Comprehensive assessment of the slice sensitivity profiles in breast tomosynthesis and breast CT

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Purpose: This study experimentally evaluated the slice sensitivity profile (SSP) and its relationship between acquisition angle, object size, and cone angle. The sensitivity profile metric was used to characterize a breast tomosynthesis system's resolution in the z-axis. The SSP was also measured on a prototype breast computed tomography (bCT) system.

Methods: The SSP was measured using brass disks placed within adipose tissue-equivalent breast phantoms. The digital tomosynthesis system (Selenia Dimensions, Hologic Corporation, Bedford, MA) acquires projection images over a 15° angular range and the bCT scanner acquires projection images over a 360° angular range. Angular ranges between 15° and 360° were studied by using a subset of the projection images acquired on the bCT scanner. The SSP was determined by measuring a background-corrected mean gray scale value as a function of the z-position (axis normal to the plane of the detector).

Results: The results show that SSP improves when the angular acquisition range is increased and the SSP approaches a delta function for angles greater than 180°. Smaller objects have a narrower SSP and the SSP is not significantly dependent on the cone angle. For a 2.5, 5, 10 mm disk, the full width at half maximum of the SSP was 35, 61, 115 mm, respectively, on the tomosynthesis system (at 15°) and was 0.5 mm for all disk diameters on the bCT scanner (at 360°).

Conclusions: The SSP is dependent on object size and angular acquisition range. These dependencies are overcome once the angular acquisition range is increased beyond 180°. © 2012 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4764908>]

Key words: tomosynthesis, breast imaging, image quality

I. INTRODUCTION

Digital mammography is a high resolution imaging modality that has been successful at detecting masses and microcalcifications, both markers of interest for breast cancer screening. Despite the success of mammography in detecting early breast cancer, it suffers from superposition issues owing to its two-dimensional acquisition geometry. The goal of digital breast tomosynthesis (DBT) is to overcome superposition issues by generating images which have limited angle tomographic properties. In February of 2011, a DBT system (Hologic Corporation, Bedford, MA) was approved by the U.S. Food and Drug Administration (FDA) for breast cancer screening. The system acquires projection images over an angular range of 15°. The work presented here was motivated by the need to understand the relationship between tomographic angle and tissue superposition properties. Given the inherent geometry used in DBT, overlapping structures are not fully resolved.¹ Breast computed tomography (bCT) has been shown to produce coherent 3D images of the breast,

with good resolution and at realistic dose levels, but has not yet been deployed as a clinical tool.^{1,2} A research prototype bCT system designed and fabricated in our laboratory produces 3D images of the breast by acquiring 500 projection images over 360°.³

The slice sensitivity profile (SSP) quantifies the amount of signal spreading from one adjacent plane to another in a tomographic imaging modality, and it is analogous to the line spread function perpendicular to the detector plane or in the z-axis.⁴ Several investigators have developed analytical models,^{5,6} simulations,⁷ or have performed experimental⁸⁻¹⁰ studies of SSP for various tomographic imaging systems. What sets this work apart is that the SSP was physically measured on a commercially available DTS system and the measured parameters were extended to larger angles up to 360° using a breast CT system. Brass disks ranging in diameter from 2.5 to 20 mm, similar to the size of glandular densities found within the breast in the (x, y) plane¹¹ were sandwiched between adipose-equivalent mammography slabs and used to measure SSP. The narrowing of SSP as angular acquisition

FIG. 1. Rendering of the system geometries and phantom used in this study. (a) DBT unit which acquires images over a 15° angular range (detector stays stationary). (b) The bCT unit where source and detector rotate 360° . (c) 100% adipose tissue equivalent mammography slabs with brass foil disks inserted between the slabs, phantom thickness varied.

range increases is well known, however, to date a comprehensive empirical analysis spanning from 15° to 360° has not been reported.

The aim of this investigation was to quantify the effects of limited angle tomography using the SSP metric using physical experiments. The work here evaluates SSPs dependency on angular acquisition range, object size, and cone angle.

