Learning objectives

- Describe the development of Digital Breast Tomosynthesis (DBT), highlighting the major technological hurdles overcome to allow the production of clinically useful DBT images.
- Review the structure and operation of a modern DBT unit.
- Discuss current understandings of the impact of altering technical acquisition parameters on DBT image quality and artefact production.
- Review current research into the clinical effectiveness of DBT.
- Highlight important areas for further DBT research.
- Explore possible future developments in DBT.

Background

Traditional analogue and more recently full-field digital mammography (FFDM) have been the gold standard imaging modalities for breast screening and symptomatic breast disease in all but a few women for decades\(^1\). Mammography is the only imaging modality proven to reduce breast cancer mortality through screening\(^1\). Mammography is not a perfect investigation however: sensitivities are around 70-90%, lower in women with dense breasts; and false positive recall rates, leading to unnecessary additional imaging and emotional distress, are significant\(^2\). Up to 10% of women screened will be unnecessarily recalled\(^1\). Overlapping fibroglandular breast tissue hampering interpretation is the most common reason both for breast cancers to be missed and also for the unnecessary recall of women\(^3\).

Digital Breast Tomosynthesis (DBT) is a novel breast imaging technique that aims to remove the problem of overlapping fibroglandular tissue, improve lesion detection and characterisation and help exclude the presence of a breast lesion when none is there.

DBT is based on decades old mathematical theory and combines FFDM, tomographic principles and reconstruction algorithms to produce multiple thin section images through the breast\(^4\). This novel technique may reduce the number of women recalled and have improved sensitivity compared with FFDM\(^3\).
**Imaging findings OR Procedure details**

1 Development of Digital Breast Tomosynthesis

1.1 Conventional Tomography

After the discovery of x-rays by William Roentgen in 1895 there was an explosion in the number and variety of imaging techniques employed\(^4\). The limitations of 2D imaging were soon recognised and work was done to develop more advanced forms of imaging. A famous paper published by Radon in 1917 described the mathematical basis for tomography and it was introduced as a medical imaging modality by des Plante in 1932\(^4\).

In the simplest form of conventional tomography the x-ray tube and imaging detector are moved linearly in opposing directions during a single exposure to generate a single focal plane\(^4\). Parallax causes out-of-plane structures to be blurred. Objects in the in-focus plane remain projected at a set position on the detector reinforcing their image, while objects above and below the plane of focus project to different positions during the acquisition and so are blurred in the final image.

Conventional tomography has several limitations which limit its usefulness\(^4\):

- Acquisitions have to be repeated for every new focal plane required increasing patient dose and the potential for motion artefact.
- Out of plane detail cannot be completely eliminated from conventional tomograms, only blurred. This results in reduced contrast resolution.

1.2 Technological Hurdles in the Development of Digital Tomosynthesis

The mathematical model underlying conventional tomography allows for the retrospective reconstruction of an arbitrary number of in-focus planes from a series of discrete radiographic projections\(^4\). Despite this knowledge it was 60 years after conventional tomography had become a useful diagnostic modality that the technical challenges required to implement tomosynthesis were overcome.

Several exposures must to be taken to reconstruct a tomosynthesis image. In order to keep patient dose low these individual exposures must be very low dose; they must also be completed quickly to minimise motion artefact. To fulfil these requirements a
detector with rapid readout, sufficient for several acquisitions to be taken in a short space of time, and sufficient detective quantum efficiency (DQE) for the examination dose to be acceptably low was required. It was not until the 1990s, with the advent of flat panel amorphous selenium and amorphous silicon digital detectors, which have DQEs of over 95% at mammographic energies and the capacity for rapid readout, that a suitable detector was available.

The second technological hurdle was that huge computational power was needed to implement the reconstruction and post processing algorithms essential to producing high quality tomosynthesis images. Attempts were made throughout the mid-twentieth century to use simple 'shift and add' reconstructions with photographic negatives. These, like conventional tomography, do not remove the blurred out-of-plane details, and so it was not until the advent of abundant affordable computing power in the 1990s that the complex algorithms required could be performed adequately.

