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Digital Breast Tomosynthesis

Technique and Cases

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Foreword

Thirty years ago in 1985, after completing a radiology residency and fellowship, I was afforded an opportunity to develop the first patient-oriented breast imaging center in Pittsburgh, Pennsylvania, USA. One of my new colleagues, a general radiologist who had interpreted mammograms for many years, often articulated her yearning for “slices” to see better into the dense breast parenchyma within the routine screening projections. This was the era of renal tomography, an important component of the intravenous urogram (IVU) that antedated computed tomography (CT), precontrast for stones and postcontrast for parenchymal abnormalities, years before tomographic techniques applied to X-ray mammography were advanced sufficiently for clinical use in breast imaging.

What was mammography like then? In many radiology departments, the method of choice was xeromammography, a radiographic procedure performed with balloon compression, where the breast’s image was recorded on thick paper. As women became aware of the benefits of breast cancer screening, the demand for mammography grew, and these light-blue xeromammograms were replaced by single-emulsion film, which required lower X-ray doses and was more suited to higher volumes. The xeromammography machines were sent to emergency departments, which used the low-contrast examinations for locating glass shards or splinters in soft tissues. The single-emulsion film had high spatial resolution with variable levels of contrast; this was enhanced by the use of grids, which increased the dose but reduced scatter, improving the signal-to-noise ratio. These films were interpreted on rotators with high luminance, or viewboxes, freestanding or wall mounted.

Gradually, the conversion from film to digital recording systems for cross-sectional imaging, and then all radiographic studies, forced the development of digital mammography, which had higher contrast resolution than film but lower spatial resolution, slowing adoption of digital mammography by breast imagers. The accuracy of film compared with digital mammography was studied in the American College of Radiology Imaging Network (ACRIN) DMIST study of nearly 50,000 women in North America, comparing film-screening mammography to digital mammography. The study concluded that digital mammography is more accurate than film in women under the age of 50 years, women with radiographically dense breasts, and pre- or perimenopausal women.1

The technologic advances underscored the need for further refinements and work continued on tomosynthesis, which now provided the thin projections my colleague had asked for many years earlier to help her decide between a summation density and a mass when explaining a finding on conventional two-dimensional mammography. As technical advances have continued, in the same time frame as publication of this clinically useful book three major manufacturers of tomosynthesis equipment have satisfied the rigorous regulatory requirements of image quality and dose and received approval of the United States Food and Drug Administration (FDA). The differences among the three different tomosynthesis systems are covered in this text, and, as the authors state, growing numbers of breast imagers have quickly and enthusiastically adopted this technology for both screening and diagnostic applications.

For new users of tomosynthesis, as well as those intending to integrate it into their breast-imaging workflow, this textbook offers the required knowledge in several chapters that detail the physics of tomosynthesis, discuss considerations of image quality and the reduction of screening recall rates, and look into concerns of dose, artifacts, interpretation time, cost effectiveness, and image archiving. With an emphasis on the technical progress that is being pursued actively, the authors provide a summary of the literature that has appeared on both sides of the Atlantic, adding the recently reported results of a large retrospective multicenter study of nearly 455,000 women that confirmed a decrease in screening recall rates and an increase in cancer detection2. These chapters are illustrated with beautiful images, but the book’s uniqueness lies in its presentation, with videoclips, of 45 tomosynthesis teaching cases, some of which are multimodality; these will equip readers with experience that is as close as possible to personal clinical experience.

Professors Barkhausen, Rody, and Schaefer should be congratulated on providing solid information to the breast health care team that will enable informed decisions about whether or not tomosynthesis should have a place among the modalities offered for screening and diagnosis of breast cancer in their facility’s practice. The benefits and weaknesses of the systems available for clinical use are summarized. As technical refinements continue, and data on sensitivity and specificity validate tomosynthesis, this well-written book will be a valuable resource. It is a pleasure to read and, especially, to lose oneself voyaging through the many beautifully prepared teaching cases that provide a virtual clinical experience.

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Digital breast tomosynthesis has been available for routine clinical use for 5 years now, and there is still no textbook devoted to this innovative technology. We want to remedy that!

This book examines the results of existing clinical studies on digital breast tomosynthesis and, based on those findings, offers sound recommendations for its routine clinical use. The second part of the book presents 45 illustrative case reports, enabling our readers to explore the practical aspects of tomosynthesis, as well as deepening and testing their clinical knowledge. We felt it was important to present high-quality images from all available modalities in breast imaging, so that the strengths and limitations of the various techniques could be compared and discussed.