II. METHODS AND MATERIALS

II.A. Imaging systems

A prototype DBT system (Hologic Dimensions, Bedford, MA) was located in our laboratory in 2009 and was used for part of this investigation. The system acquires 15 projections by rotating the x-ray tube over a 15° angular range, as shown in Fig. 1(a), at the end of the tomosynthesis acquisition, a mammogram is acquired. The detector is a selenium flat panel employing direct conversion with a pixel pitch of 0.070 mm, and 2×2 pixel binning (resulting in a 0.140 mm detector element) is used in tomosynthesis mode. The detector pivots about the axis of rotation. Detailed description of the system hardware has been previously reported.¹² The projection data acquired on the tomosynthesis system are used with a cone beam reconstruction algorithm to produce the tomographic images. The reconstructed voxel dimensions were 0.120×0.120 mm in the (x, y) plane, and the spacing between reconstructed images (the voxel pitch in the z-dimension) was 1.0 mm.

A dedicated breast CT scanner, designed and assembled in our laboratory, was also used to acquire images in this study. A detailed description of the bCT scanner, which has similar characteristics, has been previously reported.¹³ The scanner uses a flat panel detector (PaxScan 4030CB, Varian Medical Systems, Salt Lake City, UT) with a CsI scintillator and with a detector element size of 0.388 mm in 2×2 dynamic gain mode. The x-ray source to isocenter distance of the system was 511 mm and the source to detector was 1037 mm corresponding to a magnification factor of about 2.03 for an object located at the isocenter.¹⁴ The scanner acquires 500 projection images in 17 s with a continuous rotation over 360° , Fig. 1(b). Images were acquired and reconstructed using a Feldkamp cone beam CT algorithm.¹⁵ The raw data set with

a reconstruction slice spacing (voxel pitch) of 0.23 mm produces five hundred twelve 512×512 tomographic images. The inplane pixel dimensions of the bCT system are dependent upon the size of the breast, as the variable sized field of view is fit within the 512×512 matrix in the coronal plane for reconstruction.

II.B. Acquiring images

A number of circular disks made from 25 μm thick brass foil were fabricated with diameters of 2.5, 5, 10, 15, and 20 mm. The brass disks were placed between 100% adipose tissue-equivalent mammography slabs (CIRS, Norfolk, VA), Fig. 1(c). The phantom thickness was varied from 30 to 60 mm for the DBT studies and the brass disk position along the z-axis was varied by 10 mm over the full thickness of the phantom. The phantoms containing the disks were positioned in standard breast imaging positions, with the plane of the embedded disks located normal to the central ray. The auto-exposure settings on the tomosynthesis system were used to image the phantoms and disks.

To evaluate the influence of tomographic angle on the SSP, subsets of the 500 breast CT projection images were used to compute tomographic images data sets with smaller angles: 15° , 30° , 40° , 60° , 90° , 120° , and 180° . The limited-angle data sets were then reconstructed using the unmodified Feldkamp algorithm generating 512^3 bCT data volumes. The bCT images were acquired in the x-z plane but were analyzed in the y-z, axial plane, maintaining a perpendicular object-to-detector plane geometry similar to the DBT setup. The same phantom, shown in Fig. 1(c), was used for a total thickness of 10 cm. The phantom was placed at the isocenter of the bCT scanner and imaged using 80 kVp and 10 mA (166 mAs for 360°). To assess the influence of the cone angle of the bCT system, the disks were translated vertically in 2 cm increments, which corresponds to the PA dimension in the context of a breast imaged in the scanner.

II.C. Image analysis

The raw data from the DBT unit were converted to reconstructed 16-bit images using the vendor provided gView software. These images were loaded into MATLAB (7.8, The MathWorks Inc., Natick, MA, 2009) for data analysis. For each disk, a circular region of interest (ROI), with area equal to that of the disk, was drawn in the in-focus image (x-y plane), centered at the disk. The ROI dimensions and x-y locations were kept constant and translated through the image slices, along the z-axis, Fig. 2. The mean gray scale value was determined for each ROI along the entire thickness of the phantom (Fig. 2). An identical analysis was performed on the bCT image data. The image data set was corrected for any scan angle offset such that the disks would be parallel to the detector. Image data from the limited angle reconstructions were generated using a subset of frames from the full 360° acquisition. The reconstructed images were loaded into MATLAB, the ROI locations and positions were identified using the 360° image set. These ROI dimensions and locations

FIG. 2. Illustration of image analysis. For each disk, a ROI was drawn and the mean gray scale was measured and plotted against the location along the z-axis for each image throughout the phantom volume.

were kept constant for the analysis of the limited angle data. A background ROI, equivalent to the size of the ROIs used for the disks, was measured within each slice of the volume and subtracted from the mean gray scale value of the disk measured at that slice. The background corrected mean gray scale value measured at each slice corresponds to a single value along the SSP and was normalized to a maximum of unity (Fig. 2).

