Introduction to Tomosynthesis

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Atlanta, Georgia
Disclosure

• Institutional Research Collaborations:
  – Barco
  – Hologic

• Consultant:
  – Fuji Medical Systems USA
Learning Objectives

• To understand the fundamental principles behind tomosynthesis
• To explain the possible different system designs
• To explain the determinants of image quality
• To list the factors that affect radiation dose
• To understand the common artifacts in tomosynthesis
Outline

Motivation
Introduction
System Design and Design Considerations
Image Reconstruction
Radiation Dose
X-Ray Scatter
Artifacts
Synthetic Mammograms
0.16 lesion localization fraction

29% of missed cancers were missed due to being “obscured by overlying tissue”

*Birdwell et al, Radiology 219, 192-202 (2001).*
Courtesy GE Medical Systems
Computed Tomography

More expensive
Higher radiation dose
  100x chest CT over chest radiograph
  2-5x breast CT over mammography
Metal problematic
Slower to read (?)

....otherwise, fantastic!
Is there a halfway??

(can we get the best of both worlds?)
Towards Tomographic Imaging

2 D  2+ D  2.1 D  2.2 D  3 D

Standard Transmission Imaging
Stereoscopic Imaging (If your optical system can handle it!)
Linear Tomography (If you plan ahead!)
Digital Tomosynthesis
Computed Tomography (Is more always better?)
DIGITAL TOMOSYNTHESIS
Lesions of Interest

This information is used to reconstruct the volume
Shift correlates with vertical location
Recall

Courtesy of Hologic Inc.
Benefits

Similar to Radiography/Mammography

System
Workflow
Interpretation
Dose

...but with some discrimination of vertical position!
SYSTEM DESIGN AND DESIGN CONSIDERATIONS
Courtesy Joseph Lo (via youtube)
https://www.youtube.com/watch?v=g9AjqhQJwAs
<table>
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<th>Fuji AMULET Innovality</th>
<th>GE Essential Selenia Dimensions</th>
<th>IMS Giotto TOMO</th>
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</table>

**Currently not approved for clinical use in the U.S. by the Food and Drug Administration (FDA)**
projection MTF at 40 mm above the table

MTF [µ]

0.0 0.2 0.4 0.6 0.8 1.0

spatial frequency [mm⁻¹]

0 1 2 3 4 5 6 7 8

Siemens DBT
Hologic (binned) DBT
GE DBT
Hologic 2D planar

Tube - travel: In-plane MTF at 40 mm

MTF [µ]

0.0 0.2 0.4 0.6 0.8 1.0

spatial frequency [mm⁻¹]

0 1 2 3 4 5 6 7 8

Siemens DBT
Hologic DBT
GE DBT
Courtesy of Otto Zhou, Applied Nanotechnology Laboratory, University of North Carolina at Chapel Hill
~30% increase in system resolution for standard 15 degree, 15 view scan

Micro-calcification visibility

S-DBT reconstructions above

Continuous motion DBT reconstructions
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Total Angular Range
Oblique Incidence

Acciavatti and Maidment, Medical Physics, 38(11), 2011
Oblique Incidence – Direct Detectors

Blur due to oblique angle (18°, 21°, 30° in the figure)

- measured
- calculated

Zhao and Zhao, Medical Physics, 35(5), 2008
Oblique Incidence – Indirect Detectors

Mainprize et al, Medical Physics, 33(9), 2006
Acquisition Geometry

Radiography:
  1 position, 1 shot

CT:
  full revolution, 1000 shots

Tomosynthesis:
  ???
Acquisition Geometry Optimization

Acquisition parameters:

- Angular range
- Number of projection angles
Artifact Spread Function

\[ \text{ASF}(z) = \frac{I_s(z) - I_{BG}(z)}{I_s(z_0) - I_{BG}(z_0)} \]

Wu et al, Medical Physics, 31(9), 2004
Angular Range

Hu et al, Medical Physics, 35(12), 2008
Image Acquisition Optimization

Computer simulated breast volume and lesions

63 different acquisition geometries

In-plane quality and vertical resolution
Masses: Increased in-plane quality with increased angular range, fewer projections