Successful breast imaging relies on interdisciplinary teamwork between radiologists and gynecologists, who review their findings in tumor board meetings with pathologists, oncologists, and radiation oncologists. We followed this interdisciplinary approach in our selection of authors and editors: Diagnosticians and clinicians practiced in the everyday use of tomosynthesis have pooled their many years of experience, especially in compiling the illustrative case reports.

This book is intended for physicians in continuing education and for colleagues who are experienced in breast diagnosis and want to familiarize themselves with these new techniques in breast imaging. May our readers find the book both instructive and enjoyable!

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Abbreviations

2D   two dimensional
3D   three dimensional
AAPM  American Association of Physicists in Medicine
ACR  American College of Radiology (score for radiographic breast density)
AGD  average glandular dose
ART  algebraic reconstruction technique
a-Si  amorphous silicon
AUC  area under the ROC curve
BCS  breast-conserving surgery
BI-RADS  Breast Imaging Reporting and Data System (scores level of cancer suspicion)
CAD  computer-aided detection
CC   craniocaudal
CE   Communauté Européenne (European Community)
CT   computed tomography
DBT  digital breast tomosynthesis
DCIS ductal carcinoma in situ
DgN  normalized glandular dose
DQE  detective quantum efficiency
EUREF  European Reference Organization for Quality Assured Breast Screening and Diagnostic Services
FBP  filtered back projection
FFDM  full-field digital mammography
Gx, Px  number of pregnancies (G, gravida) and number of deliveries (P, para)
Gy  gray
HRT  hormone replacement therapy
HU  Hounsfield unit
IEC  International Electrotechnical Commission
kVp  peak kilovoltage
LIN  lobular intraepithelial neoplasia
mAs  milliamper–second
MB  megabyte
mGy  milligray
ML  mediolateral
MLO  mediolateral oblique
MR  magnetic resonance
MRI  magnetic resonance imaging
NST  of no special type
ROC  receiver operating characteristic (curve)
SART  simultaneous algebraic reconstruction technique
SD  standard deviation
SIRT  simultaneous iterative reconstruction technique
TFT  thin-film transistor
VAB  vacuum-assisted biopsy
W/Al  tungsten/aluminum
W/Rh  tungsten/rhodium

Glossary

Aliasing  Streak artifacts due to a limited number of projections
Artifact  Spurious signal
Autologous  Belonging to the same individual
Benign  Noncancerous
Fulcrum  Point around which the X-ray source rotates in the focal plane
Glandularity  Proportion of glandular tissue relative to all tissue
Kerma  Kinetic energy released per unit mass. Ratio of the kinetic energy transmitted to first-generation secondary particles divided by the irradiated mass
Air kerma  Measurement of the kerma, using air as a reference medium
Malignant  Cancerous
Moiré effect  Special case of the aliasing effect caused by undersampling
Mortality  Death rate
Incidence  Number of new cases of a given disease in one year
Pixel  Smallest picture element displayed in a digitized raster image
Recall  Call-back of a patient for additional testing
Shepp–Logan filter  Combination of a ramp filter and spectral filter in computed tomography
Voxel  Volume element, an image point within the volume of a scan
Chapter 1

Introduction
1 Introduction

Joerg Barkhausen and Achim Rody

In 2012, 1.7 million women worldwide were diagnosed with breast cancer and there were 6.3 million women alive who had been diagnosed with breast cancer in the previous 5 years. Today, breast cancer is the most common cause of cancer death among women (522,000 deaths in 2012) and the most frequently diagnosed cancer among women worldwide. Over the last 5 years, the incidence of breast cancer has increased by 14%. Possible reasons for this effect, besides biological factors, are mammographic screening, early detection, and significant advances in diagnostic imaging. Digital mammography, high-resolution breast ultrasonography, image-guided interventional procedures, and magnetic resonance mammography are among the standard techniques now available as a complementary protocol for curative diagnosis and screening. These technologies have advanced greatly in the past decade and are now applied on a population-wide scale, with quality assurance, for indications that are clearly specified in official guidelines.

However, currently established routine techniques and algorithms cannot always positively distinguish between benign and malignant lesions. This is illustrated by the interval cancers that develop after screening and by the high rate of negative breast biopsies, which exceeds 50% in some settings. This points to a need for further optimization of existing modalities, as well as a need to develop entirely new imaging techniques. More than 15 years after it was first described, digital breast tomosynthesis (DBT) has now entered routine clinical use.

