X-ray scatter correction in breast tomosynthesis with a precomputed scatter map library

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Purpose: To develop and evaluate the impact on lesion conspicuity of a software-based x-ray scatter correction algorithm for digital breast tomosynthesis (DBT) imaging into which a precomputed library of x-ray scatter maps is incorporated.

Methods: A previously developed model of compressed breast shapes undergoing mammography based on principal component analysis (PCA) was used to assemble 540 simulated breast volumes, of different shapes and sizes, undergoing DBT. A Monte Carlo (MC) simulation was used to generate the cranio-caudal (CC) view DBT x-ray scatter maps of these volumes, which were then assembled into a library. This library was incorporated into a previously developed software-based x-ray scatter correction, and the performance of this improved algorithm was evaluated with an observer study of 40 patient cases previously classified as BI-RADS® 4 or 5, evenly divided between mass and microcalcification cases. Observers were presented with both the original images and the scatter corrected (SC) images side by side and asked to indicate their preference, on a scale from -5 to $+5$, in terms of lesion conspicuity and quality of diagnostic features. Scores were normalized such that a negative score indicates a preference for the original images, and a positive score indicates a preference for the SC images.

Results: The scatter map library removes the time-intensive MC simulation from the application of the scatter correction algorithm. While only one in four observers preferred the SC DBT images as a whole (combined mean score = 0.169 ± 0.37 , $p > 0.39$), all observers exhibited a preference for the SC images when the lesion examined was a mass (1.06 ± 0.45 , $p < 0.0001$). When the lesion examined consisted of microcalcification clusters, the observers exhibited a preference for the uncorrected images (-0.725 ± 0.51 , $p < 0.009$).

Conclusions: The incorporation of the x-ray scatter map library into the scatter correction algorithm improves the efficiency of the algorithm. The observer study presented here is also the first test of the scatter correction algorithm with patient images and human observers, and demonstrates its potential to improve the clinical performance of DBT. © 2014 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4866229>]

Key words: breast cancer, digital breast tomosynthesis, x-ray scatter correction

1. INTRODUCTION

According to the American Cancer Society, over 232 340 new cases of breast cancer will be diagnosed in 2013, and over 39 000 people will die from the disease.¹ Digital breast tomosynthesis (DBT) imaging,² which is emerging as a potentially feasible replacement or adjunct to mammography for the screening and diagnosis of breast cancer, allows for the generation of pseudo-three-dimensional (3D) images of the breast. This overcomes one of the main limitations of mammography, the loss of information when reducing a 3D structure into a two-dimensional

image, and provides greater detail about the volumetric tissue structure. In DBT, multiple low dose projections of the breast are acquired over a limited angular range; these projections are then used to calculate a pseudo-3D reconstruction of the imaged tissue.²⁻⁶ Preliminary studies have shown that DBT has the potential to improve the clinical performance of breast cancer screening and/or diagnosis.⁷⁻¹²

Current DBT systems, including the Selenia Dimensions (Hologic Inc., Bedford, MA) used in this study, lack x-ray scatter reduction measures, be it in software or hardware. This leads to the inclusion of the entirety of the x-ray scatter signal

in the tomosynthesis projections, resulting in reconstruction artifacts and reduced contrast.^{13–15} We have previously developed a software-based x-ray scatter correction algorithm that, when applied to the acquired tomosynthesis projections before reconstruction, has shown potential in improving image quality.¹⁶

Here we present a study on the use of a library of pre-computed DBT x-ray scatter maps with the scatter correction algorithm, derived from a previously developed model of clinically relevant compressed breast shapes based on principal component analysis (PCA).¹⁷ The PCA-based breast shape model for the cranio-caudal (CC) view was used to generate compressed breast volumes that span the range of clinically encountered breast shapes and sizes. This study takes advantage of the fact that in DBT, the compressed breast is positioned in the same manner as in full field digital mammography (FFDM). Monte Carlo (MC) simulations of these breast volumes undergoing DBT were then performed to form a library of CC-view x-ray scatter maps.

We also investigated the performance of the x-ray scatter correction algorithm using this library by performing an observer study with clinical DBT cases involving masses and microcalcifications that have undergone the scatter correction process.

2. MATERIALS AND METHODS

The patient images used in this study were acquired for an unrelated HIPAA-compliant, IRB-approved observer study. The patients released the images for use in additional research projects after anonymization.

