

Breast Tomosynthesis: Present Considerations and Future Applications¹

TEACHING POINTS

See last page

*Jeong Mi Park, MD • Edmund A. Franken, Jr, MD • Megha Garg, MD
Laurie L. Fajardo, MD • Loren T. Niklason, PhD*

Mammography is an effective imaging tool for detecting breast cancer at an early stage and is the only screening modality proved to reduce mortality from breast cancer. However, the overlap of tissues depicted on mammograms may create significant obstacles to the detection and diagnosis of abnormalities. Diagnostic testing initiated because of a questionable result at screening mammography frequently causes patients unnecessary anxiety and incurs increased medical costs. Breast tomosynthesis, a new tool that is based on the acquisition of three-dimensional digital image data, could help solve the problem of interpreting mammographic features produced by tissue overlap. Although the technology has not yet been approved by the Food and Drug Administration, breast tomosynthesis has the potential to help reduce recall rates, improve the selection of patients for biopsy, and increase cancer detection rates, especially in patients with dense breasts. Supplemental material available at radiographics.rsnaajnl.org/cgi/content/full/27/S231/DC1.

©RSNA, 2007

Abbreviations: 3D = three-dimensional, 2D = two-dimensional

RadioGraphics 2007; 27:S231–S240 • Published online 10.1148/rg.27si075511 • Content Codes: **BR** **OI**

¹From the Division of Breast Imaging and Intervention, Department of Radiology, University of Iowa Hospitals and Clinics, Carver College of Medicine, 200 Hawkins Dr, Iowa City, IA 52242-1082 (J.M.P., E.A.F., M.G., L.L.F.); and Hologic, Danbury, Conn (L.T.N.). Presented as an education exhibit at the 2006 RSNA Annual Meeting. Received March 5, 2007; revision requested March 29 and received May 10; accepted May 15. Supported in part by Hologic. J.M.P. is a researcher with Hologic, and L.L.F. is a member of the board of directors of Hologic; all remaining authors have no financial relationships to disclose. **Address correspondence to** J.M.P. (e-mail: jeongmi-park@uiowa.edu).

©RSNA, 2007

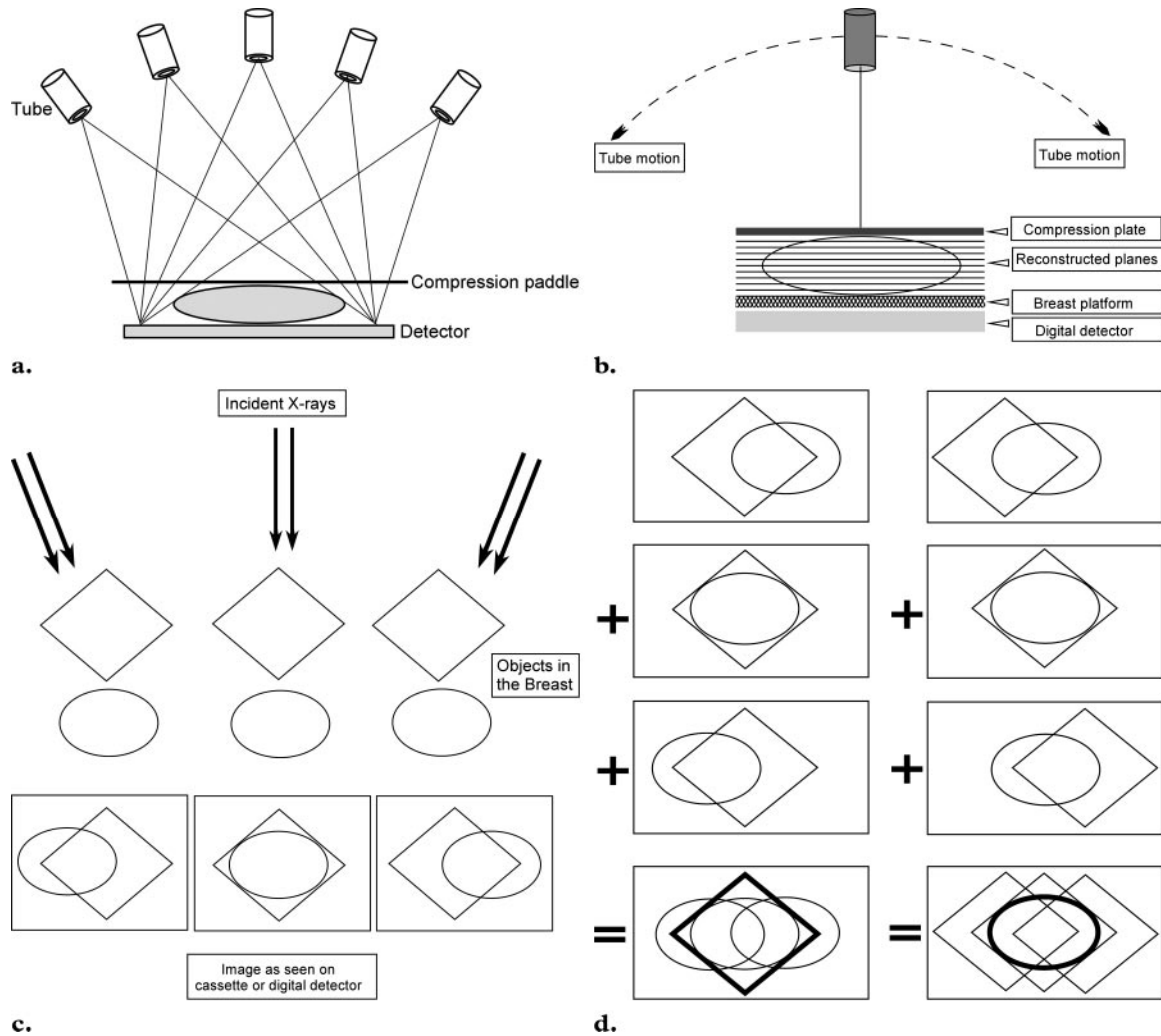


Figure 1. Basic technologic principles of breast tomosynthesis. **(a, b)** Schemas show how image data are acquired from various angles as the x-ray tube moves in an arc. Either the step-and-shoot method **(a)** or the continuous exposure method **(b)** may be used, and the detector may be moving or stationary during image acquisition. The 3D image data are subsequently reconstructed as conventional mammographic projections (cranio-caudal, mediolateral oblique, and mediolateral views). **(c, d)** Diagrams show how different 3D image data acquired from different angles **(c)** are reconstructed to provide separate depiction of two overlapping structures located in different planes **(d)**.

