An Introduction to Multiplanar Reconstructions in Digital Breast Tomosynthesis

by

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ABSTRACT

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Multiplanar reconstruction (MPR) in Digital Breast Tomosynthesis (DBT) allows for tomographic images to be portrayed in any orientation. In this thesis, an x-ray imaging phantom was designed to study MPR for DBT. The phantom has the capability of orienting a star resolution pattern in any three dimensional plane. The phantom resembles a globe with two hemispheres and latitudinal and longitudinal increments of 15° around the entire dome. The hemispheres are cut extruded with a shallow cylindrical cavity that houses the star resolution pattern. The measurements that were used to quantify resolution of MPR for DBT are limiting spatial resolution and modulation contrast. The results of two dome orientations confirm that resolution decreases as orientation obliquity increases and that super-resolution is achieved in the direction of x-ray source motion. This research describes that presented in Vent et al. [1].
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Chapter 1

Introduction

1.1 Breast cancer

Breast cancer is the second most diagnosed cancer for women in the United States. It is estimated that 40,290 women are expected to die this year from breast cancer. This is the second highest mortality rate for cancer in women – the first being lung cancer [8]. A major part in combating breast cancer is diagnosing the disease. This study examines the capabilities of a current digital breast tomosynthesis (DBT) system and multiplanar reconstructions (MPR) for it.

1.2 Computed Tomography scan

Computed Tomography (CT) scans are completed by taking raw projections of x-rays that range from 0° to 180° or 360°. The conventional view that radiologists use for this type of scan are axial slices. A multiplanar reconstruction is any plane that does not match one of the conventional axial slices. This is why CT scans are considered the x-ray imaging gold-standard for multiplanar reconstruction (MPR). This is something that is expected for CT. Since there are so many x-rays casting shadows from all different directions, they can use filtered back projection to reconstruct an image in almost any form. Some multiplanar reconstructions prove to be more useful in diagnosing disease to radiologists. As an example, the carotid artery scan can be seen as an axial plane, sagittal plane, or a 3D surface rendering shown in Figure 1.1.
Figure 1.1: This figure is an example that shows three common reconstructions for a carotid artery CT scan. Image (a) is an example of reconstruction slices that are axial. Image (b) is a perpendicular, sagittal reconstruction, and image (c) is a 3D surface rendering for CT [3].

1.3 Digital Breast Tomosynthesis

Digital breast tomosynthesis is a relatively new imaging modality – only having been used clinically since 2011 – so research is necessary to improve the capabilities of both the hardware of the machine and the software of the reconstructions. Improving the characteristics of these systems will decrease the occurrence of false positive, or even worse, false negative diagnoses.

The motivation behind this study is to validate the ability of MPR and super-resolution (sub-pixel resolution) in digital breast tomosynthesis. The Hologic © DBT system takes 15 raw x-ray projections along a circular arc from roughly -7.5° to 7.5°. These projections are then reconstructed with software and a digital three dimensional image is made by stacking reconstruction slices on top of one another. In diagnostics, a radiologist views the slices of
the reconstruction to diagnose the patients instead of viewing the three-dimensional image as a whole. The basic components of a DBT system consist of: x-ray tube, breast support, detector, and a compression paddle. A digital breast tomosynthesis system is shown in Figure 1.2.

Figure 1.2 Hologic DBT System

1.4 Multiplanar reconstructions

Multiplanar reconstruction (MPR) is an image reconstruction method that allows the reconstruction of tomographic images in any plane, at any depth, and any magnification. The conventional software installed on a DBT system is limited to slices that are reconstructed parallel to the breast support of a DBT system. It has been shown that this method of reconstruction is not always the best for showing breast micro calcifications [5]. Figure 1.3 illustrates the difference between the conventional software and the MPR software.
This study investigates resolution and contrast of MPR for DBT. The optimization of these two analyses will help improve breast cancer diagnostics. We created an MPR phantom for the purpose of testing different reconstructions for unique planar orientations.

