Optimized image acquisition for breast tomosynthesis in projection and reconstruction space

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Breast tomosynthesis has been an exciting new development in the field of breast imaging. While the diagnostic improvement via tomosynthesis is notable, the full potential of tomosynthesis has not yet been realized. This may be attributed to the dependency of the diagnostic quality of tomosynthesis on multiple variables, each of which needs to be optimized. Those include dose, number of angular projections, and the total angular span of those projections. In this study, the authors investigated the effects of these acquisition parameters on the overall diagnostic image quality of breast tomosynthesis in both the projection and reconstruction space. Five mastectomy specimens were imaged using a prototype tomosynthesis system. 25 angular projections of each specimen were acquired at 6.2 times typical single-view clinical dose level. Images at lower dose levels were then simulated using a noise modification routine. Each projection image was supplemented with 84 simulated 3 mm 3D lesions embedded at the center of 84 nonoverlapping ROIs. The projection images were then reconstructed using a filtered backprojection algorithm at different combinations of acquisition parameters to investigate which of the many possible combinations maximizes the performance. Performance was evaluated in terms of a Laguerre–Gauss channelized Hotelling observer model-based measure of lesion detectability. The analysis was also performed without reconstruction by combining the model results from projection images using Bayesian decision fusion algorithm. The effect of acquisition parameters on projection images and reconstructed slices were then compared to derive an optimization rule for tomosynthesis. The results indicated that projection images yield comparable but higher performance than reconstructed images. Both modes, however, offered similar trends: Performance improved with an increase in the total acquisition dose level and the angular span. Using a constant dose level and angular span, the performance rolled off beyond a certain number of projections, indicating that simply increasing the number of projections in tomosynthesis may not necessarily improve its performance. The best performance for both projection images and tomosynthesis slices was obtained for 15–17 projections spanning an angular arc of $\sim 45^\circ$ —the maximum tested in our study, and for an acquisition dose equal to single-view mammography. The optimization framework developed in this framework is applicable to other reconstruction techniques and other multiprojection systems. © 2009 American Association of Physicists in Medicine. [DOI: [10.1118/1.3231814](https://doi.org/10.1118/1.3231814)]

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I. INTRODUCTION

Breast tomosynthesis has been a promising new development in the field of breast imaging. While the diagnostic improvement via tomosynthesis has been notable,^{1,2} the full potential of tomosynthesis has not yet been realized. This is because the diagnostic quality of tomosynthesis is dependent on an intricate relationship between multiple underlying processes

in image formulation, each of which needs to be optimized to maximize accuracy. One important component of image formulation that fundamentally governs the image quality is image acquisition. The image acquisition parameters include dose, number of angular projections, and the total angular span of those projections (and hence the angular separation between projections).³ These factors also impact the obtain-

able SNR as well as reconstruction artifacts inherent in tomosynthesis.^{4,5} Low SNR and excessive artifacts may reduce the efficiency of tomosynthesis reading, possibly leading to lower accuracy.⁶

Although critical, there has been no consensus on the acquisition parameters, such as the total dose delivered to the patient, the number of angular acquisitions, and the total angular span of those acquisitions, to achieve an optimum tomosynthesis protocol. In prototype implementations of tomosynthesis, the total dose delivered to the patient has been comparable to that of standard mammography to match the current examination paradigm but not necessarily to optimize the acquisition. The number of angular projections has varied between 11 and 25 within a total angular span in the 30°–60° range.^{6–8} While tomosynthesis optimization has also been approached in some recent studies,^{5,9–12} thus far, no framework has been developed for complete optimization of the acquisition scheme.

In optimizing tomosynthesis, it is important to delineate the role of each of the components that affect image quality and further investigate the effect of interdependencies of these components on the overall system performance. As a key step toward that goal, we earlier proposed a mathematical observer-based framework to assess the effect of each of the acquisition parameters on the overall image quality of correlation imaging (CI) technique, a multiprojection imaging method based on projection images.¹³ The framework was based only on projection images and did not incorporate reconstruction in its analysis and thus could not be directly applied to tomosynthesis. Also, the dose levels were limited to the maximum dose level per projection used in our ongoing clinical trial, and thus were significantly lower than a typical clinical dose level. This study builds upon our earlier investigation by imaging mastectomy specimens that enable higher clinically relevant dose conditions and by including tomosynthesis reconstruction. To our knowledge, this is one of the first optimization studies (including angular range and dose) using model observer models for breast tomosynthesis optimization. The objectives of this study were threefold: (a) To investigate the role of acquisition parameters on the diagnostic quality of breast tomosynthesis at clinically relevant dose levels, (b) to qualitatively investigate the effect of reconstruction on tomosynthesis by comparing the diagnostic information content of the projection and reconstruction data, and finally, (c) to derive a comprehensive optimization rule for tomosynthesis in terms of a specific combination of the acquisition components that renders the best available diagnostic information.