Introduction

Mammography is an effective imaging tool for the detection of early-stage breast cancer, and it is the only screening modality proved to reduce mortality from breast cancer (1–3). However, the appearance of overlapping tissue on mammograms poses a significant obstacle to interpretation (4–7). When screening mammograms demonstrate a questionable finding, the results of follow-up diagnostic mammography and ultrasonography (US), magnetic resonance (MR) imaging, or biopsy ultimately determine whether the finding is significant. The process causes anxiety for patients and incurs additional healthcare costs for findings that frequently are proved benign.

Teaching Point

Breast tomosynthesis is a new tool that can be expected to ameliorate this problem by reducing or eliminating tissue overlap. Breast tomosynthesis technology is essentially a modification of a digital mammography unit to enable the acquisition of a three-dimensional (3D) volume of thin-section data. Images are reconstructed in conventional orientations by using reconstruction algorithms similar to those used in computed tomography (CT).

Efforts to use tomosynthesis techniques for clinical x-ray imaging were pioneered in the 1980s; however, poor-quality image detectors hampered those trials (8–11). Technical advances in digital receptors for breast imaging made the application of tomosynthesis possible (12–14). Several equipment manufacturers have intro-



a.

b.

Figure 2. Photographs of the experimental breast tomosynthesis unit at the authors' institution show the x-ray tube positioned at angles of -7.5° (a) and $+7.5^\circ$ (b), the angular range used during image data acquisition.

duced prototype breast tomosynthesis units for clinical evaluations and are seeking Food and Drug Administration approval. Early experience indicates that breast tomosynthesis has the well-known advantages of digital mammography and the potential to provide additional information not obtainable with mammography.

The article provides an overview of the technology of breast tomosynthesis and a description of its advantages and potential disadvantages for future applications in the clinical setting. The discussion is based on our experience during a preliminary study that was conducted in 112 consenting patients at our institution with the approval of the institutional review board.

Breast Tomosynthesis Technology

In analog (screen-film) mammography, x-rays from a stationary tube are absorbed by a phosphor screen, which then emits light and exposes a film to create an image. **In breast tomosynthesis, a moving x-ray source and a digital detector are used.** Clinical trials with breast tomosynthesis units from different vendors only recently were begun; therefore, there is as yet no universally accepted technology. Our preliminary study was performed by using a full-field selenium flat-panel digital breast tomosynthesis system (Genesis; Hologic, Danbury, Conn). Although the following description is based on our experience with that system, we included comparable information about other units when it was available.

The x-ray tube in a breast tomosynthesis system moves along an arc during exposure (Figs 1, 2). In theory, the motion of the tube could be linear, circular, or elliptic; the system we use currently is equipped with a tube that moves in an arc. An arclike linear motion is suitable for imag-

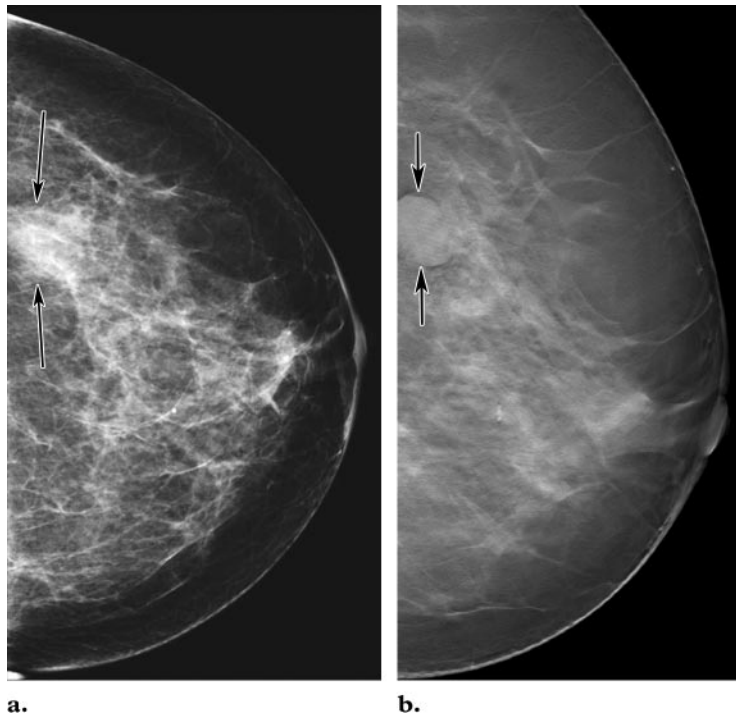
ing of breast tissue because most normal anatomic structures in the breast are oriented from the chest wall to the nipple. Other patterns of motion may work better for depicting lesions against a more complex background.

With our breast tomosynthesis unit, image data are acquired with a low-dose protocol in 11 sections at various angles (from -7.5° to $+7.5^\circ$ around the normal) while the breast is compressed in standard planes, such as craniocaudal and mediolateral oblique. With another tomosynthesis unit, image data are acquired with 11 projections at angles from -25° to $+25^\circ$ (15). The number of images and the range of angles may vary. A wider angular range allows a thinner reconstructed section thickness of the in-focus plane (and thus provides superior separation of reconstructed sections) because objects in the different planes are less blurred on images acquired at a smaller angle.

Acquisitions may be performed either with the step-and-shoot method (one exposure at each position of the tube between movements) or with a continuous exposure method (pulsed short exposures during continuous motion of the x-ray source). Short exposures are needed to obtain sharp images; data acquisition with the step-and-shoot method takes longer and results in more image artifacts due to patient motion.