This study expands upon a previously developed software-based scatter reduction algorithm for DBT imaging¹⁶ by incorporating a precomputed library of scatter maps. These maps, along with primary signal maps, are generated from MC simulations that utilize voxelized breast volumes created by an objective PCA model of breast shape. The MC simulations are implemented in C++, based on the Geant4 Monte Carlo simulation toolkit,^{18,19} and are similar to those used by Feng *et al.*¹⁶ and Sechopoulos *et al.*^{6,20,21} In each application of the improved scatter correction algorithm, the central angle projection of the DBT projections undergoes automated edge detection and PCA characterization to obtain the patient specific PCA parameters. The matching scatter and primary maps are selected from the library, and combined into a scatter-to-primary ratio (SPR) map which is then registered to the acquired breast projections. The low-frequency scatter signal is then removed from the projections, which are subsequently noise filtered. Finally, the scatter corrected (SC) projections undergo filtered backprojection (FBP) 3D reconstruction.

This procedure was tested on 40 patient DBT cases, previously classified as BI-RADS® 4 or 5, which were acquired with a Selenia Dimensions (Hologic Inc., Bedford, MA) DBT system. For the observer study, the radiologists were asked to evaluate the original (O) and scatter corrected images for conspicuity of the lesions and detail of the features relevant to diagnosis.

2.A. 3D model of breast volume undergoing digital breast tomosynthesis

This study utilizes the objective PCA model of patient breasts during acquisition of a cranio-caudal view mammographic image described by Feng *et al.*¹⁷ As the image of the compressed breast shape undergoing mammography is identical to the central angle (0°) projection of the compressed breast shape undergoing DBT, the mammography model forms the basis for the DBT model. The 3D breast volume (3DV) is built using the 2D breast shape (2DS) generated by the PCA model and an estimated curvature of the compressed breast volume. A script was written in IDL 8.0 (Exelis VIS, Boulder, CO) that generates a binary image stack that represents the modeled breast volume with a given compressed thickness (Th).

The 2DS is eroded to account for the magnification owing to the distance of half of Th , as the image of the 2DS is assumed to be that of the central slice of the voxelized breast volume. Building upon this central slice, two parabolic fits, one for the slices of the 3DV above and one for the slices below the central slice, are applied to represent the extent to which the 2DS is eroded. This erosion is necessary since the curvature of the compressed breast is assumed such that the breast tissue extends furthest from the chest wall at the center, and is closer to the chest wall at the top and bottom (Fig. 1). The parabolic fit below the center of the breast volume produces slices where the breast shape is eroded to a lesser degree than those above the center, which can be seen in Fig. 1(b).

At the outset of this study, a 3DV library large enough to encompass the range of most clinically encountered breasts was required. To create this library, the parameters of the 4-component PCA model were selected according to the values in Table I. It has previously been shown that a 6-component PCA model results in greater accuracy of the modeled breast shape,¹⁷ but the two additional latter components, which contribute the smallest amount of information to the shape, were deemed unnecessary for a low frequency signal such as x-ray scatter. This was confirmed by examination of the x-ray scatter maps resulting from five- and six-component models. The mean (μ) and standard deviation (σ) of each principal component were used for these parameter selections. As the first component, α , has been shown to be the greatest determinant of the breast shape and size,¹⁷ five values of α were chosen. For the other three components, only three values were chosen, since the differences introduced by these components on the shape of the breast, and therefore on the simulated scatter maps, were less pronounced. Th was chosen to span the range from 2 to 8 cm, in 2 cm steps. Thus, a total of 540 distinct 3DVs, each with a characteristic parameter vector $[\alpha, \beta, \gamma, \delta, Th]$, were generated from the PCA model of breast volume undergoing DBT acquisition.

2.B. X-ray scatter map library

A voxelized version of the x-ray scatter MC simulation used by Feng *et al.*¹⁶ was used to generate scatter image

FIG. 1. Generation of the 3D breast volume from a 2D breast shape. (a) The superior-inferior view of the central slice of the volume generated from the PCA model breast shape of which the four principal components α , β , γ , and δ were each set to the indicated linear combinations of the component-specific mean (μ) and standard deviation (σ). (b) The side view of the 6 cm thick breast volume from (a). Note that the curvature of the breast differs above and below the center slice. The horizontal line indicates the slice location of the image shown in (a).

sets of all 540 3DVs from the PCA breast volume model undergoing DBT. The simulation is implemented in C++ and matches the acquisition geometry of the Selenia Dimensions system for the CC view. The system acquires 15 projections over a 15° angular range, with the x-ray tube positioned directly perpendicular to the image detector for the central angle (tomosynthesis angle = 0°) projection. The detector measures 24×29 cm, with a pixel pitch of $70 \mu\text{m}$. Complete details of the system have been previously published by Ren *et al.*²² Thus, the MC simulated x-ray scatter map set of each 3DV consists of 15 scatter maps, one from each acquisition angle.