Sechopoulos and Ghetti, Medical Physics 2009, 36, 1199-1207.
µCa: Increased in-plane quality with decreased angular range (→ mammo), fewer projections (small effect)

Sechopoulos and Ghetti, Medical Physics 2009, 36, 1199-1207.
Vertical resolution increases with angular range

Sechopoulos and Ghetti, Medical Physics 2009, 36, 1199-1207.
Threshold number of projections to improve vertical resolution

Sechopoulos and Ghetti, Medical Physics 2009, 36, 1199-1207.
Acquisition Geometry and Vertical Resolution

<table>
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<tr>
<th>Angular range</th>
<th>Number of projections beyond which ASF improvement is minimal</th>
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<tbody>
<tr>
<td>$8^a$</td>
<td>5</td>
</tr>
<tr>
<td>$16^a$</td>
<td>5</td>
</tr>
<tr>
<td>24</td>
<td>9</td>
</tr>
<tr>
<td>32</td>
<td>9</td>
</tr>
<tr>
<td>40</td>
<td>9</td>
</tr>
<tr>
<td>48</td>
<td>13</td>
</tr>
<tr>
<td>60</td>
<td>13</td>
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$^a$Substantial artifacts due to narrow angular range
Subsequent studies:

Threshold number of projections for each angular range was confirmed by others

Chest Tomosynthesis

No gain in increase in projections beyond a certain number

Acquisition Geometry

↑ angular range
↑ # of projections
→ ↑ vertical resolution
→ ↑ vertical resolution
up to a point

Have to consider:
scan time
anatomy
detector size
ACQUISITION TECHNIQUE
Tube Voltage Selection

Multiple studies reported higher kV than mammo optimal for tomo


One study reported lower energies beneficial

Technique and Dosimetric Characterization of a Clinical System

Feng and Sechopoulos, Radiology, 2012; 263(3): 35-42
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<th>Tomosynthesis</th>
<th>Mammography</th>
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<td>Tube Voltage (kVp)</td>
<td>1st HVL (mm Al)</td>
</tr>
<tr>
<td>2</td>
<td>Al 26</td>
<td>0.441</td>
</tr>
<tr>
<td>3</td>
<td>Al 28</td>
<td>0.476</td>
</tr>
<tr>
<td>4</td>
<td>Al 29</td>
<td>0.490</td>
</tr>
<tr>
<td>5</td>
<td>Al 31</td>
<td>0.541</td>
</tr>
<tr>
<td>6</td>
<td>Al 33</td>
<td>0.572</td>
</tr>
<tr>
<td>7</td>
<td>Al 35</td>
<td>0.600</td>
</tr>
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<td>8</td>
<td>Al 38</td>
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Feng and Sechopoulos, Radiology, 2012; 263(3): 35-42
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(really) Filtered Back Projection

\[ H_{\text{filter}}(\omega_y, \omega_z) = H_{\text{spectrum}}(\omega_y) \cdot H_{\text{profile}}(\omega_z) \cdot H_{\text{inverse}}(\omega_y, \omega_z) \]

\[ H_{\text{spectrum}}(\omega_y) \]: Hanning filter to control noise

\[ H_{\text{inverse}}(\omega_y, \omega_z) \]: Ramp-type filter

\[ H_{\text{profile}}(\omega_z) \]: Slice profile filter for constant depth resolution

Mertelmeier et al, SPIE 6142, 61420F (2006)
Ramp filter only

Ramp filter multiplied with spectrum filter

• Modified ramp filter

Spatial Frequency (cycles/mm)
Iterative Reconstruction Methods

Guess the reconstructed volume

Simulate the projections that would result from the guessed volume

N = N_0 e^{-\Sigma \mu T}

Repeat

Adjust guess

\[ \mu^{i+1}_v = \mu^i_v + \frac{\mu^i_v \sum_p l_{vp} [E - Y_p]}{\sum_p l_{vp} R'_p E} \]

Acquired projections

Compare

Simulated projections of guessed volume
Other Reconstruction Methods

SIRT
SART
ART
MLEM
TVR
Comparison of Reconstructions

Optimal acquisition might differ for different recons

Challenging for a single group to implement and optimize all recons

Most appropriate metric(s)?
Tomosynthesis Reconstruction

Mono-energetic Assumption

- Or constant spectral beam
- No explicit definition
- Same case with CT reconstruction algorithms
Standard Tomosynthesis Spectrum

