Changing Perceptions and Updated Methods for Mammography Dosimetry

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Changing Perceptions and Updated Methods for Mammography Dosimetry

Why are things changing?

- Different anode materials (W)
- Higher Tube Potentials (digital)
- Different filter materials (e.g. Al, Ag, Pd, etc.)
- New knowledge about breast geometry & composition
  - Skin Thickness
  - Breast Density (magnitude)
  - Glandular distribution in the breast
- Breast Tomosynthesis (not addressed in this symposium)
Changing Perceptions and Updated Methods for Mammography Dosimetry

This morning’s theme:
A series of research vignettes
Examples of clinical utility
Changing Perceptions and Updated Methods for Mammography Dosimetry

- Breast CT as the Backstory
- Skin Thickness
- Breast Density / the Myth
- New Mammography Spectra
- Density Heterogeneity
- Summary
Computer aided design / computer aided manufacture (CAD/CAM)
Doheny: Mechanical Assembly
System Integration

FDK Reconstruction Code

Preprocessed Projection Images

Reconstructed breast CT images

2003 ~42 minutes
2008 ~35 minutes
2010 >100x ~20 seconds

graphics processor unit (GPU)
Pendant Geometry Imaging
(no compression)
Spatial Resolution Improvements

Bodega (2007)
Cambria (2011)
Doheny (2015)
Clinical Imaging

- Patients: women with suspicion of breast cancer (BIRADS 4 & 5’s)
- First bCT scan: Nov 22, 2004
- >600 women on UC Davis scanners
- ~2000 bCT volume data sets
- ~260 have had contrast injection
- Radiation dose same as 2V mammography
- Image reconstruction $512^3$ or $1024^3$
bCT (no injected contrast)
Mass Lesions

Microcalcifications
Contrasted Enhanced breast CT

AUC = 0.87
Invasive Mammary Carcinoma
Changing Perceptions and Updated Methods for Mammography Dosimetry

Clinical Implications
Two 2D mammograms

Volumetric breast CT data
~500 contiguous images
The effect of skin thickness determined using optical dosimetry

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(Received 24 October 2007; revised 15 January 2008; accepted 22 February 2008; published 6 March 2008)

The characterization of breast anatomical metrics for the breast CT

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(Received 17 September 2010; revised 23 February 2011; accepted 12 April 2011; published 28 March 2011)
Changing Perceptions and Updated Methods for Mammography Dosimetry

Breast CT as the Backstory

Skin Thickness

Breast Density / the Myth

New Mammography Spectra

Density Heterogeneity

Summary
Past Monte Carlo Studies typically assumed a 4 mm (or 5 mm) skin thickness for breast dosimetry


DR Dance, Monte Carlo calculation of conversion factors for the estimation of mean glandular dose, PMB 35: 1211-1219: 1990


Glandular Breast Dose for Monoenergetic and High-Energy X-ray Beams: Monte Carlo Assessment

John M. Boone, PhD

Index terms: Breast radiography, radiation dose, 00.47, 0.99
Breast radiography, technology, 00.12
Breast radiography, utilization, 00.99
Physics
Radiology 1999; 213:23–37

Medical Physics

Normalized glandular dose (DgN) coefficients for arbitrary x-ray spectra in mammography: Computer-fit values of Monte Carlo derived data

John M. Boone
Department of Radiology, University of California, Davis, Sacramento, California 95817
(Received 1 November 2001; accepted for publication 28 February 2002, published 19 April 2002)
Normalized glandular dose (DgN) coefficients for arbitrary x-ray spectra in mammography: Computer-fit values of Monte Carlo derived data

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(Received 1 November 2001; accepted for publication 28 February 2002; published 19 April 2002)

50% Glandular, 4 cm breast

![Graph showing deposition vs. X-ray Energy for breast tissue and skin.]

- breast tissue
- skin
- chest wall

- x-rays
- skin
- homogeneous breast tissue

W/Mo (50 mm)
Observation from breast CT images: Skin is not 4 mm thick on the breast.
The effect of skin thickness determined using breast CT on mammographic dosimetry

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(Received 24 October 2007; revised 15 January 2008; accepted for publication 17 January 2008; published 6 March 2008)
Verified the spatial accuracy in three dimensions using a phantom...

