Tomosynthesis Imaging

Edited by Ingrid Reiser and Stephen Glick

An innovative, three-dimensional x-ray imaging technique that enhances projection radiography by adding depth resolution, tomosynthesis imaging explores tomosynthesis, an emerging limited-angle tomographic imaging technology that is being considered for use in a range of clinical applications, and is currently being used for breast cancer screening and diagnosis. Although conventional mammography has been very successful in reducing breast cancer mortality, it is not perfect. A major limitation of mammography is that the recorded image represents the superposition of complex three-dimensional structures in the breast onto a two-dimensional plane, making detection and diagnosis of breast cancer challenging.

Tomosynthesis produces quasi-three-dimensional images that can significantly enhance the visualization of important diagnostic features. This book highlights the flexibility of tomosynthesis systems for new clinical applications, and provides a detailed discussion of the tomosynthesis acquisition process and the impact of physical factors. It explores such topics as acquisition parameters, system components, modeling, image reconstruction algorithms, and system evaluation.

- Provides in-depth coverage of system design considerations, as well as image reconstruction strategies
- Describes the current state of clinical applications of tomosynthesis, including imaging of the breast and chest, as well as its use in radiotherapy
- Illustrates the merits of tomosynthesis imaging and its potential clinical applications in imaging of the breast and chest, as well as for radiation therapy

Divided into five sections, this text delves into the history and development of tomosynthesis. It introduces tomosynthesis imaging, discusses imaging system design considerations, and reviews image reconstruction algorithms that have been developed for tomosynthesis. It also describes system evaluation methodologies, emphasizes current clinical applications, and examines the future direction for tomosynthesis.
Tomosynthesis Imaging
## IMAGING IN MEDICAL DIAGNOSIS AND THERAPY

William R. Hendee, Series Editor

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To my loving family.

To my wife Clare, for all your support, patience, and friendship.
I love you more than words can tell.

Ingrid Reiser

Stephen J. Glick
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Since their inception over a century ago, advances in the science and technology of medical imaging and radiation therapy are more profound and rapid than ever before. Further, the disciplines are increasingly cross-linked as imaging methods become more widely used to plan, guide, monitor, and assess treatments in radiation therapy. Today, the technologies of medical imaging and radiation therapy are so complex and so computer-driven that it is difficult for the persons (physicians and technologists) responsible for their clinical use to know exactly what is happening at the point of care, when a patient is being examined or treated. The individuals best equipped to understand the technologies and their applications are medical physicists, and these individuals are assuming greater responsibilities in the clinical arena to ensure that what is intended for the patient is actually delivered in a safe and effective manner.

The growing responsibilities of medical physicists in the clinical arenas of medical imaging and radiation therapy are not without their challenges, however. Most medical physicists are knowledgeable in either radiation therapy or medical imaging, and expert in one or a small number of areas within their discipline. They sustain their expertise in these areas by reading scientific articles and attending scientific talks at meetings. In contrast, their responsibilities increasingly extend beyond their specific areas of expertise. To meet these responsibilities, medical physicists periodically must refresh their knowledge of advances in medical imaging or radiation therapy, and they must be prepared to function at the intersection of these two fields. How to accomplish these objectives is a challenge.

At the 2007 annual meeting of the American Association of Physicists in Medicine in Minneapolis, this challenge was the topic of conversation during a lunch hosted by Taylor & Francis Publishers and involving a group of senior medical physicists (Arthur L. Boyer, Joseph O. Deasy, C.-M. Charlie Ma, Todd A. Pawlicki, Ervin B. Podgorsak, Elke Reitzel, Anthony B. Wolbarst, and Ellen D. Yorke). The conclusion of this discussion was that a book series should be launched under the Taylor & Francis banner, with each volume in the series addressing a rapidly advancing area of medical imaging or radiation therapy of importance to medical physicists. The aim would be for each volume to provide medical physicists with the information needed to understand technologies driving a rapid advance and their applications to safe and effective delivery of patient care.

Each volume in the series is edited by one or more individuals with recognized expertise in the technological area encompassed by the book. The editors are responsible for selecting the authors of individual chapters and ensuring that the chapters are comprehensive and intelligible to someone without such expertise. The enthusiasm of volume editors and chapter authors has been gratifying and reinforces the conclusion of the Minneapolis luncheon that this series of books addresses a major need of medical physicists.

**Imaging in Medical Diagnosis and Therapy** would not have been possible without the encouragement and support of the series manager, Luna Han of Taylor & Francis Publishers. The editors and authors, and most of all I, are indebted to her steady guidance of the entire project.

**SERIES EDITOR**

William Hendee
Rochester, Minnesota
Preface

For much of the past century, projection radiography has been the workhorse in the diagnostic imaging clinic. Tomosynthesis, which introduces depth information to the x-ray radiographic image with little or no increase in radiation dose, could potentially replace projection radiography as we move further into the twenty-first century. This book, Tomosynthesis Imaging, offers the most comprehensive resource to date for this new emerging imaging technology.

Digital tomosynthesis imaging is a novel quasi-three-dimensional x-ray imaging modality that has been primarily developed during the past two decades, owing to the availability of large-area digital x-ray detectors. The tomosynthesis image is reconstructed from a sequence of projection images acquired from a limited angle x-ray scan; therefore, conceptually, tomosynthesis might be considered as limited-angle CT. Because of the limited angle acquisition, resolution in the reconstructed volume is not isotropic. The resolution in image planes parallel to the detector surface is similar to the native detector resolution, but the resolution perpendicular to the detector surface direction is substantially worse, and depends on the scan arc length and on the size of the detail being imaged.

Tomosynthesis imaging is being actively investigated for use in a variety of clinical tasks. Currently, tomosynthesis breast imaging is at the forefront, having received approval for clinical use in Europe and Canada in 2008, and FDA approval in the United States in 2011. Although conventional mammography has been very successful in reducing the breast cancer mortality rate, its sensitivity and specificity are less than desirable, especially for women with dense breast tissue. By providing tomographic information, breast tomosynthesis promises to greatly improve visualization of important diagnostic features. In addition to breast imaging, the detection of lung nodules by chest tomosynthesis and detection of hairline fractures with tomosynthesis skeletal imaging are also being investigated. The number of clinical applications for tomosynthesis imaging will, most likely, increase in the future.

This book provides an in-depth understanding of the tomosynthesis image formation process that will allow readers to tailor tomosynthesis systems for new clinical applications. The characteristics of the tomosynthesis reconstructed volume depend strongly on system design parameters; therefore, it is important to gain an understanding of the underlying factors and their effects on the reconstructed volume. This book provides an in-depth coverage of system design considerations, as well as image reconstruction strategies. It also describes the current state of clinical applications of tomosynthesis, including imaging of the breast and chest, as well as its use in radiotherapy. While use of tomosynthesis imaging for these clinical applications is at an early stage, they illustrate the merits of tomosynthesis imaging and its breadth of potential uses.