New techniques always pose a challenge. On the one hand, they invite us to scrutinize more traditional studies. On the other, they compel us to define the patients, settings, and indications for which the new technique would be medically appropriate and economically feasible. Many of these questions on the routine clinical use of tomosynthesis cannot yet be definitively answered. This book explains the technique of tomosynthesis, describes the principal results of available clinical studies, and explores the next evolutionary steps in this technology. The explanatory chapters are followed by numerous case reports in Chapter 5, most with histologic confirmation, that will illustrate both the capabilities and limitations of breast tomosynthesis.

The key question, of course, is whether DBT is basically an adjunctive technique or whether it can replace digital mammography in the near future. A major goal in screening is to reduce recall rates and false-positive results. The detection rates of DBT need clarification for different histologic or even molecular subtypes in curative mammography. Its impact on surgical treatment planning must also be tested, especially with regard to the detection of multicentric disease. Autologous and alloplastic breast reconstructions are a particular challenge in terms of follow-up. Finally, it is essential to determine the reliability of tomosynthesis in the detection of recurrent disease.

It will definitely take time to answer all of these questions. One thing is certain, however: DBT is a fascinating technology that will continue to draw great clinical and scientific interest in the years ahead.

1.1 References

# Chapter 2
## The Physics of Tomosynthesis

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2 The Physics of Tomosynthesis

Thomas Mertelmeier

2.1 Introduction

A few years after the discovery of X-rays by Wilhelm C. Röntgen, researchers began to consider how this radiation might be used not only to create projection radiographs but also to supply three-dimensional (3D) information on the object of interest. Many years passed, however, before this idea became a technical reality. In the first 3D technique, the X-ray source was moved relative to the object, to generate a summation image on the receptor (film) of the X-rays attenuated by the object. In this technique, known as tomography or conventional tomography (Greek *tomas* = “slice” or “section”), the radiation source moves around a pivot point (fulcrum) in the focal plane. This motion keeps the plane of interest in sharp focus, while blurring out tissues above and below that level. Ziedses des Plantes made the first practical use of linear-motion tomography for imaging the skull. The source and detector moved around the fulcrum in a linear fashion. As a result, Ziedses des Plantes is often recognized as the founder of tomography, even though there were many other variants of the technique.2,3

A major disadvantage of conventional tomography was the high radiation dose required, since only one plane was in focus, as determined by the acquisition geometry. Each additional image slice required a different acquisition geometry to define the new plane of interest. This situation did not change until the advent of digital image receptors (flat-panel detectors), which permitted a rapid and distortion-free data readout. The desired image slice could then be reconstructed retrospectively by computer, from the individual stored projection images. This technology provides an obvious reduction in dose, since any desired image plane can be imaged sharply with just one movement of the acquisition system. This technique, in which the X-ray source occupies various imaging positions relative to the object, is called digital tomosynthesis or simply tomosynthesis. Sectional images are reconstructed from a set of individual projection images that are acquired at different angles. This allows the user to “look around” structures within the object to obtain 3D information in the form of individual image slices.

The main advantage of tomosynthesis is its ability to select discrete tissue planes. This principle is illustrated in Fig. 2.1, which shows images reconstructed from a breast data set. The image plane in Fig. 2.1a is located 23 mm above the breast support plate ($z = 23$ mm). It clearly demonstrates a round lesion with smooth margins. The clustered microcalcifications above the lesion are only faintly visible. They are clearly depicted in Fig. 2.1b, however, where the image plane is 27 mm above the support plate ($z = 27$ mm), whereas the round lesion itself is poorly visualized. This ability to select individual tissue planes could increase both the detection rate and the level of diagnostic confidence. Niklason et al described one of the first applications for breast imaging as early as 1997.4

![Fig. 2.1 Magnified views (18 × 29 mm) of two tomosynthesis slices in the breast. (Raw data were provided courtesy of Dr. Ingvar Andersson, Malmö University Hospital, Sweden, and Siemens AG Healthcare Sector.) (a) Image slice at level $z = 23$ mm. The round lesion is in focus. (b) Image slice at level $z = 27$ mm. The clustered microcalcifications are in focus.](image-url)
2.2 Data Acquisition and Scanning

Modified X-ray systems are most commonly used for tomosynthesis. Breast tomosynthesis may employ digital mammographic systems in which the X-ray source can be moved, occupying various positions relative to the imaged object (breast).

