Measurement of breast density with digital breast tomosynthesis

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ABSTRACT

Breast density is known as a strong risk factor for breast cancer. Clinical assessment of breast density during screening mammography is often done by radiologists through visual evaluation or by a computer program. Automated computer methods offer the potential for non-subjective density assessments. With the rapid development and increased utilization of tomosynthesis clinically, there is a practical need for systems to provide automated breast density measurements in tomosynthesis like those available in mammography.

Quantra™ is a software package using physical modeling of mammography systems, and performs volumetric assessment of breast tissue composition for conventional mammography. In this paper, we describe recent developments to extend Quantra to calculate breast density using tomosynthesis projection images. Our development took advantage of the combo imaging mode of Hologic Selenia Dimensions™ system, which allowed co-registered conventional 2D mammogram and 3D tomosynthesis images to be acquired in a single compression. We used the Quantra results of 2D mammograms as a reference to refine the new processing algorithm for tomosynthesis images. This paper describes details of the new algorithm and provides some preliminary results.

Keywords:

Digital breast tomosynthesis, mammography, volumetric breast density, scatter correction, scatter response function, Quantra.

1. INTRODUCTION

Digital breast tomosynthesis (DBT) is a 3D breast imaging technology that offers many advantages over the conventional mammography, including better lesion detection, less structure superposition artifacts, and 3D localization capability. Commercial DBT systems have been approved for sale in the U.S. since early 2011. It is hypothesized that DBT may eventually replace conventional mammography as a new screening tool for early detection of breast cancer. At the same time, the measurement of breast density, because of its strong risk factor for breast cancer, is as important with tomosynthesis as with conventional 2D mammography. Therefore there is a practical need for tomosynthesis to provide automated and non-subjective breast density measurement as are currently available in mammography. Quantra, a software package based on physical modeling of mammography systems, performs volumetric assessment of breast tissue composition for conventional mammography. In this paper, we will describe our work to extend Quantra to calculate breast density with tomosynthesis projection images.

There have been studies on calculation of breast density with tomosynthesis reconstruction slices[1, 2]. These methods will be briefly summarized. The breast glandular tissue portions in each reconstruction slice were segmented out and were summed together over all slices to generate the total glandular tissue volume of a breast. Since tomosynthesis is a limited angle tomography, each slice of reconstruction image contains out-of-focus structures originated from other slices. Theoretically it is unclear whether the above method can provide correct and robust measurement of glandular tissue volume, since the glandular tissue volume in one slice could be counted in multiple times at these out-of-focus slices. The result of glandular tissue volume could be correct only with certain carefully designed reconstruction filters. These filters usually depend on factors like the DBT scan angle, and the glandular tissue shapes, which makes the algorithm application-specific. Besides, the computation load of the method is also heavy as the algorithm needs to process all reconstruction slices, up to one hundred slices for very thick breasts.

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When the purpose is to get breast density result only, each projection image of a DBT scan is actually sufficient to carry out the calculation. This is because that projection image of a 3D DBT scan is just like a low-dose conventional mammogram in that it has the same breast structure information but measured under different test conditions. The DBT projections differ from a conventional mammogram mainly in the increased scatter content of the projections due to the lack of an anti-scatter grid. Calculation of breast density with DBT projection could be a better method than working from the slices, because it avoids the difficulty dealing with 3D limited angle reconstruction images. It also allows us to use the matured breast density algorithm from conventional mammography to process DBT images directly. In our preliminary investigation, each projection image was processed offline for scatter correction, image count scaling and pixel size up-sampling, and then processed by Quantra to get volumetric breast density (Vbd). Our development also took the advantage of combo scan mode in Selenia Dimensions system, which produced co-registered 2D conventional and 3D DBT images of the same breast. This allowed us to use the Quantra 2D breast density result as a guide to refine the new algorithm for DBT projections. In this paper, we will describe our new algorithm and provide some preliminary results.

2. THEORY AND METHOD

2.1 Difference between 2D mammogram and 3D DBT projection images

Our plan is to treat projection images of DBT scan as low dose mammograms and use Quantra to process. There are several differences between a conventional mammogram and a DBT projection image, which need to be handled properly.