II.D. Clinical trial

Women who have been identified as Breast Imaging Reporting and Data Systems (BI-RADS) category 4 or 5 lesions have been recruited to participate in an ongoing clinical study of breast CT which began in November 2004.^{16,17} All patient studies have been performed according to protocols approved by the institutional review board and Radiation Use Committee. As of 2010, protocols have been modified to include a comparison of DBT. To date there have been over 100 women imaged on both breast CT and DBT.

III. RESULTS

III.A. DBT studies

The SSPs for DBT were measured using phantom thicknesses of 20, 30, 40, 50, and 60 mm, however, the thinner phantoms did not capture the tails of the SSP and are not shown here. The SSPs shown therefore are all for the 60 mm thick phantom (Fig. 3). Images were acquired using a tube voltage of 45 kV and current of 55 mAs. Figures 3(a)–3(c) show SSPs with gray scale normalized at the location of the center of the brass disks for each profile. The disks were displaced vertically along the z-axis, normal to the detector by 20 mm increments, in Figs. 3(a)–3(c). The full width at half maximum (FWHM) value was determined for the three smallest disks—the FWHM for the larger disks could not be determined because they are wider than the field of view in the z-dimension. Figure 4 shows the FWHM as a function of disk diameter. Using linear extrapolation to zero disk diameter, it

FIG. 3. Plots of normalized gray scale values of brass disks positioned at (a) 10 mm, (b) 30 mm, (c) 40 mm from the detector on the DBT system.

is seen that an infinitesimally small object in (x, y) , would have a FWHM value of 8.0 mm. The best fit line parameters in Fig. 4 have a slope of 10.686 mm/mm with a y-intercept of 8.0 mm ($r^2 = 0.9999$). The results shown here clearly illustrate that with the geometry used in tomosynthesis, the width of the SSP is dependent on object size. That is, the effective z-axis resolution is dependent upon the structure dimensions in the (x, y) plane.

III.B. Breast CT studies

Figures 5(a)–5(c) show the normalized gray scale value as a function of angular acquisitions of 15°, 30°, 40°, 60°, 90°, 120°, 180°, and 360°. As angular acquisition range increases, the SSP narrows, approaching a delta function for all three sized disks [Figs. 5(a)–5(c)]. There is near complete overlap

FIG. 4. Full width at 50%, 75%, and 90% maximum gray scale value as a function of disk diameter for DBT. Y-intercept of the linear fits suggests that 50%, 75%, and 90% of the maximum intensity of an infinitesimally small object is blurred over 8, 6.7, and 5.1 mm, respectively.

of the 180° and 360° data. The FWHM value for the three disks was measured using the profiles in Fig. 5, and are plotted in Fig. 6. As angular acquisition range increases, the dependency of object size on FWHM is reduced and ultimately eliminated once images are acquired beyond 180° (these lines have a slope of zero). At 15° using linear extrapolation, an infinitesimally small object has a FWHM of 6.6 mm and at 360° the FWHM drops to 0.5 mm. Figure 7 is a plot of FWHM as a function of angular acquisition for the 2.5, 5, and 10 mm disks. The three disks overlap in FWHM once the acquisition angle $\geq 180^\circ$ (Fig. 7).

Figure 8 illustrates the cone angle dependency on the SSP for the 2.5 mm disk quantified by the FWHM as angular acquisition is varied from 15° to 360°. The 15° data do indicate some dependency; however, this can be attributed to the noisy nature of this limited angle data set. In general, there is no significant dependency on angular acquisition range and cone angle for the SSP. The 180° and 360° data show significant overlap in Fig. 5 as well.

