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Mammographic compression – A need for mechanical standardization

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Background: A lack of consistent guidelines regarding mammographic compression has led to wide variation in its technical execution. Breast compression is accomplished by means of a compression paddle, resulting in a certain contact area between the paddle and the breast. This procedure is associated with varying levels of discomfort or pain. On current mammography systems, the only mechanical parameter available in estimating the degree of compression is the physical entity of force (daN). Recently, researchers have suggested that pressure (kPa), resulting from a specific force divided by contact area on a breast, might be a more appropriate parameter for standardization. Software has now become available which enables device-independent cross-comparisons of key mammographic metrics, such as applied compression pressure (force divided by contact area), breast density and radiation dose, between patient populations.

Purpose: To compare the current compression practice in mammography between different imaging sites in the Netherlands and the United States from a mechanical point of view, and to investigate whether the compression protocols in these countries can be improved by standardization of pressure (kPa) as an objective mechanical parameter.

Materials and methods: We retrospectively studied the available parameters of a set of 37,518 mammographic compressions (9188 women) from the Dutch national breast cancer screening programme (NL data set) and of another set of 7171 compressions (1851 women) from a breast imaging centre in Pittsburgh, PA (US data set). Both sets were processed using VolparaAnalytics and VolparaDensity to obtain the applied average force, pressure, breast thickness, breast volume, breast density and average glandular dose (AGD) as a function of the size of the contact area between the breast and the paddle.

Results: On average, the forces and pressures applied in the NL data set were significantly higher than in the US data set. The relative standard deviation was larger in the US data set than in the NL data set. Breasts were compressed with a force in the high range of >15 daN for 31.1% and >20 kPa for 12.3% of the NL data set versus, respectively, 1.5% and 1.7% of the US data set. In the low range we encountered compressions with a pressure of <5 daN for 21.1% and <5 kPa for 21.7% of the US data set versus, respectively, 0.05% and 0.6% in the NL data set. Both the average and the standard deviation of the AGD were higher in the US data set.

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Conclusion: (1) Current mammographic breast compression policies lead to a wide range of applied forces and pressures, with large variations both within and between clinical sites. (2) Pressure standardization could decrease variation, improve reproducibility, and reduce the risk of unnecessary pain, unnecessary high radiation doses and inadequate image quality.

1. Introduction

Detection of pathological conditions in mammography depends on the quality of the obtained images. The natural shape of the breast, with thickness varying from the nipple to the chest wall, is an impediment to achieving good homogeneous signal difference-to-noise ratio (SDNR) over the entire breast image. In mammography, the breast is therefore pressed against the breast support on top of the detector using a transparent plastic compression paddle, such that the breast is deformed into a thinner shape with more uniform thickness. This deformation of the breast is referred to as breast compression. When the paddle is pressed against the breast, a contact area develops according to the size and elasticity of the breast. Breast compression results in multiple benefits, including: (1) reduced radiation dose delivered to the breast; (2) better image contrast due to a reduction of scattered radiation; (3) reduced geometric blurring; (4) better fit of the exposure into the dynamic range of the image receptor; (5) reduced overlapping of tissues; and (6) reduced risk of motion blurring [1]. A disadvantage of breast compression is the associated discomfort or pain in a considerable proportion of women [2–4], especially after breast conserving therapy [5]. The often-conflicting goals of minimizing breast thickness versus reducing discomfort for the woman are balanced by the radiographer (also called mammography technologist or breast imager), who decides how much force is to be applied by the paddle.

Quality standards are unclear as to the appropriate amount of compression force to be applied, and only subjective guidelines are mentioned [6–8]. In practice, the distribution of forces applied by the radiographers is often subject to large variation [9,10]. This variation may partly reflect that the radiographers, by observing the contact area, adjust the compression force to the natural variation in breast size and elasticity. Mercer et al. [10] found a trend of applying higher forces to larger breast volumes in their data, but even between women with similar breast volumes the variation was large. Recent studies also found the applied compression force to be more dependent on the individual radiographer than on the woman subjected to compression [10,11].

Variation in applied compression that is caused by differences in the methods employed by radiographers is not desirable, because it suggests unwanted variation in standard of care, and undermines the consistency and reproducibility of the imaging procedure. This leads to unpredictable differences in image SDNR, radiation dose, and patient experience, between and within women. Radiographer-induced variations in the pain experienced by patients should also be minimized, because even a single bad experience can adversely influence a woman's acceptation of mammography, and may lead to decreased compliance in breast screening programmes [3,12].