This book is written for clinicians and researchers. With breast tomosynthesis being approved for clinical use in several countries, medical institutions are faced with the decision to add tomosynthesis to their suite of imaging devices. Clinicians as well as other hospital personnel involved in the purchase and use of clinical tomosynthesis systems should find this book helpful in understanding the principles of tomosynthesis. This book may also be used as classroom teaching material or in workshops to improve understanding of tomosynthesis images, regardless of clinical application.

The book is divided into five sections. Section I introduces tomosynthesis imaging with a historical perspective (the principle of tomosynthesis dates back to work by Ziedsdes des Plantes in 1929). Section II discusses imaging system design considerations, including acquisition parameters, system components, optimization, and modeling schemes. The purpose of this section is to acquaint the reader with the flexibility of tomosynthesis acquisition and the impact of physical factors in the various schemes. Section III reviews image reconstruction algorithms that have been developed for tomosynthesis, including filtered back-projection methods that are used in most clinical systems, as well as advanced iterative methods that have the potential to reduce artifacts and improve image quality. Section IV describes system evaluation methodologies, including radiologist performance studies and assessment using mathematical model observer assessment. Finally, Section V is dedicated to current clinical applications, which include breast, chest and therapy applications, and concludes with a discussion of future directions for tomosynthesis.

The goal of this book is to cover the fundamentals of tomosynthesis imaging. As tomosynthesis and its applications are evolving rapidly, clinical trials to assess the clinical performance of tomosynthesis imaging are ongoing, and we hope that our readers will join us in eagerly awaiting the outcome of these trials.

EDITORS

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Ingrid Reiser, PhD, is a research associate (assistant professor) in the Department of Radiology at the University of Chicago. After earning her PhD in physics from Kansas State University in 2002, she transitioned into medical physics research where she witnessed the presentation of the first breast tomosynthesis images at RSNA 2002 (Radiological Society of North America). Tomosynthesis captivated her interest and she has since investigated many aspects of tomosynthesis imaging, such as computer-aided detection, system modeling, and objective assessment. Her research interests further include image perception and observer performance, as well as tomosynthesis and CT image reconstruction.

Stephen J. Glick, PhD, is a professor of radiology at the University of Massachusetts Medical School and the director of the Tomographic Breast Imaging Research Laboratory. He earned his PhD from Worcester Polytechnic Institute (WPI) in 1991. Dr. Glick has published over 60 journal articles and over 100 conference proceedings papers. Over the past decade, his research has been focused on 3D breast imaging techniques including digital breast tomosynthesis and breast CT with an emphasis on radiation dose, imaging technique optimization, advanced iterative reconstruction methods, detection studies for lesions and microcalcifications, and photon counting detector CT.
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The history of tomosynthesis

Mitchell M. Goodsitt

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1.1 INVENTION OF TOMOSYNTHESIS IN THE LATE 1930S

1.1.1 CONCEPT: SHIFT AND ADD

Tomosynthesis addresses one of the primary weaknesses of conventional single-projection x-ray imaging, the superposition of objects in the image. This superposition may result in the obscuring of an object of interest and/or the production of pseudoobjects that mimic a disease (e.g., pseudomasses or a reduction in bone joint space). Tomosynthesis decreases superposition by generating slice images of the body from a series of projections taken at a variety of angles. In this sense, it is much like computed tomography (CT); however, instead of acquiring projections over 360° as in CT, the projections for tomosynthesis are acquired over a limited range of angles (e.g., 10° or 60°). The resulting tomosynthesis images have much better spatial resolution than CT within the slice, but poorer resolution in the depth direction, between the slices. The basic tomosynthesis principle is illustrated in Figure 1.1. A series of snapshot radiographs (films) are taken, each from a different viewing angle, as an x-ray tube translates across a patient. These snapshots are later combined by shifting the snapshots relative to one another and superimposing (adding) them to bring different planes within the patient in focus. Today, we use digital radiographs instead of films and more sophisticated reconstruction algorithms like those employed in CT instead of the “shift-and-add” technique.

1.1.2 INVENTORS ZIEDSES DES PLANTE S AND KAUFMAN

A Dutch neuroradiologist and electrical engineer, Bernard George Ziedses des Plantes, is often credited with inventing tomosynthesis. Ziedses des Plantes published the first article about the technique, which he called “seriescopy,” in 1935 (Ziedses des Plantes 1935). He subsequently patented seriescopy in 1936 (Ziedses des Plantes 1936). In a 1938 paper (Ziedses des Plantes 1938), he described seriescopy as a “radiographic method which makes it possible to view an infinite series of parallel planes in succession by means of a few exposures.” Ziedses des Plantes built a prototype serioscope based on circular tomography in which the system took four stationary film exposures at equidistant locations along the circular path of the x-ray tube (e.g., at 0°, 90°, 180°, and 270°). Different planes of focus could be achieved by reciprocally moving the developed films above a single viewing screen. Ziedses des Plantes also described an optical method of reconstruction using mirrors to superimpose images of the films and the rocking of the mirrors to achieve the same effect as translating the films (Webb 1990). In addition, he described a device for recording the level of the plane of focus (Webb 1990).

A method very similar to seriescopy was invented by Julius Kaufman, MD, of Brooklyn, New York in 1936 (Kaufman 1936a). Kaufman called his method “planeography” and stated that with this method, “it is possible to demonstrate any plane in space, parallel to the plane of the plate from two (or more) roentgenograms (films) properly taken.” Kaufman stressed the localization and depth measurement capabilities of his method. Depth measurements were achieved “by reference to a specially constructed curve, the ‘standard depth curve,’” which related the height of a linear object in a plane parallel to the films to the spread of the projections of that object in the films. Although Kaufman is not recognized as the inventor of tomosynthesis, given the similarities between the concepts of Ziedses des Plantes and Kaufman, the fact that the inventions were made at about the same time (1935 for Ziedses des Plantes, 1936 for Kaufman) and neither was familiar with the other’s work at that time, it seems fair that both Ziedses des Plantes and Kaufman should be credited with this invention. In addition to his original paper explaining the planeography method, Kaufman published two short papers on applications of the method (Kaufman 1936b, 1938). Also, after learning of a presentation on serioscopy by Cottenot in 1937 (described in the next section of this chapter),

![Figure 1.1 Illustration of the shift-and-add technique whereby the positions of images obtained at different angles (left) are shifted relative to one another and superimposed (added) to bring different planes (e.g., plane 1 and plane 2) within the object (patient) in focus (right).](image-url)
Kaufman and a colleague, Harry Koster, MD, published a critical
analysis comparing their planeography technique to Cottenot’s
serioscopy and Ziedses des Plante’s seriescopy (Kaufman and
Koster 1940). The latter are two different spellings for the same
technique. Kaufman and Koster stated, “apparently Dr. Cottenot
rediscovered planeography independently, terming the method
‘serioscopy’” (Kaufman and Koster 1940). In their critical
analysis, Kaufman and Koster illustrated how, with serioscopy,
onequal magnification of parts of an object (e.g., the top and
bottom of a vertically oriented cylinder) at different distances
from the film detector results in an “erroneous impression
of the true size, shape and relative position of the object” in
the serioscope. They state that special measures suggested by
Kaufman in his earlier planeography publications (Kaufman
1936b, 1938) are required to correct these problems.

