Physics and Clinical Perspectives On Tomosynthesis:

1) Physics and Technology of Tomosynthesis

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– Dr. Maidment is a founder and shareholder of Daimroc, LLC.

FDA Statement
– This presentation will include off-label uses and applications and devices not yet approved for human use in the United States.

Tomosynthesis
Acquisition & Reconstruction

Linear Tomography

![Diagram of Linear Tomography]
Simple Tomosynthesis

Geometry of Breast Tomosynthesis

- DBT systems use a partial isocentric geometry with a fixed detector.
- The x-ray tube rotates around the breast in an arc.
- The detector either remains stationary or rotates with the tube.

Tomosynthesis Acquisition & Reconstruction

Fourier slice theorem

Geometry of Breast Tomosynthesis

Each projection fills a single plane in the Fourier Domain.

Each projection selects objects oriented parallel to the projection.
The angular range of the x-ray tube defines the non-zero region of the Fourier domain.

Breast CT

Breast Tomosynthesis

Courtesy J. Boone

CT, Tomosynthesis, and Radiography

360° angular range

Finite angular range (~30°)

Single projection.
Modern Multi-slice VCT scanners have nearly isotropic response with maximum spatial frequencies of 0.8 to 1.0 cycles/mm.

Unsampled frequencies along the \( \omega_y \) axis make TS and CT complimentary.

Penn Anthropomorphic Breast Phantom

Central Slice Theorem

1. Select a Central Slice of Fourier Domain
2. (Weighted) Sum thru Fourier Domain
3. iFFT
4. Digital Breast Phantom
5. Projection thru Phantom
   Central (or other) Phantom Slice

Fourier Domain
CT, Tomosynthesis, and Radiography

The more the Fourier domain is filled, the more the image looks like a slice from the phantom.

Angular range

Movie demonstrates the effect of increasing the angular range, by starting with a single projection and increasing up to 360°.

Increasing angular range in the X (top left), Y (top right), and Z (bottom) directions show that susceptibility to artifact is not uniform.
Angular range

Movie demonstrates the effect of increasing the angular range, starting with at 1° and increasing to 360°, with the same number of projections.

Axial (XY) Plane – 15 Projections

- At larger range, certain features are more in focus than others
- Undersampling artifacts are introduced

Number of projections

Movie demonstrates the effect of increasing the number of projections within a fixed angular range, starting with one projection.

Axial Plane - 15° angular range

- Although the images become progressively sharper, the difference is most noticeable from 1 projection to 5 projections
Commercial Systems

Contrast and SDNR

Angular Extent ($\theta$)

Contrast

0

0.01

0.02

0.03

0.04

0.05

0.06

0.07

0.08

Angular Spacing, $\Delta \theta$=2°

SDNR (normalized)

1

0.5

0.4

0.3

0.2

0.1

0

Angular Extent ($\theta$)

Courtesy M.J. Yaffe

X-Ray Generation

- Tungsten (W) Anode
- LFS: 0.3 mm; SFS: 0.1 mm

X-Ray Tube

- Conv: 50 $\mu$m Rh; 50 $\mu$m Ag
- Tomo: 0.7 mm Al
- I-View: 0.3 mm Cu

X-Ray Filtration

- Max mA varies with kVp
  - 20 – 39 kVp for 20
  - 30 – 49 kVp for 30
- LFS: 200 mA max; SFS: 50 mA max

X-Ray Generator

Copyright, Hologic Inc., 2019
Image Acquisition: 2D Conventional
- a-Se detector, 24×29 cm area
- 70 μm pixel size
- Rh and Ag filters
- Linear grid or HTC grid used in contact mode
- No grid in magnification mode

Image Acquisition: 15 Projection Tomosynthesis
Scan Details
- Al filter
- No anti-scatter grid
- Moving tube, 15° sweep
- Moving detector
- ~4 seconds acquisition
- Image resolution comes in two options:

Standard Resolution
- Projections: 140 μm pixel size
- Reconstruction
  - ~100 μm pixel size
  - 1 mm slice spacing

Clarity HD (Hi-Res Tomo)
- Projections: 70 μm pixel size
- Reconstruction
  - 70 μm pixel size
  - 1 mm slice spacing

Image Acquisition Modes
- **Conventional**
  - Acquires 2D image only
- **Tomo**
  - Acquires tomosynthesis images only
- **TomoHD**
  - Acquires tomosynthesis images only
  - Produces synthetic 2D image (C-View or Intelligent 2D)
- **Combo**
  - Acquires tomosynthesis images
  - Acquires 2D image
- **ComboHD**
  - Acquires tomosynthesis images
  - Acquires 2D image
  - Produces synthetic 2D images (C-View or Intelligent 2D)