A major impediment for standardization and quality control of compression is the lack of specific, objective compression indicators that can help the radiographers to decrease the variability and to improve the predictability and standardization of the compression procedure. In current mammography systems, the only mechanical compression parameters that are objectively measured and displayed real-time are compression force and breast thickness (with only the value measured during X-ray exposure being stored in the DICOM header). Standardization based on these two parameters is complicated because the variation to be reduced is also determined by individual differences in breast size and elasticity. Recently, it has been suggested that pressure (force divided by contact area) might be a better parameter to standardize compression [13,14] (in this issue).

Software has recently become available (VolparaAnalytics), which is able to retrospectively estimate the contact area (A) between the breast and the compression paddle. As the compression force (F) is reported in the DICOM header, this opens up the possibility to estimate the average pressure (P) on the breast by calculating $P = F/A$. In practice, given a certain applied force, the size of the contact area is determined by the size and the elasticity of the breast. Consequently, as a result of the division of force by contact area, pressure is a measure for compression that is independent of breast size and elasticity. Using the contact area measurements, it should be possible to determine whether and how consistently the compression is adjusted to breast size and elasticity.

The purpose of this study is to compare the current compression practice in mammography between an imaging site in the United States (US) and two imaging sites in the Netherlands from a mechanical point of view, and to investigate whether the compression protocols in these countries can be improved by standardization of pressure as proposed in [13,14] (in this issue). Objective mechanical standardization may be an important step towards an individualized, less painful and more reproducible compression procedure in mammography and potentially, in the future, breast tomosynthesis.

2. Methods

In this study we used anonymized quantitative data which, because they cannot be traced back to the actual person, may be used freely for secondary analyses in both the Netherlands and the United States.

2.1. Subjects

We retrospectively reviewed the available parameters of a set of 37,969 mammographic compressions (9188 women) obtained from the Dutch national breast cancer screening programme [15] (the NL data set) and of another set of 7416 compressions (1851 women) from a breast imaging centre in Pittsburgh, PA (the US data set). The NL data set, acquired between May 2012 and September 2013, was obtained from women aged 50–75 years that were all asymptomatic. The US data set, obtained between January 2014 and March 2014, contains both screening and diagnostic mammograms of women in the same age range. Both sets included only cranio-caudal (CC) and medio-lateral oblique (MLO) projections. At both sites, all mammograms of women aged 50–75 years recorded during the stated time periods were included.

The images in the NL data set were acquired at two sites (63.7% and 36.3%) using digital mammography systems of the same type (Hologic Selenia). The images in the US data set were acquired by 5 digital systems of two different types: Hologic Selenia Dimensions (62.7%) and GE Senographe Essential (37.3%). Because the data sets were large and acquired by a large number of radiographers (at least 14 in the Netherlands and 10 in Pittsburgh) we assume that each