A high-quality full-field flat-panel digital detector with capabilities for rapid readout and minimal image distortion is important for breast tomosynthesis (16). Current digital mammographic technology fulfills these requirements. The detector may consist of cesium iodide crystals on an amorphous silicon layer or of selenium alone.

Figure 3. Comparison of screening mammography with breast tomosynthesis in a 57-year-old woman. **(a)** Digital mammogram shows a mass (arrows) in the lower outer part of the left breast. The mass is not clearly visible because of surrounding dense tissue. **(b)** Breast tomosynthesis image provides clearer depiction of the mass (arrows), which is well circumscribed. Because its US appearance remained stable for 2 years, the mass was considered benign. (See also Movie 1 at radiographics.rsna.org/cgi/content/full/27/S231/DC1.)



Selenium is an especially suitable material in a detector because it has a high dose efficiency, with x-ray absorption of more than 95% at mammographic energies (17). The detector may be stationary or may move concurrently with the tube during the exposure. A moving detector has a wider field of view and thus allows better inclusion of peripheral breast tissues.

The breast tomosynthesis system used at our institution has a tungsten tube and an aluminum filter. The reconstructed pixel size is 110–120 μm , and the detector readout time is approximately 1 second. The total acquisition time for one breast tomosynthesis view is approximately 10 seconds. Typical exposure parameters are 29 kVp and 44 mAs (recorded during imaging of an American College of Radiology phantom), which would result in a total radiation dose value of 145 mrad (1.45 mGy) to a normal breast with a compressed thickness of 4.2 cm.

The breast tomosynthesis image data are sent from the acquisition workstation to the reading workstation. Images are reconstructed by using a mathematical algorithm similar to those used in CT reconstructions, to generate a set of thin image sections parallel to the breast platform (16, 18,19). During the image reconstruction pro-

cess, only data from the plane of interest remain registered on all images; other data from the remaining planes are blurred due to misregistration. The reconstructed section thickness may be varied, with wider tube movement resulting in thinner effective section thickness. In our study, we used 1 mm as the reconstructed section thickness. Efforts are ongoing to combine several contiguous images so as to create a 3D image of lesions. Reconstructed images may be viewed individually or sequentially in a dynamic cine mode at a soft-copy workstation. Postprocessing time is approximately 1 minute per view with our current system (Figs 1, 2).

Advantages and Disadvantages of Breast Tomosynthesis

Breast tomosynthesis is a modification of digital mammography and can be performed by using current digital mammography systems if minor adaptations are made (17). Units that are now in development for clinical use have dual functionality; that is, both two-dimensional (2D) digital mammography and breast tomosynthesis may be performed with the same unit. Breast tomosynthesis therefore has all the advantages of digital mammography, such as reproducibility, less image noise and fewer artifacts, consistent quality, and digital image processing (12).

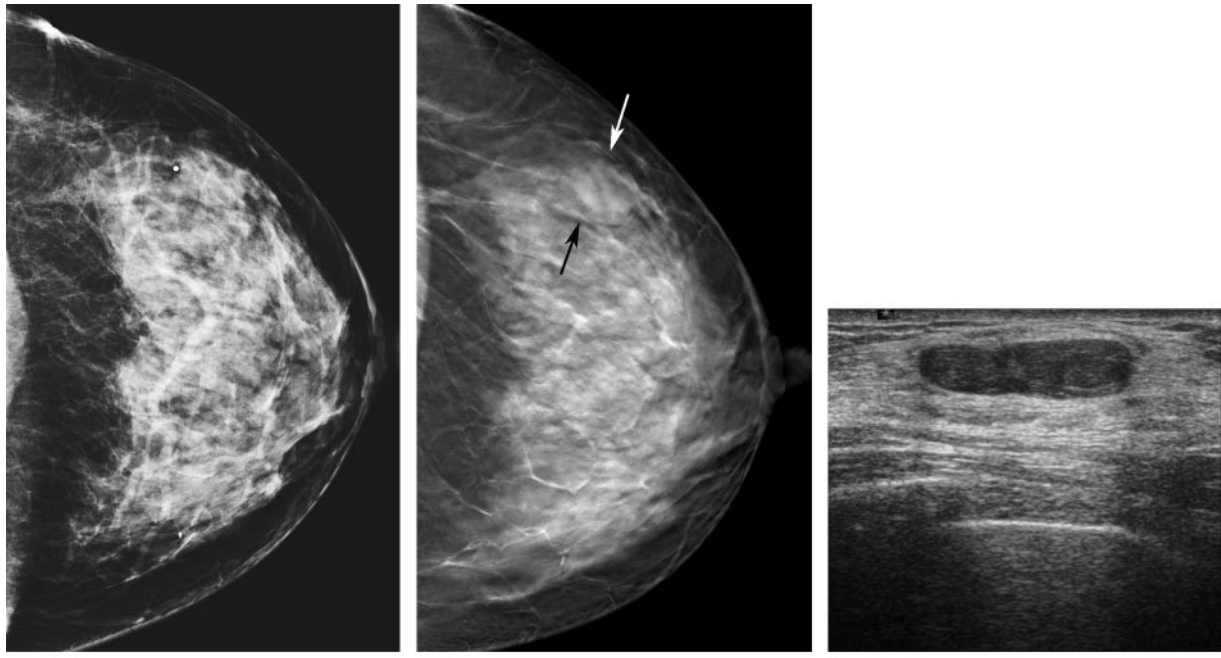


Figure 4. Fibrocystic changes and ductal hyperplasia without atypia in a 45-year-old woman with a palpable abnormality in the left breast. **(a)** Digital mammogram shows a barely visible mass, marked by a BB, in the lower outer part of the left breast. The mass is poorly depicted because of surrounding dense tissue. **(b)** Breast tomosynthesis image clearly shows the mass (arrows). (See also Movie 2 at radiographics.rsna.org/cgi/content/full/27/S231/DC1.) **(c)** US image shows a circumscribed hypoechoic mass. The diagnosis was established at US-guided core-needle biopsy.