1.1.3 COTTENOT’S EARLY CHEST
TOMOSYNTHESIS SYSTEM

In 1937, Paul Cottenot presented a paper at the Fifth
International Congress of Radiology in Chicago, Illinois, in
which he described a tomosynthesis method he developed for
the “study of pleuro-pulmonary lesions.” He called this method
“thoracic serioscopy” (Cottenot 1938). Cottenot noted that his
method was based on the work of Ziedses des Plantes. In order to
image the chest with tomosynthesis, it is critical that each of the
projection radiographs be taken at the same level of inspiration.
Cottenot accomplished this by developing a “respiratory trigger”
consisting of a pneumatic belt that was wrapped around the
patient. The belt sent a pressure wave to one side of a U-shaped
mercury manometer, the other side of which contained a metal
rod the position of which was adjusted so that the rod touched
the mercury at a desired level of inspiration. When the mercury
level on the side of the rod reached the rod, electrical contact
was made, triggering the exposure. Four exposures were made,
with the x-ray tube shifted 14 cm to the left, right, upward,
and downward of the center. In order to limit motion blur,
the exposure time for each film was set to about one-third the
exposure time for a conventional radiograph. The thoracic
serioscopy device is shown in Figure 1.2a.

The developed films were viewed on a special high-intensity
light box with screws that shifted the relative positions of the
films (Figure 1.2b). Because the imaging geometry was known
(focal distance of 1.4 m, and shifts of 14 cm, for a tomosynthesis
angle of 11.4°), the serioscope could be calibrated, and the
viewing system included a pointer and a dial that was graduated
in centimeters (Figure 1.2b). Some of the successful clinical
applications of serioscopy that Cottenot described included
determining the dimensions and locations of a pneumothorax,
abscesses of the lung, and tuberculosis foci (Cottenot 1938).

1.2 FILM-BASED SYSTEMS OF

1.2.1 GARRISON AND GRANT’S SYSTEM AT THE
APPLIED PHYSICS LAB AT JOHNS HOPKINS

There were almost no developments in tomosynthesis between
the late 1930s and the late 1960s when John Garrison and
David Grant et al. of Johns Hopkins University in Baltimore,
Maryland described their prototype system (Garrison et al. 1969).
Their prototype, like Ziedses des Plante’s, used a circular scan.
Twenty individual uniformly spaced radiographs were recorded
(Figure 1.3), photoreduced onto a single film, and reprojected
using a sophisticated optical backprojection system with mirror
assemblies (Figures 1.3b and 1.4).

![Image 1](https://example.com/image1.png)
![Image 2](https://example.com/image2.png)

Figure 1.2 (a) Cottenot’s thoracic serioscopy image acquisition
system. (b) Cottenot’s serioscope viewing system. (Reproduced with
permission from Radiology.)

![Image 3](https://example.com/image3.png)

Figure 1.3 Garrison and Grant’s image acquisition system (a). The
20 acquired images were each photoreduced onto a film strip using
a custom camera recording system and then projected onto a single
large film using the same 3D projector mirror system as was used
for final viewing (see Figure 1.4). That film was then illuminated in
the 3D projector mirror system (b) and the tomosynthesis slices
were observed on a viewing screen. (Reproduced with permission
from IEEE.)
The history of tomosynthesis

Introduction

The projections were integrated on a viewing screen that was moved up and down to display different planes (slices) in the volume (Figure 1.4), and the image on the screen was captured with a TV camera and displayed on a TV monitor.

David Grant coined the term “tomosynthesis” in a paper he published in 1972 (Grant 1972).

1.2.2 RAPID FILM CHANGER TOMOSYNTHESIS SYSTEMS

1.2.2.1 Dynatome system of Albert Richards

The first commercial film-based tomosynthesis system, the Dynatome by CFC Products, Inc., was developed in the 1970s and the 1980s by Albert Richards, MS (Physics), a professor of dentistry at the University of Michigan Dental School. Ten radiographic films were acquired at different angles along a linear tomographic sweep of the patient. A rapid film changer was employed to acquire these films at a rate of ≥2 films/s. A special film developed by Eastman Kodak specifically for the low-density exposures associated with this system was employed. A calibrator was utilized (Figure 1.5a) for determining the angle for each film and the films were trimmed and shaped based on the projection angles (Figure 1.5b).

The developed films were arranged on a custom high-intensity light box viewer (Figure 1.6) and moved with a dial in a precise relationship to each other, so information from any level common to all films could be registered. By moving the dial, the equivalent of about 100 contiguous slices could be viewed, each with a thickness of 2 mm. The total radiation dose to the patient was about equal to that of two or three plain films.

Richards described the principles of dynamic tomography, his name for tomosynthesis, in a paper published in 1976 (Richards 1976). In that paper, he stated that he found moving the x-ray source in a circular path yielded “better results than can be achieved with linear movement.” Richards demonstrated the principle of “circular-movement” dynamic tomosynthesis by taking separate films of human cadaver skulls at eight locations along a circular path, each location separated by 45°, with manual orientation of each film cassette. For viewing, the developed films were superimposed on a bright viewbox; the long axis of each film was rotated 45° relative to the previous film, and 180° opposite film pairs (e.g., 0° and 180°, 45° and 225°) were shifted together along paths through their longitudinal axes. Richards stated that all that was needed to make circular movement dynamic tomography practical for live patient imaging was the construction of an apparatus that would provide rapid changing and proper orientation of the eight film cassettes. He also prophesized that a future application of dynamic tomography would be the examination of the beating heart, layer by layer, and this would be accomplished with EKG gating and very short exposures (Richards 1976).
1.2.2.2 Rapid film changer system of Miller

A rapid film changer tomosynthesis system similar to Richard’s Dynatome was developed by Miller et al., but was never commercialized (Miller et al. 1971). Unique to Miller et al.’s rapid film changer system was the production of hardcopy films by illuminating the projection radiographs in a photographic camera, with shifting of either the camera or the radiographs to produce a film showing an image of the desired focal plane.

1.2.3 CODED APERTURE TOMOSYNTHESIS

One of the most intriguing and advanced tomosynthesis methods of the past, coded aperture imaging, was developed by Klotz and Weiss of Philips GmbH of Hamburg, Germany in the 1970s (Klotz and Weiss 1974, 1976, Weiss et al. 1977, 1979). This method could generate arbitrary tomosynthesis planes with imaging times of only milliseconds, essentially eliminating any problems associated with patient motion. They called their method “flashing tomosynthesis,” and its application to coronary angiography was described in a paper that they coauthored with Woelke et al. (1982). The coding and decoding steps are illustrated in Figure 1.7. In general, for coding, many x-ray sources were either pulsed sequentially or simultaneously (Figure 1.7a). A single 60 × 60 cm film recorded the entire set of subimages, forming the coded image. For decoding, this coded image was illuminated with a light box and a three-dimensional (3D) image of the object in space was produced with an array of lenses that were arranged according to the distribution of x-ray tubes. A ground glass screen (Figure 1.7b) was positioned within the 3D image to display different layers within the object.

