cm for the MLO view and were probably not clinically significant. However, the loss of adequate compression in approximately 10% of cases makes this level of reduction clinically unfeasible. Fewer than 10 participants (part 1) had adequate tissue coverage for clinical use by step RC3 for both CC and MLO positioning, so this level of reduced compression is also unsuitable for clinical use.

We found no statistical significance between the compression results and participant characteristics (race, cup size, and breast density).

Figure 6 shows the frequency distribution of the comparison between the pain at standard compression during this study and patients' previous experiences with mammography. From the frequency distribution, we see that in most cases the current study caused equal or less pain compared with their previous experience.

Part 2

Fifty-one women between 41 and 78 years (mean age, 56.4 ± 9.6 years) participated in part 2. Pain data from two of the 51 patients were excluded because of video recording difficulties. One patient's data were excluded from all measurements because of technical difficulties. All 51 patient images were used in the observer study. One of the 51 participants requested that the compression be stopped before standard compression. The sample means and SDs of pain (range, 0–10), compression force, breast thickness, MGD, and tube voltages are presented in Table 3.

In part 2 with MLO views, 49 of the 51 participants recorded their pain levels. One of the 49 participants was pain-free at standard compression, and seven were pain-free at reduced compression. We found a statistically significant decrease in pain from standard compression to reduced compression, similar to the reduction in pain observed in part 1. There was a statistically significant increase in breast thickness, which was larger than the difference in part 1. The distributions of force, breast thickness, and perceived pain at standard compression and reduced compression are shown in Fig. 7. Table 4 shows the results of the observer studies, for both blurring and tissue coverage, for projections and reconstructed tomosynthesis MLO images. According to the McNemar tests, none of the comparisons achieved statistical significance, with $p > 0.5$ for all comparisons, except for the third observer's rating of microcalcification blurring on the reconstructed images, which was still not significant with a p value of 0.0654. We found no statistically significant difference in microcalcification blurring or tissue coverage on the projection and reconstructed MLO images between standard compression and reduced compression, when the compression force was reduced by 47%. However, as seen in Table 4, the radiologists found the MLO projections to be more often blurrier than the DBT reconstructed images. This difference in observed blurring may be due to one of two reasons. The first is that radiologists do not typically read tomosynthesis projections in the clinic and therefore are not sure what to expect in terms of sharpness of high-contrast objects such as microcalcifications in the projections. The second is an effect called "super resolution" that is observed in tomosynthesis images as a consequence of the image of the object being shifted by subpixel increments of the detector element, which leads to improved visibility of microcalcifications in the reconstructed images [14]. We also know that an effect of blurring due to focal spot motion occurs in tomosynthesis projections that is not seen in full-field digital mammography [15]. However, although this finding is interesting, for this study we were concerned with the comparison in blurring due to motion of breast tissue between standard and reduced compression images during DBT, be they projections or reconstructions, not in comparing the observed blurring between projections and reconstructed images.

Figure 8 shows the distribution of estimated MGD in milligrays and tube voltage in peak kilovoltage (image contrast) at standard and reduced compression. We found a statistically significant difference in both these quantities ($p < 0.05$); however, the mean increases were 0.14 mGy and 0.8 kVp, respectively, which is clinically insignificant. Further, the data were analyzed for women with breast thickness greater than 7 cm because we expected the most apparent and significant effects to the breast from increased dose in women with thicker breasts. Twelve of 50 (24%) women had breast thickness greater than 7 cm at standard compression, and the mean increase in breast thickness between standard and reduced compression for this group was 0.35 cm. This is almost equivalent but lower than the 0.38 cm mean change in breast thickness between standard and reduced compression for all subjects in part 2 of this study. For this subset of thicker breasts, the mean increase in dose was 0.17 mGy, which is within one SD of the sample population's increase in dose. Hence, we found no significant change in dose corresponding to reduced compression force even in the portion of subjects already receiving the highest dose: women with thicker breasts.