In experimental imaging with phantoms in previous studies, tomosynthesis images not only met the American College of Radiology criteria for phantom images but also provided better depiction of the smallest calcifications than did conventional mammograms. Reader scores in experiments with unfixed mastectomy specimens in the same study showed the superior performance of tomosynthesis with regard to lesion visibility, margin visibility, and reader confidence in classification (16,19).

With the use of current breast tomosynthesis technology, the total radiation exposure to the patient from a two-view tomosynthesis acquisition is similar to or less than that from conventional mammography (15,17). Breast tomosynthesis also has other exclusive advantages: Relative to conventional mammograms, the reconstructed tomosynthesis images provide improved visibility of objects within the selected cross section of breast tissue and, at the same time, reduced contrast and visibility of objects in overlying locations. Better delineation of the lesion border results in a more definitive interpretation.

In cases with masses, the border of the mass, the number of masses (if multiple), and associated findings of dilated ducts or vessels and microcalcifications around the mass are better depicted on breast tomosynthesis images, especially in dense breasts. The clearer depiction with tomosynthesis should allow easier differentiation between benign and malignant lesions (Figs 3, 4). Therefore, the clinical application of breast tomosynthesis for screening should lead to a reduction in the recall rate, a higher positive predictive value for biopsy recommendation, and, eventually, a decrease in the number of unnecessary biopsies. The improvements in lesion perception and analysis also should lead to higher cancer detection rates.

In our experience with breast cancer cases, the border of the main mass, any adjacent architectural distortion, and the extent of accompanying microcalcifications are better depicted on breast tomosynthesis images than on mammograms (Figs 5–8). Tomosynthesis also provides more accurate 3D localization of the tumor for surgical planning.

Teaching
Point

Figure 5. Micropapillary-type ductal carcinoma in situ in a 65-year-old woman. **(a)** Digital mammogram shows the primary mass (arrows). **(b)** Breast tomosynthesis image more clearly depicts the border of the mass (black arrows) and adjacent ductal extension (white arrow). (See also Movie 3 at radiographics.rsnaajnl.org/cgi/content/full/27/S231/DC1.)

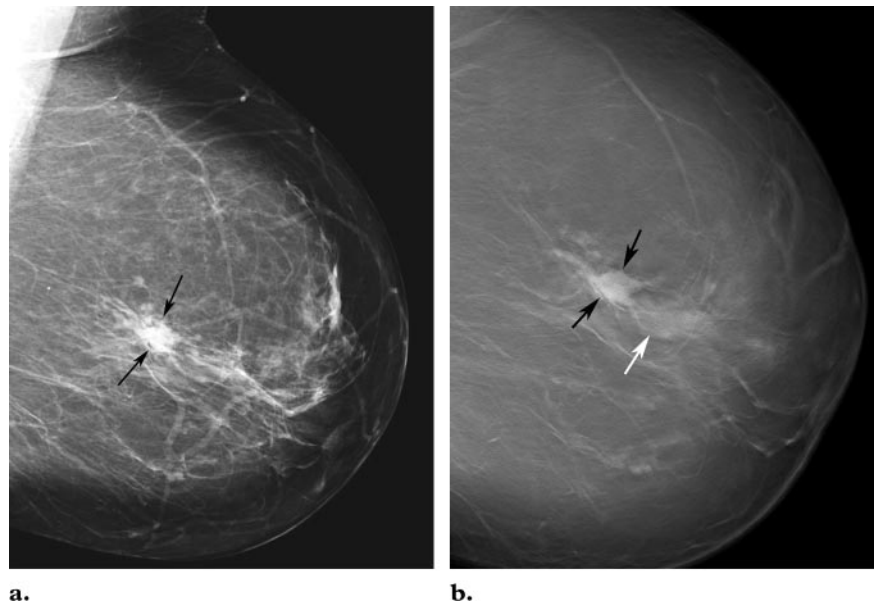


Figure 6. Metastasis from endometrioid carcinoma in a 59-year-old woman with a palpable nodule in the right breast. **(a)** Digital mammogram shows three primary masses (arrows). **(b)** Breast tomosynthesis image provides clearer depiction of the borders of the three masses and shows a fourth mass (arrow). (See also Movie 4 at radiographics.rsnaajnl.org/cgi/content/full/27/S231/DC1.)

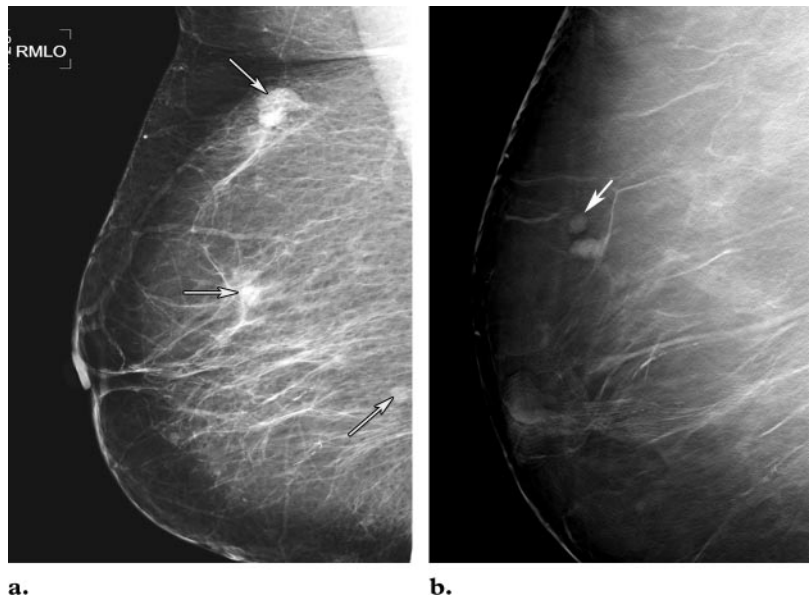
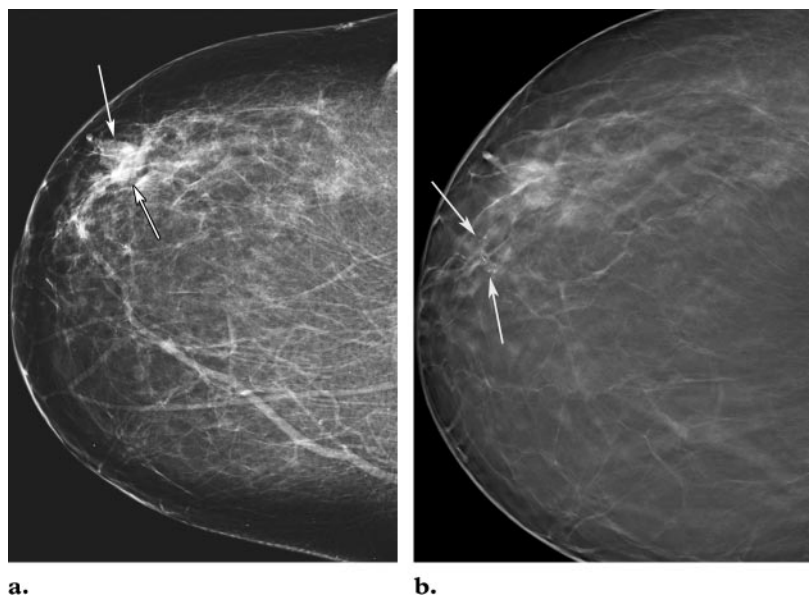