The glandular fraction of the homogeneous breast volume for all simulations was set to 14.3%, which has previously been shown to be the population average.²³ This is a reasonable assumption as it has been shown that scatter varies minimally with glandular fraction.²¹ Since it is known that x-ray scatter varies slowly over the detector, a pixel pitch of 0.7 mm was used in the MC simulations to decrease the simulation time by reducing the noise in the results.

2.C. Patient images

We obtained 40 patient cranio-caudal view DBT images classified as BI-RADS® 4 or 5. These images contained le-

TABLE I. Selected values for principal components of library. To determine the input values to the PCA breast shape model, the mean (μ) and standard deviation (σ) of each component were used. These values were obtained from Ref. 17.

Selected values for principal components of library				
Principal component	Number of values	μ	σ	Selected values
α	5	-3.185	15.78	$\mu + 2\sigma$
				$\mu + \sigma$
				μ
				$\mu - \sigma$
				$\mu - 2\sigma$
β	3	-0.296	8.225	$\mu + 2\sigma$
				μ
				$\mu - 2\sigma$
γ	3	-0.0654	3.658	$\mu + 2\sigma$
				μ
				$\mu - 2\sigma$
δ	3	-0.1286	1.994	$\mu + 2\sigma$
				μ
				$\mu - 2\sigma$

sions, previously identified by a radiologist, and are evenly divided between masses and microcalcification clusters.

2.D. Automated edge detection and patient breast shape characterization

To select the appropriate x-ray scatter map from the library, the central angle projection of each patient acquisition set was subjected to automated edge detection, as described by Feng *et al.*¹⁷ Automatic thresholding and breast tissue isolation, via the extraction of connected components, were performed to obtain a binary image of the breast tissue under examination. The breast shape edge was then located using Roberts cross gradient operators and edge thinning.²⁴⁻²⁶

The breast edge was uniformly sampled to generate a subset of 100 (x, y) coordinate points, in units of distance. This subset of points can be defined as 100 correlated observations, which can be reduced using PCA to a smaller set of linearly independent variables that encapsulates most of the information contained within the datapoints.^{27,28} To perform the analysis on each central angle projection, we formed the vector $\mathbf{x}_{acq}$ as follows:

$$\mathbf{x}_{acq} = [x_1, x_2, x_3, \dots, x_{100}, y_1, y_2, y_3, \dots, y_{100}]^T. \quad (1)$$

Using the 100×4 principal component matrix $\mathbf{E}$ and the mean edge vector, $\bar{x}$, from the CC-view PCA model from Feng *et al.*,¹⁷ the PCA parameter vector $\mathbf{r}_{acq}$, consisting of the four parameters $[\alpha, \beta, \gamma, \delta]$, was calculated as follows for each central angle projection:

$$\mathbf{r}_{acq} = (\mathbf{E}^T \mathbf{E})^{-1} \mathbf{E}^T (\mathbf{x}_{acq} - \bar{x}). \quad (2)$$

The patient compressed breast thickness is then concatenated to $\mathbf{r}_{acq}$ to obtain a five element vector that characterizes the compressed breast volume undergoing DBT. For each DBT patient case to be corrected, the MC-simulated scatter map set of the 3DV with the characteristic parameter

vector that has the minimal root mean square error (RMSE) with r_{acq} , was selected.

2.E. X-ray scatter correction

To obtain x-ray primary images free of noise, raytracing²⁹ was performed to determine the pathlength of each ray from the source to each pixel on the image detector. The pathlengths of the rays through each material in the simulation, combined with the attenuation coefficients for each material³⁰ and x-ray energies included in the spectrum³¹ used during acquisition, were used to calculate the estimated primary images. This allowed for the calculation of a scatter-to-primary ratio map, which depicts the ratio of the scatter signal to the primary signal on a pixel-by-pixel basis, for each DBT projection.

The SPR maps and primary images were then used in the x-ray scatter correction algorithm described by Feng *et al.*¹⁶ to remove the scatter signal from the DBT acquisitions. The original and scatter corrected images then underwent 3D reconstruction using the filtered backprojection reconstruction algorithm of the Selenia Dimensions system.

2.F. Observer study

Volumetric regions of interest (VOIs) centered on the lesion were isolated from the *O* and *SC* reconstructions described above. Four radiologists experienced in breast imaging were recruited for this observer study. Each observer was presented with the *O* and *SC* DBT images side by side, randomized in both order and presentation, such as those depicted in Fig. 2. The images were presented with automatically optimized window width and level for each VOI and observers could scroll through the volume stack. In addition, the overall brightness and contrast could also be adjusted by the observer. Three observers completed the study in a single one hour session, while the other observer performed the study in two half-hour sessions. The DBT reconstructions were displayed using the ImageJ image processing software (NIH, Bethesda, MD) on a DICOM calibrated^{32,33} 5 megapixel high-resolution flat-panel gray-scale dual-head display (DOME C5i, Planar Systems, Beaverton, OR).

