Published in final edited form as:

Proc SPIE. 2011 March 16; 7961: . doi:10.1117/12.878808.

Characterization of Image Quality for 3D Scatter Corrected Breast CT Images

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Abstract

The goal of this study was to characterize the image quality of our dedicated, quasi-monochromatic spectrum, cone beam breast imaging system under scatter corrected and non-scatter corrected conditions for a variety of breast compositions. CT projections were acquired of a breast phantom containing two concentric sets of acrylic spheres that varied in size (1-8mm) based on their polar position. The breast phantom was filled with 3 different concentrations of methanol and water, simulating a range of breast densities (0.79-1.0g/cc); acrylic yarn was sometimes included to simulate connective tissue of a breast. For each phantom condition, 2D scatter was measured for all projection angles. Scatter-corrected and uncorrected projections were then reconstructed with an iterative ordered subsets convex algorithm. Reconstructed image quality was characterized using SNR and contrast analysis, and followed by a human observer detection task for the spheres in the different concentric rings. Results show that scatter correction effectively reduces the cupping artifact and improves image contrast and SNR. Results from the observer study indicate that there was no statistical difference in the number or sizes of lesions observed in the scatter versus non-scatter corrected images for all densities. Nonetheless, applying scatter correction for differing breast conditions improves overall image quality.

Keywords

Scatter correction; computed mammotomography; CT; breast CT; cone beam; beam stop array

1. INTRODUCTION

Scatter is an inevitable obstacle in cone beam CT. It introduces cupping artifacts, reduces contrast, and leads to inaccurate reconstructed attenuation coefficients. We have previously implemented a robust measured scatter correction algorithm that yields quantitative attenuation values within 5% of absolute narrow beam values [3]. Upon applying scatter correction, image quality appears to be greatly enhanced but has not otherwise been quantitatively evaluated.

In this study, scatter correction is applied to a breast phantom containing various lesions with and without additional background structure. From reconstructions of these data sets, signal difference to noise ratios (SNR) and contrast were determined to quantify image quality of the scatter and non-scatter corrected reconstructed data sets. Additionally, human observer studies were performed to detect and qualitatively characterize the lesions at the different radii under the various object configuration conditions. The goal of this study was to characterize the image quality of our dedicated breast CT system for both scatter corrected and non-scatter corrected reconstructed data sets.

2. METHODS

2.1 Experimental Setup

Experiments were conducted using an anthropomorphic breast phantom containing a lesion phantom specifically designed for this experiment (FIG. 1). The lesion phantom consists of a thin ($<0.5\text{mm}$) plastic sheet supported by a thin acrylic annulus. Various acrylic spheres (density of 1.15g/cm^3) were cemented at two radial distances (2.5 and 5 cm). The uniform spheres varied in size from 1-8mm. An approximate volume of 500 mL of loosely packed acrylic yarn was used to mimic structural noise in the background by simulating connective tissue of a breast and having identical density and attenuation coefficients as the acrylic spheres used in the study (FIG. 2).

To simulate the range of breast densities, the breast phantom was filled in turn with 700mL of 3 different concentrations of methanol and water (Table1).

2.2 Data collection with dedicated breast CT

Acquisitions of the breast phantoms with the three different concentrations were performed 5 times under 4 conditions: (1) with the lesions in uniform fluid (background) conditions, (2) with lesions and with acrylic yarn in addition to fluids, (3) without lesions under uniform background conditions, and (4) without lesions and with acrylic yarn and fluids. This yielded 60 independent images that are reviewed by 6 Medical Physicists. Additional measurements were made under the identical fluid and structural background conditions but without any beads.

The CT sub-system is part of a dual-modality dedicated breast SPECT-CT scanner described in detail elsewhere [4]. Primary features include a cone beam tungsten target x-ray source (model Rad-94, *Varian Medical Systems*, Salt Lake City, UT) with a Paxscan 2520 (*Varian Medical Systems*, Salt Lake City, UT) digital flat panel detector having $127\mu\text{m}$ pixels; ultra-thick K-edge spectral beam forming filters produce a quasi-monochromatic beam. At 60kVp tube potential, a 0.051cm cerium filter ($Z=58$, $\rho=6.77\text{ g/cm}^3$, K-edge = 40.4keV, *Santoku America, Inc.*, Tolleson, AZ) was used to produce a cone beam x-ray spectrum at a mean energy of 36keV and a FWHM of 15%. The source-to-image distance (SID) is 60cm, and a 38cm source-to-isocenter distance (SOD) results in a magnification of 1.57 for an object located at the system's center of rotation.