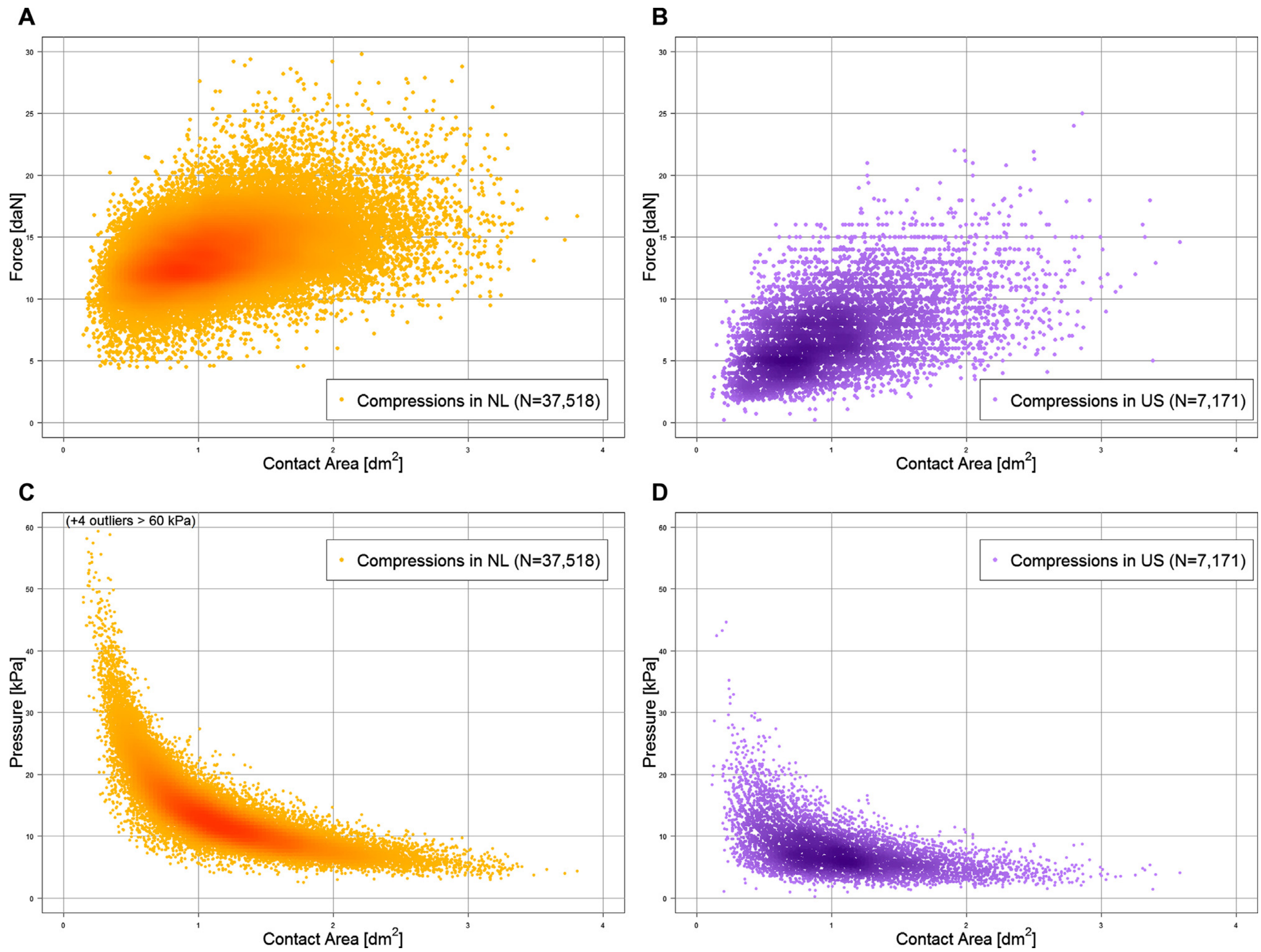

Fig. 1. Scatter plots of applied forces (top) and pressures (bottom) versus contact area in the NL (left) and the US (right) data sets. Each point corresponds to one compression, either CC or MLO. Darker colours denote higher local point density. Large variations in pressure can be observed, even larger than in force, both within and between the NL and the US data sets.

data set represents the normal routine in the corresponding region. Regarding the main purpose of this study, a relevant difference between the two data sets exists in the compression instructions provided to the radiographers. In the Dutch screening programme, the quality assurance protocol instructs radiographers to compress with a force of at least 12 daN, unless the client expresses intolerable pain. In Pittsburgh, the radiographers were instructed to compress until the breast is taut or to a degree that is just less than painful, whichever comes first, without providing a specific target force.

2.2. Data processing

All mammographic images were processed using VolparaAnalytics ([16,17], version 1.0) and VolparaDensity ([18,19], algorithm version 1.5.0) (Volpara Solutions Limited, Wellington, New Zealand) to obtain objective, device-independent estimates of breast volume, breast density, average glandular dose (AGD) and size of the contact area between the breast and the paddle. Furthermore, the applied compression force and breast thickness during exposure were extracted from the DICOM headers. No extra measurements or calibrations were performed for this study. The mean pressure in the breast (in kPa) was then estimated by dividing the applied compression force (in daN) by the size of the contact area (in dm^2).

1.2% of the images in the NL data set and 3.3% of the images in the US data set could not be processed and were excluded due to errors related to breast implants or various technical issues. The resulting NL data set contained 37,518 images (49.5% CC, 50.5% MLO) and the US data set 7171 images (49.6% CC, 50.4% MLO).