1.5 MPR phantom

In medical imaging, a phantom is a term used for anything that is imaged for the analysis of imaging devices. Phantoms have recently been used to test the capabilities and limitations of MPR for DBT [4,5]. Two of these tests are limiting spatial resolution and modulation contrast. In this study, we constructed a phantom to test resolution and contrast of MPR for a commercial DBT system. Figure 1.4 shows the MPR phantom that we created and the test object that we placed inside it. The phantom is referred to as the Dome Phantom and the test object is referred to as the star pattern [1].
1.6 Star pattern

The star pattern is used for measuring contrast and resolution. It is very thin and consists of transparent plastic and lead. The angle between the lines on the star pattern is 1°. For each plane of the star pattern, we analyzed two frequencies (phantom orientations) [1]. The plane of the star pattern is capable of being analyzed for four different phantom orientations: 0°, 90°, 180°, and 270°. We chose the 0° and 90° that change to 45° and 135° when there is a phantom rotation of 45°. The example of this is in Fig. 1.5.
1.7 Motivation

The purpose of this study is to quantify limiting spatial resolution and contrast at various frequency orientations and to quantify resolution of oblique reconstructions for DBT. We have designed and built a phantom to achieve these specific goals. This research is supplemental to research conducted with multiplanar reconstructions in 2013 [5]. That study was limited to one change in orientation (tilt of the star-pattern about the axis that is parallel to the breast support and perpendicular to the direction of x-ray tube motion), while this research addresses three variable rotations to achieve unique orientations. The reconstructions are done to view the star pattern in the plane for which it is rotated instead of viewing the slices of the reconstruction axially as most software does. This project was conducted to guide the design of new tomosynthesis imaging systems.
Chapter 2

Methods

2.1 Phantom design & fabrication

To vary the star-pattern orientation with three degrees of freedom, a multiplanar reconstruction phantom (referred to as the dome phantom) was designed with SolidWorks (Dassault Systèmes, Vélizy-Villacoublay, France). The phantom is a dome with two separate hemispheres. Each hemisphere has longitudinal and latitudinal lines on the surface. They are incremented from the center of the dome by 15° increments according to two perpendicular axes – just like a globe. Inside, each hemisphere has a cylindrical cavity that together house the star pattern. The dome is placed in a cylindrical encasement with a hemispherical cavity that contains 15° notches. The notches correspond to the grooves on the surface of the dome and guide the dome in its rotations. The point where the longitudinal lines converge is referred to as the apex. This axis of rotation goes through each apex. A test object is inserted into the middle of the dome phantom, inside of a shallow cylindrical cavity. An illustration of the design of the dome phantom can be seen in Fig. 2.1 [1].
Figure 2.1: Dome Phantom design. It consists of the (a) top hemisphere with star apex, (b) bottom hemisphere with star apex and cylindrical cavity (shallow) that houses the test object, and (c) Dome phantom in cylindrical encasement with the star apex at the 0° dome rotation (top half of the cylindrical encasement is removed for clarity).

Following its design, the phantom was printed using a 3D printer (Stratasys UPrint SE Plus, Rehovot, Israel) in Penn’s Biomedical Library. The material used was ABSPlus filament, which has a low x-ray attenuation coefficient, to minimize interference with the star pattern images and resultanty the modulation contrast. Fig. 2.2 shows the finished product.

Figure 2.2: The dome phantom after it was 3D printed.

2.2 Image acquisition

Images of the star test pattern were acquired, by means of the dome phantom, using a Hologic DBT system (Hologic, Bedford, MA USA) in the Hospital of the University of Pennsylvania. A tomosynthesis image is required to create a multiplanar reconstruction. One tomosynthesis image consists of 15 raw projections that are taken along a 15° arc. The star pattern was imaged at 45 mAs and 29 kVp with an aluminum filter and tungsten target. The
detector of this system has 140 μ resolution, making the aliasing frequency 3.6 line pairs millimeter (lp/mm).

The star pattern was imaged at four phantom angles of 0°, 45°, 90°, and 135°. These angles are all in the same plane of reconstruction. For each phantom angle, we imaged dome rotations at 0° and 90°. For each dome rotation we imaged tilts from 0° to 180° in 15° increments. The dome phantom has the capability of imaging the star pattern in any orientation, so these results are only a sample of all the possible orientations.