Finally, Figures 9 and 10 show a sample set of images from a single subject acquired in part 2 of this study.

Discussion

The results of this two-part study may be significant for breast cancer screening. We found that a substantial reduction in breast compression during DBT imaging is feasible, resulting in a significant reduction in pain during breast cancer screening with apparently no or negligible negative effects. This reduction in pain caused by reduced compression during DBT, and perhaps mammography, will decrease discomfort to patients during breast cancer screening, which may lead to better adherence and hence increased survival rates. Perceived pain and discomfort can be reduced substantially with no loss in tissue coverage or increase in motion blurring by decreasing the compression force by 45–50% of the standard. Further reduction produced inadequate support to restrict tissue motion. In the Malmö Breast Tomosynthesis Screening Trial, Lång et al. [11] acquired the tomosynthesis images at a reduced compression force of approximately 50% compared with the force used for standard mammography; the assumption was made that the inherent ability of tomosynthesis to reduce the impact of tissue superposition allowed this reduction. Our initial hypothesis concerning force reduction was with regard to tomosynthesis, although the results indicate that a similar reduction may also apply to 2D mammography. Förnvik et al. [10], in a mostly MLO view–based DBT prototype system study, compared image quality under conditions of constant tube voltage and combinations of anodes and filters (as determined by mammography) with 50% reduced compression and showed that there was no significant difference. In our study, we used a clinical DBT system (Selenia Dimensions) and allowed the AEC to change the tube voltage with change in compression force and found no significant change in blurring with microcalcifications in MLO images. We also studied the impact of reduced compression on perceived pain and tissue coverage.

Because part 1 showed promise and we identified a single feasible reduced compression level, we conducted a second patient study to understand the effect of reduced compression at that level on the possibility of motion blurring. In addition, the use of the paper ruler as a

surrogate for tissue coverage needed to be validated. Based on the results of part 2 in which both the paper ruler was present and the tissue coverage was directly evaluated by the three observers, the use of an external marker, the ruler, as a surrogate for tissue coverage, appears to have been successful.

In part 1, the participants observed that the pain felt during this study was, on average, lower than the pain felt during previous mammography. The recruited subjects included women presenting for screening, those presenting for diagnostic workup, and volunteers, with the requirement that they had undergone mammography previously. Therefore, the recollections and perceptions of their comparison of their pain to their previous experience may be biased due to the elapsed time between prior mammography and the current study, which could have varied from a few days to up to a year. However, the research technologist does not appear to have overcompressed compared with the clinical acquisitions. The research technologist who participated in the study has at least 25 years of experience acquiring mammograms, and she was involved in a prior research study, acquiring 180 two-view DBT images. None of those images were repeated or rejected for inadequate positioning.

A limitation of this study is that a single technologist performed all compressions at a single site with a single imaging system, although this configuration reduces the variability in image acquisition technique. Our findings can be used when training technologists to show that a significantly lesser amount of compression force may be sufficient for adequate tissue coverage and image quality. Finally, compression was reduced only after achieving standard compression, which is not a feasible method to achieve pain reduction. However, in preliminary efforts, these findings can be used for clinical acquisition by initially compressing the breast to standard compression and then reducing it to 50% of the standard compression force. This method will decrease the time the breast is under standard compression, especially during tomosynthesis acquisition, and reduce patient pain. Because we found no significant increase in blurring between the compression levels, influence on other image artifacts and variations in detection of different types of lesions are not expected. Förnvik et al. [10] showed that, with a 50% reduction in compression force, the image quality did not significantly change when DBT images were acquired on a prototype DBT system with constant tube voltage and a combination of anode and filter for both compression levels. From the results of their study and ours with a clinical DBT system and AEC, we expect that similar results can be achieved for lesions. Further investigation targeting women with different types of lesions (masses and painful masses) is required. A prospective study using the reduced compression scenario described here compared with standard compression would help to evaluate the generalizability of this technique and verify the statistically significant yet clinically insignificant increase in dose for both techniques.