Concept  Phantom  bCT scanner

Results

\[
\begin{align*}
\text{\(x\)-dimension:} & \quad y = (1.001 \pm 0.0151)x + 0.206 \\
\text{\(y\)-dimension:} & \quad y = (1.004 \pm 0.0076)x + 0.252 \\
\text{\(z\)-dimension:} & \quad y = (0.999 \pm 0.0097)x + 0.122 \\
\text{\(R^2\):} & \quad 0.999
\end{align*}
\]
Segmentation Algorithm

Measurements

Skin Thickness Results

average = 1.45 mm (s = 0.30 mm)

N = 100 breasts
N = 51 women
Changing Perceptions and Updated Methods for Mammography Dosimetry

Clinical Implications
Changing the skin thickness from 4.0 mm to 1.5 mm increased the DgN values by about 17-18%.

But this assumes a homogeneous breast composition.
Changing Perceptions and Updated Methods for Mammography Dosimetry

Breast CT as the Backstory

Skin Thickness

Breast Density / the Myth

New Mammography Spectra

Density Heterogeneity

Summary
The characterization of breast anatomical metrics using dedicated breast CT

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(Received 17 September 2010; revised 23 February 2011; accepted for publication 24 February 2011; published 28 March 2011)

DR Dance, Monte Carlo calculation of conversion factors for the estimation of mean glandular dose, PMB 35: 1211-1219: 1990


All of these papers assumed that “aerial glandular density” was equal to “volume glandular density”

To be clear, there is no such thing as a 100% glandular breast

Only ~4% of women have a volume glandular fraction >50%
Glandular segmentation of cone beam breast CT volume images

Nathan Packard; John M. Boone

Proc. SPIE 6510, Medical Imaging 2007: Physics of Medical Imaging, 651038 (March 17, 2007); doi:10.1117/12.713911
Original Breast CT image

After 3D Median filtering

After Adipose Flattening

After Adipose Smoothing

Final Segmented Image

glandular tissue

adipose tissue

skin
Original Breast CT image

After Segmentation Algorithm

<table>
<thead>
<tr>
<th>CT Number</th>
<th>Number of Voxels</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td></td>
</tr>
<tr>
<td>adipose tissue</td>
<td></td>
</tr>
<tr>
<td>glandular tissue</td>
<td></td>
</tr>
</tbody>
</table>

Initial threshold:

Final threshold:
The myth of the 50-50 breast

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(Received 30 April 2009; revised 23 September 2009; accepted for publication 29 September 2009; published 5 November 2009)
The Volume Glandular Fraction (VGF)

including skin:

\[ VGF = \frac{\text{glandular}}{\text{skin} + \text{glandular} + \text{adipose}} \]

excluding skin:

\[ VGF = \frac{\text{glandular}}{\text{glandular} + \text{adipose}} \]

\[ N = 191 \ (bCT \ only) \]
Validation of Toronto versus UC Davis density assessment techniques

N = 2831
Average = 19.3%
3.5% Median (~16\% VGF)
Median (~16% VGF)

10%

3.5%
\[ y = -0.4813x + 52.71 \]

\[ R^2 = 0.9665 \]
Changing Perceptions and Updated Methods for Mammography Dosimetry

Clinical Implications
28 kV
W / Rh
Thickness = 49 mm
157 mAs
$K_{ISL} = 0.99$
### Tungsten / Rhodium Combination

**Half Value Layer**

<table>
<thead>
<tr>
<th>Exposure measurements (mR)</th>
<th>150.0</th>
<th>194.3</th>
<th>236.9</th>
<th>278.6</th>
<th>320.1</th>
<th>361.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set kVp</td>
<td>22</td>
<td>24</td>
<td>26</td>
<td>28</td>
<td>30</td>
<td>32</td>
</tr>
<tr>
<td>HVL</td>
<td>0.44</td>
<td>0.45</td>
<td>0.47</td>
<td>0.498</td>
<td>0.513</td>
<td>0.528</td>
</tr>
</tbody>
</table>

**Calculations**

<table>
<thead>
<tr>
<th>Exposure measurements (mR)</th>
<th>150.0</th>
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<td>0.528</td>
</tr>
</tbody>
</table>

**Radiation Output**

- W/Rh @ 28 kV
- HVL = 0.498 mm Al
- Output (at 65.5 cm) = 4.8 mR/mAs
Mean glandular dose coefficients ($D_{gN}$) for x-ray spectra used in contemporary breast imaging systems

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4 Department of Radiology, Department of Biomedical Engineering, University of California Davis, Davis, CA 95616, USA

Table 1. Summary of modeled spectra.