Images of the star test pattern were obtained using the dome phantom on the breast support at the center of the detector’s field of view and along the chest wall edge. We hypothesized that at the center of the detector, resolution would be symmetric about the tilt angle from 0° to 180° for some of the reconstructions. The dome phantom’s encasement was secured to the breast support with paper and tape so that when the tilt angle was changed after every image, the phantom would not shift out of place [1].

### 2.3 Dome phantom rotations

The star test pattern was imaged in the dome phantom with a series of rotations (phantom, dome, and tilt). The phantom rotation refers to the rotation of the star test pattern within the dome hemispheres. Dome rotation is the rotation of the dome with respect to its cylindrical encasement about the z-axis; the dome orientation of 0° is represented in Figure 3. The source motion in Figure 2.3(a) is shown as linear for simplification, whereas the actual source motion is circular [1].
For a dome rotation of 90°, the tilt rotations occur about the x-axis. In Figure 2.4, the dome is rotated about the z-axis by 90°. This changes the phantom orientations within the dome. Figure 2.4 illustrates this change for a dome rotation of 90°.
The star test pattern has four perpendicular frequencies that are referred to as the phantom orientations. This allows for the analysis of two phantom orientations for each reconstruction plane, phantom orientations of 0° and 90° for example. The first set of frequencies analyzed were the phantom orientations of 0° and 90°, at the dome rotation of 0°. When the star pattern frequency is aligned with the positive x-axis, it refers to a phantom orientation of 0° at a 0° dome orientation. When the dome rotates, the phantom orientations change accordingly.

2.4 Image reconstruction

The images were reconstructed using commercial reconstruction software, (Piccolo, Real Time Tomography, Villanova, PA). This software allows the reconstruction plane to match the plane of the star pattern. The reconstruction plane can be oriented to view the object at a plane that is not parallel to the breast support. An illustration of these multiplanar reconstruction is displayed in Figure 2.5.

![Figure 2.5](image)

*Figure 2.5:* This figure shows the orientation of the MPR reconstructions. (a) The plane view of the star pattern at a 30° tilt. (b) is a diagram comparing the MPR reconstruction slices to the conventional slices [1].
2.5 Determinants of resolution

Once the images were reconstructed, two measures of spatial resolution were calculated. We quantified the resolution by calculating the limiting spatial frequency at the highest visible frequency. Contrast at the lowest set spatial frequency – at the circumference of the circle around the star pattern – was also calculated. Once the images were reconstructed, we used the plot profile to perform the calculations. Repeating the measurements ten times gives the 95% confidence interval for limiting spatial resolution.

2.5.1 Limiting spatial resolution

Limiting spatial resolution was calculated by finding the maximum visible frequency of the star pattern in ImageJ [7]. This value was determined by finding the highest visible frequency for which there are 14.5 distinct wave peaks in the plot profile. See Figure 2.6.

![Plot profile example](image)

**Figure 2.6:** Example of the plot profile at the maximum visual spatial resolution. [1,7]

The maximum visible frequency shows distinct wave peaks and troughs that are degraded in Figure 2.5. By inspection of the plot profile, one can see the 29 peaks and troughs. It is possible to calculate the maximum spatial resolution from this plot profile, but is easier at a lower spatial frequency. Figure 2.7 is an example of more distinguishable peaks and troughs to show the principle of calculating the spatial resolution at a lower frequency with more certainty.
Figure 2.7: This is an example of the plot profile at a low frequency [1,7].