2.3. Data visualization

We visualized the compression behaviour of the radiographers by generating scatter plots and by comparing line graphs of average applied force, applied pressure, breast thickness and AGD for each of the two data sets. Because of the large number of overlapping data points, the colour of the points in the scatter plots was varied as a function of the local point density, using a linear colour scale. All parameters were plotted against contact area on the *x*-axis, to visualize how the radiographers adjust the compression to breast size and stiffness. We also plotted breast volume against contact area and density against contact area, to investigate whether the comparison of the compression behaviours by contact area could be influenced by structural differences between the populations.

The line graphs were constructed as follows. In each of the two data sets, all data points were ordered by contact area and then grouped into 20 bins. The bin widths were chosen such that each bin contained the same number of data points. Subsequently, we calculated the average and standard deviation within each bin and plotted them as line graphs (mean ± standard deviation), one for

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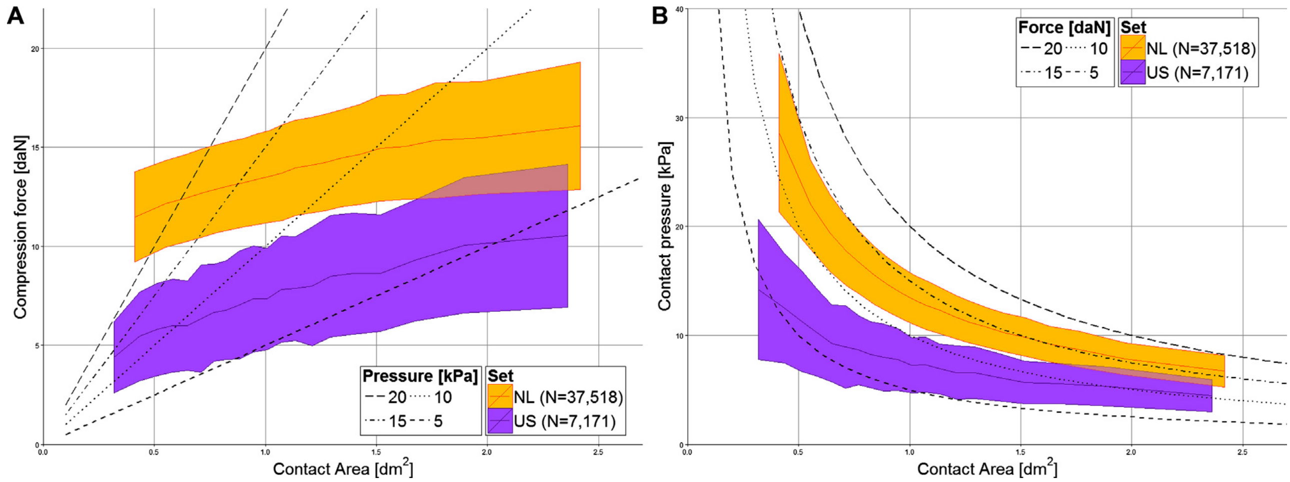

Fig. 2. Compression force (A) and pressure (B): comparison of mean ± one standard deviation between NL and US data sets, in relation to contact area. The plots show similar trends but exercised at significantly different levels.

each data set, with data points aligned to the average contact area of each bin.

2.4. Statistical analysis

Statistics were calculated using R (version 3.1, R Foundation for Statistical Computing, Vienna, Austria). Mann–Whitney *U*-tests were used to study the overall differences in applied force, applied pressure, mean breast volume, breast density, breast thickness and AGD between the NL and US data sets. Regression analysis was performed to examine the association between these differences and the size of the contact area. Furthermore, the Breusch–Pagan test was used to test whether the variance was significantly dependent on the contact area. For this test, local regression ($\alpha = .75$) was employed to fit a regression polynomial to the data without requiring assumptions on the behaviour of the radiographers. A p-value < .05 was considered to indicate a significant difference.

3. Results

In Fig. 1, the distributions of applied forces and pressures are displayed for the NL and US data sets separately. As a result of the currently used protocols, the force distributions in both data sets are characterized by large variation, and the variation in the pressure distributions is even larger. The forces and pressures applied in the NL data set are on average significantly higher than in the US data set; the means ± standard deviation (SD) are 13.8 ± 2.7 daN and 13.7 ± 5.9 kPa in the NL data set versus 7.4 ± 3.1 daN and 8.1 ± 4.1 kPa in the US data set (for both differences, $p < .001$). On the other hand, the relative standard deviation is larger in the US data set than in the NL data set; respectively 41.9% versus 19.6% for the force, and 50.6% versus 43.1% for the pressure.