<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>Target + Filter</th>
<th>HVL range (mm Al)</th>
<th>$D_{gN}$ table #</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>35–49</td>
<td>Mo + 400 μ Cu</td>
<td>2.24–3.80</td>
<td>2</td>
<td>General system</td>
</tr>
<tr>
<td>35–49</td>
<td>Rh + 400 μ Cu</td>
<td>2.21–3.79</td>
<td>3</td>
<td>General system</td>
</tr>
<tr>
<td>24–49</td>
<td>Mo + 30 μ Mo</td>
<td>0.28–0.52</td>
<td>4</td>
<td>GE essential</td>
</tr>
<tr>
<td>24–49</td>
<td>Mo + 25 μ Rh</td>
<td>0.33–0.56</td>
<td>5</td>
<td>GE senobright low energy</td>
</tr>
<tr>
<td>24–49</td>
<td>Rh + 25 μ Rh</td>
<td>0.28–0.65</td>
<td>6</td>
<td>GE essential GE senobright low energy</td>
</tr>
<tr>
<td>26–34</td>
<td>W + 50 μ Ag</td>
<td>0.48–0.69</td>
<td>7</td>
<td>Hologic dimensions IMS giotto TOMO</td>
</tr>
<tr>
<td>26–38</td>
<td>W + 500 μ Al</td>
<td>0.34–0.61</td>
<td>8</td>
<td>Philips microdose</td>
</tr>
<tr>
<td>28–49</td>
<td>W + 700 μ Al</td>
<td>0.46–0.92</td>
<td>9</td>
<td>Hologic dimensions</td>
</tr>
<tr>
<td>35–49</td>
<td>W + 200 μ Cu</td>
<td>1.68–2.89</td>
<td>10</td>
<td>Hologic contrast</td>
</tr>
<tr>
<td>35–49</td>
<td>W + 300 μ Cu</td>
<td>2.04–3.45</td>
<td>11</td>
<td>Hologic contrast</td>
</tr>
<tr>
<td>23–35</td>
<td>W + 50 μ Rh</td>
<td>0.41–0.64</td>
<td>12</td>
<td>Siemens mammomat hologic dimensions IMS giotto TOMO</td>
</tr>
</tbody>
</table>
28 kV HVL = 0.498 mm Al

**12.5% Breast Density**

<table>
<thead>
<tr>
<th>Energy (kV)</th>
<th>HVL</th>
<th>Breast Thickness (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>0.482</td>
<td>0.347</td>
</tr>
<tr>
<td></td>
<td>0.507</td>
<td>0.349</td>
</tr>
<tr>
<td>0.532</td>
<td>0.351</td>
<td>0.292</td>
</tr>
<tr>
<td>0.557</td>
<td>0.353</td>
<td>0.294</td>
</tr>
<tr>
<td>0.582</td>
<td>0.355</td>
<td><strong>0.296</strong></td>
</tr>
</tbody>
</table>

$DgN_{12\%} = 0.290 \text{ mGy/mGy}$

**50% Breast Density**

<table>
<thead>
<tr>
<th>Energy (kV)</th>
<th>HVL</th>
<th>Breast Thickness (cm)</th>
</tr>
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<tbody>
<tr>
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</tr>
<tr>
<td>0.532</td>
<td>0.311</td>
<td>0.256</td>
</tr>
<tr>
<td>0.557</td>
<td>0.313</td>
<td>0.257</td>
</tr>
<tr>
<td>0.582</td>
<td>0.315</td>
<td><strong>0.259</strong></td>
</tr>
</tbody>
</table>

$DgN_{50\%} = 0.254 \text{ mGy/mGy}$
Incident Air Kerma to Breast:

\[ 4.8 \text{ mR/mAs} \times 157 \text{ mAs} \times K_{\text{ISL}} = 746 \text{ mR} = 6.51 \text{ mGy [EAK]} \]

Dose (50%) = 6.51 mGy \times 0.254 \text{ mGy/mGy} = 1.65 \text{ mGy}

Dose (12%) = 6.51 mGy \times 0.290 \text{ mGy/mGy} = 1.89 \text{ mGy}

14.4% increase due to more accurate glandular fraction assessment

\[ 1.17 \times 1.144 = 1.34 \text{ or } 34\% \text{ greater dose} \]