- W/Al 32 kVp
- W/Al 32 kVp + 6 cm of breast tissue

Normalized Spectrum

X-Ray Energy (keV)

µ Breast Tissue (cm⁻¹)

µ = 21.7 keV

µ = 25.2 keV
Breast Tomosynthesis Acquisition Model

\[ b_i^\theta = \int_{\varepsilon} \psi(\varepsilon) e^{-\int_{L_{\theta,i}} \mu(x,\varepsilon) dl} \ v + \eta \]

- \( b_i^\theta \rightarrow \) acquired signal at pixel \( i \) for projection \( \theta \)
- \( \psi(\varepsilon) \rightarrow \) incident energy fluence at energy \( \varepsilon \)
- \( \mu(x,\varepsilon) \rightarrow \) linear attenuation coefficient of voxel \( x \) at energy \( \varepsilon \)
- \( L_{\theta,i} \rightarrow \) line from source to pixel \( i \) for projection \( \theta \)
Breast Tomosynthesis Acquisition Model

Minimize Poisson likelihood:

\[ X_{MLE} = \arg \min \left\{ \sum -L_\theta (X) \right\} \]

\[ -L_\theta (X) = \sum \left( b^i_\theta + \bar{\eta} \right) - b^i_\theta \log \left( b^i_\theta + \bar{\eta} \right) \]

Using iterative gradient descent optimization method
Homogeneous Phantom + Masses
Homogeneous Phantom + Masses

![Graph showing SDNR vs Lesion Glandular Density (%)]

- **Spectral**
- **MLEM**
- **FBP**
Homogeneous Phantom + Microcalcifications

FBP  Spectral
Homogeneous Phantom + Microcalcifications

FBP

Spectral
RADIATION DOSE
Breast Tomosynthesis Dosimetry Model

• Mammography:

\[ AGD_{\text{MAMMO}} = D_g N_{\text{MAMMO}} AK \]

• Tomosynthesis:

\[ AGD_{\text{TOMO}} = D_g N_{\text{MAMMO}} AK \left( \sum_{\alpha=\alpha_{\text{MIN}}}^{\alpha_{\text{MAX}}} \frac{\text{RGD}(\alpha)}{N_{\alpha}} \right) \]
Relative Glandular Dose

(a) Glandular fraction

(b) Thickness

(c) Chest wall to nipple distance

(d) X-ray spectrum

### Calculated Results for MGD for FFDM

<table>
<thead>
<tr>
<th>Breast Thickness (cm)</th>
<th>1% Glandular Fraction</th>
<th>14.3% Glandular Fraction</th>
<th>25% Glandular Fraction</th>
<th>50% Glandular Fraction</th>
<th>75% Glandular Fraction</th>
<th>100% Glandular Fraction</th>
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<tbody>
<tr>
<td>2</td>
<td>0.764</td>
<td>0.735</td>
<td>0.727</td>
<td>0.670</td>
<td>0.657</td>
<td>0.857</td>
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<tr>
<td>3</td>
<td>0.813</td>
<td>0.774</td>
<td>0.744</td>
<td>0.703</td>
<td>0.721</td>
<td>0.624</td>
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<tr>
<td>4</td>
<td>1.21</td>
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<td>0.994</td>
<td>0.989</td>
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<td>5</td>
<td>1.56</td>
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<td>1.41</td>
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<td>6</td>
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<td>7</td>
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<td>2.23</td>
<td>2.45</td>
<td>2.71</td>
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<td>3.07</td>
<td>2.93</td>
<td>2.64</td>
<td>3.08</td>
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**Note.**—Data are MGDs (in milligrays).
## AGD Ratio of Tomo / Mammo

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# Mean AGD [mGy]