The calculation of limiting spatial resolution is represented in the following equation. For simplicity, the number of line pairs is represented by $\kappa$ and the distance that all of the peaks span is represented by the character, $\delta$.

$$\text{Resolution} = \frac{\text{line pairs}}{\text{distance (mm)}} \equiv r = \frac{\kappa}{\delta} \quad (2.1)$$

The limiting spatial resolution was measured by visual inspection for each orientation ten different times, therefore $n = 10$. This was done to perform the calculation of uncertainty in the limiting spatial resolution. The error represented in our results of the resolution is given by the standard 95% confidence interval in the following equation:

$$95\% \text{ confidence interval for } r = \bar{r} \pm 1.96\left(\frac{\sigma}{\sqrt{n}}\right) \quad (2.2)$$

The $\sigma$ in the equation represents the standard deviation and $n$ represents the number of repetitions of the measurement. The yellow box in Figure 2.6 is an example of the visual representation of this error. This means that one viewing this file should determine the maximum visible frequency to be somewhere within this box. The value, $\bar{r}$, is the average resolution of the ten measurements [1].
2.5.2 Modulation contrast

To calculate the contrast at every tilt, we measured the intensities at the lowest spatial frequency of the star-pattern in the plot profile. This is the point at which the frequencies meet the circumference of the circle around the star pattern. A representation of this analysis can be seen in Figure 8.

![Figure 2.8: Modulation contrast is calculated where the frequency meets the circumference of the circle on the star pattern [1].](image)

The equation for modulation contrast is given by the Michelson equation:

$$\text{Contrast} \equiv C = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}$$  \hspace{1cm} (3)

Contrast was calculated by determining the maximum and minimum gray values ($I_{\text{max}}$, $I_{\text{min}}$) in the plot profile for each line pair. As can be seen in the plot above, not all of the peaks and troughs are the same. Because of the deviation, the uncertainty was calculated by averaging the calculation of each line pair. The uncertainty is represented in the results by the 95% confidence interval, just like limiting spatial resolution. In this case $n = 14$, (the number of line pairs) and $\bar{C}$ is the average of contrast for each line pair.

$$95\% \text{ confidence interval for } C = \bar{C} \pm 1.96 \left( \frac{\sigma}{\sqrt{n}} \right)$$  \hspace{1cm} (4)
Chapter 3

Analysis and Results

3.1 Overview

This chapter summarizes the results for each of the different orientations. The results of limiting spatial resolution and modulation contrast are shown side by side for each orientation to give clarity to the reader. The following diagrams represent each orientation. Each dome orientation was imaged 13 times in 15° increments from 0° to 180°.

3.2 Dome orientation of 0° phantom orientation of 0°

This first orientation resembles the study conducted by Acciavatti in 2013 [4,5]. At the 0° tilt, the frequency of the star pattern is parallel to x-ray source motion. As the plane is tilted, super-resolution (sub-pixel resolution) is expected based on previous work [5]. A diagram showing this orientation, and the results of limiting spatial resolution and modulation contrast are shown in Figure 3.1.

(a)  
(b)  
(c)

Figure 3.1: Diagram and results for the dome 0° and phantom 0° orientation [1].
In Figure 3.1(a), the frequency being analyzed is represented by the sinusoidal wave in the tilt plane. The black dots show the x-ray source positions for the scan. The diagram shows the tilt plane of 30° as an example. Figure 3.1(b) shows the calculated results for the limiting spatial resolution. The thick black line represents the aliasing threshold. Super-resolution is achieved up to near 60° of tilt angle. Figure 3.1(c) shows the modulation contrast. Many of the confidence intervals overlap, suggesting that the modulation contrast is constant until higher tilt angles. The contrast does not degrade significantly until near 60°, like the graph of limiting spatial resolution. Figure 3.2 qualitatively shows the degradation of the limiting spatial resolution for this orientation.

![Figure 3.2: Limiting spatial resolution is shown in the images of the star pattern frequency for the phantom orientation of 0° [1].](image)

The highest limiting spatial resolution of the three sample angles in Figure 3.2 is seen at the 0° tilt. The limiting spatial resolution is near 6 lp/mm, coinciding with the results of
Acciavatti’s study in 2013 [5]. The highest limiting spatial resolution at the 60° tilt is below the aliasing frequency. The limit of resolution is higher in the reconstructions than it is in the raw projections. The raw projections also show more artifacts from the plastic of the dome phantom than the reconstructions. Figure 3.3 shows the difference between the raw projections and the reconstruction. The limit of resolution in the reconstruction is near 6 lp/mm whereas the limit of resolution in the raw projection is slightly above 3 lp/mm.