Figure 7. Infiltrating ductal carcinoma and ductal carcinoma in situ in a 51-year-old woman with a lump in the right breast for 1 month. **(a)** Digital mammogram shows an irregularly shaped primary mass and accompanying microcalcifications (arrows). **(b)** Breast tomosynthesis image provides better depiction of accompanying architectural distortion and of the direction and extent of the microcalcifications (arrows). (See also Movie 5 at radiographics.rsnaajnl.org/cgi/content/full/27/S231/DC1.)



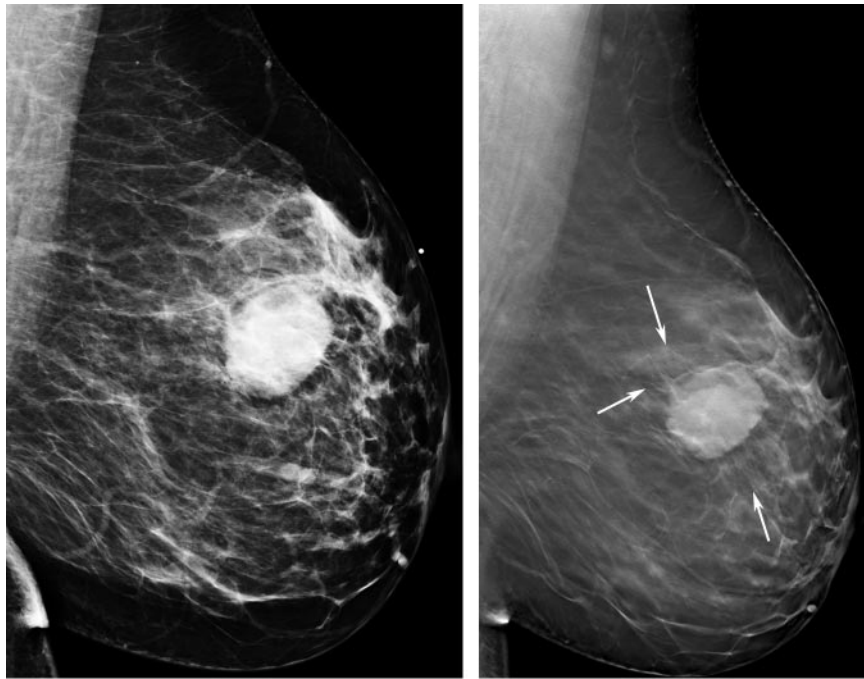


Figure 8. Invasive ductal carcinoma in a 45-year-old woman with a lump in the left breast for 6 months. **(a)** Digital mammogram clearly shows an oval-shaped relatively well-circumscribed primary mass. **(b)** Breast tomosynthesis image provides better depiction of the microlobulated, spiculated border of the mass (arrows), a finding suggestive of malignancy. (See also Movie 6 at radiographics.rsnajnl.org/cgi/content/full/27/S231/DC1.)

a.

b.

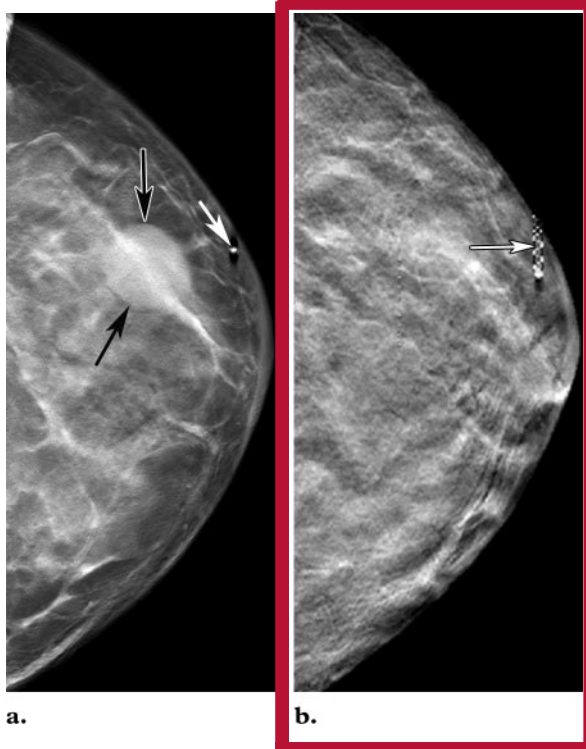


Figure 9. Artifacts due to a large calcification in the left breast of a 79-year-old woman. **(a)** Breast tomosynthesis image shows a mass (black arrows) and an artifact from a large calcification (white arrow). On the basis of the US appearance, the mass was diagnosed as a cyst. **(b)** Breast tomosynthesis image shows a more exaggerated calcification-related artifact (arrow). (See also Movie 7 at radiographics.rsnajnl.org/cgi/content/full/27/S231/DC1.)

a.

b.