1. In Selenia Dimensions system, the 2D conventional mammogram is taken with anti-scatter grid in the beam. However, the 3D DBT scan is taken without the grid, which leaves lots of scatters in the projection images. For a 4.5 cm thick breast, the scatter to primary ratio (SPR) is only a few percent with HTC anti-scatter grid, and is over 50% without the grid. In tomosynthesis, scatter signal is usually an order of magnitude higher than that in conventional mammography.
2. A 3D DBT scan uses Al filter; a 2D mammography uses either Rh or Ag filters.
3. In 3D mode, the detector is readout in 2x2 binning mode; in 2D mode, the detector is readout in full resolution.
4. In 3D detector uses a higher electronics gain to boost the signal since x-ray dose is low in each image.
5. In 3D mode, the detector is read out dynamically at 4 frames per second, therefore DBT data exhibit certain phenomena related to detector physics like lag, which, while minor, can be corrected.
6. Each 3D projection has a different tube angle to the breast; but the 2D image is taken at the zero degree tube position.

2.2 The x-ray scatter model

The major challenge in breast density calculation with DBT data is to model the scatter signal closely in each projection image. Both the amplitude of scatter and the spatial spread of scatter need to be known in order to carry out scatter correction.

The scatter signal amplitude is commonly described by the parameter scatter-to-primary ratio (SPR). In this study, the SPR of the Dimensions system without anti-scatter grid was evaluated experimentally for thickness between 2 cm to 9 cm at 0.5 cm per step, and with three different phantom sizes at each thickness. We performed curve fitting to generate a smooth function of SPR versus the phantom size at each thickness. Our experimental results were also compared with published SPR results by others in the literature [3-6].

The scatter kernel in mammography can be described by line spread function (LSF) in spatial domain or MTF in frequency domain [3, 4]. The shapes of LSF or MTF of scatters have been found to be thickness dependent. We took the published one-dimensional (1D) MTF and LSF of scatter response function [3] as reference and assumed the scatter kernel had Gaussian shapes in this study. The width of Gaussian curve was set to match the width of scatter's MTF and LSF from the literature at each phantom thickness. Then a two-dimensional (2D) Gaussian function was constructed with the assumption that the X and the Y directions were symmetric and independent to each other. The primary x-ray photon was modeled by a delta function in spatial domain in the study.

With the scatter's amplitude (SPR) and its spread function available, we constructed a system response function to describe both primary and scatter photons. The 2D system response function (PSF) was assumed to be a weighted sum of the delta function and the Gaussian function at each thickness. The weighting factor was found by matching the SPR of the PSF to the measured SPR of the thickness.

2.3 Implementation procedure

The following are the major steps of our algorithm to process the DBT projection images to calculate breast density.

1. Use empirical SPR and Gaussian-shaped scatter spread function to construct a system response function (2D PSF) at each thickness.
2. Get the inverse filter of the 2D PSF
3. Correct the lag effect in 15 projection images in a DBT scan.
4. Convolute a projection image with the inverse filter to get a "scatter-free" image
5. Up-sample the projection image from 140 um pixel resolution to 70 um pixel resolution, and re-scale the signal count to account for the detector electronic gain difference between 2D and 3D mode.
6. Process the corrected projection images with Quantra and get breast density results from all 15 projections.