![Raw Projection vs Reconstruction](image)

**Figure 3.3:** This figure shows the difference in quality between the raw projections and the reconstruction. [1].

### 3.3 Dome orientation of 0° phantom orientation of 90°

The second orientation analyzed is of the same reconstruction plane, but a different frequency. The phantom orientation of 90° corresponds to the frequency that is aligned perpendicular to the plane of x-ray source motion. The tilts of this orientation are the same as before. With the frequency perpendicular to x-ray source motion, it is assumed that aliasing will be present in the reconstructions and that there will be minimal change in resolution and contrast. The diagram and results of this orientation can be seen in Figure 3.4.
Figure 3.4: Diagram and results for the dome 0° and phantom 90° orientation [1].

The orientation being analyzed is again represented by the sinusoidal wave in the diagram. It is parallel to what is defined as the y-axis or the posteroanterior direction. The results of Figure 3.4(b) for limiting spatial resolution show that the resolution is constant up to a tilt angle of 75° and symmetric about the tilt angle of 90°. The resolution is always below the aliasing threshold, determining that this orientation does not achieve super-resolution. For the modulation contrast the error bars overlap to an even higher tilt angle than the phantom orientation of 0° [1].

3.4 Dome orientation of 90° phantom orientation of 0°

The dome rotation of 90° and the corresponding tilt angles are shown in Figure 3.5(a). This orientation also changes the plane of reconstruction. Now the tilt occurs about the x-axis. The 0° phantom orientation now corresponds to the frequency that is parallel to the y-axis at the 0° tilt. The diagram of this orientation and the results can be seen in Figure 3.5. The tilt is now occurring about the x-axis, and as a result, there is more degradation of limiting spatial resolution as the obliquity increases. The limiting spatial resolution for this
orientation is the lowest for all tilt angles. The current orientation shows degradation of limiting spatial resolution as soon as 30° of obliquity. The modulation contrast shows the same pattern, degrading at lower tilt angles than the dome 0° phantom 90° orientation, but the error bars still overlap at the lowest tilt angles.

This orientation is the same reconstruction plane, but the frequency being analyzed is now different. The frequency is parallel to the plane of x-ray source motion at all tilt angles. There is minimal change in the limiting spatial resolution and contrast until higher obliquities. The diagram and results for this orientation can be seen in Figure 3.6. This orientation shows the broadest range for achieving super-resolution. Most of the reconstruction planes have a limiting spatial resolution value around 6 lp/mm. The only angle for which super-resolution is not achieved is the 90° tilt orientation. The modulation contrast also remains high and constant for the same number of tilt angles as the dome 0° and phantom 90° orientation.

3.5 Dome orientation of 90° phantom orientation of 90°

Figure 3.5: Diagram and results for the dome 90° and phantom 0° orientation [1].

![Diagram and results for the dome 90° and phantom 0° orientation](image)

![Diagram and results for the dome 90° and phantom 0° orientation](image)
3.6 Dome orientation of 0° Phantom orientations of 45° and 135°

The following two orientations correspond to a phantom rotation within the dome. The phantom orientation of 45° reorients the frequencies that are being analyzed. This phantom rotation now aligns the frequency across the diagonal of the pixels in the detector. This changes the aliasing frequency threshold to 5.09 lp/mm, which is given by: 3.6 (lp/mm) · sec(45°). This phantom rotation is shown in Figure 3.7. The tilts are the same as they were for the dome orientation of 0° in Figure 2.3. The results of this orientation for both of the phantom angles of 45° and 135° can be seen in Figure 3.8.

Figure 3.6: Diagram and results for the dome 90° and phantom 90° orientation [1].