Figure 9 shows the coronal image for the disks as a function of angular acquisition range. Visually, it is clear from this composite image that the z-axis resolution improves with increasing angular coverage. Given the near “truth” images of the cross section of the disk along the right column in Fig. 9 (360°), the images in the left column (15°) demonstrate considerable out-of-plane blur that extends through much of the breast volume.

Figure 10 makes use of a clinical example to illustrate the impact of the relative widths of the SSP between modalities. In Fig. 10(a), a cranial caudal mammogram is illustrated showing a soft tissue mass, as indicated by the arrow. A composite of 12 tomosynthesis images are shown in Fig. 10(b), and the arrow indicates the location of the lesion throughout the entire thickness of the breast, from 0 to 55 mm along the z-axis. The contrast of the lesion runs throughout the breast, and is plotted in Fig. 10(c). Figure 10(d) illustrates the axial breast CT images of this same lesion, and it is clear that the lesion is only visible in two of the 12 images spaced 5 mm apart. This lesion is approximately 10 mm in diameter, and therefore it would be expected to span at least two of the CT

FIG. 5. Normalized gray scale values as a function of slice sensitivity profile for angular ranges of 15°–360°. (a) 2.5 mm disk, (b) 5 mm disk, (c) 10 mm disk. These data were measured using breast CT images.

images with 5 mm spacing. Figure 10 illustrates a clinically realistic example of the differing extent of the SSP between tomosynthesis and breast CT. In a more complicated (denser) breast, it can be assumed that the contrast leakage through the entire extent (along the z-axis) of the breast [as seen in Fig. 10(b)] has the potential to contribute to the anatomical complexity of the individual tomosynthesis images, and this is fundamentally due to the considerable extent of the SSP in tomosynthesis. The consequences of this have been demonstrated by quantitative measures of the anatomical noise in the breast,¹¹ where the anatomical noise metric (β) between

FIG. 6. Full width half maximum measured as a function of disk diameter at angular acquisition ranges of 15°–360°.

tomosynthesis and mammography was equal, while that of breast CT was significantly different.

IV. DISCUSSION

There is a direct relationship between the improvement of z-axis image resolution and increasing angular coverage during image acquisition. The results of this investigation support previous simulation and theoretical studies on DBT system optimization, which demonstrate that the slice sensitivity profile improves with increasing angular acquisition range.^{6,18–23} Wu *et al.*²⁴ described out-of-plane blurring as the artifact spread function (ASF) and showed that the amount of blurring is affected by the reconstruction algorithm employed. The ASF improves (less blurring) as the angular acquisition range is increased.²³ It is clear that structures with larger extent in the (x, y) plane have a broader SSP along the z-axis; this effect has a greater impact at lower angular acquisition ranges and essentially disappears at acquisition angles greater than 180°.

There is a slight SSP dependency on cone-angle at 15°, but the data (Fig. 8) suggest that little or no cone angle dependency is seen with larger acquisition angles. Note that the

FIG. 7. Full width half maximum plotted as a function of angular acquisition (in degrees) for 2.5, 5, and 10 mm disks.

FIG. 8. Full width at half maximum as a function of cone angle for 2.5 mm disk.

15° data set uses 15/360 (4.2%) of the radiation of a full 360° scan. In general, no substantial cone-angle dependency was observed.

Figure 4 illustrates the dependency of the SSP (in the z-dimension) on the dimensions of an object in the (x, y) plane in 15° tomosynthesis. The extrapolated values to the vertical axis are for an object with very small (x, y) dimensions, such as a microcalcification. However, the size scale of glandular islands in the adipose breast background, which comprise the anatomical noise in the breast, are much larger than this. From Fig. 4, it can be seen that a hypothetical glandular structure with circular symmetry and with a diameter of 2 mm would have a SSP of approximately 30 mm and a structure with a 3 mm diameter would cast >50% of its contrast to about 40 mm. Glandular structures of these dimensions are prevalent in the dense breast and correspond approximately to spatial frequencies ranging from 0.17 to 0.25 cycles/mm.¹¹ The implication of Fig. 4 is that the limited angle nature of tomosynthesis does not completely remove anatomical noise due to superpositioning—indeed, the contrast generated by a 3 mm diameter spherical glandular island in an otherwise adipose background spans 80% of the thickness of a 50 mm thick breast (i.e., 40/50 mm). These observations may have implications as to how efficient tomosynthesis is in terms of reducing the anatomical (structured) noise in the breast, and recent work demonstrates that the anatomical noise in tomosynthesis is equivalent to that of mammography and far different from breast CT.¹¹ This was also illustrated here by example in Fig. 10.