2.3 Acquisition and Scatter Correction

For each phantom condition, 360 projections were collected azimuthally with and without a beam stop array (BSA). The BSA is a $9.5\times9.5\text{cm}^2$ acrylic plate that consists of 130 2mm diameter lead balls spaced 5mm apart on a Cartesian grid (FIG. 3). The BSA is statically mounted on the custom collimator, and scans are performed sequentially. We have previously implemented an algorithm to determine the scatter distribution using the BSA[3]. A 2D scatter distribution for each projection is estimated by cubic spline interpolating the measured average values located behind the shadow of each beam stop inside the object [3]. The final scatter-corrected projections were calculated by subtracting the scatter images containing only a mask of the object from the original corresponding projections without the beam stops.

2.4 Reconstruction and Analysis

The data was reconstructed using a ray-driven ordered subset convex (OSC) algorithm which provided an estimate of the non-uniform attenuation distribution of the object. Reconstruction parameters were set to 5 iterations, 16 subsets, $350\times350\times400$ reconstruction grid, and $508\mu\text{m}^3$ voxel size. Data analysis of the resulting attenuation coefficients used

ROIs to calculate signal-difference-to-noise ratios (SNR) and contrast of all scatter corrected and non-scatter corrected reconstructed data sets.

2.5 Observer Study

Five medical physicists participated in an observer study in order to determine the number of detectable spheres at the different radii under the different measurement and correction conditions. All image readings were done in a controlled environment, typical of a radiology reading room. Each study contained 120 randomly presented stacks of images (approximately 20 slice-stacks per image set) of each of the sphere-containing conditions, as well as non-sphere containing but identical background conditions. Presented images had a fixed window and level, and observers were able to scroll through the 20+ slices per image set. The observers were provided with a schematic of the spheres and given a short training set with obvious and not-so-obvious examples. Each reader was given a form and asked to indicate how many spheres they saw in each of the inner and outer radii. The resulting data was compared for significance using a Student's t-test assuming equal variances at significance level of $p < 0.05$. First, a comparison was done between uniform and yarn background for each of the inner and outer radii, respectively. The Student t-test was used to compare number of spheres seen in the inner vs. outer radius. Finally statistical differences were calculated between scatter and non-scatter corrected images.

3. RESULTS

3.1 Observer Study

The t-test revealed no statistically significant differences between the smallest observable spheres seen in the yarn vs. uniform condition in both the inner and outer radius (FIG. 4). There were also no statistical differences between smallest observable spheres seen in the inner or outer radius for the three different concentrations (FIG. 5). Finally the t-test showed there were no obvious qualitative differences between the average number of observable spheres in scatter corrected and non-scatter corrected conditions for all densities (FIG. 5). As expected, the observer study did show that most of the spheres were detected with the smallest variance in the least dense background (100% methanol). Fewer spheres were detected (along with increasing variance) as background density increased (FIG. 6).

3.2 Line Profiles

As expected, the line profiles through all the images show that attenuation values improve (increase) and cupping artifacts decrease for scatter corrected images (FIG. 7,8,9,10). The line profiles also suggest an increase in contrast of the spheres.

3.3 SNR and Contrast Analysis

Significant improvements were measured in both SNR and contrast in the scatter corrected images (FIG. 11). For the 100% methanol concentration, the increase in SNR ranges from 1% to 23% for the inner radius, corresponding to the reduction in cupping. The scatter corrected SNR of the outer radius follows that of the non scatter corrected SNR closely. The errors range from 0 to 4.8 for the data points. The increase in contrast ranges from 22 to 50% for the inner radius, and 18 to 34% for the outer radius with error bars ranging from 0.006 to 0.01 (FIG. 12). For the 50-50 concentration, the SNR of the scatter corrected image is similar to the non scatter corrected image with error bars ranging from 0.3 to 1.3 (FIG. 11). Contrast improvement for this concentration ranges from 0 to 65% for the inner radius and 0 to 44% for the outer radius with error bars ranging from 0.65 to 1.65. For the 100% water concentration, differences between inner- and outer-ring SNRs and contrasts were

unclear due to large signal variability resulting from a low overall signal. Signal variability ranged from 0.0056 to 1.4 for SNR and 0.003 to 0.016 for contrast (FIG. 12)

4. DISCUSSION AND CONCLUSION

The image quality of our system has been evaluated under scatter corrected and non scatter corrected conditions for a variety of breast compositions.