Tomosynthesis systems can operate in one of two modes. In the sweep mode, the X-ray tube moves continuously and is pulsed at the frame rate of the detector. In the “step-and-shoot” mode, the tube moves to the next position between two acquisitions and transmits the X-ray pulse while the tube is stationary. The tube may move in an arc around a point within the object, or it may move along a linear path.

During scan acquisition, the detector may be stationary (Fig. 2.2) or may move simultaneously with the tube. In the case of a moving detector, the system may have an isocentric C-arm geometry, in which the detector and source both rotate around a common point, or it may have a partial isocentric geometry. In this type of system, the tube and detector move in a synchronous way, but the detector is not rigidly connected to the tube. For example, it may move on a linear path in the receptor plane.5 In most imaging systems, the breast is positioned close to the detector, so there is little or no synchronous movement of the detector (Fig. 2.2).

Because each individual projection contributes to forming an image point within the scanned volume (volume element, voxel) during image reconstruction, a tomosynthesis data set can be acquired at approximately the same dose as a two-dimensional (2D) projection radiograph (see Chapter 2.5). The total exposure is distributed over the individual projections, however, so the detector must be able to supply a low-noise signal even at low dose levels. This means that the detector must have high detective quantum efficiency (DQE), even at a very low dose (see Chapter 2.5). Moreover, the detector must have a fast readout and high frame rate, to minimize the scan time and shorten the necessary breast-compression time.6 Both detector requirements pose a significant challenge, given the spatial and contrast resolution required for breast imaging. The scan time can be shortened by “binning” the pixels during detector readout. The associated loss of resolution and possible increase in the signal-to-noise ratio depend on the technical details of the system in use.

Breast tomosynthesis systems currently on the market (see example in Fig. 2.3) employ direct-conversion detectors based on amorphous selenium with thin-film transistor (TFT) arrays made of amorphous silicon (a-Si-TFT). There is also a system with a scintillator and photodiodes made of amorphous silicon with a-Si-TFT readout arrays, as well as a prototype scanner equipped with silicon direct-conversion line detectors.

The X-ray spectrum used for tomosynthesis is either the same as, or similar to, that used in digital mammography, and the tube voltage depends on the thickness of the compressed breast. The X-ray energy, or tube voltage, may be increased slightly to keep the dose as low as possible. Another option is to use more filtering, which increases the mean quantum energy. Tungsten/rhodium (W/Rh) is a typical anode/filter combination. Tungsten/aluminum (W/Al) can also be used.

Vertical image resolution and depth of focus depend mainly on the acquisition geometry, i.e., the tomosynthesis angle (Fig. 2.4). The tomosynthesis angle is defined as the angular range over which the X-ray tube is moved relative to the pivot point. The greater the tomosynthesis angle, the better the depth resolution and the smaller the effective slice thickness. This results in less image blurring from adjacent tissues due to out-of-plane artifacts. A large tomosynthesis angle can also improve contrast resolution at low spatial frequencies (i.e., for relatively large objects) because the greater angular range can supply more information, especially at small spatial frequencies (see Chapter 2.3).7,8 It should be added, however, that a stationary detector that does not move simultaneously with the tube will reduce the accessible scan volume, owing to the oblique incidence of the X-ray beams.

It is not possible to state an “optimum” angular range, because depth resolution is not the only parameter affected by the tomosynthesis angle. For example, a large tomosynthesis angle prolongs the scan time for a given angular velocity of the X-ray tube, increasing the risk of motion artifacts. Current scanners have tomosynthesis...
angles between 11 and 60°, all of which yield good results. To date, however, there have been no systematic clinical studies on how the tomosynthesis angle affects the detection of clinically relevant structures (spiculated lesions, microcalcifications) in the breast.

In addition to the limited angular range, the limited number of projections (sparse sampling) presents a challenge for 3D scanners. In the imaging of high-contrast objects, undersampling leads to Moiré effects (aliasing), which appear as streak artifacts similar to those seen in computed tomography (CT). The principle is the same in tomosynthesis, where the angular increment between exposures should not exceed several degrees, in order to prevent streak artifacts. In practice, the maximum number of projections is determined by the minimum dose at the detector per exposure to yield a total dose comparable to that of a conventional mammogram. The scan time, which translates to breast-compression time for the patient, depends on the number of projections for a given detector frame rate. Current tomosynthesis scanners, including prototypes, usually acquire between 7 and 30 projections in one examination.