II. MATERIALS AND METHODS

II.A. Image database

Five fresh mastectomy specimens were obtained from patients undergoing surgery at Duke hospital and imaged for this study. The mastectomy specimens were obtained from both patients with proven malignancies as well as those undergoing prophylactic mastectomy. Multiprojection images of these specimens were then acquired per an approved IRB

protocol. Under this protocol, images were acquired about the CC orientation from 25 different but fixed angular positions using a prototype clinical tomosynthesis system (Mammomat Novation^{TOMO}, Siemens Medical Solutions, Erlangen, Germany).¹⁴ The mastectomy specimens were immobilized by the compression paddle of the system. The compressed thicknesses were in the clinical realistic 30–60 mm range, with a mean of 45 mm. In order to increase the total sample size of our experiment using the available specimens, four out of the five specimens were rotated approximately 90° and recompressed and imaged again, thus potentially imaging different sets of anatomical arrangement each time. Thus starting with five specimens, recompression resulted in an overall dataset of nine specimens.

The system used a selenium-based, flat-panel detector with an array size of 2816×3584 and a pixel pitch of 85 μm . The tube settings ranged between 28 and 30 kVp at 600 mAs to maintain consistent and high image SNR across the nine specimens. This setting represented the highest exposure level possible with our prototype tomosynthesis device. The acquisition protocol was based on the compressed thickness of specimens and was consistent with thickness-based clinical protocol used in our ongoing clinical trial with human subjects. Specifically, the acquisition dose in our clinical trial was equivalent to 1.33 times that of typical single-view mammography dose level. To achieve this dose level for a 45 mm compressed breast, the clinical protocol recommended a mean setting of 127 mAs. Thus, in general, single-view mammography dose level corresponded to a setting of $127/1.33=95.5$ mAs. As a result, for a 45 mm average compression of mastectomy specimens, acquisition at 600 mAs corresponded to an average overall radiation dose of 6.2 ($600/95.5$) times typical single-view breast glandular dose to each specimen. This dose was equally divided among all the projections, resulting in dose per projection of a quarter that of single-view mammography dose level.

Following acquisition, multiple 3 mm simulated masses were embedded at different locations within each specimen. Specifically, 84 nonoverlapping 100×100 pixel regions of interests (ROIs) were identified for each projection image resulting in a total of 756 ROIs ($84 \text{ ROIs} \times 9 \text{ specimens}$) for each of the 25 angular projections. The 756 ROIs without the embedded masses were also used as signal-absent dataset for control purposes. Across projection images of each specimen, the projections of masses were added so to simulate 3D masses “implanted” inside the specimens at a distance of 3 cm above the detector surface. The masses were added to the projection images in the log space such that the contrast of the lesion over the background was independent of the specimen composition or thickness. The lesion addition routine was based on an algorithm reported earlier.¹³ Figure 1 shows example images of a mastectomy specimen acquired at -22° , 0° (CC), and $+23^\circ$.

Following lesion addition, a noise modification routine was used to add radiographic noise to each of the lesion-supplemented images to create images with a noise appearance similar to that caused from a reduction in radiation

FIG. 1. Example projection images of mastectomy specimens acquired at -22° (a), 0° (CC) (b), and $+23^\circ$ (c). Also shown are 3 mm simulated lesions embedded at the center of multiple ROIs. Note: Contrast of the lesions was enhanced manifold for display purposes only.

dose. The routine was based on an algorithm reported earlier.¹⁵ The algorithm accounted for the quantum noise variance, the detector transfer properties and its noise characteristics, and the impact of varying attenuation of breast structures. Several sets of dose-reduced images were simulated such that the cumulative dose of the 25 projections resulted in 10 discrete dose levels between $0.25D$ to $6.2D$, where D is the typical single-view mammography dose level. Figure 2 shows a representative CC projection of a specimen at three different noise/dose levels.

