Breast Imaging

Digital breast tomosynthesis: Image acquisition principles and artifacts

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ABSTRACT

Digital breast tomosynthesis (DBT) is a new technology that is being used more frequently for both breast cancer screening and diagnostic purposes and its utilization is likely to continue to increase over time. The major benefit of tomosynthesis over 2D-mammography is that it allows radiologists to view breast tissue using a three-dimensional dataset and improves diagnostic accuracy by facilitating differentiation of potentially malignant lesions from overlap of normal tissue. In addition, image processing techniques allow reconstruction of two-dimensional synthesized mammograms (SM) from DBT data, which eliminates the need for acquiring two dimensional full field digital mammography (FFDM) in addition to tomosynthesis and thereby reduces the radiation dose. DBT systems incorporate a moveable x-ray tube, which moves in a prescribed way over a limited angular range to obtain three-dimensional data of patients’ breasts, and utilize reconstruction algorithms. The limited angular range for DBT leads to incomplete sampling of the object, and a movable x-ray tube prolongs the imaging time, both of which make DBT and SM susceptible to artifacts. Understanding the etiology of these artifacts should help radiologists in reducing the number of artifacts and in differentiating a true finding from one related to an artifact, thus potentially decreasing recall rates and false positive rates. This is becoming especially important with increased incorporation of DBT in practices around the world. The goal of this article is to review the physics principles behind DBT systems and use these principles to explain the origin of artifacts that can limit diagnostic evaluation.

1. Introduction

Multiple studies have shown the benefit of screening mammography in early detection of breast cancer, which has lowered disease specific mortality ranging between 19 and 40% [1–3]. These studies were all reported when film screen mammography was the only technology available. Accuracy of mammography has been reported to be related to the type of mammography performed: the Digital Mammographic Imaging Screening Trial (DMIST) compared the accuracy of film screen mammography and full field digital mammography (FFDM) and demonstrated higher accuracy for digital mammography in women under the age of 50, women with heterogeneously or extremely dense breasts, and premenopausal or peri-menopausal women [4]. Even though FFDM improved accuracy in these patient populations, the issue of superimposed tissue persisted, as FFDM still produced two-dimensional images. Tissue superposition contributes to higher recall rates, which may lead unnecessary diagnostic imaging, increased medical costs and patient anxiety [5]. Tissue superposition may also lead to false-negative exams resulting in missed cancers [6].

The advent of digital breast tomosynthesis (DBT) brought the potential for improved performance. With DBT, exposures are obtained at multiple angles, which are reconstructed into projections forming a three-dimensional dataset that is subsequently processed into viewable images [7,8]. Access to 1 mm nominally thick slices in DBT improves the radiologist’s ability to differentiate normal breast tissue from potentially malignant lesions. As a result, a decrease in false positive call back rates by 6 to 67% has been reported with DBT compared to FFDM (2D-mammography) [9–12]. Furthermore, tomosynthesis (i.e. 3D mammography) along with full-field digital mammography (i.e. 2D-mammography) has been shown to increase cancer detection rate by 9.5% compared to digital mammography alone [13].

Initially, DBT was approved by the United States Food and Drug Administration (FDA) to be used in combination with FFDM, as FFDM allowed for better comparison to prior examinations and certain
findings like microcalcifications were poorly evaluated with DBT [14]. However, the combined use of DBT and FFDM resulted in a two-fold increase in radiation [15–17]. In part to address the added radiation dose and in part to allow enhancement of certain lesion features, synthesized 2D mammography (SM), a technique in which two-dimensional images are generated from the data for DBT, was developed and approved by the FDA in 2013. Several studies have found that SM has similar performance to FFDM and this has led to wider adoption of DBT with SM [18–21].

There are substantial advantages of DBT, yet this technique is susceptible to several artifacts that are not seen with FFDM. Given the widespread use of DBT, awareness, recognition and understanding of DBT imaging artifacts is imperative.