Mertelmeier *et al.* showed two 1 mm diameter metal balls with a center-to-center distance of 6 mm in the z-direction could only be resolved at an angular acquisition range greater than 40°. At lower angular ranges these objects were seen as one.²² The clinical impact of this is that the localization of two clusters of interest may be overlapped.

A simulation study of a GE prototype breast tomosynthesis system reported by Zhang *et al.* at the University of

FIG. 9. Coronal bCT images of 2.5–15 mm diameter disks at increasing angular ranges. Z-axis resolution improves significantly beyond 180°.

FIG. 10. A soft tissue mass is visible on axial (or CC) views of three modalities. (a) The mass lesion is clearly visible on the CC mammogram (arrow). (b) The arrow points to the same lesion as seen on the CC tomosynthesis images, and the contrast of the lesion is visible throughout the extent of the breast—from the superior edge (0 mm) to the inferior edge (55 mm) of the breast. (c) Plots of the lesion contrast in the CC tomosynthesis image and breast CT. (d) In comparison, the breast CT images are illustrated in the same plane as the tomosynthesis images, and here it is apparent that the lesion is only visible in the axial images corresponding to 35 and 40 mm through the breast—there is no discernable lesion contrast that extends beyond the lesion, either in the inferior or posterior directions.

Michigan investigated different imaging parameters and two reconstruction algorithms.¹⁰ The dimension of the point object imaged was equal to the size of one reconstructed voxel and the projection images generated were noiseless. The FWHM at 15° for the back projection (BP) reconstruction algorithm was about 7.5 mm. Our experimental findings, which included noise, were produced on the Hologic unit which reconstructs using a filtered BP is 8 mm, Fig. 4. Similarly, the FWHM of the SSP measured on the breast CT system at 15° was 6.5 mm. The coefficient of variation for these measurements is 10.4%, quite good given the difference in geometry and design between the GE and Hologic tomosynthesis units and the bCT system. Zhang showed improvements to SSP by utilizing a simultaneous algebraic reconstruction technique; others have also showed improvement by means of iterative reconstruction algorithms.²⁴

Using an analytical method, Li *et al.* derived a theoretical model for the SSP of linear trajectory tomosynthesis. This work was validated using simulation studies, an edge phantom and an anthropomorphic chest phantom imaged at 20°, 40°, and 60° using body tomosynthesis.²¹ The results of their work are difficult to compare directly to the findings that are presented here given the numerous differences in the experimental setup, acquisition parameters, and phantom. The authors reported half width at half maximum (HWHM) values for the SSP calculated in their edge phantom to be 3.04 and 2.01 mm for 40° and 60°, respectively. Our HWHM values from the bCT studies at 40° and 60° have a range of 3.7–4.8 and 2.8–4.7 mm, respectively, depending on disk diameter (Fig. 5). It is observed that the measured values here are within the same magnitude to those made by previous investigators.

Moving away from two-dimensional imaging of the breast and toward the use of tomographic imaging techniques is a step toward better understanding the breast anatomy with the potential of earlier detection of suspicious lesions.^{2,3,25–27} This work demonstrates these improvements when angular acquisition range is increased using physically acquired images.

There are several factors to be considered when optimizing tomosynthesis for breast imaging. Several investigators have studied the effects of system geometry, imaging technique factors, dose to the patient, and reconstruction algorithm.^{19,22,24,28–34} The dependencies described in this investigation may be useful when considering the geometry of new imaging systems for the breast and other clinical applications.

V. CONCLUSION

An experimental based evaluation of the SSP and its dependency on angular acquisition range was investigated. It was found, as expected, that as angular acquisition range increases, the SSP becomes narrower, approaching a delta function above 180°. The SSP does not have a dependency on cone angle, however, the object dimension in the (x, y) plane has a profound impact on the z-axis resolution.

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