We noticed that vessels, especially those that are tortuous, are more easily traced and that lymph nodes in all types of parenchymal patterns are more visible on breast tomosynthesis images. Breast tomosynthesis also provides an advantage when identifying skin lesions, because the location on the skin is automatically verified from the position of the reconstructed section.

Many patients avoid mammography because of pain from breast compression. Breast tomosynthesis requires less compression than does 2D mammography, because it is not necessary to compress and spread the breast tissue exactly parallel to the detector. The main purpose of compression in breast tomosynthesis is to achieve immobilization and to minimize the radiation dose by reducing the breast thickness (12).

Although we observed no substantial disadvantages of breast tomosynthesis, the following are potential disadvantages: *(a)* Special training of technologists is needed for positioning, which is slightly more difficult because of the larger detector size. *(b)* Motion artifacts are more likely to occur because of the slightly longer exposure time. *(c)* There are no substantial artifacts from small microcalcifications, but large calcifications cause significant artifacts (Fig 9). *(d)* The large number of reconstructed images lengthens interpretation time for radiologists. *(e)* Breast tomosynthesis

Teaching Point

Figure 10. Appearance of glandular tissue in the breast of a 45-year-old woman. Normal glandular tissues are more clearly depicted on the breast tomosynthesis image (arrows in **a**) than on the digital mammogram (**b**).

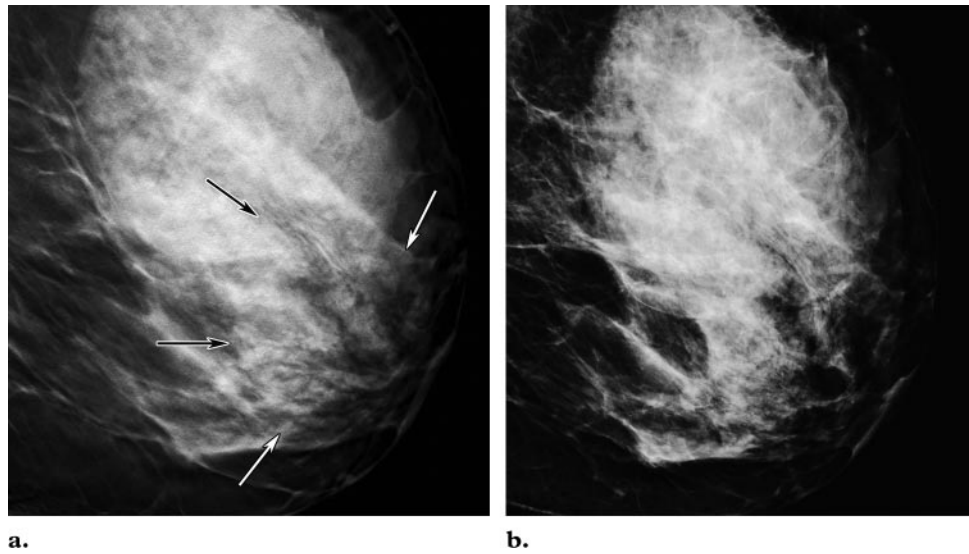


Figure 11. Appearance of lactiferous ducts at screening mammography in a 53-year-old woman. Normal ducts are more prominently depicted on the breast tomosynthesis image (arrows in **a**) than on the digital mammogram (**b**).