With flat panel detectors and cheap powerful computing available from the 1990s onwards much research has been performed into digital tomosynthesis imaging. Digital tomosynthesis has been applied to chest imaging, angiography, small joint imaging, dental imaging and much more. However it is in breast imaging that the most advanced applications of digital tomosynthesis are seen.

2 Structure & Function of Modern Digital Breast Tomosynthesis Units

DBT units are based on standard mammography units, and indeed often units will provide both types of imaging. Figure 1 shows a typical DBT unit. The advantages of DBT are due to its ability to retrospectively reconstruct an arbitrary number of in focus planes parallel to the detector. This is done by rotating the x-ray tube through an arc, acquiring several exposures at set intervals and then using reconstruction and post processing algorithms to create the slices and 'de-blur' the images. For a standard breast around fifty 1mm slices are produced.
Fig. 1: A typical DBT unit. Courtesy of Hologic, Inc.

Fig. 2: Illustration of the operation of a DBT unit. Courtesy of Hologic, Inc.


Most DBT units use similar anode/filter combinations to standard mammography, usually a combination of rhodium, tungsten and molybdenum. As discussed before, modern flat panel amorphous silicon or amorphous selenium detectors are used for DBT as they offer the high read-out rate and DQE required for low-dose, high-speed acquisitions. A grid is not utilised for DBT as this would attenuate the obliquely travelling x-rays. As most units perform both mammography and DBT, often during a single compression, the grid must be easily and quickly removable.

Breast compression is required for DBT, however the forced used to compress the breast can be as little as half of that required for standard mammography; meaning DBT may be a more pleasant examination to undergo. Compression can be reduced because for DBT the purpose of compression is only minimise patient movement. In mammography compression is also required to spread overlapping fibro glandular breast tissue.

Usually one or two DBT projections are taken; the mediolateral oblique (MLO) and craniocaudal (CC) projections are the most commonly used in both mammography
and DBT, although others can be performed. There is still debate as to how many DBT projections are optimal and whether they should be supplemented with standard mammographic images or not.

Various manufacturers produce DBT units\(^3\). The different units all have varying scan angles and take different numbers of exposures as the tube travels over the breast. The number of exposures varies from around 11-49, and the angle of the arc from approximately 15-50 degrees\(^{11,12}\). There is no consensus as to the optimal angular range or optimal number of acquisitions for DBT\(^{11,12}\).

Manufactures also use two different types of 'scan motion'. Some will use 'step and shoot' scan motion where the x-ray tube is rotated through a set angle then stops moving to take the acquisition; others use continuous movement where the tube does not become stationary to take the exposure\(^4\). 'Step and shoot' scans may reduce blur due to tube motion during the acquisition but take longer to perform the whole scan and there may also be additional problems arising from vibration of the tube as it stops and starts\(^13\).

Once the initial projections have been obtained they are reconstructed to produce a stack of around fifty 1mm slices orientated parallel to the detector. Image reconstruction is usually performed by filtered back projection however, just as for CT, manufacturers are begining to utilise iterative reconstructions algorithms. Iterative algorithms require greater computing power but may provide superior edge sharpness when assessing microcalcifications (an indicator of early malignant change)\(^4,7,14\).

Image interpretation and display provide additional challenges. For DBT of two breasts in two orientations there may be over 200 images for the radiologist to review - compared with only 4 for standard mammography. Currently most DBT images are viewed on proprietary workstations and scrolled through as a stack, much like CT or MRI images. Some research has measured reporting times for DBT of double that required for mammography; increased reporting time and initial training are factors that will have to be accounted for in any cost-analyses\(^3\). A DBT examination will also require 50 times greater storage space than the equivalent mammographic exam, which can come at significant cost.

3. Technical Factors Impacting on Image Quality in Digital Breast Tomosynthesis

The factors that vary from one DBT unit to another include:
Despite almost two decades of prototype DBT units being produced there is still no consensus on what combination of scanning angle, number of acquisitions, scan motion, reconstruction algorithm and dose are optimal\(^{11,12,15}\). I shall briefly discuss the impact of scan motion, reconstruction algorithm and dose on DBT imaging before expanding on the two most researched variables: scanning angle and number of acquisitions.