3. EXPERIMENTAL RESULTS

3.1 The scatter to primary ratios

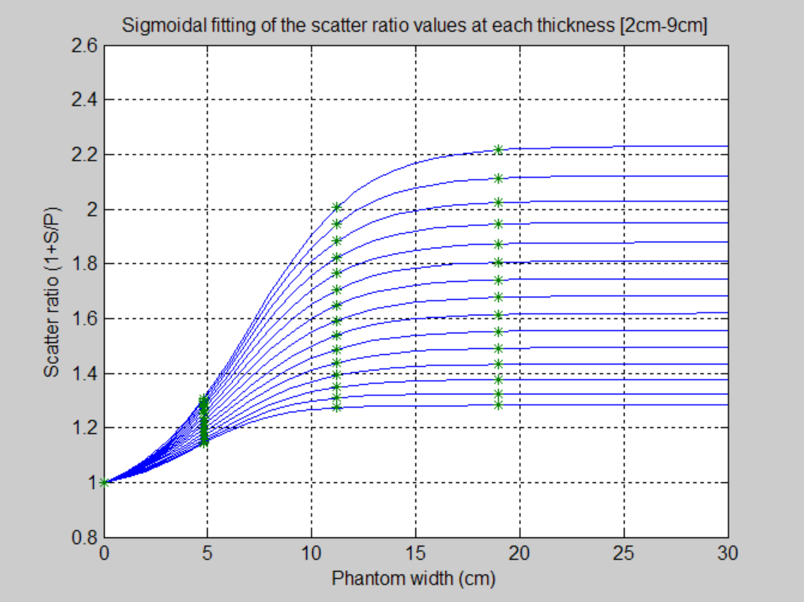

Fig. 1: Measured SPR and curve fitting for phantom thickness from 2 cm to 9 cm, and for three different phantom area sizes of about 25, 150 and 380 cm^2. The horizontal axis is the phantom width (squared root of the area size). There are a total of 15 fitting curves for thickness from 2 cm to 9 cm at 0.5 cm per step from the bottom to the top.

The SPRs of Selenia Dimensions were measured with BR50/50 phantom from 2 cm to 9 cm thick, at 0.5 cm per step. At each phantom thickness, we first measured the primary x-ray signal alone by using with a tiny lead pinhole in the beam and by positioning the phantom next to the tube exit window (far away from detector). The large air gap (>50 cm) between the phantom and the detector plus the tiny beam aperture set by the pinhole made sure that the measured signal in this geometry was from primary x-ray photons only. We then positioned the phantom on the detector surface and measured x-ray signals with three effective phantom sizes, 25 cm^2, 125 cm^2 and 375 cm^2. These three signals were normalized by the primary signal first, and the ratios are presented in Fig. 1. We did a sigmoidal curve fitting to these raw data to get a smooth SPR function versus the phantom size (squared-root of the phantom area size) at each thickness. There were a total of 15 curves in Fig. 1, corresponding from 2 cm to 9 cm thick at 0.5 cm per step, from the bottom to the top. Our results agreed well with those published result of SPR in mammography [5, 6].

3.2 The scatter kernel and the inverse function

The scatter's LSF was modeled by a Gaussian function in this work. From Fig. 8 of Ref. 3, the scatter MTFs were all close to each other at 4 cm, 6 cm and 8 cm except for the thickness of 2 cm. So the widths of scatter spread function for normal breast thicknesses were expected to be close, and did not vary much with thickness unless it was very thin. We chose the width of Gaussian function to be 1 cm in the study and this parameter was fine-tuned at each thickness in order to get better agreement between 2D and DBT breast density results.

The system response function was a weighted sum of the scatter's LSF and a delta function for the primary beam. The relative weighting factor was found by matching the SPR of the response function to the experimental SPR value at that thickness. The system response function was further normalized so that the area underneath had a unit value, which is refereed as the scatter kernel in the paper. An example of 1D scatter kernel for 6 cm thickness is shown in Fig. 2. The scatter kernel is characterized by a large delta function in the center and weak scatter tails around. We use a small display window in Fig. 2 to show tails of the scatter profile better. Besides, the scatter kernel is thickness dependent in this study, due to the fact that SPR is thickness dependent.