Besides projection images, reconstructed slice volume was also generated for each mastectomy specimen. To that end, the projection images with and without supplemented lesions were reconstructed using Siemens' proprietary filtered backprojection (FBP)-based reconstruction algorithm, TomoEngine.¹⁶ Variable image slice volumes were generated depending on the compressed size of the specimens to generate fixed slice thickness of 1 mm.

II.B. Optimization framework

To optimize the acquisition scheme of projection images and reconstructed slices, the key acquisition components, namely, dose, number of acquisitions, and the angular range, were systematically changed in each of the imaging modes to determine which one of the many possible combinations of acquisition parameters maximized the detection of embedded lesions.

FIG. 2. Example images of a mastectomy specimen, acquired with 25% of single-view mammography dose (a) and with added noise corresponding to a reduction in dose by 50% and 25%, respectively [(b) and (c)].

FIG. 3. Schematic of the optimization space used in this study to analyze both projection images and reconstructed slices.

Optimization was investigated under two acquisition dose conditions based on the number of projections used, namely, an isoimage dose condition and an isostudy dose condition. Under the isoimage dose condition, the dose level of each angular projection remained unchanged. Ignoring the slight variations in dose levels with angular projections,¹⁷ this resulted in increased dose level with an increase in the number of projections. Under isostudy dose condition, the total dose was kept constant by equally dividing the total dose among the projections used, i.e., less dose per projection with an increase in the number of projections. Using the noise modified images, three clinically relevant iso-study dose conditions were simulated, namely, 1, 1.5, and 2 times single-view mammography.

For each dose level, the angular projections were systematically changed between 1 and 25 projections, while the angular ranges were varied within the 7.5° – 44.8° range. The performance of the system (detailed below) was determined as a function of the number of angular projections and the total angular span of those projections in both projection and the reconstruction space. The AUC values at angular projections not sampled by the acquisition system were determined by interpolating the existing data using a least squares approach. These values were then fitted with a third-order polynomial curve to determine the trends underlying the variation in AUC values with the number of projections. The combination that yielded the maximum performance was deemed the optimized acquisition parameters set. Thus by changing the total dose level, a controlled yet exhaustive evaluation of optimization scheme in terms of dose, number of projections, and angular span was performed. Figure 3 provides a visual illustration of this multifactorial optimization scheme.

II.C. Evaluation of detection performance

The diagnostic performance of the system was evaluated in terms of the detectability of the embedded masses. The detectability of the mass was measured in terms of receiver operating characteristic (ROC) curves and the area under ROC (AUC) curves. For assessing the performance on projection images without reconstruction, the premise of CI, first the 756 lesion-supplemented ROIs per angle were ex-

tracted. Next, based on the known characteristic of the embedded lesion and statistical nature of the mammographic background, the detectability of the lesions was determined using a Laguerre–Gauss channelized Hotelling observer (LG CHO).¹⁸ Observer model-based merits of detectability have been shown to characterize the image quality for clinically relevant visual tasks such as detection of lesions in real anatomical backgrounds.^{19–21} The specific observer model-based methodology employed in this study has been reported previously in Ref. 13. Detectability was measured at each of the 25 angular projections, thus resulting in 25 ROC curves. ROCs corresponding to a given acquisition configurations were then combined using a decision fusion technique based on Bayesian statistics. This technique used *a priori* information to fuse binary detection decisions from each of the angular projections.^{13,22} The area under the combined ROC curve (AUC) was employed as an overall figure of merit representative of clinical performance of the projection images at that acquisition configuration.

For evaluating the reconstructed slices, the in-focus slice corresponding to the lesion plane 3 cm above the detector surface was extracted from the reconstructed image slices for each specimen. The specific parameters for reconstruction were dictated by the acquisition configuration considered. The 84 lesion-supplemented ROI/specimens were then extracted from the slice resulting in 756 ROIs for all the specimens. These ROIs were analyzed for the presence of signal using the mathematical model-based methodology similar to that used for CI. At the end of this analysis, a single ROC curve was derived corresponding to the overall detectability of lesions in a reconstructed slice. It may be noted that this single ROC curve corresponded to the “combined” ROC curve of projection images as the reconstruction of the central slice effectively served as the fusion mechanism that was complementary to the Bayesian fusion scheme used for combining projection images.

