Design Considerations in Optimizing a Breast Tomosynthesis System

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Introduction

Breast tomosynthesis, also referred to as three-dimensional (3D) mammography, has been available for clinical use in numerous countries outside of the United States (U.S.) since 2009. In February 2011, the U.S. Food and Drug Administration (FDA) approved the Hologic Selenia® Dimensions® 3D (breast tomosynthesis) system, making it the first, and currently, the only commercially available breast tomosynthesis system in the U.S. As such, interest in the area of breast tomosynthesis has grown tremendously.

The FDA based its approval on Hologic's clinical studies, which showed that tomosynthesis imaging combined with conventional digital mammography results in superior system performance compared to 2D mammography alone.[1]

This paper looks at the physics of a breast tomosynthesis system and discusses the parameters that Hologic considered in designing the Selenia Dimensions 2D/3D system (Dimensions).

Selenia Dimensions 2D/3D Technical Parameters

Parameter	Value
Scan time	< 4 seconds
Total scan angle	15 degrees
Number of projections	15
Acquisition modes	2D, 3D, Combo (2D and 3D in one compression)
kVp range	25-49 kVp
X-ray tube current	200 mA maximum
Reconstructed slice separation	1 mm
Reconstruction time	2-5 seconds
Reconstructed pixel size	Approximately 100 microns
2D pixel size	70 microns

Table 1. Technical parameters used in the Hologic Dimensions® tomosynthesis system

The Physics of Breast Tomosynthesis Imaging

Conventional x-ray mammography is a 2D imaging modality, and as such, pathologies of interest are sometimes difficult to visualize. As shown in Figure 1, overlapping or superimposed tissues create a clutter of signals above and below the objects of interest. This occurs because the signal detected at a location on the digital detector is dependent upon the total attenuation of all the tissue between the detector and the x-ray beam.

In a 2D image, overlapping tissue can hide objects of interest, potentially resulting in missed cancers. Conversely, normal structures in the breast that overlap may give the appearance of lesions, leading to unnecessary recalls.

Tomosynthesis is a 3D imaging modality that can reduce or eliminate the tissue superimposition effect.

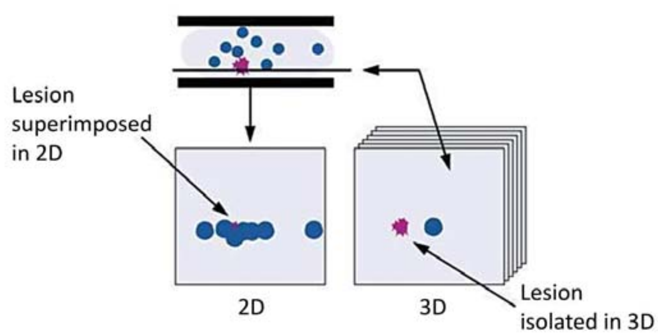

Figure 1. Overlapping structures can hide lesions in 2D that are clearly seen in a 3D cross-sectional slice.

Figure 2 shows the basic design of a breast tomosynthesis system. The breast is compressed in the standard way between a compression paddle and the detector housing. While keeping the breast stationary, the x-ray tube is moved in an arcuate motion, and a series of low-dose images, known as projections, are taken at different angular

[1] The Hologic clinical studies presented to the FDA as part of Hologic's PMA submission showed that 2D plus 3D imaging resulted in superior system performance compared to 2D mammography alone. See http://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfTopic/pma/pma.cfm?num=P080003

locations of the tube. The total angular range covered by the x-ray tube is known as the scan angle.

Following the scan, the projections undergo a reconstruction process, which consists of computing high-resolution images with planes parallel to the breast support plate. The number of reconstructed slices will depend upon the thickness of the compressed breast and the desired separation between slices, which is typically around 1 mm. The reconstructed slices are then transmitted to a diagnostic workstation for review by a radiologist.