Acknowledgments

We thank Petronella G. M. Peer (Radboud University Medical Center, Nijmegen, The Netherlands) for her advice on statistical tests, which significantly improved the manuscript.

Supported in part by grant R01CA163746 from the National Cancer Institute, National Institutes of Health and by grant IIR13262248 from the Susan G. Komen Foundation for the Cure. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Cancer Institute, the National Institutes of Health, or the Susan G. Komen Foundation for the Cure.

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Fig. 1. Flowcharts of methods. DBT = digital breast tomosynthesis, CC = craniocaudal, MLO = mediolateral oblique.

A, Part 1 of study.

B, Part 2 of study.

Fig. 2. Schematic representation of adhesive tape (*light gray rectangles*) positions for craniocaudal (CC) (*left*) and mediolateral oblique (MLO) (*right*) views. Also shown are positions of support and compression paddles (*dark gray rectangles*). (Illustration by Agasthya G, used with permission)

Fig. 3.

Patient characteristics for part 1 of study.

A–C, Distributions of breast density (**A**), race (**B**), and cup size (**C**) for craniocaudal (*black bars*) and mediolateral oblique (*gray bars*) views.

Fig. 4.

Box-and-whisker plots of measurements obtained for craniocaudal view in part 1 of study. Center line denotes median; top and bottom of box denote 75th and 25th percentiles, respectively; whiskers denote 95% CI; and plus signs denote outliers.

A–C, Distributions of compression force (**A**), breast thickness (**B**), and pain (**C**) at standard compression and after first reduction in compression ($\approx 50\%$ reduction in compression force).

Fig. 5.

Box-and-whisker plots of measurements obtained for mediolateral oblique view in part 1 of study. Center line denotes median; top and bottom of box denote 75th and 25th percentiles, respectively; whiskers denote 95% CI; and plus signs denote outliers.

A–C, Distributions of compression force (**A**), breast thickness (**B**), and pain (**C**) at standard compression and after first reduction in compression ($\approx 50\%$ reduction in compression force).

Fig. 6.
Distributions of pain in part 1 of study compared with previous experience of compression for craniocaudal (*black*) and mediolateral oblique (*gray*) views.

Fig. 7.

Box-and-whisker plots of measurements obtained for mediolateral oblique view in part 2 of study. Center line denotes median; top and bottom of box denote 75th and 25th percentiles, respectively; whiskers denote 95% CI; and plus signs denote outliers.

A–C, Distributions of compression force (**A**), breast thickness (**B**), and pain (**C**) at standard compression and after approximately 50% reduction in compression force.

Fig. 8.

Box-and-whisker plots of measurements obtained for mediolateral oblique view in part 2 of study. Center line denotes median; top and bottom of box denote 75th and 25th percentiles, respectively; whiskers denote 95% CI; and plus signs denote outliers.

A and **B**, Distributions of tube voltage (**A**) and mean glandular dose (MGD) (**B**) at standard compression and after approximately 50% reduction in compression force.

Fig. 9. Sample slices of reconstructed mediolateral oblique digital breast tomosynthesis images acquired in part 2 of study with calcifications in focus.

A, Standard compression (breast thickness, 58 mm; compression force, 178 N).

B, Reduced compression (breast thickness, 60 mm; compression force, 113 N).

Fig. 10.

Central tomosynthesis projections from set acquired for images in Figure 9, with calcifications in focus in central projection of mediolateral oblique view acquired in part 2 of study.

A and B, Standard compression image (**A**) and magnification (**B**, $\times 4.5$) of area with calcification.

C and D, Reduced compression image (**C**) and magnification (**D**, $\times 4.5$) of area with calcification.

TABLE 1

Distribution of the 72 Recruited Participants at Different Steps of the Analysis for Part 1

View	No. of Participants	Analyzed at SC	No. of Participants With Adequate Compression ^a at Reduced Compression Level		
			RC1	RC2	RC3
Craniocaudal	62	58	58	53	9
Mediolateral oblique	62	53	52	47	8

Note—SC = standard compression; reduction in compression achieved by counterclockwise rotation of manual control knob was as follows: RC1 = one-quarter turn, RC2 = one-half turn, RC3 = three-quarter turn.