III. RESULTS

Figure 4 shows variation in AUC with the number of angular projections at different angular ranges for projection images (CI) and reconstructed slices (tomosynthesis), respectively, under isoimage dose condition with dose level of each projection fixed at 1/25th fraction of typical single-view mammography. For both imaging modes, regardless of the angular span, the AUCs first increased with an increase in the number of projections but leveled off beyond a certain number of projections. The maximum value of AUC, however, increased with an increase in the angular span. Projection images yielded a slightly higher maximum AUC than reconstructed slices, indicating slight benefit in the detection performance in using just the projection images over tomosynthesis. Most importantly, the peak performance for both imaging modes was between 15 and 20 projections for an angular span of about 45°.

Figures 5 and 6 show reconstructed in-focus slice of a mastectomy specimen under isoimage dose condition of single- and two-view mammography dose levels, respec-

FIG. 4. Variation of AUC with number of projections for CI (a) and reconstructed slices (b) at different acquisition dose levels under *isoimage dose condition* (the dose of each projection was fixed at 1/25th fraction of typical single-view mammography). The angular spans of these projections were in the 7.5°–45° range.

tively. The slice was generated using 5 (a), 13 (b), and 25 (c) projections spanning a fixed angular range of 44.8°. There is a notable subjective improvement in the detectability of lesions as the number of projections increases from 5 to 13; however, the detectability does not appear to improve by increasing the number of projections to 25. This provides a visual evidence of the saturation in AUC values shown in Fig. 4(b).

Figure 7 shows the variation in AUC with the angular span and number of projections for projection images and reconstructed slices under fixed dose levels (*isostudy dose condition*) at total dose level equivalent to that of a single-view mammography. Both projection images and tomosynthesis showed improvement in diagnosis when information from multiple images was combined, confirming the benefit

FIG. 5. In-focus tomosynthesis slice at the central plane of lesions embedded in a mastectomy specimen. The slice was reconstructed using 5 (a), 13 (b), and 25 (c) projections under isoimage dose condition (the dose of each projection used for reconstruction was fixed at 1/25th fraction of typical single-view mammography). (d) shows reference lesion embedded in a high-dose image. The detectability of the lesion evidently improves from 5 to 13 projections and then appears to remain steady beyond 13, thus visually confirming saturation in AUC values shown in Fig. 4(b).

of both methods over standard mammography. However, for all angular spans, the AUC first increased and then decreased as the number of projections was increased. The number of projections at which the AUC values peak was dependent on the angular span. Most noteworthy, the maximum AUC value for both projection images and reconstructed slices was obtained at an angular span of 44.8° with 15–17 projections. This suggests that current implementations of breast tomosynthesis with 25 projections may be suboptimal. Reconstructed slices were also noted to have slightly lower performance than projection images possibly due to reconstruction artifacts that limit the efficiency of tomosynthesis. The higher performance of projection images is thus potentially indicative of the maximum achievable performance via tomosynthesis.

Figures 8 and 9 provide a visual evidence of change in detectability of the embedded lesions in the central slice under isostudy dose condition at dose levels equivalent to that of single- and two-view mammography, respectively. The number of angular projections used to reconstruct the slice was varied from 5 (a) to 13 (b) to 25 (c) spanning a fixed angular arc of 44.8° . At both the dose levels, the detectability

FIG. 6. In-focus tomosynthesis slice at the central plane of lesions embedded in a mastectomy specimen. The slice was reconstructed using 5 (a), 13 (b), and 25 (c) projections under isoimage dose condition (the dose of each projection used for reconstruction was fixed at 1/12.5th fraction of typical single-view mammography). (d) shows reference lesion embedded in a high-dose image. The detectability of the lesion evidently improves from 5 to 13 projections and then appears to remain steady beyond 13.

of the lesions evidently improved from 5 to 13 projections but decreased when the number of projections was increased to 25.

While the total dose in Figs. 7 and 8 was fixed, Figs. 10 and 11 show variation in AUC for projection images and reconstructed slices at three different dose levels, of 0.5, 0.75, and 1 times that of single-view mammography. Two different angular spans of 7.5° (Fig. 11) and 44.8° (Fig. 11) are shown. For both imaging modes at each dose level, performance was optimized at a particular number of projections. Regardless of the angular spans, the AUC values increased by increasing the dose level.