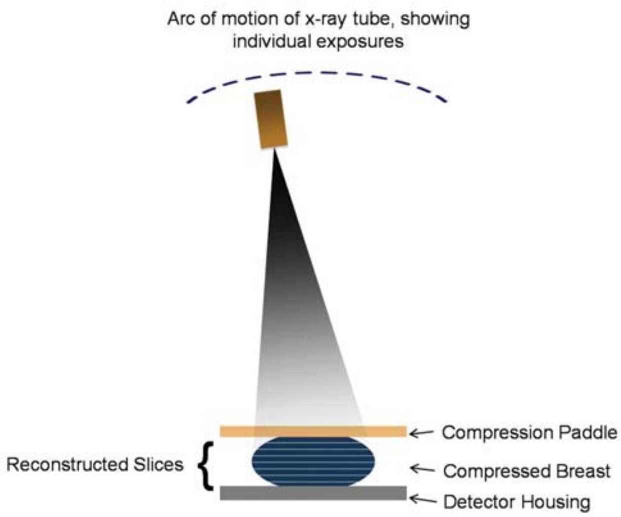

Figure 2. Schematic showing principle of operation of tomosynthesis system.

Selection of System Design Parameters

The design of a tomosynthesis system involves the optimization of many different parameters. First and foremost, a breast tomosynthesis system must successfully reduce the effect of overlapping tissue. Of equal importance, the design criteria should be balanced to ensure an end product that functions properly in both screening and diagnostic applications. Design parameters for an optimally effective system should satisfy the following requirements:

- Works well for screening imaging (asymptomatic women)
- Works well for diagnostic imaging (symptomatic patients)
- Supports both conventional 2D imaging and tomosynthesis
- Improves clinical performance over digital mammography alone
- Provides fast scan time to reduce patient motion
- Can acquire tomosynthesis images in all desired orientations (i.e. CC, MLO, LM, ...)
- Provides rapid reconstruction to support screening patient throughput
- Facilitates comparison to priors
- Supports tomosynthesis-guided interventions and biopsies
- Keeps radiologist reading times short enough to be suitable for screening

In addition to overcoming the effects of superimposed tissue, the optimal tomosynthesis system must also provide the image quality needed to properly visualize calcifications, masses, architectural distortions and asymmetries.

Although the highest value for tomosynthesis may be in screening applications, the optimum tomosynthesis system must also work well in diagnostic imaging. The system must allow all standard conventional diagnostic – as well as tomosynthesis – imaging. Conventional diagnostic imaging is needed because some views, such as magnification views, cannot be done with tomosynthesis and may still be needed for patient work-ups. In addition, an ideal breast tomosynthesis system must be able to support tomosynthesis-guided interventional procedures, as some abnormalities that require biopsy may only be visible in the tomosynthesis mode.

The following sections describe different design parameters and how they affect the functionality of a tomosynthesis system.

Scan Time

Scan time is probably the single most important performance metric for a breast tomosynthesis system.

Scan times must be short for two key reasons: to support a reasonable patient throughput and more importantly, to reduce blurring caused by patient motion. Currently, no tomosynthesis system is capable of matching the short scan times associated with conventional mammography. Even mammography has occasional cases of patient motion; therefore, it is expected that patient motion will be present in some tomosynthesis cases. This problem is exacerbated for tomosynthesis scans longer than a few seconds.

Through the evolution of its tomosynthesis technology, Hologic has seen a significant reduction in the incidence of patient motion, from 18 seconds in its early prototype to 10 seconds in the system used for the clinical trial to

3.7 seconds in its commercially released Hologic Selenia Dimensions system.[2] Reduction of scan time to an absolute minimum is therefore critical, as patient motion as small as 0.1 mm can degrade the sharpness of microcalcifications and tumor spiculations. Figure 3 demonstrates the effect of patient motion on microcalcifications.

