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Detailed Characterization of 2D and 3D Scatter-to-Primary Ratios of Various Breast Geometries Using a Dedicated CT Mammotomography System

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Abstract

With a dedicated breast CT system using a quasi-monochromatic x-ray source and flat-panel digital detector, the 2D and 3D scatter to primary ratios (SPR) of various geometric phantoms having different densities were characterized in detail. Projections were acquired using geometric and anthropomorphic breast phantoms. Each phantom was filled with 700ml of 5 different water-methanol concentrations to simulate effective boundary densities of breast compositions from 100% glandular (1.0g/cm^3) to 100% fat (0.79g/cm^3). Projections were acquired with and without a beam stop array. For each projection, 2D scatter was determined by cubic spline interpolating the values behind the shadow of each beam stop through the object. Scatter-corrected projections were obtained by subtracting the scatter, and the 2D SPRs were obtained as a ratio of the scatter to scatter-corrected projections. Additionally the (un)corrected data were individually iteratively reconstructed. The (un)corrected 3D volumes were subsequently subtracted, and the 3D SPRs obtained from the ratio of the scatter volume-to-scatter-corrected (or primary) volume. Results show that the 2D SPR values peak in the center of the volumes, and were overall highest for the simulated 100% glandular composition. Consequently, scatter corrected reconstructions have visibly reduced cupping regardless of the phantom geometry, as well as more accurate linear attenuation coefficients. The corresponding 3D SPRs have increased central density, which reduces radially. Not surprisingly, for both 2D and 3D SPRs there was a dependency on both phantom geometry and object density on the measured SPR values, with geometry dominating for 3D SPRs. Overall, these results indicate the need for scatter correction given different geometries and breast densities that will be encountered with 3D cone beam breast CT.

Keywords

Computed mammotomography; breast CT; cone-beam; scatter correction; SPR; beam stop array

1. INTRODUCTION

The purpose of this study is to characterize scatter-to-primary ratios (SPR) in detail for a large variety of (breast) densities, including the clinically unrealizable extremes of 100% fatty and 100% glandular composition, by using the quasi-monochromatic cone beam x-ray CT sub-system of the dual modality dedicated breast SPECT-CT scanner developed in our

lab. Often, 2D SPRs are only determined for a single regular geometrical object as a measure of the system performance and object scatter characteristic that needs correction. However, these simple cylindrical geometries do not adequately address the intersection of the incident 3D cone beam with the spectrum of complex geometrical shapes posed by various pendant breast geometries, nor the consequent interactions modulated by these complex object geometries. By starting with two simple geometrical shapes containing varying densities of uniform fluid, and additionally evaluating an anthropomorphic breast phantom, we can better understand the nature and impact of size, shape and density on the ultimately measured images acquired with dedicated breast CT. These shapes allow for straightforward and intuitive evaluations due to the cone beam irradiation of the target volumes. Use of the anthropomorphic breast phantom better approximates what would be expected to be encountered clinically. By precisely varying the overall phantom shapes and filled densities, we can characterize the effect that both geometrical degradative factors and object composition will have on the SPR in dedicated cone beam breast CT.

2. METHODS

2.1 Object Density Variation

For this study, we investigated various liquids that could potentially be used to simulate different breast densities; we have previously shown that oil and water serve as excellent bounds on simulation breast tissue in the lab². Water and methanol are the closest matches for simulating 100% glandular tissue and 100% fatty tissue respectively (Table 1). Since methanol and water are miscible, varying concentrations of water and methanol can be mixed and used to simulate breast densities with varying uniform glandular/fatty compositions (Table 2). The aqueous nature of methanol also makes it usable for emission radioactive measurements in the breast background when using the SPECT component of our dual-modality imaging system.

2.2 Data collection using the dedicated breast CT sub-system

We utilized two geometric phantoms (conical and cylindrical) and an anthropomorphic breast phantom, each filled in turn with 700mL of varying concentrations of water ($\rho = 1.0 \text{ g/cm}^3$) and methanol ($\rho = 0.79 \text{ g/cm}^3$), to simulate the effective boundary densities from 100% glandular to 100% fat (Table 2). The diameters of the phantoms range from 12 to 20 cm. Not only do the geometric phantoms represent the extremes of the range of breast shapes that are expected to be encountered, but precisely varying the overall breast densities allows us to control both geometrical degradative factors in cone beam CT as well as simulated breast composition.