Figure 3.7: Example of the change in orientation for a phantom rotation of 45°.
These two orientations are shown together because of their symmetry. The results show that they are very similar. For limiting spatial resolution (Fig. 3.8(b)), all of the confidence intervals for the 45° overlap with those of the 135° orientation. It is important to note that the aliasing frequency required to achieve super-resolution has now changed to the thicker black horizontal line at 5.09 lp/mm. This means that for these two phantom orientations, super-resolution is only achieved until an obliquity of just under 30°.

3.7 Dome orientation of 90° phantom orientations of 45° and 135°

The final orientation that was analyzed was of a dome rotation of 90° for the previous phantom orientations. This changes the orientation of the tilts to be about the x-axis. The orientation of the frequencies that are being analyzed has now changed. The aliasing frequency for this orientation is still 5.09 lp/mm.

The results show the lowest range of obliquities that achieve super-resolution. It is important to note, however, that the phantom orientations of 45° and 135° are anti-symmetric about the tilt angle of 90°. Regarding limiting spatial resolution, the phantom orientation of
135° has higher limiting spatial resolution than the orientation of 45° until an obliquity of 90° and vice-versa from 90° to 180°. This shows that resolution is greater near the edge of the breast support and degrades as the frequency moves farther into the field of the detector. The diagram and results of this orientation can be seen in Figure 3.9.

**Figure 3.9:** Diagram and results for the dome 90° and phantom 45° and 135° orientations [1].
Chapter 4

Conclusion

4.1 Conclusion

We have shown that tomosynthesis supports oblique reconstructions over a broad range of obliquities. We have quantified the quality of oblique reconstructions in terms of low-frequency contrast and limiting spatial resolution. Low-frequency contrast is nearly constant over a broad range of obliquities. The contrast also drops to near zero at high obliquities [1]. We have also shown that limiting spatial resolution decreases with increasing obliquity. Super-resolution (sub-pixel resolution) is achieved for any component of the frequencies that are aligned parallel to x-ray source motion. This was previously shown by Acciavatti in 2013. That study was conducted at the dome 0° and phantom 0° orientations for tilts from 0° to 90° [5]. We verified that super-resolution is not achieved for frequencies perpendicular to x-ray source motion. We verified that super-resolution and the alias frequency vary with phantom angle due to the orientation of the frequency with respect to the detector’s pixels.

The dome MPR phantom is a useful tool in analyzing limiting spatial resolution, but has limitations. Due to its construction, the dome phantom interfered with the calculation of modulation contrast. The plastic filament created artifacts in the images for orientations at low obliquities, but few artifacts for the higher obliquities. Inside the dome phantom, the density of the plastic filament differs, and the x-ray images show a cross-hash pattern. The pattern of artifacts resulted in high uncertainties for the calculation of modulation contrast at
lower obliquities. They did not interfere with the calculation of limiting spatial resolution.

Figure 4.1 shows the more prominent artifacts at the plane of 0° tilt and less at a tilt of 30°.

![Figure 4.1: The artifacts at a 0° tilt are more prominent than at a 30° tilt for a dome orientation of 0° [1].](image)

### 4.2 Future work

The dome MPR phantom is capable of orienting the star pattern in any plane. This study considered only two dome rotations, but many other dome rotations should be analyzed with corresponding tilts. The rotation of the star pattern with respect to the phantom should also be analyzed. 104 frequencies have been analyzed with this data set. The dome phantom is capable of orienting the star pattern at 15° incremental angles for dome rotations, tilt rotations, and phantom rotations from 0° to 360°. Due to the artifacts in the images, future MPR phantoms will be constructed with solid plastic.

In regard to calculations of limiting spatial resolution and modulation contrast, the assumption of normality of the Gaussian distribution was assumed for the error. The variables of $C$ and $r$ of equations (1) and (3) assume Gaussian distribution. An analysis of this representative error will be investigated in the future. As the final results suggest, the
dependence of resolution and contrast with respect to the position of the dome phantom on the breast support should also be analyzed for MPR. We assume that the results will not be symmetric for different positions on the detector. The symmetry of the x-ray source changes according to the position of the object on the breast support. We assume that it is not symmetric at other positions on the breast support and will be investigated in the future.
References


Appendix A

Presentation slides are online.