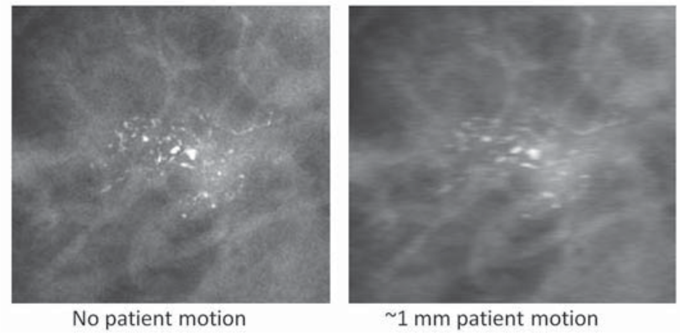

Figure 3. Effect of patient motion on sharpness of microcalcifications

Scan Angle

There are a number of factors that must be considered in the selection of the scan angle to be used in a breast tomosynthesis system. Determining the optimum scan angle should be based on which factors most effectively support system design goals. The scan angle for a system designed for both screening and diagnostic applications must support rapid scan times, while preserving the ability to effectively visualize microcalcification clusters and masses.

Narrow scan angles allow the most rapid scans. However, because the depth of field decreases as the scan angle increases[3], they may not reduce overlapping structures as much as wider scans. In general, as the scan angle increases, the out-of-plane resolution is superior; however, the trade-off is a degradation of the in-plane resolution.

As scan angles increase, confounding effects of superimposed tissue might decrease, but microcalcifications will appear less sharp due to the degradation of the in-plane resolution.

Some other issues with a wide scan angle include:

- A reduced field of view due to shadows of the breast missing the detector at the widest angular projections
- Increased noise and scatter due to the thicker effective breast thickness
- Degraded detector resolution due to oblique incidence of the x-rays.

Another issue with wide scans angles is the potential for the edge of the compression paddle to interfere with the beam path, as seen in Figure 4. While this can be solved by making the compression paddle wider than the detector, it can lead to breast positioning issues. However, by far the most significant disadvantage of a wide-angle scan is the difficulty in keeping the scan times short enough to reduce the likelihood of patient motion and to support screening throughput.

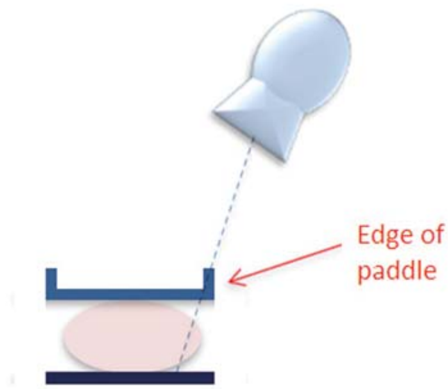

Figure 4. The edge of the compression paddle can interfere with projections at wide scan angles.

Field of View Versus Scan Angle

The field of view (area that is visible) is affected by scan angle. With a stationary detector, shadows of some parts of the breast will miss the detector when large scan angles are used, reducing field of view. It will always be possible for tissue to be outside of the field of view, even in 2D imaging; however, the fraction of additional missed tissue is insignificant for shallow projection angles and increases to significant levels for wide scan angles.

Figure 5 illustrates the field of view for a 50° total scan angle compared to the 0° stationary conventional mammographic acquisition. As the scan angle increases, the effective size of the breast that can be fully imaged decreases. For an 8-cm thick breast and a 50° total scan angle (±25°), the field of view is reduced by approximately 4 cm on each breast side. This reduces the size of the breast that can be fully imaged by almost 8 cm.

[2] Ren B, Zhang Y, Ruth C, et al. Automatic patient motion detection in digital breast tomosynthesis. Proc SPIE 2011 (in press).
[3] Ren B, Ruth C, Stein J et al. Design and performance of the prototype full-field breast tomosynthesis system with selenium-based flat-panel detector. Proc SPIE 5745 (2005): 550-561.