Hologic Selenia Dimensions / 3Dimensions
- 2D and 3D under same compression
- Tube Anode: W
- Focal Spot: 0.1 mm / 0.3 mm
- Filtration: Rh/Ag (2D) / Al (3D)
- 15 degree continuous sweep
- 15 images, 3.7 s acquisition
- 70 cm SID
- Retractable grid
- 24 x 29 cm Selenium Direct detector
- 70 μm detls (140 μm, when binned)
- FBP Reconstruction
- 70 μm / 100 μm Reconstruction
- 1 mm slice spacing
- Synthetic 2D images
Fuji ASPIRE Cristalle

- 2D and 3D under same compression
- Tube Anode: W
- Focal Spot: 0.1 mm / 0.3 mm
- Filtration: Rh (2D) / Al (3D)
- 15/40 degree continuous sweep
- 15 images, 4/9 s acquisition
- 65 cm SID
- Retractable grid
- 24 x 30 cm Selenium Direct detector
- 70/140 μm hex. dels (2D 50 μm eff.)
- FBP Reconstruction
- 1 mm slice spacing
- Synthetic 2D images

Siemens Revelation / Inspiration

- 2D and 3D under same compression
- Tube Anode: W
- Focal Spot: 0.1 mm / 0.3 mm
- Filtration: Mo/Rh (2D) / Rh (3D)
- 50 degree continuous sweep
- 25 images, 25 s acquisition
- 65 cm SID
- Grid or software scatter removal
- 24 x 30 cm Selenium Direct detector
- 85 μm dels
- FBP Reconstruction
- 80 μm Reconstruction
- 1 mm slice spacing
- Synthetic 2D images

GE Senoclaire/Pristina

- 2D and 3D under same compression
- Tube Anode: Mo/Rh
- Focal Spot: 0.1 mm / 0.3 mm
- Filtration: Mo/Rh (2D) / Rh/Ag (3D)
- 25 degree step & shoot
- 9 images, 9 s acquisition
- 66 cm SID
- Moving grid
- 24 x 30 cm CsI Indirect detector
- 100 μm dels
- Iterative Reconstruction
- 100 μm Reconstruction
- 0.5 mm or 1 mm slice spacing
- Synthetic 2D images

Technical Specs

<table>
<thead>
<tr>
<th></th>
<th>Hologic</th>
<th>GE</th>
<th>Siemens</th>
<th>Fuji</th>
<th>IMS</th>
<th>Metaltronica</th>
<th>Planned</th>
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<tbody>
<tr>
<td>Tube Motion</td>
<td>Continuous</td>
<td>Step &amp; Shoot</td>
<td>Continuous</td>
<td>Continuous</td>
<td>Step &amp; Shoot</td>
<td>Continuous</td>
<td>Sync &amp; Shoot</td>
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<td># Projections</td>
<td>15</td>
<td>9</td>
<td>25</td>
<td>15</td>
<td>13</td>
<td>11/13/19</td>
<td>15</td>
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<tr>
<td>Sweep Angle</td>
<td>15/24/36</td>
<td>30</td>
<td></td>
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<tr>
<td>Scan Time (s)</td>
<td>3.7</td>
<td>9(*)</td>
<td>25</td>
<td>15/40</td>
<td>40</td>
<td>11/13/19</td>
<td>7</td>
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<tr>
<td>Grid</td>
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<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
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<tr>
<td>Recon Algo.</td>
<td>FBP</td>
<td>Iterative</td>
<td>FBP+</td>
<td>FBP</td>
<td>Iterative</td>
<td>FBP</td>
<td>Iterative</td>
</tr>
<tr>
<td>Del Size (μm)</td>
<td>70/140</td>
<td>100</td>
<td>85</td>
<td>70 (50)</td>
<td>85</td>
<td>85</td>
<td>80</td>
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<tr>
<td>Voxel Size (μm)</td>
<td>70/100</td>
<td>100</td>
<td>80</td>
<td>100/150</td>
<td>85</td>
<td>85</td>
<td>96/140</td>
</tr>
</tbody>
</table>
Contrast Sensitivity

Mammo-like (Hologic/GE/Fuji)  CT-like (Siemens)

In-plane Spatial Resolution (MTF)

Observations:
- The resolution is asymmetric in X and Y.
- Reconstruction algorithm affects resolution.
- Voxel size affects resolution.