Thus, the following quantities depend on acquisition geometry, scan parameters, and system hardware components:

- Resolution.
- Noise.
- Artifact level.
- Dose.
- Accessible volume.
- Examination time.

![Fig. 2.3 Breast tomosynthesis scanner, shown in the mediolateral-oblique position.](Image)

![Fig. 2.4 Effect of the tomosynthesis angle on depth resolution. (a) A small tomosynthesis angle gives poorer separation of adjacent object points in the vertical direction. (b) A large tomosynthesis angle provides better separation of adjacent points in the vertical direction.](Image)
2.3 Image Reconstruction

In tomosynthesis image reconstruction, the spatial distribution of the n-dimensional attenuation coefficient of the object is computed from (n-1)-dimensional projection images of the n-dimensional object acquired at different angles. Since the acquisition of tomosynthesis data is based on 2D projection images, the 3D attenuation coefficient is computed. Owing to the limited angular range of data acquisition (limited-angle tomography), this problem cannot be solved exactly, but its solution can be closely approximated using mathematical methods. Also, there is no objective, quantitative grayscale unit for the reconstructed slices that is comparable to the Hounsfield unit (HU) used in CT.

Moreover, the limited tomosynthesis angle makes it impossible to achieve isotropic resolution. Resolution is lower in the direction of the central ray, hereafter called the vertical or z-axis, than along the x- and y-axes, because projections characterized by an angle larger than the tomosynthesis angle, which carry the additional information necessary for isotropic depth resolution, are not measured. As a result, only image slices that are perpendicular to the vertical axis are reconstructed in tomosynthesis. In systems with a stationary detector, these slices are parallel to the detector plane.

In principle, two broad classes of method are available for tomosynthesis reconstruction:
- Analytical reconstruction.
- Iterative reconstruction.

2.3.1 Analytical Reconstruction

Analytical methods for tomosynthesis reconstruction are based on standard algorithms used in CT. Analytical methods employ specially designed reconstruction filters to compensate for scanning over a limited angular range and minimize artifacts. Various algorithms for tomosynthesis reconstruction have been described in the literature.\textsuperscript{5,11,12} The methods are called “analytical” because the solution is formulated analytically using an inverse Radon transformation. This solution is then fed into a computer and calculated by numerical methods. The basic technique for this type of reconstruction is described next (Fig. 2.5).\textsuperscript{13}

First, the projection images necessary for slice reconstruction are determined from the 2D acquisition data, by taking the logarithm and by normalization with the non-attenuated intensity. According to Beer’s attenuation law, the projections necessary for the inverse Radon transform are represented by the line integrals through the object for rays that connect the X-ray focus to a point on the detector. These 2D projections are transformed with suitable reconstruction filters, to obtain filtered projection values. For better computer efficiency, this filtering is usually done by Fourier transformation in frequency space. The filtered projections are then back projected into the object volume (filtered back projection, FBP).

This means that for a given voxel in the object volume, all projection values whose rays run precisely through that voxel, and thus contribute to the image, are summed and then averaged. The filter consists of a ramp filter like that used in CT. It has the property of inverting the ideal 2D CT problem, i.e., compensating for blurring caused by the angular sampling scheme, based on the acquisition geometry. However, because the ramp filter amplifies the high spatial frequencies, it also increases image noise. These high spatial frequencies must therefore be suppressed with a “spectral filter.” CT employs a combination of both filter types (ramp filter and spectral filter) called the Shepp–Logan filter.\textsuperscript{13}

Because the tomosynthesis problem does not have an exact mathematical solution, different FBP techniques use different filter designs, leading to differences in image appearance and artifact suppression.\textsuperscript{14,15,16,17} Fig. 2.6 illustrates how different filter designs can affect the appearance of an image. Fig. 2.6a shows a tomosynthesis slice reconstructed with an edge-enhancing filter, generating an image that resembles a CT scan. Fig. 2.6b shows the same slice from the same data set, reconstructed with a different filter. By accentuating the glandular breast tissue, this image looks more like a mammogram.