There are two main types of scan motion; they are 'step and shoot' and continuous motion\(^{13}\). 'Step and shoot' scans may reduce blur due to tube motion during the acquisition but take longer to perform the whole scan and there may also be additional problems arising from vibration of the tube as it stops and starts\(^{13}\). There is however little published research into the impact of changing the type of scan motion on DBT images.

The impact of reconstruction algorithm is complex and current studies are limited in that they assess the impact using 'model observers' i.e. computer programs, and have almost exclusively been performed using breast phantoms\(^{6,14}\). What evidence there is suggests that iterative reconstruction, although more computationally intense, may provide better high spatial frequency resolution with comparable low spatial frequency resolution compared to filtered back projection\(^3\). In breast imaging low spatial frequency lesions may be tumours and high spatial frequency lesions may be microcalcifications (an indicator of underlying malignancy) so good resolution at both high and low spatial frequencies is required.

Most manufacturers have a stated goal of producing DBT units which will produce a single DBT acquisition at doses not greater than those for standard 2 view FFDM\(^ {9,16}\). I believe this is the reason, along with the difficulties in receiving ethics approval for higher dose studies, that little research has been performed into altering dose levels above those for a standard 2 view FFDM. Reducing dose will increase image noise and may obscure fine, particularly low contrast, detail.

**Scanning Angle**

Various authors have found that the positive effects of increasing the scanning angle are\(^ {11,12,15}\).
• Increased out of plane (z) resolution i.e. thinner slices.
• Increased contrast resolution, particularly at low spatial frequencies.

The negative consequences of increasing the scanning angle are\textsuperscript{11,12,15}:

• Increased noise.
• Reduced in-plane (x-y) spatial resolution.
• Increased streak artefact (unless the number of acquisitions is also increased).

**Number of Acquisitions**

The only positive impact of increasing the number of acquisitions for DBT images that has been reported is:

• Decreased streak artefact\textsuperscript{15}.

The potential negative impacts of increasing the number of acquisitions acquired include\textsuperscript{11,12,15}:

• Longer scan time.
• Increased electronic noise, if the total dose remains the same.

**4 Digital Breast Tomosynthesis vs FFDM**

**4.1 Technical Considerations**

DBT has superior contrast resolution compared with FFDM because overlying structures are not only blurred by the tomographic motion but also removed by de-blurring algorithms\textsuperscript{3,4}. This should make breast lesions more easily discernable and so improve sensitivities and reduce false positive rates. Figure 3 illustrates a lesion which is more easily identifiable on DBT\textsuperscript{5}. 
Fig. 3: Comparison of left breast CC mammogram (a) with DBT image (b) from the same patient shows the benign breast mass (arrows) is more easily identified and its margins more clearly delineated on the DBT image.


The in-plane spatial resolution of DBT is slightly worse than that of FFDM\(^3\). As measured by pixel pitch, the spatial resolution of DBT is around 70-140µm\(^3\). Spatial resolution of FFDM can be as low as 50µm\(^17\). High spatial resolution is important in breast imaging as it helps in the characterisation of microcalcifications which can be an indicator of underlying malignancy. There is some debate as to whether spatial resolutions as low as 50µm are
required for the accurate characterisation of calcifications however\textsuperscript{17}. Coarse califications can produce artefact on DBT images, Figure 4 shows an example\textsuperscript{5}. 
Fig. 4: Breast tomosynthesis image shows a mass (black arrows) and an artifact from a large calcification (white arrow). On the basis of the US appearance, the mass was diagnosed as a cyst.


Dose is a very important consideration in breast imaging. If DBT is to be considered for use as a screening modality then the risk of exposing healthy people to ionising radiation has to be balanced against any potential benefit gained\(^1\). The dose for 2-projection DBT is variably quoted as 3-6mGy; 1-2 times the dose of two view FFDM\(^{18}\).

4.2 Published Research

One of the first studies examining the performance of DBT was performed by Poplack et al (2007)\(^{19}\). In this study 98 women who had been recalled due to abnormal screening FFDM underwent DBT. The images were compared in an unblinded fashion with the original screening FFDM and observers scored the quality of the DBT images for several characteristics.