The system Woelke et al. employed consisted of 24 small stationary x-ray tubes that were fired simultaneously. The exposure time was about 50 ms, the radiation exposure to the skin was about 1 roentgen, and the slice thickness was about 1 mm. In addition to the multiple x-ray tubes, the hardware in the system included an optical postprocessing unit, a TV monitor on which reconstructed layers were displayed, and a film hardcopy unit (Woelke et al. 1982). In a study of 20 left coronary artery stenoses within 10 postmortem hearts that were placed within a thorax phantom, Woelke et al. found that the correlation between the degree of stenosis determined with flashing tomosynthesis and morphometry (r = 0.92, p < 0.001, SE = 9%) was better than the correlation between the degree of stenosis determined with conventional 35-mm cine film cardiac imaging and morphometry (r = 0.82, p < 0.001, SE = 16%). They also successfully employed their flashing tomosynthesis technique on five patients with coronary artery disease. Limitations of the flashing tomosynthesis method included restriction to a small 9-cm-diameter field of view, and the inability to evaluate blood flow dynamics due to the use of a single “flash” exposure (Woelke et al. 1982). Additional papers that have been published on flashing and coded aperture tomosynthesis include those of Groh (Groh 1977), Nadji et al. (1980), Stiel et al. (Stiel 1989, 1992, 1993), Haaker et al. (1985a,b, 1990), and Becher et al. (1983, 1985).

1.3 COMPARISON OF SERIOSCOPY, TOMOSYNTHESIS, AND CODED APERTURE TOMOGRAPHY

The distinctions between serioscopy, tomosynthesis, and coded-scan tomography are discussed in detail in a paper by Mandelkorn and Stark (1978).

1.4 FLUOROSCOPIC TOMOSYNTHESIS

Fluoroscopic applications of tomosynthesis were developed separately by Baily et al. of the University of California, San Diego (Lasser et al. 1971, Baily 1973, 1974) and Hoefer et al. of Philips in Hamburg, Germany (Hoefer 1974) in the early 1970s. The image intensifier–TV camera detector in fluoroscopic systems offered the advantages of high frame rates and good contrast for low radiation doses. Components of the early fluoroscopic tomosynthesis systems were similar. Those of Hoefer et al. included a linear tomography device with a pulsed x-ray source and an image intensifier–TV camera detector, a video disk recorder to sequentially save the tomographic projection video images, a minicomputer to store the positions of the x-ray tube and image intensifier at the time of each x-ray pulse and to compute the shift values for tomosynthesis, and a lithium storage tube on which the projection images from the disk recorder were shifted and added to create tomosynthesized images. Those images (layers) were in turn recorded on the disk recorder and displayed on a video monitor.

The video signal from the image intensifier–TV camera chain of the fluoroscopic tomosynthesis system could also be digitized and processed to create digital projection images from which a set of tomosynthesis slices could be reconstructed. A set of slices generated before contrast injection could be subtracted from subsequent corresponding sets generated after intravenous or intra-arterial iodine contrast injection to produce digital subtraction angiography (DSA) tomosynthesis images that improved the perception of blood vessels. Pioneers in applying tomosynthesis to DSA included Kruger et al. of the University of Utah (Kruger et al. 1983, 1984, Anderson et al. 1984, deVries et al. 1985) and Maravilla et al. of the University of Texas (Maravilla et al. 1983a,b, 1984, Murry and Maravilla 1983).

Skelbitz and Haendle (1983) developed a real-time fluoroscopic tomography “tomoscopy” system that combined a fluoroscopic detector with a 16 x-ray tube source. A new type of x-ray tube was developed for this system. It had a large rotating anode (target) that was surrounded by 16 grid-controlled cathodes. The result was the equivalent of 16 x-ray tubes that were arranged in a circle and were pulsed sequentially, creating a source that electronically moved in a circle. The detected region of the image intensifier was magnetically adjusted in real time to electronically move in synchrony with the moving x-ray source. Each entire scan was accomplished in the time for one TV field (about 20 ms). The 16 projections were superimposed on a fluorescent screen for display, with electronic shifting of the projections to produce tomosynthesis slices at different heights.

A limitation of all of the image-intensifier-based tomosynthesis systems was geometric (e.g., pin cushion) distortion arising from poorer focusing of electrons within the image intensifier toward the outer edges of the image.

1.5 DIGITAL DETECTOR-BASED TOMOSYNTHESIS

There was a marked reduction in tomosynthesis research and development in the later 1980s because of the rising popularity of CT and because there were no suitable distortion-free, high-frame-rate digital detectors for tomosynthesis. There was a rebirth of tomosynthesis in the late 1990s with the development of high detective quantum efficiency (DQE) flat-panel and charge-coupled device (CCD) digital x-ray detectors with rapid readout, and the application of tomosynthesis to full-field breast imaging by Niklason and Kopans et al. of Massachusetts General Hospital (MGH) of Boston, MA, and scientists at General Electric (GE) Corporate Research and Development, Schenectady, New York (Niklason et al. 1997), the application of tomosynthesis to small (5 × 5 cm) field breast imaging by Webber of Bowman Gray School of Medicine, Winston-Salem, Chapel Hill, North Carolina and Instrumentarium Imaging, Inc. of Tuusula, Finland (Webber 1994–2000, Lehtimaki et al. 2003), and the application of tomosynthesis to chest imaging by Dobbins et al. of Duke University, Durham, North Carolina (Dobbins et al. 1998, 2008, Dobbins 2009).

1.5.1 DIGITAL DETECTOR BREAST IMAGING SYSTEMS

1.5.1.1 System developed by Niklason, Kopans, and GE

A picture of the system that was used by Loren Niklason and Daniel Kopans in their early breast tomosynthesis studies is shown in Figure 1.8.

It consisted of a GE DMR mammography system that was modified to incorporate a stationary GE-developed flat-panel digital detector made of a cesium iodide (CsI) phosphor backed by an amorphous silicon (a-Si) transistor–photodiode array. This detector had a pixel pitch of 100 microns and a readout time of 300 ms. The gantry was modified to permit manual positioning of the x-ray source along an arc. The tomosynthesis angle was 40° (±20°) with nine equally (5°) spaced views, and the radiation dose was about 1.4 times that of a standard film-screen mammogram. The projection images were transformed from the actual “x-ray source motion along an arc” geometry to “x-ray source motion in a horizontal plane parallel to the detector” geometry so that linear shift-and-add reconstruction could be employed (Niklason et al. 1997). Based on preliminary phantom and breast specimen studies, Niklason et al. concluded that “tomosynthesis may improve the specificity of mammography with improved lesion margin visibility and may improve early breast cancer detection, especially in women with radiographically dense breasts” (Niklason et al. 1997). The research group at MGH also published early work comparing a variety of tomosynthesis reconstruction methods for breast imaging (Wu et al. 2004).