From the observer study, we found that the most spheres detected with the smallest variance occurred in the least dense background (100% methanol), and fewer spheres were detected (along with increasing variance) as background density increased. This is not surprising. All 8 spheres (down to 1mm diameter) were seen in the lower density cases, while only 4 spheres (down to 3mm in one case) were seen in the most dense background cases. This result is consistent with our earlier results on observability in variously-dense breast phantoms [4]. Results from the observer study did not show statistically significant differences between the average number of observable spheres in scatter corrected and non-scatter corrected conditions for all densities. This result indicates that scatter corrected images did not affect the observers' ability to see more or smaller spheres in the inner or outer radius, in either the uniform or yarn background conditions for all densities. Additionally, there were little differences between observer performance for the least dense and the 50-50 background conditions.

The observer study can likely be improved if we incorporate different concentrations of methanol and water (eg. 70% water 30 % methanol) to get more varied levels of signal differences. More observers could also be included to further study the statistical significance between scatter correction and non scatter correction's influence on number of spheres detected.

As expected, the line profiles of scatter corrected images indicate fewer cupping artifacts, higher attenuation numbers, and increased contrast.

Finally, the plots of SNR and contrast illustrate improvements in the scatter corrected images for all densities and noise conditions. For the 100% methanol concentration, the increase in SNR ranges from 1% to 23% for the inner radius, indicating a reduction in cupping. The scatter corrected SNR of the outer radius follows that of the non scatter corrected SNR closely. The increase in contrast ranges from 22 to 50% for the inner radius, and 18 to 34% for the outer radius. For the 50-50 concentration, the SNR of the scatter corrected image is similar to the non scatter corrected image. Contrast improvement for this concentration ranges from 0 to 65% for the inner radius and 0 to 44% for the outer radius. For the 100% water concentration, differences between inner- and outer-ring SNRs and contrasts were unclear due to large signal variability resulting from a low overall signal.

Based on the results of our study, it is somewhat ambiguous whether scatter correcting images will play a role in clinical lesion detectability. While the observer study did not indicate a significant improvement in the number of spheres detected in the scatter corrected case, the quantitative image metrics including line profiles, SNR, and contrast do suggest an improvement in image quality when the images are scatter corrected.

Acknowledgments

The authors gratefully thank K. Perez, S. Mann, E. McCracken, J. Salazar, and L. Cumberbatch for participating in the long and detailed observer study. The authors also thank Dr. P. Madhav for her assistance and guidance in the scatter correction procedure.

MPT is an inventor of this dedicated CT imaging technology, and is named as an inventor on the patent for this technology awarded to Duke. If this technology becomes commercially successful, MPT and Duke could benefit financially.

6. REFERENCES

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Figure 1.
Lesion phantom used in this study containing acrylic spheres at two radial distances.
Spheres ranged in size (mm) as indicated.

Figure 2.
Photo of the anthropomorphic breast phantom containing acrylic yarn.

Figure 3.
Breast phantom at center of FOV in front of the beam stop array.

Figure 4.

Comparison of smallest observable spheres (mm) for all background mixtures in uniform or yarn background for (RIGHT) Inner radius and (LEFT) Outer Radius with corresponding t-values with $p < 0.05$.

Figure 5. Comparison of smallest observable sphere in (RIGHT) Inner and Outer radius and (LEFT) non scatter and scatter corrected with corresponding t-values using a two-sample t-test assuming equal variances comparing with $p < 0.05$.

Figure 6. Results for observer study indicating mean and standard deviation for number of spheres detected.

Figure 7.
Line profiles in 100% water density in (LEFT) uniform and (Right) yarn background.

Figure 8. Slice through (LEFT) scatter corrected and (RIGHT) non scatter corrected breast phantom containing 100% water in uniform background. Arrows indicate where line profiles in Fig. 7 were taken.

Figure 9.
Line profiles in 100% methanol density in (LEFT) uniform and (Right) yarn.

Figure 10. Slice through (LEFT) scatter corrected and (RIGHT) non scatter corrected breast phantom containing 100% Methanol in uniform background. Arrows indicate where line profile was taken

Figure 11. SNR plots for all densities comparing scatter corrected to non scatter corrected images for the inner radius spheres.

Figure 12.

Contrast plots for all densities comparing scatter corrected to non scatter corrected images for the inner radius spheres.

Table 1

Concentration of methanol and water used to simulate different breast densities.

Composition/ Fluid	Density (g/cm ²)
100% methanol	0.791
50% methanol 50% water	0.896
100 % water	1.00