Figures 7 and 8 suggest that the optimum number of projections is dependent on the total angular span used. Figures 12 and 13 depict that finding for projection images and tomosynthesis. Figure 12 shows the number of projections that yield maximum AUC at different angular ranges, while Fig. 13 shows the corresponding AUCs at each of those angular ranges. The maximum AUC is obtained using a 44.8° angular span and 15–17 projections. As 44.8° was the maximum angular span tested in this study, it is expected that a wider angular span might yield even higher performance. The slope of the linear fit in Fig. 12 reveals that for both projection

FIG. 7. Variation in AUC with the number of projections for projection images (a) and reconstructed slices (b) under isostudy dose conditions at different angular ranges in 7.5°–45° range. The total dose level was fixed to that of single-view mammography. Similar results (not shown here) were also obtained at a lower dose levels.

images and reconstructed slices, the optimum angular separation that realizes maximum performance is approximately 2.75°.

IV. DISCUSSION

Tomosynthesis is a multiprojection imaging technique where performance is affected by several possible combinations of acquisition parameters including the acquisition dose level, the number of angular acquisitions, and the total angular span of those projections. Not all of these combinations, however, are optimal—certain combination of these parameters may distort pathological indicators. It is important to determine an optimum acquisition scheme that could make tomosynthesis maximally effective.

FIG. 8. In-focus tomosynthesis slice at the central plane of lesions embedded in a mastectomy specimen. The slice was reconstructed using 5 (a), 13 (b), and 25 (c) projections. (d) shows reference lesion embedded in a high-dose image. The total dose was fixed at that of single-view mammography regardless of the number of projections. The detectability of the lesion evidently improves from 5 to 13 projections and then appears to deteriorate at 25 projections due to increased noise per projection, thus visually confirming the roll off in the AUC values shown in Fig. 7(b).

Tomosynthesis is based on a unique imaging paradigm in that both the projection images and the reconstructed slices have identical in-plane resolution thus making both sets of images valuable for diagnosis. Although reconstructed slices provide easier visualization of complex 3D data, there has been no conclusive study on a rendering technique (e.g., slice rendition, stereoscopy of 3D data) that provides the best visualization of tomosynthetic slices. Image rendering is further complicated by out-of-plane artifacts inherently present in tomosynthetic slices. Moreover, since reconstruction algorithms do not use any prior information in processing projection data, projection images should intrinsically contain most information. However, projection images contain anatomical overlaps that limit their efficacy.²³ Thus, there may be a relative merit in using one imaging mode over the other. In a previous article, we demonstrated potential clinical advantages of using projection images;²⁴ however, no comparison of performance between projection images and reconstructed slices was presented. In this study, we designed a framework to assess the impact of reconstruction on tomosynthesis image quality and to compare optimized performance of projection images to that of tomosynthesis. Most importantly, the effect of acquisition parameters on reconstructed slices as

FIG. 9. In-focus tomosynthesis slice at the central plane of lesions embedded in a mastectomy specimen. The slice was reconstructed using 5 (a), 13 (b), and 25 (c) projections. (d) shows reference lesion. The total dose was fixed at that of two-view mammography regardless of the number of projections. The detectability of the lesion evidently improves from 5 to 13 projections, and then appears to deteriorate at 25 projections due to increased noise per projection.

well as projection images was analyzed that provided a method to derive an optimization rule for both imaging modes.

Results showed that under isoimage dose condition of cumulative dose level equivalent to that of single-view mammography (i.e., when the combined dose level from all of the projections was equivalent to single-view mammography), the performance of both projection images and reconstructed slices increased with an increase in the number of projections and subsequently appeared to reach an asymptote at higher number of projections. A similar trend in the performance of reconstructed slices was observed at a higher isoimage dose setting of two-view mammography dose, as demonstrated in Fig. 14. The figure illustrates the asymptotic behavior in reconstructed slices in rendering breast masses on two example human cases selected from our ongoing tomosynthesis clinical trial. The subfigures show slices reconstructed using 5, 13, and 25 projections. The improvement in detectability of the mass in going from 5 to 13 projections, followed by its apparent saturation from 13 to 25 projections provides a visual evidence of the performance of reconstructed slices seen in Fig. 4(b). While the angular span in this example was

FIG. 10. Variation of AUC with the number of projections for projection images (a) and reconstructed slices (b) under isostudy dose conditions at an angular range of 7.5° . These values are also plotted at different dose levels (denoted in the legend as the multiple of that of typical single-view mammography).

fixed at 44.8° , Fig. 4(b) shows that this behavior was expected across all angular spans. However, the threshold in the number of projections at which the performance saturated was angular span dependent. Most notably, both this threshold and the absolute value of AUC increased with the increase in the angular span. In tomosynthesis, the performance was further limited by reconstruction artifacts at the smaller number of projections, yielding lower detection performance compared to projection images in that zone [Fig.