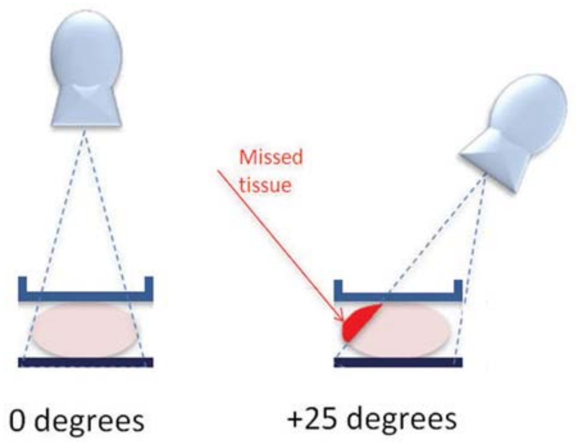

Figure 5. The field of view is impacted by the tomosynthesis scan angle. As the scan angle increases, the effective size of the breast that can be fully imaged decreases.

Figure 6 shows the field of view reduction that occurs as a function of tomosynthesis total scan angle for an 8-cm thick breast. Wider scan angles lead to a progressively larger loss of field of view. Projections from the wider scan angles do not contribute to the reconstructions at the upper slices. If not properly normalized and accounted for, they can increase noise due to fewer projections available in the reconstruction; in addition artifacts can be introduced. Artifacts can also occur at wider scan angles unless care is taken to ensure such objects as the face shield and/or the patient's head do not appear in the field of view.

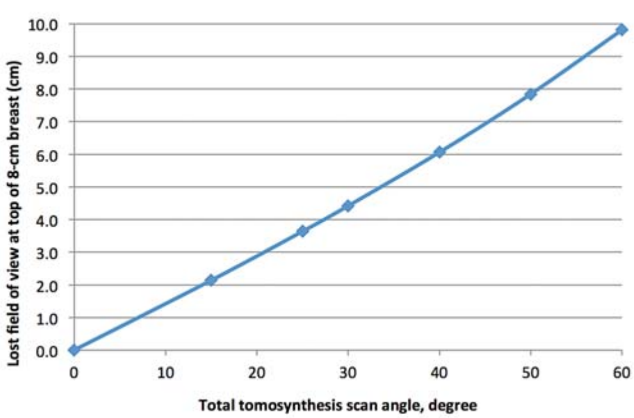

Figure 6. The total field-of-view reduction at the top of an 8 cm breast as a function of scan angle. Larger scan angles can reduce the field of view significantly. The field-of-view loss is smaller for smaller breasts, larger for larger breasts.

Effect of Scan Angle on Image Resolution

Objects appear sharpest for the narrowest scan angles, with the limit of a non-scan such as 2D mammography having the highest theoretical resolution. This somewhat non-intuitive result is shown in Figure 7. In this figure, the appearance in a given slice of an object that extends axially for a certain distance is simulated, shown here to be about 3 in arbitrary units. With a single overhead exposure (0º scan), the object's width is seen to be its original size of 1.00. For a 15º scan, the projection into the slice is broadened slightly to about 1.05, and for a 50º tomosynthesis scan, the object's size is blurred to 2.11. A larger scan angle can broaden the object, decreasing the resolution and sharpness of objects in the slice.

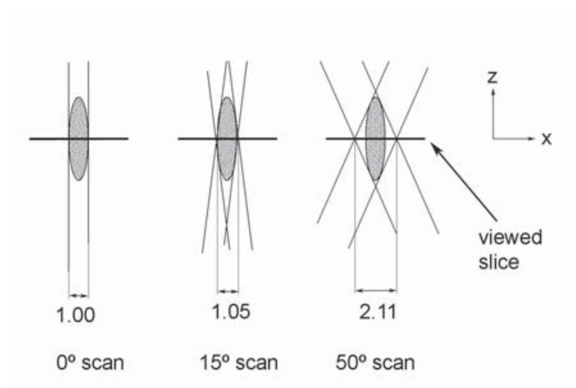

Figure 7. In-plane sharpness of objects degrades at larger scan angles.

Oblique Incidence Versus Scan Angle

The absorption of x-rays in a radiation detection layer will occur at various depths. For x-ray trajectories at larger scan angles, this will degrade the resolution of the image.[4] As illustrated in Figure 8, the x-ray could be absorbed at points "a," "b" or anywhere along the line. If the absorption occurred at point "a," it would be detected in pixel 1, whereas if it were absorbed at point "b," it would be detected in pixel 2. This effect of resolution degradation becomes worse as the scan angle increases. This effect occurs in both cesium iodide (CsI) and amorphous selenium (a-Se) detectors.