1.5.1.2 Tuned aperture CT digital spot tomosynthesis: Webber and instrumentarium

Tuned aperture computed tomography (TACT) is a tomosynthesis method that was originally developed by Richard Webber, DDS, PhD, of Bowman Gray School of Medicine, Winston-Salem, North Carolina for dental applications (Webber 1994, 1997, Webber et al. 1995, 1996, 1997, 1999), and later for breast imaging applications (Webber et al. 2000). It is based on optical aperture theory and requires the use of a fiducial reference point. The method was licensed to Instrumentarium Imaging Inc., and they developed a commercial system called the Delta 32 TACT® 3D breast imaging system. The Delta 32 system debuted at the 1997 Radiological Society of North America meeting in Chicago, Illinois, and it received FDA approval in 2000. This was a spot imaging system that employed a 5 × 5 cm CCD detector. A fiducial marker was placed on the compression paddle and images were acquired at seven angles. According to a paper by Mari Lehtimaki et al. (Lehtimaki et al. 2003) of Instrumentarium Imaging, the TACT process includes (1) stacking the acquired images and recognizing the reference point corresponding to the fiducial marker in each image, (2) determining the center of gravity of the set of reference points, (3) drawing lines between each reference point and the center of gravity, (4) shifting each of the stacked images the same relative amount along its line between the reference point and center of gravity, and (5) averaging the superimposed pixels in the shifted stacked images to create a TACT image. Different TACT images were obtained by using different shift values. A unique feature of TACT is the use of the external fiducial marker, which defines the geometry, enabling the use of arbitrary acquisition projection angles.
1.5.1.3 Other early flat-panel digital tomosynthesis breast imaging systems

Others who pioneered the development of digital flat-panel tomosynthesis for breast imaging included Suryanarayanan and Karrelas et al. of the University of Massachusetts, Worcester, Massachusetts (Suryanarayanan et al. 2000, 2001). They employed a GE 2000D digital mammography system that was similar to the system employed by Niklason and Kopans at MGH; however, instead of a 40° tomosynthesis angle with nine 5° increments, Suryanarayanan and Karrelas et al. employed a 36° tomosynthesis angle with seven 6° increments. They also evaluated a variety of tomosynthesis reconstruction algorithms, including TACT backprojection, TACT maximization, TACT minimization, TACT-iterative restoration, and expectation maximization and Bayesian smoothing iterative methods (Suryanarayanan et al. 2000, 2001).

1.5.1.4 Optimization of acquisition parameters in breast tomosynthesis

Several research groups have been investigating the optimization of acquisition parameters (e.g., total sweep angle, angle increment, and radiation dose) for breast tomosynthesis (Wu et al. 2003, Godfrey et al. 2006b, Deller et al. 2007, Zhao et al. 2007, Zhou et al. 2007, Gifford et al. 2008, Reiser et al. 2008, Chan et al. 2008, Sechopoulos and Ghetti 2009, Chawla et al. 2009, Lu et al. 2010, 2011). This topic is discussed in great detail in Chapter 2 on geometry and systems design considerations in this textbook.

1.5.2 DIGITAL TOMOSYNTHESIS FOR BODY IMAGING

1.5.2.1 Chest imaging

Dobbins and his research group at Duke University, Durham, North Carolina constructed a prototype flat-panel detector tomosynthesis system for chest imaging (Godfrey et al. 2003). It employed a stationary commercial GE Revolution 41 × 41 cm CsI phosphor, a-Si detector flat-panel detector with 200 micron pixel pitch, a custom-made x-ray tube mover, and matrix inversion tomosynthesis (MITS) reconstruction. A linear actuator was used to move the x-ray tube vertically during the tomosynthesis scan, and a second actuator was employed to adjust the angle of the x-ray tube so the x-ray beam collimator was centered upon the detector for each projection. The digital detector could be operated at frame rates up to 5.8 frames/s. Typical acquisition parameters for chest tomosynthesis studies included 61 projections, -10.5 s total scan time, 20° total tube motion, and 10 ms per exposure. The x-ray tube was moved continuously during the scan rather than use a step-and-shoot technique. A theoretical investigation indicated that for the chosen exposure time and scan rate, continuous motion of the x-ray tube would be satisfactory since the resulting blur at the detector was minimal even for objects in the most posterior thoracic plane of large subjects. One concern with digital detectors is image retention or ghosting in which faint versions of previous frames remain on the detector and corrupt successive frames. This would have a detrimental effect on tomosynthesis reconstructions. A solution is to employ scrub frames in which a blank frame is readout without x-ray exposure before each x-ray image is acquired. This scrub frame readout process cleans the detector of the majority of the information from prior images, but since twice as many frames are needed, it slows the total readout time by 50%. An experimental study was performed with and without scrub frames, and it was determined that for this detector and the chosen acquisition speed without scrub frames (5.8 frames/s), the difference between projections acquired with and without scrub frames was minimal, so scrub frames were not necessary (Godfrey 2003). The prototype system developed at Duke served as the basis for the commercial body tomosynthesis system presently marketed by GE Healthcare (VolumeRad). The GE system also uses continuous x-ray tube motion, but it uses a different reconstruction algorithm.

In 2009, Dobbins and McAdams published a review article titled “Chest Tomosynthesis: Technical Principles and Clinical Update” (Dobbins and McAdams 2009). In this article, Dobbins and McAdams described the initial results of a clinical trial for lung nodule detection that was conducted at Duke University. This trial compared tomosynthesis using their prototype unit to PA digital chest radiography using a GE Healthcare commercial unit (Dobbins et al. 2008). They found that when they “counted as true positives only those nodules that were scored as definitely visible, sensitivities for all nodules by tomosynthesis and PA radiography were 70% (±5%) and 22% (±4%), respectively (p < 0.0001).” They also described the results of a prospective human observer study of chest tomosynthesis that was conducted at the Sahlgrenska Academy of the University of Gothenburg, Sweden using the GE VolumeRad tomosynthesis system. In that study, it was found that on average, three times as many lung nodules were detected by tomosynthesis as by conventional chest radiography (Vikgren et al. 2008).

Other publications on the application of tomosynthesis to the evaluation of the chest, lung, and lung nodules include Rimkus et al. (1989), Sone et al. (1991, 1993, 1996), Matsuo et al. (1993), Dobbins et al. (1998), Godfrey et al. (2001a, b), Godfrey and Dobbins (2002), Fahrig et al. (2003), Yamada et al. (2011), Asplund et al. (2011), Gomi et al. (2011), Kim et al. (2010), Quaia et al. (2010, 2012), Johnsson et al. (2010a, b), Santoro et al. (2010), Zachrisson et al. (2009), and Jung et al. (2012).

1.5.2.2 Orthopedic, dental, radiotherapy, and other applications of tomosynthesis


1.5.2.3 Optimizing parameters in body tomosynthesis
Recently, Machida et al. published a tutorial in the Radiographics journal on optimizing parameters in flat-panel digital detector body tomosynthesis (Machida et al. 2010). The parameters that are discussed in this paper include “sweep angle, sweep direction, patient barrier–object distance, number of projections, and total radiation dose.” In addition to these parameters, this paper also describes acquisition-related artifacts and ways to minimize those artifacts. Some of the artifacts include blurring from high-contrast objects that are oriented perpendicular to the sweep direction, ripple from high-contrast structures far from the plane of focus that are not sufficiently blurred, and ghosting or parasitic streaks from high-contrast objects located outside the plane of focus whose long axis is parallel to the sweep direction. Machida et al. demonstrate how blurring and ghosting artifacts can be minimized by appropriate selection of the sweep direction, and how ripple can be minimized by increasing the number of projections.