^a Adequate compression was the compression force applied by the compression paddle under which the breast was stationary.

TABLE 2

Mean and SD of Measured Parameters for Craniocaudal and Mediolateral Oblique Views for Part 1

View	Pain Level (range, 0–10)	Compression Force (daN)	Breast Thickness (cm)	Breast Compression
Craniocaudal				
SC ^a	4.10 ± 2.70	9.00 ± 2.66	5.89 ± 11.18	Adequate
Mean difference ± SD				
SC to RC1	−1.53 ± 1.63	−4.32 ± 1.94	0.02 ± 0.25 ^b	Adequate
SC to RC2	−2.96 ± 2.23	−7.22 ± 2.24	0.07 ± 1.50	Inadequate
SC to RC3	−3.22 ± 2.10	−9.80 ± 2.87	0.78 ± 0.54	Inadequate
Mediolateral oblique				
SC ^a	6.12 ± 2.73	13.79 ± 4.02	6.16 ± 1.39	Adequate
Mean difference ± SD				
SC to RC1	−1.75 ± 1.08	−6.55 ± 2.80	0.09 ± 0.23	Adequate
SC to RC2	−4.03 ± 2.09	−10.13 ± 3.29	0.25 ± 0.37	Inadequate
SC to RC3	−7.37 ± 2.44	−12.54 ± 1.79	0.65 ± 2.44	Inadequate

Note—For the ordinal scale of pain, the Wilcoxon signed rank test was used to calculate *p* values; otherwise, two-sample paired two-tailed *t* tests were used. Except where otherwise indicated, *p* < 0.05. For mean differences, negative numbers represent a decrease from the absolute value; positive numbers represent an increase. SC = standard compression; reduction in compression achieved by counterclockwise rotation of manual control knob was as follows: RC1 = one-quarter turn, RC2 = one-half turn, RC3 = three-quarter turn.

^a Absolute values.

^b *p* > 0.05.

TABLE 3

Mean and SD of Measured Parameters for Mediolateral Oblique View in Part 2

Compression Step	Pain Level (range, 0–10)	Compression Force (daN)	Breast Thickness (cm)	MGD (mGy)	Tube Voltage (kVp)
SC ^a	6.14 ± 2.44	13.92 ± 3.52	5.90 ± 1.48	2.14 ± 0.69	32.7 ± 2.97
SC to RC ^b	-2.92 ± 1.62	-6.56 ± 1.26	0.38 ± 0.09	0.14 ± 0.09	0.8 ± 0.57

Note—MGD = mean glandular dose, SC = standard compression, RC = reduction in compression of approximately 50%.

^a Absolute values at standard compression.

^b $p \ll 0.05$, t test. Negative numbers represent a decrease from the absolute value; positive numbers represent an increase.

TABLE 4

Results of Observer Tests for Blurring of Microcalcification and Tissue Coverage in Part 2

Image Set	Blurring			Tissue Coverage	
	None	With Adequate Diagnostic Quality	With Poor Diagnostic Quality	Adequate	Inadequate
MLO projections					
Radiologist 1					
SC	13	26	12	49	2
RC	12	23	16	48	3
Radiologist 2					
SC	13	20	18	31	20
RC	14	18	19	32	19
Radiologist 3					
SC	0	11	40	49	2
RC	0	11	40	50	1
MLO DBT images					
Radiologist 1					
SC	22	21	8	47	4
RC	18	26	7	49	2
Radiologist 2					
SC	20	20	11	32	19
RC	22	19	10	32	19
Radiologist 3					
SC	14	24	13	48	3
RC	8	23	20	47	4

Note—MLO = mediolateral oblique, SC = standard compression, RC = reduction in compression of approximately 50%, DBT = digital mammography and breast tomosynthesis.