[4] Badano A, Kyprianou I, Jennings R. Anisotropic imaging performance in breast tomosynthesis. Med Phys. 34 (11): 4076-4091 (2007).

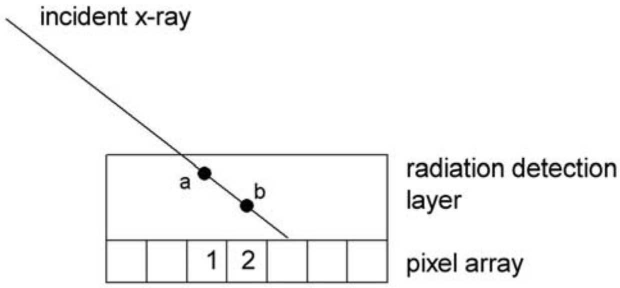

Figure 8. Resolution degrades due to oblique incidence at the largest scan angles. An incoming x-ray can be detected in more than one pixel.

As seen in Figure 9, for shallower scan angles, there is no resolution degradation. Regardless of whether the x-ray is absorbed at point "a" or "b," the signal will be detected in the same pixel 1.

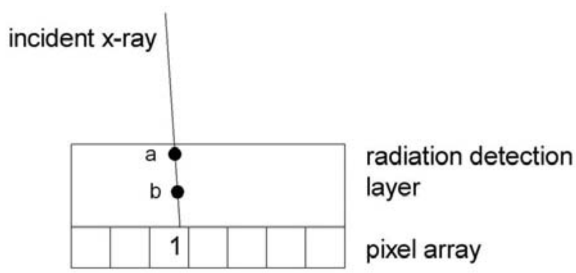

Figure 9. The resolution does not degrade when the incidence angle of the x-ray is narrow.

Number of Projections

Another tomosynthesis system design consideration intertwined with scan angle refers to projection sampling, or the number of projections per degree-scan-angle taken during the scan. Too few projections result in missed sampling and can generate reconstruction artifacts. Too many projections result in a fixed total dose being divided among many projections, which results in a very small dose per projection. With too many projections, electronic noise could begin to dominate. Wider scan angles need more projections to avoid the under-sampling problem and the introduction of image artifacts.[5] Even if electronic noise is not a significant design concern, it is difficult to keep scan times short as the number of projections increase. Detector readout times can then become a limiting factor, unfavorably increasing the scan time.

Continuous Scan Versus Step-and-Shoot Scans

There are two common methods of moving the x-ray tube during the acquisition: continuous and step-and-shoot. In step-and-shoot systems, the x-ray tube moves to each angular position, then stops and takes an exposure, then moves to the next location. In a continuous scan system, the x-ray tube moves in a generally uniform velocity throughout the scan.

The rationale of the step-and-shoot motion is that the x-ray tube is stationary during the exposure, avoiding problems with focal spot blur due to tube motion. However, it is very difficult to make a step-and-shoot system that mechanically works in a very rapid scan time. In addition, any residual mechanical shaking or instability associated with stopping the tube in such a system can also introduce focal spot blur.

With a continuous scan, the x-ray tube is being pulsed during the tube motion. The challenge is to have a short pulse width to avoid blurring of the image. Pulse widths can be made quite small through the use of high mA x-ray generators and x-ray filters designed specifically for 3D imaging. The existing 2D filters are usually thicker and would reduce x-ray flux, resulting in longer exposures. A smaller scan angle will reduce the angular speed for a given scan time, contributing to a reduction in focal spot blurring.

On the contrary, a larger scan angle will contribute to increased focal spot blurring with a potential negative effect on microcalcification sharpness. Longer scan times reduce the focal spot blur through slower tube velocity, but a more appropriate solution for a screening mammography system is to narrow the scan angle.