For 31.1% of the compressions in the NL data set, the applied force was higher than 15 daN, versus 1.5% in the US data set. Correspondingly in the NL data set, a pressure higher than 20 kPa (150 mmHg) was applied in 12.3% of the compressions, versus 1.7% in the US data set. Both sets contained pressures even higher than 40 kPa (300 mmHg). With regard to the low compressions, 21.1% in the US data set were obtained with forces below 5 daN, whereas this almost never occurred in the NL data set (0.05%). For 21.7% of the compressions in the US data set, a pressure lower than 5 kPa (37.5 mmHg) was applied, versus only 0.6% in the NL data set.

Fig. 2 shows how the averages and variations in applied force and pressure change with the contact area, providing insight in whether and how the radiographers adjust compression to size and elasticity. The force and pressure isolines illustrate how the mechanical parameters force and pressure are related by contact area. As already shown in Fig. 1, the average applied force and pressure are significantly higher in the NL data set. Fig. 2a additionally demonstrates that the average force applied by the radiographers increases with contact area in an approximately linear fashion in both the NL and the US data set, and the slope is almost the same. In other words, the Dutch radiographers seem to employ a strategy similar to that applied in the US clinical site, but starting from a higher base line force. Neither of these strategies leads to a standardized pressure. Fig. 2b shows for both data sets that the smaller the contact area, the higher the average applied pressure and the larger the difference in average pressure between the NL and the US data set. Fig. 2b also shows that both compression strategies introduce a substantial variation in the applied pressure. The amount of variance depends on the contact area; the smaller the contact area, the higher the variance, both in the Netherlands and in the US ($p < .001$).

In Fig. 3, the breast density and volume are compared in relation to contact area between the NL and US data sets. The difference in estimated breast density between the NL and the US data sets is relatively small over the entire range of contact areas (on average, 7.02 ± 4.73% (mean ± SD) in the NL data set versus 7.71 ± 5.82% in the US data set, $p = .0018$). Breast density decreases on average in a non-linear way with contact area, but the relationship is weak due to the large variation. The relation between contact area and estimated breast volume is proportional, which can be expected since volume is calculated based on contact area, and very similar between both data sets. No structural differences in breast density and volume that are dependent on contact area can be identified between the two populations.

Fig. 4a shows that larger contact areas are associated with larger breast thicknesses. The difference in mean breast thickness between the data sets was small over the entire contact area range, despite the differences in applied force and pressure. Averaged over all compressions, the measured breast thickness was 0.8 mm (1.3%) higher in the NL data set (60.7 ± 11.8 mm (mean ± SD) versus 59.9 ± 13.9 mm in the US data set, $p = .0013$). The standard deviation was 18% larger in the US data. Fig. 4b shows that the US data set has a higher mean AGD value (1.83 ± 0.73 mGy) and a larger standard deviation compared to the NL data set (1.54 ± 0.35 mGy, $p < .001$).

4. Discussion

The results obtained in this study show that current mammographic compression policies in the involved sites in the US and