Observers were asked to indicate their preference for either the left or right image on a scale from -5 (left) to $+5$ (right), with 0 indicating no preference, based on the conspicuity of the lesion and the diagnostic detail conferred by the image features. Ratings were normalized such that a preference for the *O* image is negative, whilst a preference for the *SC* image is positive. These ratings were then averaged to determine if each clinician exhibited a preference for either the *O* or *SC* images.

3. RESULTS

3.A. X-ray scatter map library

The addition of the breast volume PCA model and the x-ray scatter map library to the scatter correction algorithm

FIG. 2. Scatter correction observer study. Shown here are two distinct DBT patient images. Observers were presented with these images, which consist of volumes of interest centered on lesions, such as a glandular mass (top) and microcalcification clusters (bottom, arrow added for this example). Here labels have been added to indicate which of the two images in each case has undergone x-ray scatter correction. Each image pair is shown with optimized window width and level.

successfully reduced the execution time of the algorithm for the correction of a clinical case from hours to minutes. Comparison of the central angle patient-specific MC-simulated scatter image with the registered scatter map image of the 3DV with the closest matching characteristic parameter vector revealed that the images are very similar (Fig. 3). The signal profiles drawn through the center of the breast in both images were also very similar.

After all 40 patient cases were subjected to the automated edge detection and PCA characterization, it was discovered that the initial library of 3DVs described by Table I was insufficient in terms of both range and granularity. The patient breast shapes exhibited finer variation in the β , γ , and δ parameters, thus necessitating an increase in the number of values selected for those parameters. In particular, the initial library used a step size of two standard deviations (2σ) for these parameters, but the patient breast shapes exhibited values that suggested that a step size of σ is more appropriate. For *Th*, 39 of the 40 patient images spanned the range of 2 to 8 cm, but it was determined that a smaller step size of 1 cm is required. One patient case had a *Th* of 9 cm. Additional 3DVs were generated to match those patient cases and additional MC simulations were performed. It was determined that a library would need to consist of scatter map sets of 3DVs characterized by the principal component values listed in Table II. As a total of 16087 scatter maps sets would be needed to complete this library for the CC view for this specific DBT system, an estimated 210 000 h of computing time

FIG. 3. Comparison of scatter images. A patient-specific x-ray scatter map, generated from the Monte Carlo simulation, is shown in (a) and the closest matching scatter map from the library after registration is shown in (b). The graph in (c) depicts the signal profile through the center of both the Monte Carlo simulated (black) scatter map and the library selection (gray).

and 120 gigabytes of storage space would be required. Since this would need to be computed only once for a particular DBT system design, this amount of computing time is feasible with the current availability of multicore computer clusters.

3.B. X-ray scatter correction

Examination of the SC images and the O images, including the VOIs, revealed that the image contrast was enhanced by the scatter correction algorithm with the precomputed scatter map library. It was found that no apparent artifacts were introduced by the algorithm.

3.C. Observer study

The combined total mean score for all images and observers was 0.169 ± 0.37 ($p > 0.39$), which indicates that

TABLE II. Range and granularity of principal components of library. Shown here are the values for the PCA breast shape model required for a fully developed x-ray scatter map library. The mean (μ) and standard deviation (σ) of each component were used to determine the values.

Range and granularity of principal components of library				
Principal component	Number of values	μ	σ	Selected values
α	7	-3.1852	15.7792	$\mu + 4\sigma$
				$\mu + 3\sigma$
				$\mu + 2\sigma$
				$\mu + \sigma$
				μ
				$\mu - \sigma$
				$\mu - 2\sigma$
β	7	-0.2959	8.2254	$\mu + 4\sigma$
				$\mu + 3\sigma$
				$\mu + 2\sigma$
				$\mu + \sigma$
				μ
				$\mu - \sigma$
				$\mu - 2\sigma$
γ	7	-0.0654	3.6579	$\mu + 4\sigma$
				$\mu + 3\sigma$
				$\mu + 2\sigma$
				$\mu + \sigma$
				μ
				$\mu - \sigma$
				$\mu - 2\sigma$
δ	7	-0.1286	1.9939	$\mu + 4\sigma$
				$\mu + 3\sigma$
				$\mu + 2\sigma$
				$\mu + \sigma$
				μ
				$\mu - \sigma$
				$\mu - 2\sigma$
				$\mu - 3\sigma$

overall there was no preference for either the O or SC images (Table III). The combined mean score for images that contained a soft tissue mass was 1.06 ± 0.45 ($p < 0.0001$), with all observers averaging positive scores for these images. However, when the lesion in the image consisted of microcalcification clusters, the combined mean score of these images was -0.725 ± 0.51 ($p < 0.009$), which indicated that for these lesions the observers preferred the O images.