Taking all factors into consideration, the continuous scan motion is probably preferable because of the fast scan capability, and because, despite the continuous motion, the level of pulse width blurring is clinically insignificant.

Spatial Resolution

Pixel size or final image spatial resolution must meet the clinical requirements for mammography. A commonly used feature to decrease detector readout time and reduce noise is binning. This refers to the summation of multiple smaller pixels in a detector to generate a larger signal. State-of-the-art detectors can seamlessly switch from binned to non-binned mode as a mammography unit switches between 3D and 2D imaging modes.

[5] Ren B, Wu T, Smith A. The dependence of tomosynthesis imaging performance on the number of scan projections. Astley et al (Eds.): IWDM 2006, LNCS 4046: 517-524 (2006).

Binning detector pixels does result in a reduction of the intrinsic spatial resolution, but with a-Se detectors, their intrinsically high resolution results in a high-resolution image, even with 2x2 binning. This is illustrated in Figure 10. As shown, the modulation transfer function (MTF) resolution performance of a 2x2 binned 70-micron a-Se detector is, in fact, superior up to about 4 lp/mm, compared to a 100-micron mammography detector using CsI as the radiation detection element.[6] Studies have also shown how appropriate reconstruction methods can generate extremely high-resolution tomosynthesis images using binned detectors.[7]

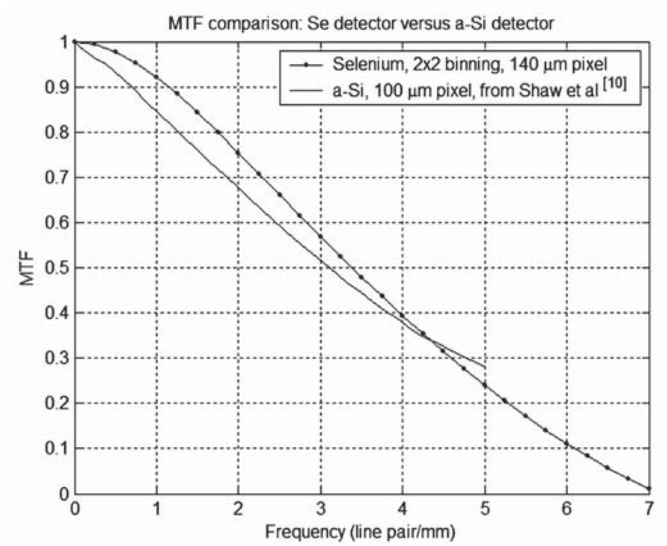

Figure 10. MTF of binned selenium detector compared to 100 micron CsI detector

The advantages of detector binning in allowing faster scan times can outweigh the disadvantage of lower resolution – as long as the final resolution meets the clinical needs. Ultimately, clinical trials prove the performance and efficacy of the system.

2D and 3D Imaging

A breast tomosynthesis system that can perform both 2D and 3D imaging is convenient and has a number of advantages. In normal clinical use, alternating between 2D and 3D imaging of different patients requires a system with the capability of switching modes quickly. Therefore, being able to rapidly switch between both modes is key.

In screening applications, acquiring images for both the 2D and 3D examinations under the same compression is also desired. The 2D image is useful for many reasons: for comparison to 2D priors, for evaluating left/right asymmetry and for the rapid appreciation of microcalcification clusters. Microcalcifications are not as affected by superimposed tissues as masses are, and they are generally well visualized in a 2D image, particularly in systems with intrinsically high resolution. The 3D image is valuable for identifying masses and distortions, as well as for overcoming the effects of superimposed tissue.

Combo-mode

Combo-mode imaging with the Selenia Dimensions system provides the ability to acquire 2D images and 3D scans in the same compression. Not only is this convenient for the technologist, but it also benefits patients because it minimizes the number of compressions and the time under compression. In combo-mode, the Hologic system first performs a 3D scan, and then the x-ray tube returns to the perpendicular and acquires a 2D image. Because the 2D and 3D scans are acquired in the same compression, the image sets are co-registered. Therefore, any object in a given x, y location in the 3D image will have the same object in the same x, y location in the 2D image.[8] Reviewing co-registered images allows readers to toggle back and forth between the two datasets. Combo-mode is also useful for Computer-aided Detection (CAD), which will be discussed in further detail later in this paper.