NB: These MTF graphs show the relative response in X & Y. They have been normalized to a maximum of 1. The OTF in X and Y has a common value at zero frequency.

Slice-Sensitivity Profile (SSP) and Artifact Spread Function (ASF)

SSP for four systems. Results show the impact acquisition geometry and reconstruction method.

Ortenzia, et al. Physical characterisation of four different commercial digital breast tomosynthesis systems 2018 RPD DOI: 10.1093/rpd/ncy024

Slice Sensitivity Profile
Slice Sensitivity Profile

Maki, et al., Medical Physics, 2016

Clinical Performance

Masses vs. Calcs
Using probability of malignancy scores; curves represent average ROC performance for 12 readers in study 1 and 15 in study 2.

Pooled ROC by Lesion Type

Calcifications

Non-calcified

Digital mammography image of an invasive ductal carcinoma.

Tomosynthesis image of an invasive ductal carcinoma.
Visualization of micro-calcifications

Conventional mammography:
- Clustered µCa are projected onto a 2-D plane.
- The pattern of µCa distribution is obvious.
- The pattern of µCa distribution contains important diagnostic information.

Simulated pattern of clustered µCas
(Pattern: Big Dipper and Pole Star)
Distribution along z-direction

The pattern of µCa cluster is lost.

"Slab View" for showing clustered µCa:
- Combine multiple slices into a "slab"
- Maximum intensity projection (MIP) within the slab
- Slide the "slab window" through the reconstruction

Thin MIPS
Visualization of microcalcifications

DBT reconstruction (1 mm slice)

Z = 13 mm
Z = 17 mm
Z = 22 mm
Z = 24 mm

Visualization of microcalcifications

Slab View: 10 mm slab

Z = 13 mm
Z = 17 mm
Z = 20 mm
Z = 22 mm

Synthetic 2D Images
(Thick MIPS)

True 2D
Synthesized 2D
**2D vs 3Ds**

*Hologic FDA data:*
- 302 subjects
- 15 readers
- 3Ds superior to 2D alone
- ∆AUC = 0.04 (p=0.005)
- Recall Rate reduced by 30.2%

### Table:

<table>
<thead>
<tr>
<th>Mode</th>
<th>FFDM Views</th>
<th>DBT Views</th>
<th>Synthesized Views</th>
<th>Exam Dose per Breast</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFDM</td>
<td>MLO + CC</td>
<td>-</td>
<td>-</td>
<td>2.4 mGy</td>
</tr>
<tr>
<td>FFDM + 3D MLO</td>
<td>MLO + CC</td>
<td>MLO + CC</td>
<td>-</td>
<td>3.85 mGy</td>
</tr>
<tr>
<td>FFDM + DBT</td>
<td>MLO + CC</td>
<td>MLO + CC</td>
<td>MLO + CC</td>
<td>5.3 mGy</td>
</tr>
<tr>
<td>DBT + Synthesized 2D</td>
<td>-</td>
<td>MLO + CC</td>
<td>MLO + CC</td>
<td>2.9 mGy</td>
</tr>
</tbody>
</table>
Determinants of Dose

X-ray Beam Quality
- kVp
- Filtration
- Total mAs

Angular Exposure
- Change in SID
- Collimation
- Dose Depth Dependence

Projection Factors
- Number of projections
- mAs per projection
- Technical Limitations (det./gen.)

High Dose
Medium Dose
Low Dose

Dose Determines Lesion Detectability

For an ideal detector, the dose for tomosynthesis should be equal to or less than the dose for digital mammography

DBT Dose (Phantom)

DBT Dose vs. DM Dose


Average dose per image

This can be attributed to the difference in phototimer operation in 2D and 3D. As shown here, the 3D dose is primarily determined by breast thickness. The dose is only increased for very dense breasts. In 2D, the dose is determined by breast thickness and glandularity.

Average dose per patient*

<table>
<thead>
<tr>
<th>Mode (Combined MLO and CC)</th>
<th>No. Patients</th>
<th>View Position</th>
<th>No. Images Acquired</th>
<th>Average Dose per Patient (mGy)</th>
<th>Average Compressed Breast Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomo Combo (2D)</td>
<td>2,454</td>
<td>CC</td>
<td>5,129</td>
<td>1.84</td>
<td>58.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MLO</td>
<td>5,799</td>
<td>2.52</td>
<td>64.54</td>
</tr>
<tr>
<td>Tomo Combo (3D)</td>
<td>2,454</td>
<td>CC</td>
<td>4,901</td>
<td>2.16</td>
<td>58.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MLO</td>
<td>4,853</td>
<td>2.49</td>
<td>64.54</td>
</tr>
</tbody>
</table>

The 2D component of the Tomo Combo acquisition accounted for nearly half of the average dose per patient in 2014.