The study found that DBT images were of equal or superior diagnostic quality when compared to FFDM images in 89% of cases\(^{19}\). DBT was however felt to be inferior at assessing calcifications than FFDM in 8 of 14 cases. The study concluded that unnecessary recalls could have been reduced by 40% - reducing additional imaging costs, further patient exposure to ionising radiation and emotional distress\(^{19}\). This study was limited by the small number of subjects, the lack of blinding and the subjective nature of the results.

The largest DBT trial conducted to date was carried out by Hologic and is not peer reviewed\(^3\). Hologic performed 2 projection screening DBT, alongside standard 2 view FFDM for 310 women. Images were reviewed by 15 radiologists and the area under the ROC curve for FFDM alone, DBT alone, and DBT plus FFDM were compared. There was a significant improvement with DBT alone compared to FFDM alone and a further significant improvement with DBT plus FFDM compared to DBT alone\(^3\).

Gur et al (2008) also performed a study comparing FFDM, DBT and FFDM plus DBT\(^{20}\). They included 125 subjects whose images were review independently by 5 radiologists. They found no increased sensitivity with the addition of DBT to FFDM but did find
increased specificity, with a 30% reduction in their recall rate\textsuperscript{20}. There was no statistically significant difference between DBT alone and FFDM alone\textsuperscript{20}.

Early DBT trial results are promising, suggesting improved specificity with equal or improved sensitivity, but are limited in their quality. Only one peer reviewed study examined more than 100 subjects. Initial comparisons suggest that FFDM plus DBT yields better results than either FFDM or DBT alone. Further investigations will be required to assess what combination of FFDM and DBT projections are required for optimum results. Table 1 summarises the strengths and weaknesses of FFDM and DBT.

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<tr>
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<th>FFDM</th>
<th>DBT</th>
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<tbody>
<tr>
<td><strong>Sensitivity</strong></td>
<td>70-90%\textsuperscript{21}</td>
<td>Early studies suggest sensitivity is likely to be at least equivalent to FFDM and better in dense breasts\textsuperscript{3,20}</td>
</tr>
<tr>
<td><strong>Specificity</strong></td>
<td>76-97%\textsuperscript{21}</td>
<td>Improved when combined with FFDM; reduction in recall rates of 30-40%\textsuperscript{20}</td>
</tr>
<tr>
<td><strong>Contrast Resolution</strong></td>
<td>Limited by overlapping tissues\textsuperscript{3}</td>
<td>Excellent\textsuperscript{3,4}</td>
</tr>
<tr>
<td><strong>Spatial Resolution</strong></td>
<td>Pixel sizes as low as 50µm\textsuperscript{17}</td>
<td>Pixel sizes of 70-140 µm\textsuperscript{3}</td>
</tr>
<tr>
<td><strong>Calcifications</strong></td>
<td>FFDM may offer better characterisation of calcifications, although newer techniques (e.g. iterative reconstruction) may increase DBT quality\textsuperscript{5,17}</td>
<td></td>
</tr>
<tr>
<td><strong>Comfort</strong></td>
<td>Mean compression of up to 10dN\textsuperscript{5}</td>
<td>May be possible to reduce to 5dN\textsuperscript{5}</td>
</tr>
<tr>
<td><strong>Costs</strong></td>
<td>Well known</td>
<td>May be associated costs with training, extra time required for reporting and storage of images\textsuperscript{3}</td>
</tr>
<tr>
<td><strong>Dose</strong></td>
<td>Approximately 3mGy\textsuperscript{20}</td>
<td>3-6mGy\textsuperscript{20}</td>
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*Table 1. Comparison of FFDM and DBT.*
5 Further Research Required

DBT is a promising novel breast imaging technique but there are many questions which remain about how it should best be utilised and exactly what its strengths and weaknesses are. Current research into the technical factors impacting on DBT image quality is limited by its use of computer generated observers and use of artificial breast phantoms which often do not possess truly equivalent features to breast tissue. Studies comparing DBT to FFDM have been completed and initial results are promising but numbers of patients included in peer reviewed publications so far are low.