Researchers are currently looking into methods for creating a reconstructed 2D image from the 3D dataset, which would eliminate the need to separately acquire a 2D image during the procedure. When this technology is optimized, clinical trials will be needed to validate the performance of the reconstructed 2D image.

Reconstructed Slice Thickness

If reconstruction is done with too few slices, a sharp object may never be properly visualized. If there are too many slices, reading time may be increased without improving diagnostic outcome. For example, with a scan angle of 15°, a small microcalcification object will remain sharply in focus in approximately two 1-mm-thick slices. In this case, reconstructing the object into 0.5 mm slices will double the number of slices that need to be reviewed and would likely not improve diagnostic performance because now, the same calcification will be seen sharply in four slices. There will be too many adjacent slices that appear similar. If, on the other hand, reconstruction is done in slices with 2 mm separation, potentially in no slice would an object appear maximally

[6] Ren B, Ruth C, Stein J et al. Design and performance of the prototype full-field breast tomosynthesis system with selenium-based flat-panel detector. Proc SPIE 5745 (2005): 550-561.
[7] Acciavatti RJ, Maidment ADA. Investigating the potential for super resolution in digital breast images. Proc SPIE 2011 (in press).
[8] Ren B, Ruth C, Wu T et al. A new generation FFDM/tomosynthesis fusion system with selenium detector. . Proc SPIE 7622 (2010): doi: 10.1117/12.844555

sharp. Thus, there is a relationship between scan angle and slice thickness. For wider scan angles, there is a need to reconstruct objects into thinner slices to avoid the problem of the objects never appearing sharply in focus. Thinner slices mean more slices and an increase in the radiologist's reading time. At the moment, no breast tomosynthesis clinical studies exist showing any value for slices thinner than 1 mm.

Thinner slices can also degrade the user's ability to appreciate a microcalcification cluster, since in a given slice, only a subset of the calcifications will appear sharply in focus. One way to improve calcification cluster visibility is to do some type of summation to create thicker slices; however, these summation algorithms often degrade resolution, and add additional steps for the reviewing radiologist.

Reconstruction Algorithms

Reconstruction time is another important design parameter in tomosynthesis systems. Of course, image quality is critical, but reconstruction times must obviously be fast enough to support screening patient throughputs, and they must be performed in seconds if tomosynthesis is going to be used in interventional procedures.

Investigations have been made using such iterative reconstructions methods including variants of Maximum Likelihood (ML), Algebraic Reconstruction Techniques (ART), as well as the simpler, but more computationally efficient Filtered Back Projection (FBP) method. Filtered back-projection algorithms are able to reconstruct a volume much more rapidly, and through the use of appropriate filtering, they appear virtually indistinguishable from the slower iterative methods.[9] Hologic uses FBP because customer preference studies found no significant image quality differences between ML, ART and FBP. Moreover, the rapid reconstruction speed is enormously advantageous, particularly for screening throughput.

Reading Time, File Sizes, PACS Issues, Workstation Tools and More

There are many issues that arise in a tomosynthesis system based on the large datasets inherent in a 3D image. The Picture Archiving and Communication System (PACS) must have adequate bandwidth to transmit the large images, as well as sufficient storage. Perhaps the biggest challenges are in the design of diagnostic workstations. These workstations must support virtually instantaneous loading and display of the tomosynthesis images. In addition, they must provide tools to support viewing and navigating through the slices, as well as measuring x, y, z locations. Some researchers suggest tools like "slabbing," where the effective slice thickness is increased, to better facilitate the appreciation of microcalcification clusters.[10] Finally, tools to toggle between the 2D and 3D image may enable radiologists to more quickly review images.

The development of such workstations, particularly by PACS companies, is in its infancy, and as a result, significant advances in reviewing efficiencies are expected in the future.