The goal of this work is to review the principles behind DBT image

Fig. 1. (a) Motion artifact on CC view of a synthesized mammogram shows a blurry image with loss of spatial resolution. Breast calcifications (white arrow) are blurred and are duplicated upon reconstruction due to patient motion. (b) Exam performed again without patient motion results in improved spatial resolution on the synthesized mammogram CC view.

Fig. 2. (a) Magnified image of the MLO view shows a scar marker in the upper breast of the DBT slice where the marker is located. (b) As one scrolls farther from the slice of interest, the slinky artifact arises (arrow) from the scar marker in the same patient.
acquisition and describe the artifacts as well as the relationship of these artifacts to acquisition parameters for radiologists using DBT in clinical practice.

2. Digital breast tomosynthesis techniques

The concept of tomosynthesis in radiology dates back to the 1930s, yet its implementation for breast imaging is much more recent and began in the 1990s [22,23]. Since the advent of DBT, multiple systems have been designed that vary in parameters such as geometry, gantry motion, scan angle, angular sampling and number of projections [24]. The geometry of DBT systems is related to the path and relationship of the x-ray tube to the detector. In the case of full isometric geometry, the x-ray tube and the detector both move around a pivot axis [25].
designs using partial isometric geometry, the x-ray tube rotates around a pivot axis while the detector remains stationary [25]. The x-ray tube can move in several ways, including in an arc, circular or linear sweep direction. These descriptions are based on which direction the x-ray tube moves relative to the breast [26–28]. Most DBT systems utilize an arc motion for the x-ray tube.

In addition to variations in the motion of the x-ray tube, the sequential images may be acquired by different methods. These techniques include a step and shoot or continuous motion acquisition [25]. In the step and shoot technique, the x-ray device takes an exposure and then moves to a new position, comes to a halt, obtains another exposure, and then moves to a new position and so on. This process is repeated until the full angular range is completed. In the continuous image acquisition technique, the tube moves constantly at a steady set rate over the prescribed range of motion during the x-ray exposure [25]. Multiple exposures are acquired with either technique in order to generate data for the 3D dataset. Regardless of the process, in order to keep the total radiation exposure as low as reasonably achievable, the dose with each exposure is designed to be very low. As a result, the overall radiation dose is maintained at an acceptable level similar to FFDM and well below the Mammography Quality and Standards Act (MQSA) dose limits [9].

The scan angle of the x-ray tube is defined as the angular range between the first and last exposure that is acquired. This x-ray tube angular range is in reference to the pivot and this is typically from 15 to 50 degrees depending on the DBT device and manufacturer. The detector can also have an angular range in full isometric geometry systems. For example, certain Hologic models have a detector angular range of ± 2.1° [8]. Other manufacturers like General Electric, Siemens, Internazionale Medico Scientifica have detectors that are stationary, and therefore do not have a detector angular range [8].

In addition to x-ray tube and detector angular ranges, other important features are present in the design of DBT units. One example is angular sampling, which is the angle between successive image acquisitions. Depending upon the distance between the pivot and the detector surface, the effective angular range will vary. Furthermore, the scan angle divided by the angular sampling equals one less than the number of projections; i.e. number of projections = (scan angle / angular sampling) + 1. Modifications of these parameters for image optimization have shown improved detectability with increased angular range, provided there are adequate number of projections and a dependence on lesion size [29–32]. To form viewable images, the

**Fig. 5.** (a) Magnified image of the synthesized mammogram LM view shows multiple surgical clips, biopsy clip and scar marker in the upper left breast. Additional tomosynthesis images (b–d) through the left upper breast of the same patient demonstrate the varying length of the slinky artifact. Using the upper most surgical clips (arrows in a–d) as the example, scrolling away from the slice of interest from b to d increases the size of the slinky artifact.
projection dataset is reconstructed via filtered back-projection or iterative techniques, which creates the image slices parallel to the detector.

All of the aforementioned variable features used for DBT acquisition may contribute to artifacts that are unique to DBT. As synthesized mammograms are generated using the same data as DBT, they also present with unique artifacts that can lead to false positives. Artifacts associated with DBT and SM are discussed below.