Further research required to optimise both the image acquisition and clinical utilisation of DBT includes:

- Further examination of the impact of changing the scanning angle.
- More research on the impact of scan motion.
- Investigation of the impact of different reconstruction algorithms on image quality; particularly the impact iterative reconstruction techniques may have on improving high spatial frequency resolution to improve characterisation of microcalifications.
- Large independent blinded multicentre controlled trials comparing the performance of FFDM and DBT. The TOMMY trial, currently recruiting in the UK, aims to recruit 7000 women recalled with abnormal screening mammograms to do just this\textsuperscript{19}.
- Comparisons of 1 and 2 projection DBT, and various combined FFDM and DBT projection combinations.

6 Horizon Scanning

Despite the large number of questions which remain to be answered about how to best utilise DBT currently there are several research groups aiming to improve the technique further. Two particularly promising potential future adjuncts to DBT include: contrast enhanced DBT (CE-DBT) and computer aided diagnosis (CAD) applied to DBT.

Contrast enhanced DBT is performed by obtaining pre-contrast DBT images in one or more projection\textsuperscript{10}. Iodinated contrast medium is then injected intravenously and further DBT acquisitions are taken after a delay of 1-3 minutes\textsuperscript{10}. Taking pre and post contrast acquisitions allows digital subtraction of the two data sets to highlight areas of contrast enhancement (Figure 5)\textsuperscript{10}. Malignant lesions in the breast are often hypervascular and show a particular pattern of contrast enhancement with early uptake and early 'wash-
out’. Currently contrast enhanced MRI is used to produce enhancement curves for breast lesions. CE-DBT could potentially take on a role similar to MRI at a much reduced cost\(^\text{10}\).

**Fig. 5**: Craniocaudal DBT and CE-DBT images show the increased conspicuity of two malignant lesions. Courtesy of Hologic, Inc.

CAD programs are available for standard mammographic reading and have been shown to be non-inferior to a second reader\(^9\). Designing CAD programs for DBT will be a challenge due to the 3D nature of the dataset and the large number of images\(^9\). Although the increased contrast resolution and improved edge identification provided by DBT may make it particularly suited to CAD programs. Figure 6 shows an example of CAD highlighting microcalcifications on a DBT image\(^{21}\). One potential problem with CAD programs is that they have a very low specificity\(^{22}\); applying them to DBT, a modality designed to reduce unnecessary recalls of healthy women may be counterproductive.
Fig. 6: CAD can be used in tomosynthesis to mark potentially suspicious microcalcifications, offering the potential to speed case review and increase accuracy. Courtesy of Hologic, Inc.


Images for this section:

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**Fig. 4:** Breast tomosynthesis image shows a mass (black arrows) and an artifact from a large calcification (white arrow). On the basis of the US appearance, the mass was diagnosed as a cyst.

**Fig. 5:** Craniocaudal DBT and CE-DBT images show the increased conspicuity of two malignant lesions. Courtesy of Hologic, Inc.
**Fig. 6:** CAD can be used in tomosynthesis to mark potentially suspicious microcalcifications, offering the potential to speed case review and increase accuracy. Courtesy of Hologic, Inc.
Conclusion

DBT is a hugely promising novel breast imaging technique based on the principles of conventional tomography developed in the early 1900s and utilising modern technologies such as flat panel detector and complex reconstruction algorithms. DBT produces stacks of millimetre slices through imaged breasts.

DBT improves breast imaging by removing a major limitation of mammography - overlapping fibroglandular breast tissue - which can both simulate and obscure cancers. DBT has the potential to reduce unnecessary recalls of women imaged and so reduce additional imaging costs, radiation exposure and emotional distress.

As well as the potential benefits of DBT there are potential limitations too: DBT will be more costly and time consuming to perform, and may not be as sensitive in characterising microcalcifications.

Initial research is promising, suggesting improved specificity with equivalent or improved sensitivity compared with FFDM. Studies are limited however, both in the number of subjects involved and, in some instances, by lack of peer review. More research into the optimal imaging parameters for DBT and large multicentre trials, such as the TOMMY\textsuperscript{20} trial beginning in the UK, are required to gain a fuller understanding of DBT so this novel modality can be exploited to its maximum potential.

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