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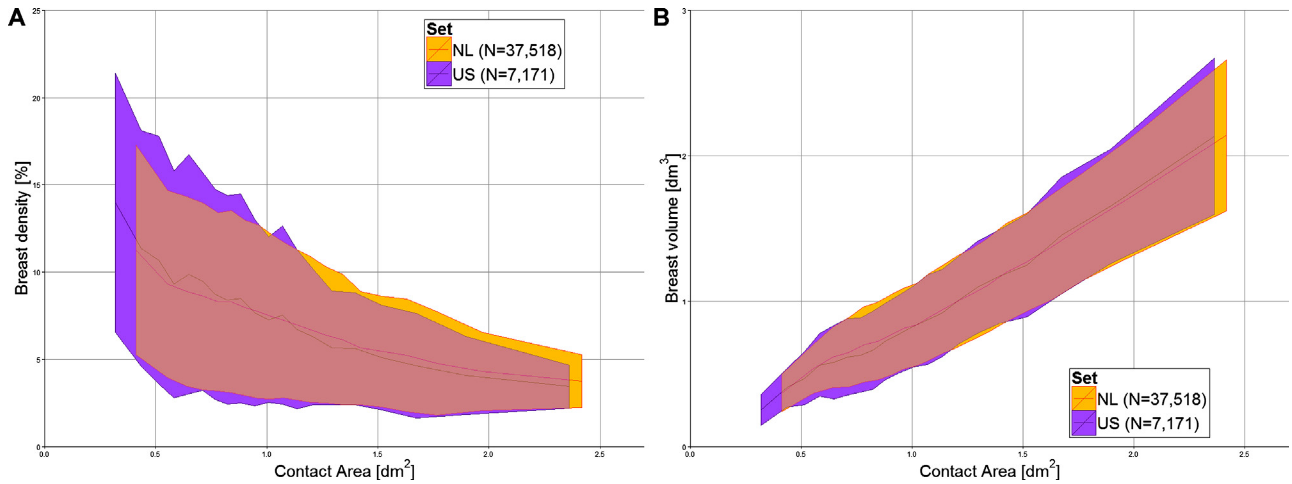

Fig. 3. Comparing the NL data set with the US data set: breast density (A) and volume (B) versus contact area: mean ± one standard deviation. The almost complete overlap indicates the similarity of both populations with regard to breast density and breast volume.

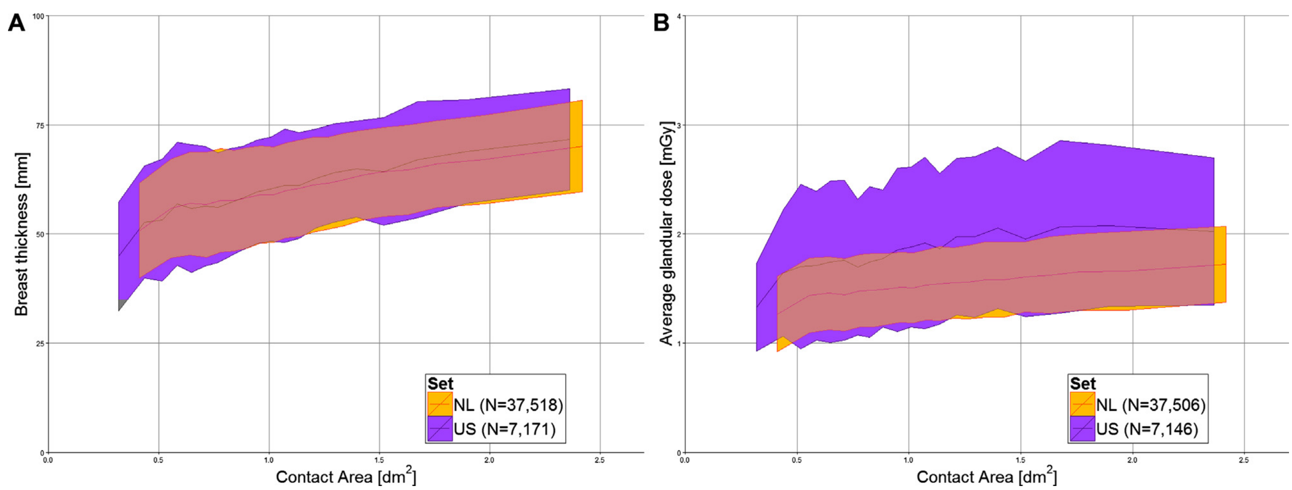

Fig. 4. Breast thickness (A) and average glandular dose (B): comparison of mean ± one standard deviation between NL and US data sets, in relation to contact area. Breast thickness is similar in both populations. The AGD is different, with a higher mean level and a higher standard deviation in the US data set.

Europe do not only lead to a wide range of applied forces but also to a wide range of pressures. Despite a trend of applying lower forces to smaller contact areas, the resulting average pressure and variance become higher as the size of the contact area decreases. Even for breasts with similar contact areas, representative for a combination of breast size and elasticity, we found large differences and high variation in applied pressure, both between and within the two data sets. This indicates that in the example sites studied here, the applied compression procedures are inconsistent and site-dependent, and that the reproducibility of the procedures regarding the pressure applied to breasts is not ideal. For the individual woman, the amount of applied pressure is currently almost unpredictable.