FIG. 11. Variation of AUC with the number of projections for projection images (a) and reconstructed slices (b) under isostudy dose conditions at an angular range of 44.8° . These values are also plotted at different dose levels (denoted in the legend as the multiple of that of typical single-view mammography).

4(b)]. This behavior in performance for both imaging modes indicates an interplay of anatomical and quantum noise in the overall detection performance of a multiprojection system: The performance improves as system overcomes anatomical noise by using information from an increasing number of projections; however the influence of anatomical noise diminishes beyond a certain number of projections as the performance becomes quantum noise limited and therefore saturates.¹³

FIG. 12. The number of projections per angular range that yield maximum AUCs for projection images (a) and reconstructed slices (b). These are plotted for different dose levels (denoted in the legends as the multiple of that of single-view mammography).

While isoimage dose condition illustrates the trend in the performance of projection images and tomosynthesis, it does not delineate the role of the acquisition dose level on the optimization of the acquisition scheme. This is because an increase in the number of projections also increases the total delivered dose; the performance variation seen in Fig. 4 may thus be due to the dual role played by the change in the number of projections and dose.

Decoupling the dose from the number of projections, the performance at constant dose level for variable angular span

FIG. 13. Maximum obtainable AUC values for different angular ranges for projection images (a) and reconstructed slices (b). These are plotted for different dose levels (denoted in the legends as the multiple of that of single-view mammography).

and number of projections is depicted in Fig. 7. Regardless of the angular span, the detectability of the mass approximately followed a bell curve as a function of the number of projections. This suggests that the current implementations of tomosynthesis in which the total dose is divided among 25 projections may be suboptimal and that the performance of tomosynthesis may potentially be improved by using an optimum number of projections less than the maximum possible number and dividing the total dose among the smaller number of projections. Furthermore, the highest performance

FIG. 14. Representative in-focus tomosynthetic slice showing breast lesions in two human subjects [(a)–(c) and (d)–(f)] from our ongoing tomosynthesis clinical trial. The slice was reconstructed under isoimage dose condition using 5 [(a) and (d)], 13 [(b) and (e)], and 25 [(c) and (f)] projections, respectively. The detectability of the lesion evidently improves from 5 to 13 projections and then appears to remain steady beyond 13, thus visually confirming saturation in AUC values shown in Fig. 4.

was achieved at the maximum angular span (of $\sim 45^\circ$), which suggests that an increase in the angular span may further improve the absolute value of the AUC, though with diminishing returns as the angular range widens.

If the angular span is kept constant, depicted in Figs. 11 and 14, the best performance was achieved at a dose of single-view mammography. Although this result indicates that a further increase in mammography dose level may further increase performance, there were diminishing returns at higher dose levels. This asymptotic nature of the increase in dose level indicates diminishing role of quantum noise in multiprojection imaging as further depicted in the plateaus in Fig. 4.

If the number of projections is kept constant, an increase in the angular span necessitates a larger number of projections for improved performance. The finding further summarized in Figs. 11 and 12 indicate an optimum angular sampling of 2.75° for multiprojection breast imaging. Data

further showed a higher performance in the projection space (i.e., CI) than tomosynthesis, suggesting potential room for improvement in tomosynthesis.

One limitation of this study was that the performance could not be evaluated at arbitrary number of angular projections for a given angular range. This was due to the uniform sampling configuration of the acquisition system, making it necessary to interpolate the results for missing angular samples. The interpolation might have introduced some artifacts in the results. This possibly explains the uncharacteristic dip in the AUC values in Fig. 4(b). By and large, however, comparison of the interpolated values and the original values indicated a faithful reproduction of the trends. Also, the AUC values in Fig. 14(b) are observed to be higher for a lower dose level than those for a higher dose level at smaller angular ranges. Since such a trend was not observed with projection images, it is suspected that this inconsistency may be due to possible artifacts associated with using tomosynthesis reconstruction with limited number of projections at smaller angular ranges.