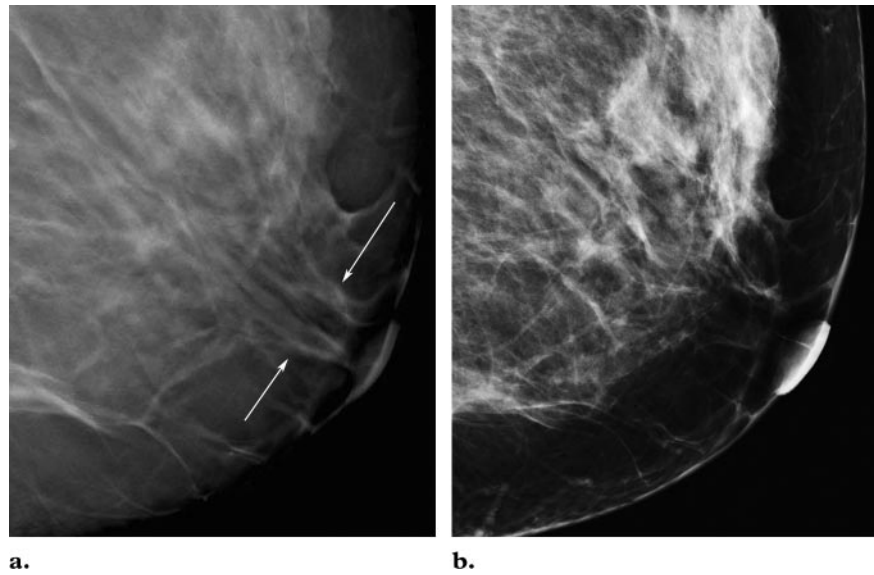
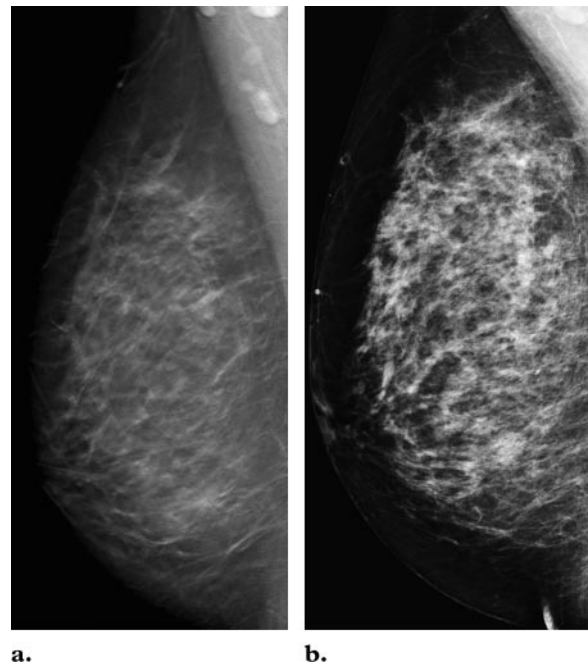
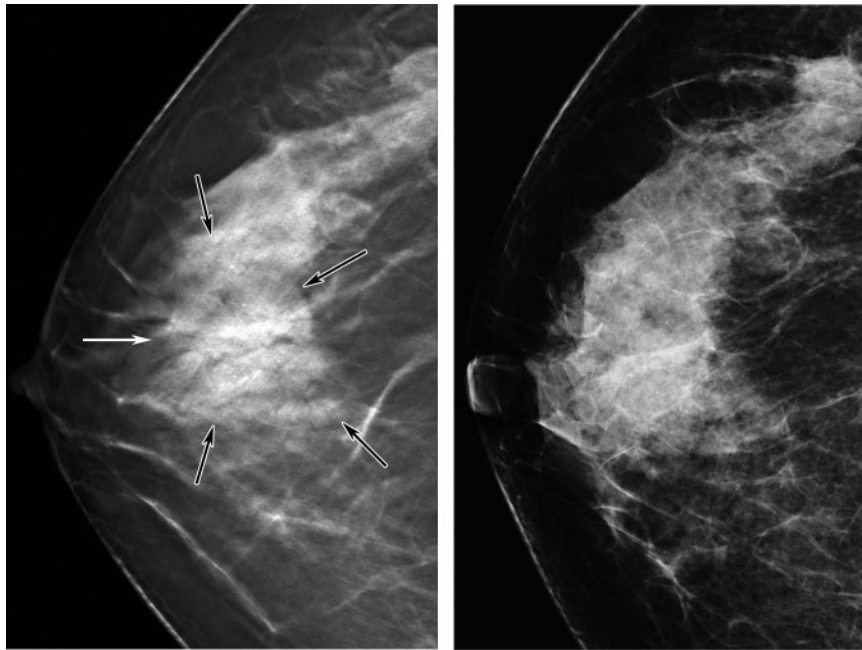


Figure 12. Appearance of the breast parenchyma in a 40-year-old woman. **(a)** Single-section breast tomosynthesis image shows a parenchymal pattern of scattered fibroglandular tissue. **(b)** Digital mammogram shows heterogeneously dense parenchyma.





a.

b.

Figure 13. Benign lesion in a 56-year-old woman. (a) Breast tomosynthesis image shows prominent architectural distortion, an apparent mass, and loosely grouped microcalcifications (arrows), features suggestive of malignancy. Although the 2D mammographic appearance (b) had been stable for many years, a core-needle biopsy was recommended on the basis of findings at tomosynthesis. The diagnosis established at pathologic analysis was ductal epithelial hyperplasia without atypia, fibrocystic change, ductal rupture with chronic inflammation, and microcalcifications.

adds no significant value in the interpretation of lesions that are well demonstrated on 2D mammograms. (f) The appearances of the parenchyma and normal structures on breast tomosynthesis images may diverge from those on 2D mammograms: Normal glandular tissue and ducts might be prominently visible, and heterogeneous parenchyma may appear much less dense on a single breast tomosynthesis image than on the 2D mammogram (Figs 10–13). For these reasons, we believe that radiologists need additional training to interpret 3D breast tomosynthesis images. In addition, it is better to compare breast tomosynthesis images with follow-up breast tomosynthesis images than with 2D mammograms.

Future of Breast Tomosynthesis

A number of questions that arose during the preliminary developmental stages of breast tomosynthesis remain to be resolved. With regard to image acquisition, what is the optimal angular range of tube motion, and what is the optimal number of exposures? These parameters significantly affect the exposure dose and time and the possibility of patient motion. What is the optimal reconstructed section thickness? Thinner sections give better resolution but also result in a huge number of reconstructed images. A faster reconstruction process is essential if 3D breast tomosynthesis is to provide visual guidance for interventional procedures. There are other problems to be solved as well, such as the avoidance or minimization of reconstruction-induced artifacts and scatter radiation (15,20).

What clinical uses are appropriate for this technology? Should we use breast tomosynthesis only for diagnostic imaging in a carefully selected small subset of patients with specific abnormalities, or should we apply it as a general screening tool? If we use it for screening, should we acquire two breast tomosynthesis views or only one? The clinical efficacy of the method for reducing recall rates, increasing the positive predictive value for biopsy recommendation, and increasing the rate of cancer detection must be investigated in well-designed large-scale clinical trials before the technology will be applicable in daily clinical practice.

Despite the many issues yet to be resolved, breast tomosynthesis holds promise for future applications in contrast-enhanced 3D imaging (21), tumor volume estimation, evaluation of multifocal or multicentric disease for surgical planning, improved 3D guidance of procedures with better information about lesion depth, tomogalactography with or without contrast material, and computer-aided diagnosis (22,23). Currently, the only reconstruction planes available at tomosynthesis are those parallel to the detector; reconstruction in other planes specific to the patient's needs could be achieved later. The ability to obtain 3D image data of the whole lesion would help reduce the number of images needed at diagnostic mammography, with a resultant decrease in the amount of radiation to which the patient is exposed (16). If breast tomosynthesis

provides enough information about multifocality and multicentricity of malignant lesions at a lower cost than MR imaging, it would make a significant difference in the clinic.

Conclusions

Breast tomosynthesis provides a 3D imaging capability that allows the more accurate evaluation of lesions by enabling better differentiation between overlapping tissues. **A lower recall rate, higher positive predictive value for a biopsy recommendation, and higher cancer detection rates are expected to result from the use of this technology.** Breast tomosynthesis should be a strong adjunct to both screening mammography and diagnostic mammography.