4.1. Variation in current practice

This is the first study on compression practices in which not only the applied force but also the applied pressure is compared between two large data sets from different countries. Large variations in applied forces in mammography have been reported before [9,10] and are a logical consequence of current compression policies in which radiographers are expected to fixate the breast based on experience, observation of the woman and estimates of tautness of the breast tissue [6–8]. The radiographers thereby empirically adjust the force to a certain extent according to the breast size, elasticity and pain. A large variation in applied forces can therefore be expected, as these parameters are highly variable over the population. If the compression force would be consistently adjusted to the observed contact area, this would lead to a similar pressure in all breasts [13]. In the results presented here, the applied average pressure is instead inconsistent and, moreover, highly variable. Factors contributing to this variation include the pain threshold of the woman, the radiographer's sensitivity for pain expression, the uncertainty or inaccuracy in estimating the pressure on the breast, the radiographer's opinion of what is a good compression, and local conventions. Except for the woman's pain threshold, all other sources of variation in applied pressure are under the influence of the radiographer. Therefore, there is room for improvement by standardization of the mechanical execution of compression. In addition to the advantage of reduced variation, the radiographers might also appreciate clearer standards because it could aid them during mammographic compression.

4.2. A proposal for standardization

A conventional approach to decrease the variation between radiographers is instructing them to apply the same target force unless the woman expresses too much pain [13]. This approach,

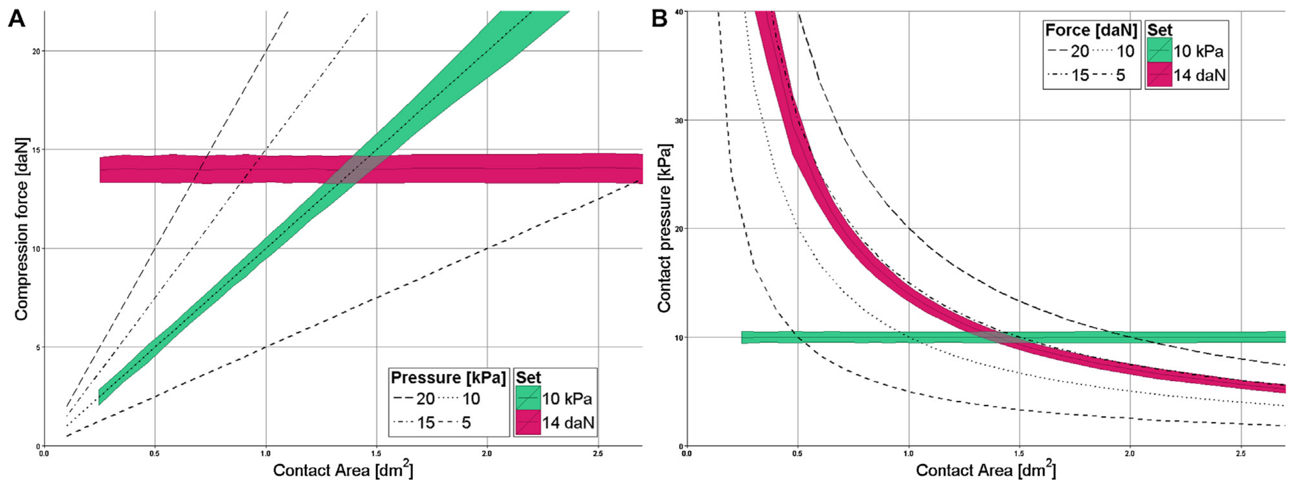

Fig. 5. A proposal for mechanical standardization by pressure (10 kPa; green) and the consequence of mechanical standardization by force (14 daN; pink). These simulated model data show an assumed mean ± standard deviation for applied force (A) and applied pressure (B) in relation to contact area (graphs generated from idealized virtual data sets). The force standardization (pink) is characterized by a constant force (A) and extremely high pressures for small contact areas (B). In the pressure standardization (green), the pressure is constant (B) and the force is proportional to the contact area (A).

which ignores differences in breast size and elasticity, leads to extremely high pressures (Fig. 5, pink) for smaller contact areas and higher odds for extreme pain [13]. A more reasonable approach might be to standardize the pressure (Fig. 5, green), because this inherently results in an objective and therefore more consistent adjustment to the combination of breast size and elasticity (by contact area). Because the size of the contact area changes during the compression, the adjustment of the compression would preferably be guided by a real-time indicator. The policies proposed in Fig. 5 were both implemented and investigated in the consecutive article in this issue [14].