1.6 BRIEF HISTORY OF TOMOSYNTHESIS RECONSTRUCTION METHODS

The methods that have been employed to reconstruct tomosynthesis slices range from shift and add, which was employed in the first film-based systems, to iterative reconstruction, which is employed in modern digital detector-based systems. A brief description of these methods including their history follows.

1.6.1 SHIFT AND ADD

The shift-and-add method may be considered unfiltered backprojection. It has been used since 1935 (Ziedses des Plantes 1935). This method brings in-plane objects in focus while blurring out-of-plane features.

1.6.2 TUNED APERTURE CT

The TACT method is basically shift and add with fiducial markers. It allows images to be acquired at random angles and orientations and reconstructed in arbitrary planes. It has been employed since 1994 (Webber 1994).

1.6.3 MATRIX INVERSION

MITS employs linear algebra to solve and correct for out-of-plane blur using known blurring functions of all other planes when a given plane is reconstructed. It was developed by Dobbins et al. and has been used since 1987 (Dobbins et al. 1987, Dobbins 1990, Godfrey et al. 2001a,b, 2002, 2003, 2006b, Warp et al. 2000).

1.6.4 FILTERED BACKPROJECTION

Filtered backprojection is the most common CT reconstruction method. Low-pass filters are used in the spatial frequency domain to compensate for incomplete and/or nonuniform sampling of the tomography acquisition in the spatial domain to suppress high frequencies. Filtered backprojection has been applied to tomosynthesis since 1998 (Lauritsch and Harer 1998, Badea et al. 2001, Stevens et al. 2001).

1.6.5 ALGEBRAIC RECONSTRUCTION TECHNIQUES

Algebraic reconstruction was the method employed in the first commercial CT scanners made by EMI Ltd (London, England). It involves an iterative solution to a set of linear equations, ray by ray. It has been employed in reconstruction since 1970 (Gordon et al. 1970, Meyer-Elbrecht and Wagner 1975). Several variants have also been employed including “simultaneous algebraic reconstruction” (SART) (Andersen and Kak 1984), “simultaneous iterative reconstruction technique” (SIRT) (Colsher 1977), and “iterative least squares technique” (ILST) (Colsher 1977, Bleuet et al. 2002).

1.6.6 STATISTICAL RECONSTRUCTION

Statistical reconstruction methods such as maximum likelihood (ML) determine the 3D model of x-ray attenuation coefficients, which maximize the probability of obtaining the measured projections. Some variants include “maximum likelihood–expectation-maximization” (ML-EM) (Lange and Fessler 1995) and “maximum likelihood with convex algorithm” (ML-convex) (Lange 1990, Lange and Fessler 1995, Wu et al. 2003, 2004).

1.7 METHODS TO REDUCE BLUR FROM OUT-OF-PLANE DETAILS

Although tomosynthesis reconstructions produce planes that are in focus, as illustrated in Figure 1.1, there are still contributions from out-of-plane objects to the focal planes. The blur from outside the focal plane reduces in-plane contrast. Various methods have been developed to address this problem. Edholm and Quiding created a photographic negative of the original reconstruction, blurred it in the tomosynthesis direction, and added the result to the original (Edholm and Quiding 1969, 1970). This unsharp masking method was in effect a high-pass frequency filter. Other high-pass frequency filter methods included those of Chakrobatry et al. (1984), van der Stelt et al. (1986a,b), Liu et al. (1987), and Sone et al. (1996). Sone et al. (1991) also developed a band-pass frequency filter method. Other methods include the use of wavelets (Badea et al. 1998), and a method introduced by Ghosh Roy et al. (1985) that “used knowledge of the blurring functions to solve exactly for the distortion generated by a handful of planes immediately adjacent to the plane of interest” (Dobbins and Godfrey 2003). Methods similar to that of Ghosh Roy were developed by Kolitsi et al. (1993) and Sone et al. (1996), and Dobbins’s MITS reconstruction technique is an extension of Ghosh Roy’s method to the entire set of “conventionally reconstructed planes, enabling the exact solution of in-plane structures from a complete set of tomosynthesized plans” (Dobbins and Godfrey 2003).

1.8 PRESENT-DAY TOMOSYNTHESIS SYSTEMS

Many tomosynthesis systems have been developed, but only a few have received FDA approval and that approval was not obtained until very recently. GE Healthcare received FDA approval for their VolumeRad Tomosynthesis system for imaging the body.
(chest, knee, legs, etc.) in 2006, and Shimadzu received FDA approval for their Sonialvision Safire II body tomosynthesis system in 2008. On February 11, 2011, Hologic was the first company to receive FDA approval for their Selenia Dimensions digital breast tomosynthesis system (dimensions 3D). FDA approvals for the other manufacturers’ breast tomosynthesis systems are anticipated in the near future.

Characteristics of the prototype and commercial breast and body tomosynthesis systems are described in detail in Chapters 2 and 13, respectively. A brief summary of some of the features of the breast imaging systems appears in Table 1.1. A brief summary of some of the features of the tomosynthesis systems that are currently available for body (e.g., chest, knee, and leg) imaging appears in Table 1.2.

### 1.9 Promising New Applications and Developments in Tomosynthesis Imaging

Recently, researchers have been developing and investigating new applications of tomosynthesis imaging, including contrast-enhanced tomosynthesis of the breast and combinations of tomosynthesis with ultrasound, nuclear medicine, and optical imaging.

#### 1.9.1 Contrast-Enhanced (DSA) Applications

As discussed previously, digital subtraction angiographic applications of tomosynthesis were developed many years ago using image intensifier–TV camera detectors. The advent of flat-panel digital detectors makes it feasible to now employ similar techniques to image blood vessels and masses in the breast. The topic “contrast enhanced tomosynthesis of the breast” is discussed in detail in Chapter 16 of this book.

#### 1.9.2 Multimodality Breast Imaging Systems

Information from tomosynthesis breast imaging can be combined with that from other imaging modalities for improved detection and characterization of masses. Three systems of this type have been developed. All involve imaging of the breast with two modalities in the same mammographic geometry, thereby insuring that there is a one-to-one correspondence between the masses observed with each modality. This solves the noncorresponding mass problem that sometimes occurs when the imaging geometry is different for the modalities. For example, it has been estimated that in at least 10% of cases, lesions found with free-hand ultrasound scanning (in the supine geometry) are different from lesions found in a mammogram (Conway et al. 1991).

#### 1.9.2.1 Combined Tomosynthesis and Automated Ultrasound Imaging

Scientists at the University of Michigan and at GE global research teamed up to develop a combined x-ray tomosynthesis automated 3D ultrasound breast imaging system (Kapur et al. 2004, Carson et al. 2004, Booi et al. 2007, Sinha et al. 2007). Ultrasound imaging supplements x-ray tomosynthesis by enabling the distinction between cysts and tumors and by providing additional information.