Experiments are conducted with the CT sub-system of the dual-modality dedicated breast SPECT-CT scanner¹. The phantoms are positioned near the isocenter of the cone beam CT imaging system (FIG 1). The CT component uses a rotating tungsten target x-ray source (model Rad-94, *Varian Medical Systems*, Salt Lake City, UT) with a 0.4/0.8mm nominal focal spot size and 14° anode angle and a 20×25cm² FOV CsI(Tl)-based amorphous silicon digital x-ray detector (model Paxscan 2520, *Varian Medical Systems*, Salt Lake City, UT) with a grid size of 1920 × 1536 pixels and 127μm pitch. A custom-built collimator is attached to the x-ray source to hold ultra-thick K-edge beam shaping filters to produce a quasi-monochromatic beam.² For these studies, a 60kVp x-ray beam with a 1.25mAs exposure per projection and a 0.051cm cerium filter ($Z = 58$, $\rho = 6.77 \text{ g cm}^{-3}$, K-edge = 40.4keV, *Santoku America, Inc.*, Tolleson, AZ) is used. This filter yielded a spectrum that had a mean energy of approximately 36keV and the FWHM of 15%. The source-to-image distance (SID) is 60cm and source-to-object distance (SOD) is 38cm resulting in a

magnification of 1.57 for an object located at the center of rotation of the system. A total of 360 exposures are acquired over the complete 360-degree azimuthal scan.

2.3 Scatter Correction and 2D SPR

For each phantom, projections are collected with and without a beam stop array⁴ (BSA) (FIG. 2). The BSA used is a 9.5×9.5 cm² acrylic plate that consisted of 130 2mm diameter lead balls spaced 5mm apart on a Cartesian grid. It is placed in front of the collimator (~15cm from the x-ray source). The algorithm to determine the scatter distribution using the BSA is based on our previously reported work¹. 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. The final scatter-corrected projections are then calculated by subtracting the scatter images containing only a mask of the object from the original corresponding projections without the beam stops (FIG 3)⁷. 2D SPRs are calculated from the ratios of the scatter projection-to-scatter corrected (primary) projection.

2.4 Reconstruction and 3D SPR

Reconstructions are done using a ray-driven convex ordered subsets algorithm⁵ which provided an estimate of the nonuniform attenuation distribution of the object. Reconstruction parameters were set to 5 iterations, 16 subsets, 350×350×400 reconstruction grid, and 508 μm³ voxel size. The un-corrected data was also individually reconstructed. The uncorrected 3D volume is then subtracted from the corrected 3D data to obtain the scatter volume (FIG 4). 3D SPRs are calculated from the ratios of the scatter volume-to-scatter corrected (primary) volume.

3. RESULTS

3.1 2D Scatter-to-Primary Ratio

SPR profiles through 2D SPR images are measured at 4 indicated locations – Chest (Top), Mid, Nipple (Bottom) and Vertical (FIG 5A, 5B). Thresholding was applied to all images in order to exclude the values outside the breast, which are of no importance for our SPR measurements. SPR values peak centrally in the phantoms, and gradually decrease towards the edges. A comparison of 100% methanol and 100% water-filled phantoms reveals that, water yields the highest SPR, irrespective of breast geometry (Fig 5C).

3.2 3D Scatter-to-Primary Ratio

Measurements are repeated on the 3D reconstructed volumes. Profiles were measured on the transverse slices (FIG 6A). A different profile is seen with the 3D SPR than for the 2D SPRs: there is a distinct peak at the edges of the volume (due to both edge effects and the plastic materials used in the phantoms) with a much lower central value.

These experiments are performed with 5 different uniform background densities. For both, 2D and 3D, the average peak SPR values are measured using a circular ROI that covers parts of the posterior, mid and anterior area of each phantom in the pendant breast geometry. The ROI selection was constant for all geometries and various concentrations. Based on the measurements, we plot the mean 2D and 3D SPRs vs. Density (FIG 7). SPR values for water and methanol form the boundaries and the SPRs for all other background concentrations lie within these bounds.