Average dose per patient

<table>
<thead>
<tr>
<th>Mode (Combined MLO and CC)</th>
<th>No. Patients</th>
<th>View Position</th>
<th>No. Images Acquired</th>
<th>Average Dose per Patient (mGy)</th>
<th>Average Compressed Breast Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomo Combo (2D + 3D)</td>
<td>2,454</td>
<td>CC</td>
<td>10,026</td>
<td>4.00</td>
<td>58.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MLO</td>
<td>10,692</td>
<td>5.01</td>
<td>64.54</td>
</tr>
<tr>
<td>Tomo HD (C-View + 3D)</td>
<td>2,064</td>
<td>CC</td>
<td>4,290</td>
<td>2.29</td>
<td>57.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MLO</td>
<td>4,427</td>
<td>2.77</td>
<td>63.47</td>
</tr>
</tbody>
</table>

The switch to Tomo HD in 2015 eliminated the acquisition of 2D images. This resulted in an overall dose reduction of 44% in our patient population.

*Information provided by the DICOM header that corresponds to the mean glandular dose in mGy (Organ Dose 0040,0316).

* p-value is infinitesimal
### Average dose per patient

<table>
<thead>
<tr>
<th>Mode</th>
<th>No. Patients</th>
<th>Average Dose per Patient (mGy)</th>
<th>Average Compressed Breast Thickness (mm)</th>
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</thead>
<tbody>
<tr>
<td>Tomo Combo (3D)</td>
<td>2,454</td>
<td>4.905</td>
<td>61.52</td>
</tr>
<tr>
<td>Tomo HD (3D)</td>
<td>2,064</td>
<td>4.65</td>
<td>63.47</td>
</tr>
</tbody>
</table>

In changing from Tomo Combo to Tomo HD, the 3D component of the patient dose is increased by 9%, due to additional images.

* p < 1e-38

### Patient dose by breast thickness

**Tomo Combo (2D)**

- CC
  - Dose (mGy): 2.50, 2.55, 2.70, 2.85, 3.00, 3.15
  - Compressed breast thickness (mm): 60, 65, 70, 75, 80

- MLO
  - Dose (mGy): 2.50, 2.55, 2.70, 2.85, 3.00, 3.15
  - Compressed breast thickness (mm): 60, 65, 70, 75, 80

**Tomo HD (3D)**

- CC
  - Dose (mGy): 2.50, 2.55, 2.70, 2.85, 3.00, 3.15
  - Compressed breast thickness (mm): 60, 65, 70, 75, 80

- MLO
  - Dose (mGy): 2.50, 2.55, 2.70, 2.85, 3.00, 3.15
  - Compressed breast thickness (mm): 60, 65, 70, 75, 80

The amount of breast compression and radiation dose that is applied during the mammography exam influences image quality.

Thick breasts are exposed to substantially increased radiation dose.

### Patient dose by breast thickness

**Tomo Combo (3D)**

- CC
  - Dose (mGy): 1.17, 1.28, 1.32, 1.55, 1.97, 2.56
  - Compressed breast thickness (mm): 60, 65, 70, 75, 80, 90

- MLO
  - Dose (mGy): 1.17, 1.28, 1.32, 1.55, 1.97, 2.56
  - Compressed breast thickness (mm): 60, 65, 70, 75, 80, 90

The increase of dose with breast thickness is more significant with 3D images than 2D images.

The relative increase in dose is thickness and projection dependent.

**Tomo HD (3D)**

- CC
  - Dose (mGy): 2.00, 2.15, 2.30, 2.45, 2.60, 2.75
  - Compressed breast thickness (mm): 60, 65, 70, 75, 80, 90

- MLO
  - Dose (mGy): 2.00, 2.15, 2.30, 2.45, 2.60, 2.75
  - Compressed breast thickness (mm): 60, 65, 70, 75, 80, 90

There is only a slight difference in the dose of the 3D images in the Tomo HD and Tomo Combo modes, when stratified by thickness.