### Table 1.1 Some characteristics of present-day breast tomosynthesis systems

<table>
<thead>
<tr>
<th>UNIT</th>
<th>TOMO ANGLE</th>
<th># VIEWS</th>
<th>PIXEL PITCH</th>
<th>2 × 2 BINNING</th>
<th>DETECTOR</th>
<th>SCAN TIME (S)</th>
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<tbody>
<tr>
<td>GE Gen2</td>
<td>60°</td>
<td>21</td>
<td>100 micron</td>
<td>No</td>
<td>CsI-a-Si</td>
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<td>GE DS</td>
<td>40°</td>
<td>15</td>
<td>100 micron</td>
<td>No</td>
<td>CsI-a-Si</td>
<td>11–20</td>
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<tr>
<td>GE Essential</td>
<td>25°</td>
<td>9</td>
<td>100 micron</td>
<td>No</td>
<td>CsI-a-Si</td>
<td>&lt;10</td>
</tr>
<tr>
<td>IMS Giotto (Dexela)</td>
<td>40°</td>
<td>13</td>
<td>85 micron</td>
<td>Yes and no</td>
<td>a-Se</td>
<td>12</td>
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<tr>
<td>Hologic</td>
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<td>15</td>
<td>70 micron</td>
<td>Yes</td>
<td>a-Se</td>
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<tr>
<td>Planned</td>
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<td>15</td>
<td>85 micron</td>
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<td>a-Se</td>
<td>14</td>
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<tr>
<td>Sectra (Philips)</td>
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<td>21</td>
<td>50 micron</td>
<td>No</td>
<td>Silicon</td>
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<tr>
<td>Siemens</td>
<td>50°</td>
<td>11–49</td>
<td>85 micron</td>
<td>Yes and no</td>
<td>a-Se</td>
<td>12–40</td>
</tr>
<tr>
<td>XCounter</td>
<td>24°</td>
<td>48</td>
<td>60 micron</td>
<td>No</td>
<td>Gas</td>
<td>12–18</td>
</tr>
</tbody>
</table>

*a* Binning involves combining information from adjacent pixels. For example, the Hologic system combines 2 × 2 blocks of 70 × 70 micron pixels to create 140 × 140 micron “binned” pixels.

*b* The IMS Giotto system uses nonuniform angle increments—smaller increments at the center of the scan, larger increments toward the beginning and end of the scan, also different doses at different view angles.

*c* The XCounter system is no longer being manufactured.

### Table 1.2 Some characteristics of present-day body tomosynthesis systems

<table>
<thead>
<tr>
<th>UNIT</th>
<th>TOMO ANGLE</th>
<th># VIEWS</th>
<th>PIXEL PITCH</th>
<th>2 × 2 BINNING</th>
<th>DETECTOR</th>
<th>SCAN TIME (S)</th>
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<td></td>
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<tr>
<td>GE</td>
<td>40°</td>
<td>40</td>
<td>200 micron</td>
<td>No</td>
<td>CsI-a-Si</td>
<td>8 s</td>
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<td>150 micron</td>
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<td>a-Se</td>
<td>2.5 s</td>
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<tr>
<td>Chest Study</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>GE</td>
<td>30°</td>
<td>60</td>
<td>200 micron</td>
<td>No</td>
<td>CsI-a-Si</td>
<td>11.3 s</td>
</tr>
<tr>
<td>Shimadzu</td>
<td>40°</td>
<td>75</td>
<td>150 micron</td>
<td>Yes</td>
<td>a-Se</td>
<td>5 s</td>
</tr>
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</table>
The history of tomosynthesis

The ultrasonic waves are detected with a large two-dimensional ultrasound transducer translator (see Figure 1.9). The ultrasound transducer is in its down position, where it scans just above the dual-modality mesh paddle (b). (The mesh paddle is shown compressing a breast simulating phantom.) The ultrasound scanning system is flipped up and back out of the x-ray field for the x-ray tomosynthesis acquisition.

for characterizing lesions. The combined x-ray/ultrasound system consists of a GE GEN II prototype tomosynthesis unit with a dual-modality (x-ray–ultrasound) mesh compression paddle and an ultrasound transducer translator (see Figure 1.9).

The Gen II tomosynthesis system has a stationary high-DQE CsI-aSi flat-panel x-ray detector similar to the one on the commercial GE Essential digital mammography system. The x-ray tube moves in an arc in a step-and-shoot mode, with a tomosynthesis angle of 60° and 21 angle increments (pulsed exposures/projection views) in 7.5 s. The patient is seated in a chair throughout the dual-modality procedure. The breast compression paddle is made of a material that is both x-ray and ultrasound compatible. The paddle is flipped up out of view for tomosynthesis acquisition and it is flipped down for ultrasound acquisition. For ultrasound imaging, acoustic coupling gel is used between the transducer and the paddle and the breast. A GE Logiq 9 ultrasound system is employed with an M12 L transducer operated at 10 MHz. The transducer is translated above the breast in an x–y raster mode and it is externally triggered to produce an image every 0.8 mm. Software was written to automatically register volumes of interest in the tomosynthesis and ultrasound images (Goodsitt et al. 2008). Recently, the group at the University of Michigan has been developing a photoacoustic tomography system (Wang et al. 2010) that can also be combined with the x-ray tomosynthesis and automated ultrasound unit.

In photoacoustic tomography, short pulses (e.g., <25 ns) of near infrared laser light (e.g., 720–900 nm) are directed at the breast, the light heats up the inner tissues, and the resulting thermoexpansion leads to the emission of ultrasonic waves. The ultrasonic waves are detected with a large two-dimensional receiving ultrasound transducer array and a backprojection reconstruction algorithm is employed to produce an image of the optical absorption in the breast. For implementation with the combined system, the laser light is coupled to the compression paddle above the breast with a fiber optic array, and the ultrasound transducer receiving array is placed beneath the breast.

By using two different wavelengths of laser light in a technique called spectroscopic photoacoustic tomography, oxygenated and deoxygenated hemoglobin can be distinguished, allowing for functional imaging.

1.9.2.2 Combined x-ray tomosynthesis and nuclear medicine imaging

Mark Williams and his research group at the University of Virginia, Charlotte, Virginia developed a combined x-ray tomosynthesis and molecular breast imaging tomosynthesis system to provide coregistered anatomic and functional images of the breast in three dimensions (Williams et al. 2010).

The x-ray tomosynthesis part employs a full isocentric scanning motion in which both the x-ray tube and the digital detector are attached to a gantry that rotates about an axis. The breast support and compression paddle devices are independent of the rotating gantry, and the breast is positioned near the axis of rotation. The x-ray detector is a CCD device with a 20 × 30 cm field of view. It was not optimized for tomosynthesis and has a readout time of 2 s. Thirteen projections are acquired over a total angular range of 24° (±12°) and the total x-ray tomosynthesis scanning time is about 30 s. The gamma camera of the molecular breast imaging tomosynthesis system can be moved out of the way for x-ray imaging and into the field for gamma-ray imaging.