Furthermore, the optimization framework was based on mastectomy specimens that provided the best approximation of the real breast anatomical structures. However, since the specimens are detached from the body, they could not be compressed in a clinically realistic fashion during acquisition. As a result, the actual dose delivered to the specimens may be slightly different than assumed in this study. Furthermore, the performance of the system most relevant to observer tasks associated with microcalcification was not modeled since the present study focused only on detection of masses. Also, the effects of focal spot blurring were not included. This is because our acquisition setup based on a narrow angular span of $\pm 23^\circ$ was not expected to significantly impact spatial resolution as a function of projection angle. Furthermore, the effects of different reconstruction techniques on the optimization of tomosynthesis acquisition were not considered. Reconstruction techniques other than the one used in this study such as iterative techniques may render different results for tomosynthesis.^{25,26} Also, only the central slice was evaluated to determine the overall detectability of the embedded mass in the reconstructed slices. Combining multiple slices may potentially change the reported tomosynthesis performance. However, since the lesion size was comparable to the slice thickness, such a combination may not significantly alter the performance of tomosynthesis. Finally, although previous studies have used observer models to evaluate the performance of human observers over anatomical backgrounds such as those used in this study, a correlation between model and human observers has not yet been rigorously established [although a possible correlation between computer reader (CAD) and observer model may exist²⁷]. Moreover, Laguerre-Gauss channel-based Hotelling observer employed in this study was originally designed to model ideal linear observer for a signal-known exactly task and was not intended to emulate complex detection process involved in actual clinical tasks. The results of this study thus require additional verification for clinical implementation. Most notably, however, both tomosynthesis and

CI show mutually reinforcing trends in performance with a change in the acquisition parameters that may potentially serve as important guidelines for optimization of tomosynthesis. Our study was further limited to a maximum of $\sim 45^\circ$ angular span, one lesion type (i.e., breast mass) and a maximum dose of single-view mammography. Although a total dose of two-view mammography was used for demonstration purposes (Figs. 6 and 9), the optimization analysis was not conducted at this dose because of the unavailability of data at fewer than five projections. Notwithstanding these limitations, the framework implemented was generic in nature and may be easily extended to incorporate other aspects of imaging performance not explored in the present study.

V. CONCLUSIONS

Suboptimized implementation of breast tomosynthesis can potentially compromise its maximum achievable diagnostic performance. In this study, we developed an algorithmic observer-based framework to assess the impact of various acquisition parameters of tomosynthesis performance, namely, dose, number of projections, and angular span. The performance was investigated with and without reconstruction, thus linking projection-based optimization to optimization of tomosynthesis. Although specific to the particular analysis employed in the study, the results demonstrated the interplay of anatomical and quantum noise in the overall performance. The following conclusions may be drawn from this study:

- (1) Increasing the number of projections while keeping the overall dose and angular span constant decreased the performance of tomosynthesis, indicating that the current implementations of tomosynthesis may be suboptimal.
- (2) When optimized, slightly higher performance was achieved without reconstruction, i.e., by using only projection images.
- (3) Increasing the angular span and acquisition dose level improved the maximum obtainable AUC.
- (4) The number of projections required to maximize performance was found to be linearly related to the angular span. This number was found to be independent of the acquisition dose level. The best performance in both projection images and tomosynthesis was obtained when the angular separation between each projection was approximately 2.75° .
- (5) Finally, the results revealed that the peak performance for both projection and tomosynthesis images at the clinically relevant dose level of single-view mammography was achieved at 15–17 projections spanning an angular arc of $\sim 45^\circ$, the widest angle tested in this study.

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¹L. Niklason *et al.*, "Digital tomosynthesis in breast imaging," *Radiology* **205**, 399–406 (1997).

²J. T. Dobbins and D. J. Godfrey, "Digital x-ray tomosynthesis: Current state of the art and clinical potential," *Phys. Med. Biol.* **48**, R65–R106 (2003).

³J. Zhou, B. Zhao, and W. Zhao, "A computer simulation platform for the optimization of a breast tomosynthesis system," *Med. Phys.* **34**, 1098–1109 (2007).

⁴T. Wu, R. H. Moore, and D. B. Kopans, "Voting strategy for artifact reduction in digital breast tomosynthesis," *Med. Phys.* **33**, 2461–2471 (2006).

⁵L. Zhou *et al.*, "Low-contrast lesion detection in tomosynthetic breast imaging using a realistic breast phantom," *Proc. SPIE* **6142**, 61425A1–A61412 (2006).

⁶I. Reiser *et al.*, "Computerized mass detection for digital breast tomosynthesis directly from the projection images," *Med. Phys.* **33**, 482–491 (2006).

⁷Y. Zhang *et al.*, "A comparative study of limited-angle cone-beam reconstruction methods for breast tomosynthesis," *Med. Phys.* **33**, 3781–3795 (2006).