Figure 11. Example of tomosynthesis diagnostic workstation

Tomosynthesis in the Future

Tomosynthesis Interventional Procedures

Because tomosynthesis exams may uncover lesions that would not be visible using other imaging modalities, a tomosynthesis system should support the ability to perform tomosynthesis-guided interventional procedures. Consideration should be given to the system requirements needed to support tomosynthesis-guided biopsy. For example, a long source-to-image distance (SID) is useful to allow room for installation and deployment of biopsy device hardware. In addition, image reconstruction algorithms that minimize the artifacts from metal objects such as needles are needed.

Reconstruction time affects how long the patient is continuously under compression, as well as enables an efficient workflow, which is particularly important in a busy practice. As a result, reconstruction time in the order of seconds is critically important in tomosynthesis-guided interventional procedures. A biopsy procedure can entail several acquisitions, including scout, pre-fire and post-fire scans, so rapid scans are also highly desirable in such a system.

[9] Ren B, Ruth C, Zhang Y, et. al. The CNR method in scan angle optimization of tomosynthesis and its limitations. Proc. SPIE 7258 (2009); doi:10.1117/12.813918.
[10] Kopans DB. Breast Imaging. Lippincott Williams & Wilkins. 3rd edition, e.g. 1075-1077.

Computer-aided Detection (CAD)

3D CAD could potentially work in a superior way compared to current 2D CAD performance on a tomosynthesis dataset. However, the large number of cases needed for developing a CAD algorithm will probably limit the availability of 3D CAD in the near future.

One advantage of performing a combo-mode exam is that 2D CAD is available on the 2D image. With a combo-mode scan acquiring 2D and 3D in the same compression, the 2D CAD mark can be placed in the appropriate and correct x, y location on the 3D image. This allows the use of 2D CAD, while gaining the advantages of tomosynthesis imaging.

Conclusion

The design of a tomosynthesis system requires careful consideration of a large number of parameters. From many years of research and clinical experience, it is obvious that rapid scan times are essential in order for a commercial tomosynthesis system to be successful. Hologic chose to create a completely new mammography unit – the Selenia Dimensions 2D/3D system – to deliver the rapid scan time needed, along with other optimized parameters, including scan angle, pixel size and slice thickness. This design ensures that the needs of both screening and diagnostic mammography may be met effectively.

Glossary

2D	Conventional digital mammography
3D	Breast tomosynthesis
ART	Algebraic Reconstruction Techniques, a method of reconstructing tomosynthesis images
a-Se	Amorphous selenium, a radiation detector material used in direct conversion detectors
Binning	The summation of multiple smaller pixels in a detector to generate a larger signal and faster image readout
CAD	Computer aided detection. Software algorithm that marks areas with characteristics suggestive of breast malignancy.
Combo-mode	A protocol where both the 3D and 2D images are acquired in the same compression, with the second acquisition following immediately after the first
Continuous scan	A method of moving the x-ray tube during a tomosynthesis scan, where the x-ray tube rotates continuously throughout the scan
CsI	Cesium Iodide, a radiation detector material used in indirect conversion detectors
FBP	Filtered Back Projection, a method of reconstructing tomosynthesis images
Field of view	Area that is visible
ML	Maximum Likelihood, a method of reconstructing tomosynthesis images
MTF	Modulation Transfer Function. The ability of an imaging system to faithfully translate the modulation of the transmitted x-ray beam into a visible image is measured by the Modulation Transfer Function.
Projections	The low dose images taken at differing angles around the breast as the x-ray tube rotates. In the Hologic Dimensions system, there are 15 projections acquired over a total 15° arc
Reconstruction	The process of computing high-resolution images (slices) from projections. The planes of the reconstructed slices are parallel to the breast support plates
Scan angle	The total angular range covered by the x-ray tube
SID	Source-to-image distance
Slabbing	Increasing the effective slice thickness
Step-and-shoot scan	A method of moving the x-ray tube during a tomosynthesis scan, where the x-ray tube comes to a stop for each projection's exposure, and then moves to the next angular location.

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