Teaching
Point

References

- Nystrom L, Rutqvist LE, Wall S, et al. Breast cancer screening with mammography: overview of Swedish randomised trials. *Lancet* 1993;341(8851):973–978. [Published correction appears in *Lancet* 1993;342(8883):1372.]
- Tabar L, Fagerberg CJ, Gad A, et al. Reduction in mortality from breast cancer after mass screening with mammography: randomised trial from the Breast Cancer Screening Working Group of the Swedish National Board of Health and Welfare. *Lancet* 1985;1(8433):829–832.
- Lewin JM, D’Orsi CJ, Hendrick RE. Digital mammography. *Radiol Clin North Am* 2004;42(5):871–884, vi.
- Holland R, Mravunac M, Hendriks JH, Bekker BV. So-called interval cancers of the breast: pathologic and radiologic analysis of sixty-four cases. *Cancer* 1982;49(12):2527–2533.
- Martin JE, Moskowitz M, Milbrath JR. Breast cancer missed by mammography. *AJR Am J Roentgenol* 1979;132(5):737–739.
- Feig SA, Shaber GS, Patchefsky A, et al. Analysis of clinically occult and mammographically occult breast tumors. *AJR Am J Roentgenol* 1977;128(3):403–408.
- Bird RE, Wallace TW, Yankaskas BC. Analysis of cancers missed at screening mammography. *Radiology* 1992;184(3):613–617.
- Maravilla KR, Murry RC Jr, Diehl J, et al. Digital tomosynthesis: technique modifications and clinical applications for neurovascular anatomy. *Radiology* 1984;152(3):719–724.
- Kruger RA, Sedaghati M, Roy DG, et al. Digital angiography: matched filtration versus mask-mode subtraction. *Radiology* 1985;154(1):217–220.
- deVries N, Miller FJ, Wojtowycz MM, et al. Tomographic digital subtraction angiography: initial clinical studies using tomosynthesis—work in progress. *Radiology* 1985;157(1):239–241.
- Sone S, Kasuga T, Sakai F, et al. Development of a high-resolution digital tomosynthesis system and its clinical application. *RadioGraphics* 1991;11(5):807–822.
- Niklason LT, Kopans DB, Hamberg LM. Digital breast imaging: tomosynthesis and digital subtraction mammography. *Breast Dis* 1998;10(3–4):151–164.
- Chan HP, Wei J, Sahiner B, et al. Computer-aided detection system for breast masses on digital tomosynthesis mammograms: preliminary experience. *Radiology* 2005;237(3):1075–1080.
- Rafferty EA, Georgian-Smith D, Kopans DB, Hall DA, Moore R, Wu T. Comparison of full-field digital tomosynthesis with two view conventional film screen mammography in the prediction of lesion malignancy [abstr]. *Radiology* 2002;225(P):268.
- Wu T, Moore RH, Kopans DB. Voting strategy for artifact reduction in digital breast tomosynthesis. *Med Phys* 2006;33(7):2461–2471.
- Niklason LT, Christian BT, Niklason LE, et al. Digital tomosynthesis in breast imaging. *Radiology* 1997;205(2):399–406.
- Smith A. Full-field breast tomosynthesis. *Radiol Manage* 2005;27(5):25–31.
- Wu T, Moore RH, Rafferty EA, Kopans DB. A comparison of reconstruction algorithms for breast tomosynthesis. *Med Phys* 2004;31(9):2636–2647.
- Suryanarayanan S, Karellas A, Vedantham S, et al. Comparison of tomosynthesis methods used with digital mammography. *Acad Radiol* 2000;7(12):1085–1097.
- Sechopoulos I, Suryanarayanan S, Vedantham S, D’Orsi CJ, Karellas A. Scatter radiation in digital tomosynthesis of the breast. *Med Phys* 2007;34(2):564–576.
- Chen SC, Carton AK, Albert M, Conant EF, Schnall MD, Maidment AD. Initial clinical experience with contrast-enhanced digital breast tomosynthesis. *Acad Radiol* 2007;14(2):229–238.
- Reiser I, Nishikawa RM, Giger ML, et al. Computerized detection of mass lesions in digital breast tomosynthesis images using two- and three dimensional radial gradient index segmentation. *Technol Cancer Res Treat* 2004;3(5):437–441.
- Reiser I, Nishikawa RM, Giger ML, et al. Computerized mass detection for digital breast tomosynthesis directly from the projection images. *Med Phys* 2006;33(2):482–491.

Breast Tomosynthesis: Present Considerations and Future Applications

Jeong Mi Park, MD, et al

RadioGraphics 2007; 27:S231–S240 • Published online 10.1148/rg.27si075511 • Content Codes: BR OI

Page S232

When screening mammograms demonstrate a questionable finding, the results of follow-up diagnostic mammography and ultrasonography (US), magnetic resonance (MR) imaging, or biopsy ultimately determine whether the finding is significant. The process causes anxiety for patients and incurs additional healthcare costs for findings that frequently are proved benign. Breast tomosynthesis is a new tool that can be expected to ameliorate this problem by reducing or eliminating tissue overlap. Breast tomosynthesis technology is essentially a modification of a digital mammography unit to enable the acquisition of a three-dimensional (3D) volume of thin-section data. Images are reconstructed in conventional orientations by using reconstruction algorithms similar to those used in computed tomography (CT).

Page S233

In breast tomosynthesis, a moving x-ray source and a digital detector are used.

Page S235

In cases with masses, the border of the mass, the number of masses (if multiple), and associated findings of dilated ducts or vessels and microcalcifications around the mass are better depicted on breast tomosynthesis images, especially in dense breasts.

Page S237

There are no substantial artifacts from small microcalcifications, but large calcifications cause significant artifacts (Fig 9).

Page S240

A lower recall rate, higher positive predictive value for a biopsy recommendation, and higher cancer detection rates are expected to result from the use of this technology.