TABLE III. Observer study results. Shown here are the mean scores for each observer for the images with a mass, microcalcification clusters, and the combined case total, as well as the total for all observers. Positive scores indicate a preference for the scatter corrected images, while negative scores indicate a preference for the uncorrected images.

Observer study results				
Observer	Years of experience in breast imaging	Mean total score	Mean mass score	Mean microcalcification score
A	2	1.575	2.6	0.55
B	37	-0.175	0.05	-0.4
C	4	-0.375	0.55	-1.3
D	24	-0.35	1.05	-1.75
Combined		0.169	1.06	-0.725

Of note is that one radiologist, Observer A, consistently preferred the SC images, with a total mean score of 1.575 ± 0.45 ($p < 0.002$), and positive mean scores for both the images with masses and for those with microcalcifications.

4. DISCUSSION

The study presented here demonstrates that a library of x-ray scatter maps computed from MC simulations that incorporate compressed breast volumes generated by a PCA model can be successfully integrated into a DBT scatter correction algorithm, which can reduce the processing time by 2 orders of magnitude. In addition, the incorporation of the PCA model of breast shape into the algorithm, and the testing on 40 DBT patient cases, led to the delineation of the parameter space that such a library must cover (Table II). It was found that a total of 16 087 scatter map sets would be needed to complete this library for CC view DBT. A complete study of the granularity of the parameter space can be performed in the future to determine the most appropriate step size for each of the principle component parameters.

The required expansion of the initial scatter map library described in Table I suggests that the PCA model of breast shape may need to be expanded or revised. First, the mammographic images that formed the basis of the PCA model measure 19.14×22.94 cm, while the detector of the Selenia Dimensions measures 24×29 cm. It is possible that the breadth of the FFDM database of the PCA model is limited by the detector size of the Senographe 2000D (GE Healthcare, UK) mammography system used to acquire those mammograms.¹⁷ Second, the patient cases used in this study have a mean $Th = 5.91$ cm and the average calculated parameter value of the first principal component, α , which was shown to be the greatest determination of 2DS size, is more than one standard deviation greater than the mean [$\text{average}(\alpha) = \mu + 1.04\sigma$] from the PCA model. An expansion of the set of images of the PCA model could be performed in the future by including mammograms and central angle DBT projections acquired by the Selenia Dimensions system.

The observer study reveals that the scatter correction algorithm has the potential to improve the conspicuity and image quality of masses in DBT images. The contrast enhancement of masses conferred by the algorithm was also previously shown in phantoms by Feng *et al.*¹⁶ The observers' preference for the *O* reconstructions when presented with images depicting microcalcification clusters could be due to two factors. The first is that each VOI was displayed with individually optimized windows. In addition, upon discussion with the observers after the study, we believe that the contrast enhancement of glandular tissue by the scatter correction process reduced the microcalcification contrast, resulting in a preference for the unenhanced image. It is important to note that this preliminary study is limited to conspicuity of lesions, not actual detection or diagnostic performance, with small VOIs, and for BI-RADS® 4 and 5 findings only. The impact on the effectiveness of scatter of including only small VOIs could be substantial, since the window/level of each VOI was automatically set according to the histogram of

the VOI only. Considering that scatter correction is expected to have a large impact on the wide-area homogeneity of the reconstructed image, this benefit of scatter correction may have been minimized by this study design, especially considering that window/level adjustments are not normally performed by the physicians during interpretation of images in the clinical realm. A larger observer detection study that includes negative patient cases, where observers are asked to evaluate the reconstructions as a whole, would need to be performed to better evaluate the clinical impact of the algorithm on detection and/or diagnosis. Finally, this study focused on the CC view of DBT images only. A similar study would need to be performed for the medio-lateral oblique (MLO) view.

5. CONCLUSION

The incorporation of the CC view PCA model of breast shape into the scatter correction algorithm improves the efficiency of the algorithm and provides insight into the size and range required of a precomputed DBT CC view x-ray scatter map library. The observer study presented here is the first test of the scatter correction algorithm with patient images and human observers, and demonstrates the potential to improve the clinical performance of DBT.

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