4.3. Effects on lesion detectability

Prior studies have shown that, at least in current digital mammography systems and breast tomosynthesis systems, there may be a relatively large range of pressures for which the resulting image is diagnostically equally useful [14] (in this issue), [20–22]. The exact influence on the detectability of pathologic conditions has never been investigated in a large in vivo study and is, therefore, unknown. However, since image quality is clearly degraded if no compression is applied (some examples can be found in [14] (in this issue) and [1]), there has to be a minimum below which the quality of the image will be compromised. Therefore, the effects of extremely low pressures require further investigation.

4.4. Benefits for the women

For the women, the advantages of mechanical standardization are evident: more consistent experiences, and a good and reproducible compromise between lower doses and image quality. Further, the data presented here show that the current techniques underlying compression lead to high pressures for a substantial proportion of women in both the NL and US data sets, sometimes even higher than twice the systolic blood pressure. These high pressures may or may not be painful, but since less pressure is apparently applied to many other breasts of similar size and elasticity, and still adequate images are (apparently) obtained, any potential extra pain caused by extra pressure may be unnecessary. Enduring high pressures may be particularly undesirable when acquisition times are longer, which is typically the case in most current tomosynthesis systems.

4.5. Radiation dose

In this study, we found that the AGD was more variable and on average significantly higher in the US data set, even though no structural differences in breast volume and density were visible between the two populations. Higher average AGD can be a consequence of higher average breast thickness at exposure, but in our data, we found only a very small thickness difference. Average thickness was even slightly higher in the Netherlands. Since the average tube voltage (kVp) was similar between the two datasets, the difference in AGD is most probably related to differences in the automatic exposure controller settings, which are vendor-dependent [23] and also adjustable according to local policies. Notably, the Selenia machines in the US data set used on average 149 mAs compared to 107 mAs in the NL data set. Future studies should make sure that the machine types and technical settings are equal between datasets, if radiation dose is an important outcome measure of the study.

4.6. Limitations

The existence of differences in AGD reflects a limitation of this study; the reported differences may be biased because the data were obtained from only one site in the US. To generalize our findings to country level, a multi-centre study would be necessary involving a sufficiently high number of different sites in each country, with the mammograms preferably differentiated as screening or diagnostic. Another limitation is that the force measurements on some systems may not have been correctly calibrated. Calibration errors may explain part of the differences observed between the data sets, but we think that such errors are small compared to the variation and differences in applied force and pressure between the data sets. Nevertheless, we recommend for future studies to ensure that all systems are appropriately calibrated. Furthermore, the NL data set consists solely of screening mammograms whereas the US data set contains both screening and diagnostic mammograms. The diagnostic population may be more prone to pain and variability of compression due to the higher incidence of symptomatic breasts and prior breast surgery. If this effect would have a strong influence, it would also lead to increased variation in breast thickness at exposure. However, Fig. 4a shows that the variation in breast thickness is almost the same between the two data sets.

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5. Conclusion

Current mammographic compression protocols in both the Netherlands and the US clinical sites involved in this study lead to large differences and variation in applied force and pressure; currently, neither of these mechanical parameters is effectively standardized. Standardization, potentially based on pressure rather than force, would:

1. make the procedure and the resulting image more reproducible between and within women;
2. avoid extremely high pressure outliers causing unnecessary pain;
3. avoid very low pressure outliers to reduce the radiation dose related to insufficient compression and the risk of insufficient image quality;
4. enhance quality control of mechanical compression.

Conflict of interest

W. Branderhorst is an employee at Sigmascreening. C.A. Grimbergen is an employee, founder, board member, and patent holder of Sigmascreening. G.J. den Heeten is a founder of Sigmascreening and co-patent holder on behalf of the Academic Medical Center Amsterdam. Ralph Highnam is an employee and shareholder of Volpara Solutions Limited. Ariane Chan is an employee of Volpara Solutions Limited. J.E. de Groot, M.J.M. Broeders and M. Böhm-Vélez have no conflicts of interest to declare.

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