3. DBT artifacts

3.1. Patient related artifacts

As mentioned above, DBT requires obtaining multiple exposures in either a continuous or step and shoot manner. This results in a longer exposure time compared to full-field digital mammography. This additional acquisition time makes DBT more susceptible to motion artifacts than FFDM [24]. Patient motion during image acquisition will result in loss of spatial resolution (Fig. 1). Of note, the patient motion artifacts are accentuated by the continuous motion DBT design [18].

In DBT systems that have continuous x-ray tube motion, there is resolution degradation due to focal spot motion resulting in blur on each reconstructed image [24]. If there is patient motion during imaging acquisition, this contributes to additional loss in spatial resolution. The concept is similar to respiratory motion obscuring detail in the lung bases on a Chest CT. One way to lower the impact of patient motion on spatial resolution in DBT is to use short x-ray pulses, referred to as step and shoot [22].

DBT systems that use the step and shoot exposure techniques obtain images in a stationary position before moving to a new position and repeating the exposure. This eliminates the focal spot motion associated blur. However, it results in an even longer study time than the continuous approach. Given the longer duration, this could lead to higher probability for patient motion between each image acquisition, contributing to resolution loss [24]. The result is that there is a tradeoff between focal spot motion and increased time of exposures potentially increasing patient motion.

Mammography technologists can help to decrease artifacts related to motion through careful positioning and compression, coaching the patient not to breathe during the acquisition time for each image, and managing patient discomfort and anxiety during the procedure.

3.2. 3D reconstruction artifacts

Since the limited angular range for DBT leads to incomplete sampling of the object, it is susceptible to 3D reconstruction artifacts. There are three main types of 3D reconstruction artifacts – slinky artifact, edge artifact and incomplete halo artifact.

Fig. 6. Synthesized mammogram of the LM view of the left breast shows halos of low attenuation on each side of high density structures along the x-ray tube movement direction, with examples of halo artifact indicated by the arrows. The orientation of the high-density structure affects the spatial extent of the artifact. A high-density structure with its long axis oriented parallel to the x-ray tube motion (arrow 1) has a larger spatial extent than a structure with its long axis oriented perpendicular to the x-ray tube motion (arrow 2).

Fig. 7. Edge Artifact leads to apparent skin thickening on the lateral and far posterior medial aspects of the right breast on this CC view of a synthesized mammogram.
prominent (Fig. 5). On the other hand, the projection density, which is the number of projections divided by the angular range, is inversely related to the likelihood of the artifact \([35]\). Machida et al. demonstrated with their work on phantoms that increasing the projection density led to decrease and even complete elimination of this artifact on the reconstructed images \([33]\). In summary, increasing the number of projections within the angular range or decreasing the angular range with the same number of projections will reduce this artifact. It is also important to note that it is possible to partially alleviate this artifact during image reconstruction or by post-processing \([36–38]\).

### 3.2.2. Halo artifact

In DBT, bright objects like calcifications or biopsy clips may demonstrate a half halo of low attenuation adjacent to them (Fig. 6). This artifact is caused by the relatively small angular range, which results in limited sampling of the breast, and by preferential attenuation of lower energy x-ray photons as they traverse through high density structures resulting in beam hardening. This artifact appears as a low intensity shadow adjacent to high-density structures along the direction of the x-ray tube motion or the sweep direction \([39]\). There are several factors contributing to the severity of this artifact including the angular range, the material content of the high-density structure and its orientation relative to the x-ray tube motion. The severity of the artifact increases with the density of the attenuating structure in a manner similar to computed tomography (CT). Since DBT utilizes a limited angular range, the orientation of the high-density structure also affects the severity of the artifact. Specifically, when the long axis of the structure is oriented parallel to the x-ray tube motion, the severity or the spatial extent of the artifact increases.