⁸X. Gong *et al.*, "A computer simulation study comparing lesion detection accuracy with digital mammography, breast tomosynthesis, and cone-beam CT breast imaging," *Med. Phys.* **33**, 1041–1052 (2006).

⁹A. R. Pineda *et al.*, "Optimization of a tomosynthesis system for the detection of lung nodules," *Med. Phys.* **33**, 1372–1379 (2006).

¹⁰H.-P. Chan *et al.*, "Detection of masses in digital breast tomosynthesis mammography: Effects of the number of projection views and dose," *Proceedings of International Workshop on Digital Mammography (IWDM)* (Springer, Berlin/Heidelberg, 2008), Vol. 9, pp. 279–285.

¹¹I. Reiser, B. A. Lau, and R. M. Nishikawa, "Effect of scan angle and reconstruction algorithm on model observer performance in tomosynthesis," *Proceedings of International Workshop on Digital Mammography (IWDM)* (Springer, Berlin/Heidelberg, 2008), Vol. 9, pp. 606–611.

¹²Y. Chen, J. Y. Lo, and J. T. Dobbins, "Importance of point-by-point back projection correction for isocentric motion in digital breast tomosynthesis:

Relevance to morphology of structures such as microcalcifications," *Med. Phys.* **34**, 3885–3892 (2007).

¹³A. Chawla *et al.*, "A mathematical model platform for optimizing a multi-projection breast imaging system," *Med. Phys.* **35**, 1337–1345 (2008).

¹⁴M. Bissonnette *et al.*, "Digital breast tomosynthesis using an amorphous selenium flat panel detector," *Proc. SPIE* **5745**, 529–540 (2005).

¹⁵R. S. Saunders and E. Samei, "A method for modifying the image quality parameters of digital radiographic images," *Med. Phys.* **30**, 3006–3017 (2003).

¹⁶T. Mertelmeier *et al.*, "Optimizing filtered backprojection reconstruction for a breast tomosynthesis prototype device," *Proc. SPIE* **6142**, 61420F (2006).

¹⁷I. Sechopoulos *et al.*, "Computation of the glandular radiation dose in digital tomosynthesis of the breast," *Med. Phys.* **34**, 221–232 (2007).

¹⁸H. H. Barrett, C. K. Abbey, and B. Gallas, "Stabilized estimates of Hotelling observer detection performance in patient-structured noise," *Proc. SPIE* **3340**, 27–43 (1998).

¹⁹H. H. Barrett, "Objective assessment of image quality: Effects of quantum noise and object variability," *J. Opt. Soc. Am. A* **7**, 1266–1278 (1990).

²⁰B. D. Gallas and H. H. Barrett, "Validating the use of channels to estimate the ideal linear observer," *J. Opt. Soc. Am. A* **20**, 1725–1738 (2003).

²¹A. E. Burgess, F. L. Jacobson, and P. F. Judy, "Human observer detection experiments with mammograms and power-law noise," *Med. Phys.* **28**, 419–437 (2001).

²²J. L. Jesneck *et al.*, "Optimized approach to decision fusion of heterogeneous data for breast cancer diagnosis," *Med. Phys.* **33**, 2945–2954 (2006).

²³F. O. Bochud *et al.*, "Estimation of the noisy component of anatomical backgrounds," *Med. Phys.* **26**, 1365–1370 (1999).

²⁴A. Chawla *et al.*, "Multi-projection correlation imaging as a new diagnostic tool for improved breast cancer detection," *Proceedings of International Workshop on Digital Mammography (IWDM)* (Springer, Berlin/Heidelberg, 2008), Vol. 9, pp. 635–642.

²⁵G. Wu, J. Mainprize, and M. Yaffe, "Characterization of projection ordering in iterative reconstruction methods for breast tomosynthesis," *Proceedings of International Workshop on Digital Mammography (IWDM)* (Springer, Berlin/Heidelberg, 2008), Vol. 9, pp. 601–605.

²⁶D. J. Godfrey, H. P. McAdams, and J. T. Dobbins, "Optimization of the matrix inversion tomosynthesis (MITS) impulse response and modulation transfer function characteristics for chest imaging," *Med. Phys.* **33**, 655–667 (2006).

²⁷A. Chawla *et al.*, "Toward optimized acquisition scheme for multi-projection correlation imaging of breast cancer," *Acad. Radiol.* **16**, 456–463 (2009).