4. DISCUSSION AND CONCLUSIONS

The measured 2D SPR with different geometries and background densities are consistent with our and others' previous measurements and simulations³. While detailed values may differ due specifically to differences in geometrical shapes and object densities, the 2D SPR trends obtain: values are peaked in the central regions and decrease peripherally; narrower objects have lower overall SPR values; the changing SPRs are smoothly varying for all geometrical shapes. The peak value results here indicate that there is an increasing 2D SPR as the object density increases (Fig. 7), though there is some residual effect due to object geometry.

The measured 3D SPRs have an uncommon appearance, due mainly to the fact that their image representation is a surrogate to the scatter probability at a given point, or voxel. Each voxel in the 3D SPR image can be thought of as the average probability of scatter from all azimuthal angles during the tomographic acquisition of an arbitrary object. The 3D SPR results are in fact quite similar to un-attenuation corrected PET images, which have demonstrably greater scatter and photon penetration at the periphery of an object (there's less attenuation at an object's edges there, along with a larger scatter solid angle away from the object itself). The cone beam breast CT measured 3D SPRs here, similarly demonstrate a maximum at the edges of the phantoms and reduced central region. These results are consistent with the idea of finite point scatters throughout the 3D volume. In 2D (projection mode), this phenomenon is otherwise unobtainable. The peak value results here indicate that there is a relatively unchanging 3D SPR as the object density increases (Fig. 7), though there appears to be a greater effect due to object geometry, however minor the overall values.

The SPR values are overall highest for 100% water (similar to a fully glandular breast), and lowest for 100% methanol (similar to fatty replaced breast). The 2D and 3D SPR values for the other compositions lie somewhere between these boundaries. The 2D values are primarily dependent on the densities of the phantoms, and the 3D values appear to be dependent on object geometry. Future work may more clearly tease apart these results.

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FIG 1.
Photographs of the cylinder (LEFT), cone (CENTER) and anthropomorphic breast (RIGHT) phantoms placed near the isocenter of the cone beam CT sub-system.

FIG 2.
Beam Stop Array (LEFT) and Projection image of a water filled cylinder with the BSA (RIGHT)

FIG 3.
2D projections of a water filled cylinder. Total (Left) – Scatter (Center) = Primary (Right).
The Scatter is higher near the edges (yellow) and lower near the center (blue).

FIG 4.

Reconstructed coronal image slice of the cylinder (FIG 3) for Total (LEFT) and Primary (CENTER) volumes and Scatter volume (RIGHT) calculated as the difference between the reconstructed Total and Primary volumes. The Scatter is higher (yellow) in the center and lower (blue) near the edges.

FIG 5.

FIG 5A: Measured 2D SPRs for the Cylinder (LEFT), Cone (CENTER) and Anthropomorphic Breast (RIGHT) for the 100% water case. SPR values are highest (Yellow) at the center and gradually reduce (blue) toward the edges. Arrows indicate locations of the 4 profiles.

FIG 5B: 2D SPR profiles through the CHEST, MIDDLE and Nipple of 100% water filled Cylinder (LEFT), Cone (CENTER) and anthropomorphic breast phantom (RIGHT). SPR values peak at the center and gradually reduce toward the edges

FIG 5C: 2D SPR profile through the MIDDLE of cylinder (LEFT), cone (CENTER) and anthropomorphic breast (RIGHT). SPR values peak at the center and gradually reduce toward the edges. SPR values for water are always higher than methanol.

FIG 6A

FIG 6B

FIG 6.

FIG 6A: Measured 3D SPR for Cylinder (LEFT), Cone (CENTER) and Anthropomorphic Breast (RIGHT) for the 100% Water case. Arrow indicates location of the profile.

FIG 6B: 3D SPR profile through the MIDDLE of cylinder (LEFT), cone (CENTER) and anthropomorphic breast (RIGHT). SPR values sharply peak at the edges and are reduced centrally. SPR values for water are always higher than methanol.

FIG 7. SPR vs. Density plots for 2D (Left) and 3D (Right). X axis corresponds to the densities simulated by different water-methanol concentrations.

Table 1

Densities (g/cm³) of various fluids investigated.

Fluid	Density
Glucose	1.350
Water	1.000
Corn Oil	0.930
Mineral Oil	0.840
Methanol	0.791
Ethanol	0.789

Table 2Water-Methanol concentrations and their calculated densities (g/cm³)

Water (%)	Methanol (%)	Density (g/cm ³)
100	0	1.000
67	33	0.930
50	50	0.896
33	67	0.861
0	100	0.791