When in use, a motor drive continuously adjusts the position of the camera to minimize the distance between the camera and the breast as the camera rotates, thereby maximizing spatial resolution and signal-to-noise ratio. The gamma camera has a 15 × 20 cm field of view. Five evenly spaced gamma camera views over a 40° angular range are employed for molecular breast imaging tomosynthesis with an imaging time of 2 min per view and a total scan time of 11 min. A pilot study was performed involving 17 women who were scheduled to undergo breast biopsy. Each was intravenously injected with 30 mCi (1110 MBq) of 99 mTc sestamibi for the molecular breast imaging portion of the study. It was found that adding “molecular breast imaging tomosynthesis notably improves specificity and positive predictive value compared with the specificity and positive predictive value of x-ray tomosynthesis alone.” Close scrutiny of the published results (Williams et al. 2010) indicate the performance metrics (sensitivity, specificity, positive predictive value, negative predictive value, and accuracy) for x-ray tomosynthesis were worse than those for molecular breast imaging, and those for dual modality (x-ray/molecular) were identical to those for molecular breast imaging alone. Thus, for this study, the primary advantage of dual-modality over molecular breast imaging alone was the coregistration and improved localization. Future improvements in the x-ray and molecular imaging devices such as larger fields of view and shorter imaging times may result in additional advantages for the dual-modality mode.

1.9.2.3 Combined tomosynthesis and optical imaging

Qiangian Fang and his colleagues from MGH, Tufts University, and Northeastern University have developed a combined x-ray tomography and diffuse optical tomography system for imaging the breast (Fang et al. 2009, 2011). Diffuse optical tomography is a form of functional imaging. It employs near-infrared lasers to probe tissues and the resulting optical absorption and scattering of the laser light “are related to tissue physiological parameters,
such as the concentrations of hemoglobin, deoxygenated hemoglobin, water, and lipids” (Fang et al. 2011). A disadvantage of diffuse optical tomography by itself is its poor spatial resolution. Fang et al. employed the anatomical information from coregistered x-ray tomosynthesis images to improve the optical tomography reconstructions.

The x-ray tomosynthesis system is a GE DS clinical prototype. It acquires 15 projections over a 45° tomosynthesis angle. The pixel size is 0.1 mm, and the reconstructed slice thickness is 1 mm. The optical system is described in detail in Fang et al. (2009). Two continuous wave (CW) frequency encoded laser systems are employed. One system has three lasers with wavelengths of 685, 810, and 830 nm. A fast Galvo scanner is used to direct these lasers to a maximum of 110 locations with a dwell time of 200 ms per location. The second system consists of 26 lasers, 13 at a wavelength of 685 nm and 13 at a wavelength of 830 nm, and these are used to continuously monitor tissue changes at 26 locations. Thirty-two avalanche photodiode (APD) detectors are employed and the CW signals are demodulated for each channel and wavelength. The laser source probes are placed in a cassette just above the x-ray detector and the detector probes are placed in an optically transparent dual-modality (x-ray and light) compression paddle. The optical data are employed to generate 3D maps of total hemoglobin concentration, oxygen saturation, and tissue-reduced scattering coefficients, and these are interpreted by relating them to coregistered x-ray tomosynthesis images. In the imaging protocol, the optical source and detector probes are initially attached to the tomosynthesis unit and the patient’s breast is compressed. Optical data is acquired for 45 s. Then the optical probes are removed while the breast is maintained in compression, and the x-ray tomosynthesis image is acquired, which takes 23 s. In a study of 189 breasts in 125 subjects, Fang et al. found that “in 26 malignant tumors of 0.6–2.5 cm in size, the total hemoglobin concentration was significantly greater than that in the fibroglandular tissue of the same breast (P = 0.0062)” (Fang et al. 2011). Also, “solid benign lesions (n = 17) and cysts (n = 8) had significantly lower total hemoglobin concentration contrast than did the malignant lesions (P = 0.025 and P = 0.033, respectively)” (Fang et al. 2011).

### 1.10 Conclusion

Tomosynthesis has had an exciting history, starting in 1935 and continuing to the present day. Some parts of this chapter on the history of tomosynthesis is based on two excellent, meticulously documented reviews of tomosynthesis imaging (Dobbins and Godfrey 2003, Dobbins 2009) and an excellent book on the origins of radiological tomoscopy (Webb 1990). The reader is referred to those references and others in the reference list for additional information about the history and development of tomosynthesis. Finally, early this year, after this chapter on the history of tomosynthesis was finalized, Ioannis Sechopoulos published two excellent reviews of breast tomosynthesis (Sechopoulos 2013), Part I: The image Acquisition Process, and Part II: Image Reconstruction, Processing and Analysis, and Advanced Applications. These reviews are available online only at http://dx.doi.org/10.1118/1.4770279 and http://dx.doi.org/10.1118/1.4770281.

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Conclusion
Chapter 1 The history of tomosynthesis


Chapter 2 System design and acquisition parameters for breast tomosynthesis


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digital mammography alone: Results of a multi-center, multi-reader trial. 96th Annual Meeting of the Radiological Society of North America, Chicago, IL.

Chapter 3 Detectors for tomosynthesis

Sysem design

Chapter 5 Tomosynthesis with circular orbits


Chapter 6 Tomosynthesis system modeling

7 Chapter 7 Filtered backprojection-based methods for tomosynthesis image reconstruction


Figure 7.8 A large calcification in a mammogram sharply displayed in slice 31 (a) is replicated as an out-of-plane artifact in slice 45. The slice separation is 1 mm. The image size is approximately 46 × 52 mm. In the left image, the overshoot artifact is exhibited as well.

Figure 7.9 Overshoot artifacts manifest themselves as black rims in the scan direction around high-contrast objects such as a calcification. At the left side of the picture, a calcification located in a different slice is visible by its out-of-plane artifact. (The image size is ~36 × 36 mm.)
Chapter 8 Iterative image reconstruction design for digital breast tomosynthesis


30. X. Pan, E. Y. Sidky, and M. Vannier, Why do commercial CT scanners still employ traditional, filtered back-projection for image reconstruction? Inv. Prob., 25,


Figure 9.13 NEQ relative \( (f) \) of FBP for different imaging configurations. (a) The impulse was located 4 cm away from the chest wall and (b) the impulse was located near the chest wall.


Chapter 10 Spatial-domain model observers for optimizing tomosynthesis

Sayer
nemperor


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11 Chapter 11 Observer experiments with tomosynthesis


Figure 12.5 Mean glandular dose in milliGray (mGy) of different anode types for DM and DBT with range of film-screen mammography exposure as recorded by the Digital Mammography Screening Trial (DMIST). (Courtesy of Jay Stein PhD, Hologic Inc.) Clinical applications of breast microcalcifications. Abstract presented May 2, 2011. ARRS Annual Meeting, Scientific Session 1, no. 007.


Figure 13.8 (See color insert.) (a) A close-up of a chest tomosynthesis section image containing a 5-mm nodule in the middle lobe and (b) the corresponding image at the follow-up examination after 2 years. The images reveal no apparent nodule growth.

Clinical applications


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Chapter 14 Tomosynthesis applications in radiation oncology


Chapter 15 Future developments in breast tomosynthesis