GE SenoClaire Essential

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<th>Breast Thickness</th>
<th>N</th>
<th>Mammo</th>
<th>Tomo</th>
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<tbody>
<tr>
<td>All</td>
<td>236</td>
<td>1.62</td>
<td>1.49</td>
</tr>
<tr>
<td>&lt;40 mm</td>
<td>28</td>
<td>1.13</td>
<td>1.14</td>
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<tr>
<td>41-50 mm</td>
<td>46</td>
<td>1.34</td>
<td>1.33</td>
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<tr>
<td>51-60 mm</td>
<td>74</td>
<td>1.48</td>
<td>1.41</td>
</tr>
<tr>
<td>61-70 mm</td>
<td>55</td>
<td>1.82</td>
<td>1.62</td>
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<tr>
<td>&gt;70 mm</td>
<td>33</td>
<td>2.39</td>
<td>1.98</td>
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*Paulis et al, Investigative Radiology, online ahead of print*
## Chest Imaging Effective Dose [mSv]

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<th>2-View CXR</th>
<th>Chest Tomo</th>
<th>Chest CT</th>
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<tr>
<td></td>
<td>0.056</td>
<td>0.124</td>
<td>7</td>
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*Sabol, Medical Physics, Vol. 36, No. 12, 2009*
Does the exposure distribution have to be uniform?
How about:

$y < x$?

$y > x$?
Or even:

\[ y < x \, ? \]
\[ y > x \, ? \]
µCa detectability: center projection < single center slice of reconstruction

Mass detectability: no statistically significant difference

Das et al, Medical Physics 2009, 36(6), 2009
Uneven distribution of exposure and non-uniform angular sampling used by one commercial manufacturer in systems outside the US.
What if??

Improved image quality?
Dose reduction?
Single-pass contrast enhanced imaging?
Dual Spectrum Single Pass Tomo

Sechopoulos et al, European Congress of Radiology, 2015
8 cm Homogeneous Phantom + Masses

AEC (38 kVp, 84 mAs)  

AEC + 49 kVp/0.254 mm Cu

Sechopoulos et al, European Congress of Radiology, 2015
p = 0.412826
$p = 0.232631$
## Results

<table>
<thead>
<tr>
<th>Thickness</th>
<th>SDNR Difference</th>
<th>Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 cm</td>
<td>-16.0 ± 9.25%</td>
<td>-48%</td>
</tr>
<tr>
<td></td>
<td>(p&gt;0.08)</td>
<td></td>
</tr>
<tr>
<td>8 cm</td>
<td>-3.2 ± 19.9%</td>
<td>-28%</td>
</tr>
<tr>
<td></td>
<td>(p&gt;0.41)</td>
<td></td>
</tr>
</tbody>
</table>

Sechopoulos et al, European Congress of Radiology, 2015
X-RAY SCATTER
**Effect of Scatter in Tomosynthesis**

**Figure 5.** (a) The degrading effect of scatter radiation on contrast is illustrated for different breast thickness. (b) Scatter radiation markedly reduces the SDNR.

*Wu et al, Proc SPIE, 2007*
How is Scatter Normally Dealt With?

A clinical grid transmits ~80% of primary and ~20% of scatter x-rays
Grids in Tomosynthesis

Cut-off at higher projection angles
Primary photon absorption
Prone to image artifacts
GE SenoClaire Essential

Uses anti-scatter grid for DBT acquisition
Septa perpendicular to standard position
High number of lines per unit length
Alternatives

Post-acquisition processing
Correction during reconstruction
TOMOSYNTHESIS ARTIFACTS
High contrast off-plane objects introduce artifacts

“Voting” strategy to identify projections in which appropriate information is included, others ignored

Especially important for acquisitions with low number of projections

“Mask” to reconstruct only inside the breast

Faster reconstruction

Avoids artifacts outside breast

Breast tissue outside reconstructed volume but that contributes to attenuation

Breast tissue outside wide projection FOV

Reconstructed volume

Sechopoulos, Medical Physics, Vol. 40, No. 1, 2013
Varying number of projections contributes to the volume update, introducing discontinuities: introduced equalization using neighbor values updated by previous projection.

Bright artifact due to tissue attenuation outside volume: assume extension of “average” breast tissue outside of field of view to avoid bright artifact.