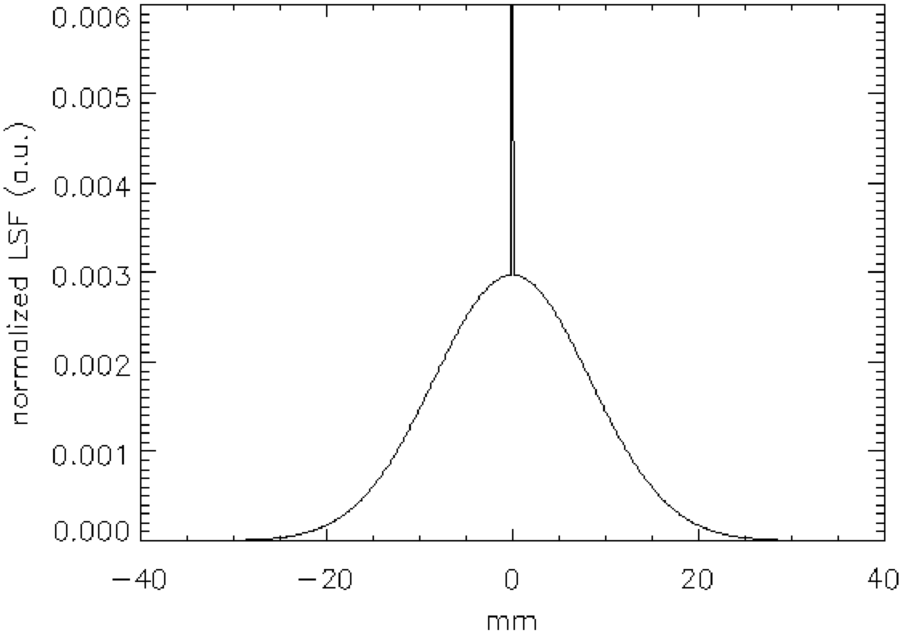

Fig. 2: A model of 1D system response function with scatter effect, which is a weighted sum of a Gaussian function with a delta function. The amplitude of the peak of the normalized LSF is about 0.6. This plot only shows the zoomed view of the tails region of the scatter part. This plot is an example for 6 cm thickness with S/P = 0.65.

The scatter kernel in Fig.2 is the approximate system function at 6 cm thickness. As a first order approximation, we could remove the scatter contents of DBT projection image by doing a de-convolution with this kernel. We could also invert the scatter kernel first, and then do convolution of projection images with the inverse filter instead. The inverse filter was obtained numerically in our study and an example of the inverse filter is shown in Fig. 3.

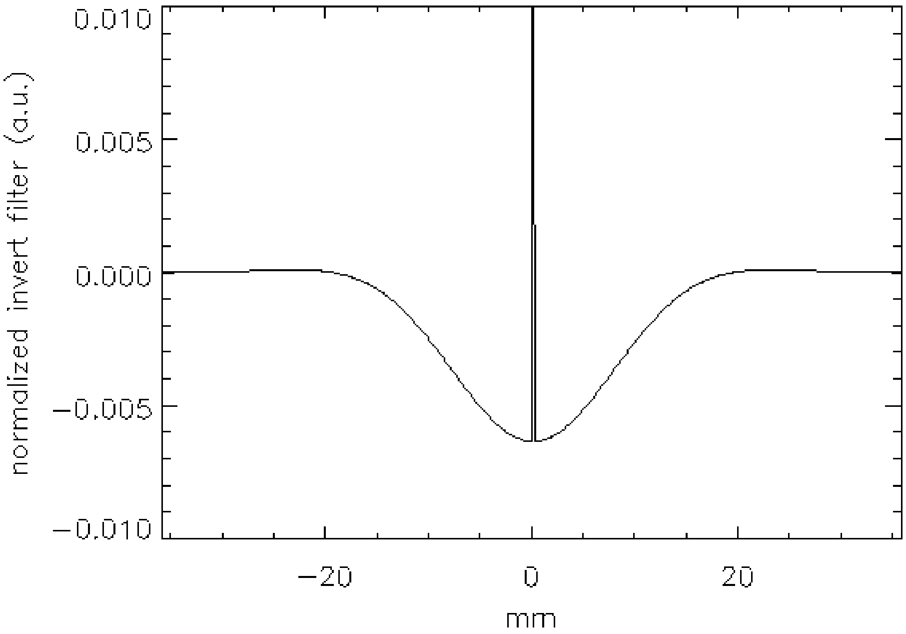

Fig. 3: The inverse system response of the example shown in Fig. 2. The amplitude of the peak is about 1.8. This plot is shown in a narrow display window to view tails better. The filter is used to convolute with the projection images to remove scatters.