The greatest increase in dose is associated with thick (i.e., large) breasts.
Generally, it is expected that older women have less glandular breast tissue, i.e., lower breast density. Thus, patient dose decreases with age. This is true with the Tomo Combo 2D image dose. This trend is not seen to the same degree with Tomo Combo 3D or TomoHD 3D images (next slide).
Object location

- This video demonstrates the effect of location on contrast and spatial resolution.
- The effect is varies with object height
- The image is always best at the chest wall.
- The difference is most noticeable at the bottom, where the phantom is thicker.
Depending on the plane, borders may be easier or harder to resolve at a given angular range. The same is seen with borders at different orientation within each plane.

A looping vessel is not equally visualized at all angles. The image to the right shows vessels in both parallel and perpendicular orientations, with the vessel parallel to the chest wall less well visualized.

Object orientation

Object location and size

The location and size of an object can affect the image.

Object Size

- Note the diagonal region of blurring across the phantom.
- This represents the height at which the border of 2 adjacent objects cannot be resolved.

Object Size

- Below this line, the order of the air gap and the plastic is switched
- This is called aliasing. DBT is sensitive to aliasing.
Divergent Beam Anisotropy

- "Thick" Radial phantom examines various frequencies and orientations in a small region
- The mid chest wall is in better focus than other locations, in agreement with the Defrise phantom

Attenuating Materials

- Iterative reconstructions can reduce these artifacts. The zipper artifact is largely eliminated, while shadowing is diminished but still evident.

Motion Artifacts

- DBT and s2D images are more greatly affected by patient motion than DM because of the long acquisition time
Future Directions

1) Super-Resolution

Acquiring multiple low resolution images at sub-pixel spacing generates a high resolution (i.e., super-resolution) image.

Central Projection

Reconstruction

The reconstruction can distinguish frequencies higher than the detector alias frequency $0.5a^2$ (3.6 lp/mm). This is not possible with a single projection.

Clinical Super-resolution

4x Mag

4x Super-resolution
Shimadzu – HD Tomosynthesis

2) Oblique Reconstructions

- Clinical MPR

Recon. at 0° Pitch
Recon. with 35 μm voxels at 0° pitch
Recon. at 30° Pitch
Recon. with 35 μm voxels at 30° pitch
Translation of Recon. Plane at 30° pitch

Shimadzu – Oblique Tomosynthesis
3) Volume Visualization

- Synthetic mammograms are created from perspective of the central projection.
- Volume Visualization (VV) is a dynamic method of visualizing the breast from a set of oblique angles.
- VV images provide the radiologist with a rotating 3D volume providing better perception of the tissue overlap.

Next-Generation DBT

Isotropic in-plane limiting resolution - 10.5 lp/mm.
Traditional Acquisition  vs. New Acquisition

3D NPS: Conventional Acquisition Geometry

3D NPS: Bowtie Acquisition Geometry

Wax Calcification Phantom

3D
Wax Calcification Phantom

3D

Conventional Acquisition Geometry

Bowtie Acquisition Geometry

Advantages:

- Avoids depth dependent magnification
- Same pixel size for every slice
- Avoids blurred zone in slices near the detector
- Breast, correctly, is largest at the midplane
- Structures oriented laterally (L-R) are better removed

Anthropomorphic Phantom

Geometry I:
Conventional

Geometry III:
PA Tube Motion

Magnification Digital Breast Tomosynthesis

Contact

Magnification 1.3

Magnification 1.6
### Hologic Prototype CE-DBT System

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target</strong></td>
<td>W</td>
</tr>
<tr>
<td><strong>Kvp</strong></td>
<td>49 (HE) / 32 (LE)</td>
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<td><strong>Filter</strong></td>
<td>Cu (HE) / Al (LE)</td>
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<tr>
<td><strong>SID</strong></td>
<td>70 cm</td>
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<tr>
<td><strong>Detector</strong></td>
<td>3 fps, 2x2 binning</td>
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<td><strong>Angular Range</strong></td>
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</tr>
<tr>
<td><strong>Scan Time</strong></td>
<td>7.3 seconds</td>
</tr>
</tbody>
</table>

- Separate calibrations for LE and HE images
- Manual technique, no AEC
- DE subtraction factor $k$ derived from CIRS Model 20 BH3D phantom

Advantages of tomosynthesis

- Improves conspicuity by removing overlying structures
- Sectional imaging with high resolution
- Can be performed in high volume screening
- Similar radiation dose to mammography
- Similar cost to mammography
- Good platform for quantitative imaging