2.3.2 Iterative Reconstruction

Unlike analytical reconstruction, iterative techniques solve the inverse problem by first formulating the system equation for the relationship between the object and projection data, as an algebraic equation in the form of a large system of equations, and then solving it numerically. Because the system of equations is extremely large, it can only be solved with iterative techniques. As the iterations are carried out, the projection values computed from the object of interest are compared with the measured projection values in each iterative step. Based on the
Fig. 2.6 Tomosynthesis slice using different filters in the filtered back-projection method. (Raw data were provided courtesy of Dr. Nachiko Uchiyama, National Cancer Center, Tokyo, Japan, and Siemens AG Healthcare Sector.) (a) Edge-enhanced image. (b) Accentuation of glandular breast tissue.
discrepancy, the object distribution is improved in a step-by-step fashion, until the solution fulfills a certain optimality criterion (Fig. 2.7). This can be done by various iterative methods, such as the algebraic reconstruction technique (ART), simultaneous ART (SART),\textsuperscript{18} or simultaneous iterative reconstruction technique (SIRT). By basing the formulation of the problem on the Poisson statistics for X-ray quanta, a statistical iterative method can be supplied, using a “maximum-likelihood” reconstruction algorithm.\textsuperscript{19} Additionally, constraints and prior knowledge may be available during the solution process. This yields a more stable solution with low image noise (maximum a posteriori methods or penalized maximum-likelihood algorithms).

All these iterative techniques differ in their update strategies, i.e., how the solution is successively improved in each iterative step, what constraints are assumed, available prior knowledge, and the numerical solution techniques.

### 2.3.3 Combined Reconstruction Methods

Besides these main classes of analytical and iterative reconstructions, there are a number of modified algorithms that combine analytical methods with iterative algebraic techniques. The goal of these methods is to keep blurring and other artifacts to an absolute minimum. Examples of methods used in breast tomosynthesis are iterative de-blurring\textsuperscript{20,21} and nonlinear back projection.\textsuperscript{22,23}

### 2.3.4 Visualization

Regardless of the type of reconstruction used, tomosynthesis always generates a nonisotropic volume data set, in which vertical resolution is much poorer than in planes perpendicular to the optical axis. Because most artifacts also occur in the vertical direction, image slices parallel to the detector are best for visualization. Thus, viewing multiple sequential slices in the “stack mode” is preferred. True volume rendering is only possible over a very limited angular range that is roughly equal to the tomosynthesis angle.

Compared with digital mammography, the size of an image data set in tomosynthesis poses a definite challenge in both the reconstruction and viewing of images. If the detector has a 2800 × 3600 pixel matrix at 16 bits per pixel, this gives 20 megabytes (MB) of raw data per projection. A raw data set with \( N_p \) projections would require a storage capacity of \( N_p \times 20 \text{ MB} \). For 15 projections, this would be 300 MB.

Typically, the images are reconstructed with a slice separation of 1 mm, and the reconstructed pixel size in the image plane should never be larger than one detector pixel. The average size of an image slice is slightly smaller than that of one projection, because the average breast does not cover the whole detector. Assuming, for example, that a reconstructed tomosynthesis slice consists of 2000 × 3000 pixels, 12 MB (at 16 bits per pixel) are obtained for the data content of one slice. An average compressed breast thickness of 50 mm would result in 50 slices containing 600 MB of data. In this example, then, a data set consisting of raw projections plus reconstructed slices would be 900 MB in size. A complete examination in four planes (left and right, cranio-caudal, lateral oblique) would require 3600 MB of storage. The exact figure will vary depending on specific technical details (detector size, pixel size, number of projections, slice interval).

### 2.4 Artifacts

Because the object is not sampled completely in tomosynthesis, owing to the limited angular range, the inverse problem cannot be solved exactly. This undersampling leads to artifacts that result mainly from the fact that the point spread function deviates from spherical symmetry. As a result, point objects will be spread along the vertical \( z \)-axis and extend over multiple planes. Since the individual projections are also separated from one another by a finite angular increment (usually a few degrees), these artifacts are not distributed uniformly but reflect the individual projections. They are called “out-of-plane artifacts” because they cause unwanted visualization of structures outside the plane of interest.

Fig. 2.8a shows a calcification in the focal plane. The calcification is still visible several slices above or below the image plane, appearing as out-of-plane artifacts with a typical replicated structure (Fig. 2.8b). The intensity of these artifacts depends on the size and contrast of the object. The larger the structure, the more the artifact is spread out along the \( z \)-axis, affecting more slices adjacent...