### 3.2.3. Edge artifact

In DBT, related to the shape and curve of the breast, there can be an artifact which leads to blurring of the skin. This can appear as skin thickening when none is actually present (Figs. 7 and 8). On the other hand, actual skin thickening can be seen in patients with infection, inflammatory breast cancer, congestive heart failure or post-radiation changes. Differentiating true skin thickening from artifact can be difficult in some cases, and therefore clinical history and prior exams are very helpful. Unlike the edge artifact, infection/mastitis is usually unilateral, patients have indurated, red and painful skin and may have systemic signs/symptoms such as fever and leukocytosis. While both edge artifact and congestive heart failure are usually bilateral, other mammographic findings such as edema and thickening of cooper’s ligaments should raise the suspicion for congestive heart failure. Obtaining history of prior radiation and visually inspecting the breast may be necessary to differentiate edge artifact from post-radiation changes and inflammatory breast cancer, respectively. Furthermore, in cases where distinguishing true skin thickening from artifact is challenging using DBT alone, utilizing a separately acquired digital mammogram could be beneficial as the edge artifact is not seen with FFDM. The effective slice thickness in DBT is more than the nominal slice thickness due to limited angular range used for DBT acquisition. This leads to the pseudo skin thickening that manifests as the edge artifact. This artifact can be partially suppressed by post-processing \([38]\) and has been used to quantify skin thickness \([40]\).

### 3.3. Synthesized mammography (SM) artifacts

Recently there has been more emphasis placed on radiation exposure in general for radiology and this is also an important aspect for screening mammograms, as they occur annually. The concept of “ALARA”, i.e. as low as reasonably achievable, is the guiding principle in the use of DBT. As mentioned above, studies have compared the performance of DBT and FFDM vs DBT and SM, with the latter obviously resulting in lower radiation exposure to the patient. Skaane et al. demonstrated that the performance of the two aforementioned
methods was comparable in one of the earliest versions of SM for the Hologic Selenia system [18]. The advantages of SM are clear, however, there are some artifacts related to the technique. Since the synthesized 2D mammograms (SM) are formed from the DBT data, the halo artifact observed in DBT will also be observed in SM images. Additionally, the processing and image enhancement algorithm used during generation of SM can also contribute to pseudocalcifications described below.

3.3.1. Pseudocalcifications artifact

The pseudocalcifications artifact is the appearance of calcifications on the synthesized 2D mammogram (SM) that do not represent true calcifications. In order to differentiate pseudocalcifications as an artifact rather than a real finding, the radiologist must scroll through the 3D dataset. While true calcifications will continue to exist, pseudocalcifications will not be seen as a discrete finding on the 3D images. In addition, utilizing the slab feature may help to distinguish real calcifications from pseudocalcifications in the screening environment. Furthermore, as shown in Figs. 9 and 10, pseudocalcifications will not be seen on diagnostic 2D mammograms either. These artifacts are thought to be related to thickened or more prominent structures in the

Fig. 9. (a) Synthesized mammogram of the MLO view shows grouped high density structures that look like calcifications in the posterior right breast (black circle). (b) On the subsequently performed diagnostic mammogram with magnification view of the right breast, the calcifications are not visible. This is compatible with pseudocalcifications artifact on the synthesized mammogram (a).

Fig. 10. (a) Synthesized mammogram of the CC view shows calcifications (black circle) in the inner left breast. (b) On the subsequently performed diagnostic mammogram with magnification view of the left breast, the calcifications are not visible. This is another example of pseudocalcifications artifact on the synthesized mammogram (a).
breast seen in cross section, such as Cooper's ligaments, that are over-enhanced during the synthesis of 2D mammograms and appear dense like calcifications.

4. Conclusion

The use of DBT is widespread and likely to continue increasing in practices throughout the world. While DBT has been shown to improve diagnostic accuracy compared to FFDM, incomplete data sampling, longer examination time and reconstruction algorithms as detailed make DBT susceptible to artifacts. We believe that awareness and understanding of the physics principles that lead to DBT artifacts and the appearance of these artifacts will help radiologists differentiate them from true pathology, resulting in more accurate interpretation and potentially decreasing call back and false positive rates.

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