Improved estimation of x-ray path length in tissue outside field of view

SYNTHETIC MAMMOGRAMS
### Recall Rates

<table>
<thead>
<tr>
<th></th>
<th>DBT + FFDM</th>
<th></th>
<th>DBT + Synthetic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>False Positive Rate</td>
<td>% Detected Cancers</td>
<td>False Positive Rate</td>
</tr>
<tr>
<td>1\textsuperscript{st} Generation</td>
<td>53.1</td>
<td>83.5</td>
<td>46.1</td>
</tr>
<tr>
<td>2\textsuperscript{nd} Generation</td>
<td>45.6</td>
<td>87.3</td>
<td>45.2</td>
</tr>
</tbody>
</table>

*Skaane et al, Radiology, Vol 271(3), 2014*
Synthetic Mammograms

Included in various commercial systems
Current Research

CADe and CADx for tomosynthesis
Need to lower reading time
Contrast enhanced tomosynthesis
Phase contrast tomosynthesis
Tomosynthesis elastography
Multimodality Imaging

Tomosynthesis
  + US
  + SPECT
  + Electrical Impedance
  + Optical
Summary

Fast digital detectors $\rightarrow$ Advanced imaging

Need to lower anatomic noise

Tomosynthesis similar to planar radiography
  System footprint
  Workflow
  Image interpretation
Summary

Acquisition geometry large impact on image quality

Dosimetry > but similar to planar radiography

Ongoing research in:
  Reconstruction algorithms
  Other techniques (enhanced, phase, etc.)
  Multimodality
QUESTIONS
In terms of image acquisition, what is the main difference between linear tomography and digital tomosynthesis?

1. Linear tomography acquisition takes substantially longer than digital tomosynthesis.

2. Linear tomography results in a single plane being in focus per acquisition while in digital tomosynthesis any number of planes can be reconstructed to be in focus.

3. Linear tomography results in circular images while digital tomosynthesis results in rectangular images.

4. In linear tomography the x-ray tube moves in a straight line while in digital tomosynthesis it moves in a circle.
In terms of image acquisition, what is the main difference between linear tomography and digital tomosynthesis?

(2) In linear tomography, the in-focus plane has to be selected before acquisition, while in digital tomosynthesis, the reconstruction of the acquired projections results in many planes being in focus.

Bushberg et al, “The Essential Physics of Medical Imaging”, 3rd Edition
How does increasing the angular range of the tomosynthesis scan affect the vertical resolution of the reconstructed image?

1. Consistently decreases
2. Decreases up to a point, then remains constant
3. Vertical resolution does not increase with increasing angular range
4. Increases up to a point, then remains constant
5. Consistently increases
How does increasing the angular range of the tomosynthesis scan affect the vertical resolution of the reconstructed image?

(5) Increasing the angular range covered by the swing of the x-ray source consistently increases the vertical resolution of the reconstructed tomosynthesis image.

Sechopoulos and Ghetti, Medical Physics 2009, 36, 1199-1207.
How does increasing the number of projections of the tomosynthesis scan affect the vertical resolution of the reconstructed image?

1. Consistently decreases
2. Decreases up to a point, then remains constant
3. Vertical resolution does not increase with increasing number of projections
4. Increases up to a point, then remains constant
5. Consistently increases
How does increasing the number of projections of the tomosynthesis scan affect the vertical resolution of the reconstructed image?

(4) Increasing the number of projections during a tomosynthesis acquisition increases the vertical resolution up to a certain threshold, beyond which the resolution remains constant unless the angular range is increased.

Sechopoulos and Ghetti, Medical Physics 2009, 36, 1199-1207.
Why is there a high interest in chest tomosynthesis?

1. Much lower dose than chest radiography with out-of-plane blurring
2. Much lower dose than chest CT with out-of-plane blurring
3. Same vertical resolution as chest CT but lower dose
4. Improved vertical resolution as chest CT at same dose
5. Same vertical resolution and dose as chest CT, but considerably cheaper
Why is there a high interest in chest tomosynthesis?

(2) Chest tomosynthesis involves, in general, higher dose than chest radiography, but considerably lower than chest CT. Although it doesn’t result in true tomographic images as chest CT, it provides enough vertical resolution to be superior to chest radiography and sufficient for some clinical applications.

Sabol, Medical Physics, Vol. 36, No. 12, 2009
Dobbins and McAdams, European Journal of Radiology 72 (2009) 244–251
Introduction to Tomosynthesis

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