Table 1: Comparisons of breast density results between DBT and 2D mammogram for 6 cases for thickness between 6 cm to 7 cm

	Case #1	Case #2	Case #3	Case #4	Case #5	Case #6
thickness mm	70	62	63	65	64	63
3D_kV	35	33	33	34	33	33
3D_filter	Al	Al	Al	Al	Al	Al
view_1	13.8	18.8	17.8	17.8	19.6	15.8
view_2	13.7	20.8	17.1	22.5	22.2	16.8
view_3	12.2	19.6	18.1	17.7	20.4	18.2
view_4	12.7	19.5	18.7	19.7	20.7	19.1
view_5	13.3	20.5	16.7	14.4	21.4	17.2
view_6	14.2	20.5	17	12.3	22.6	17.7
view_7	13.7	19.3	18	19	21.7	18.2
view_8	13	19.3	18.9	18.3	21.4	16.6
view_9	13.4	19.4	18	17.9	21.9	17.4
view_10	13.7	20.3	18.6	18	19.8	18
view_11	12.1	20.4	16.4	18.5	20.4	16.4
view_12	13	21	17.1	19.2	21.1	17.1
view_13	13.9	19.2	17.9	17.3	22.1	18
view_14	12.3	19.8	18.7	na	20.4	18.8
view_15	13.1	20.8	17.1	na	21.3	17.4
3D mean Vbd (%)	**13.21**	**19.95**	**17.74**	**17.89**	**21.13**	**17.51**
2D_kV	32	31	31	32	31	31
2D_filter	Ag	Rh	Rh	Rh	Rh	Rh
2D Vbd (%)	**13.4**	**18.3**	**17.4**	**16.7**	**19.2**	**16.1**
error	-1%	9%	2%	7%	10%	9%

3.3 Comparison of clinical breast density results: DBT versus 2D mammogram

The scatter correction to projection images were done outside Quantra (offline). The images were re-scaled to account for the detector gain change between 3D and 2D, and the lag effect. At last the images were up-sampled from 140 um pixel back to 70 microns resolution before they were processed by Quantra. We selected six combo DBT scans (2D+3D) with thickness between 6 cm – 7 cm as examples to show the performance of our algorithm here. The breast density Vbd of 2D mammogram and 15 DBT projections are given in Table 1. In this study, Vbd was calculated without skin-removal. (In one case, case 4, only 13 of the 15 projection views had Vbd results from Quantra, so for this case alone we present the results using the Vbd of the remaining 13 projections of the scan, and the results are adequate for this paper's comparison and discussion.)

4. DISCUSSIONS

The performance of our algorithm with six clinical cases for thickness between 6 cm and 7 cm demonstrated a relative error between 3D and 2D calculation of within 10%. Since the offline processing was highly manual at this time, we have not processed enough cases to demonstrate the performance at other thicknesses. However, we find that the scatter kernel needs to be finely adjusted for each thickness range to bring the 2D and 3D result into good agreement.

In this study we have ignored the impact from the different tube angle to the breast in DBT projection images, and assumed that each projection image had a zero degree tube angle just like a 2D mammogram. In Selenia Dimensions system, the DBT scan angle θ is from -7.5 degree to +7.5 degree. For a projection with non-zero incident tube angle, the x-ray path length through breast will increase by a factor of $1/\cos(\theta)$ times. When the value of θ is between +/- 7.5 degree, this factor is very close to 1. Therefore the effect of x-ray path length increase inside breast due to non-zero DBT tube angle would be small and can be ignored in this study.

In this study, the shape of scatter LSF was modeled by a Gaussian function, with its width adjusted to match the width of the experimental scatter response curve. As we know, Gaussian function is not the best shape to model the actual scatter response function. We expect that if we refine the shape model to be closer to the experimental, or simply use the experimental shape directly, the scatter correction might be better done. These subjects will be investigated in the follow up study.

5. CONCLUSIONS

A framework to calculate breast density with DBT projection images has been established and our preliminary study with limited number of cases shows promising results. Further development work is needed to make it a more robust algorithm to handle various clinical cases including different thickness, size and density. Our study also shows a unique advantage in using combo 2D+3D scan data in this work, which allows us to develop and optimize the new algorithm against a well-established method.

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