- skin thickness
- glandular fraction
Changing Perceptions and Updated Methods for Mammography Dosimetry

Breast CT as the Backstory
Skin Thickness
Breast Density / the Myth
\[\text{New Mammography Spectra}\]
Density Heterogeneity
Summary
Why do we need another spectral model

- Limited kV range: 18 to 42 kV
- Derived from measurements on x-ray tubes of the past
Monte Carlo Simulation Geometry

**GE SENOGRAPE**
- Rh
- Mo
- Be window
- central ray
- detection plane
- large & small focal spot on each target

**HOLOGIC DIMENSIONS**
- W
- Be window
- large & small focal spot

**SIEMENS MAMMOMAT**
- W
- Mo
- Be window
- large & small focal spot on each target

**PHILIPS MICRODOSE**
- W
- Be window
- large focal spot
Field of View at Detector

LARGE
- Width: 30 cm
- Height: 27 cm
- Depth: 24 cm

MEDIUM
- Width: 25 cm
- Height: 14 cm
- Depth: 14 cm

SMALL
- Width: 18 cm
- Height: 12 cm
- Depth: 12 cm
• 0.4 % difference in HVL, averaged across all vendors, after conventional filtration is applied.

=> The FOV at the detector does not affect spectral shape
• 1.8 % difference in HVL, averaged across all vendors, after conventional filtration is applied.

=> Focal spot size does not affect spectral shape
- 0.4 % difference in HVL, for Mo anode systems, after conventional filtration is applied.

- 0.3 % difference in HVL, for W anode systems, after conventional filtration is applied.
For a given anode composition, vendor-specific geometrical differences do not affect spectral shape.

- 0.3 % difference in HVL, for W anode systems, after conventional filtration is applied.
A single mammography geometry can be used for modelling all commercial systems

methodology for new spectral model adopted from:

Tungsten anode spectral model using interpolating cubic splines: Unfiltered x-ray spectra from 20 kV to 640 kV
Andrew M. Hernandez and John M. Boone
Molybdenum, Rhodium, and Tungsten Anode Spectral Model using Interpolating Cubic Splines

Mo–Mo (30 µm)
Rh–Rh (25 µm)
W–Ag (50 µm)

- 20 to 60 kV (1 kV intervals)
- 0.5 keV energy resolution
- Minimal filtration (0.77 mm Be)
Changing Perceptions and Updated Methods for Mammography Dosimetry

Clinical Implications
Mean glandular dose coefficients (DgN) for contemporary mammography systems
Changing Perceptions and Updated Methods for Mammography Dosimetry

Breast CT as the Backstory

Skin Thickness

Breast Density / the Myth

New Mammography Spectra

Density Heterogeneity

Summary
Glandular dose is the metric of interest!

“Detailed information will have to be obtained on the amount and distribution of gland tissue in many individual cases before individual risk estimates can be made.”
Homogeneous
(VGF = 20%)

Heterogeneous
(VGF = 20%)
10 – 43% overestimation using structure phantoms

9 – 59% overestimation using unstructured phantoms

27% overestimation using simulated mechanical compression of bCT images in 20 patients.
The characterization of breast anatomical metrics using dedicated breast CT

Shih-Ying Huang and John M. Boone

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MEDICAL PHYSICS
Radial Glandular Fraction (RGF)


RGF_1
Relative radial distance (r)

RGF_2
Relative radial distance (r)

RGF_3
Relative radial distance (r)

Courtesy of S.Y. Huang
Phantom Design

cranial-caudal view

1.5 mm skin thickness

coronal view

T
b
a

219 bCT volume data sets

Size Dependence

10 %tile
50 %tile
90 %tile

25 %tile
50 %tile
75 %tile

Density Dependence
Modeled RGFs in compressed breast phantoms

$\min rVGF$  $\max rVGF$

$rVGF \equiv VGF$ for a given contoured region
Validating Methodology

HOMOGENEOUS
(VGF = 20%)

SPATIALLY-INDEPENDENT HETEROGENEOUS
(VGF = 20%)

$y = 0.999x - 0.0001$

$R^2 = 0.999$

$DgN(E)_{homo}$ (mGy/mGy)

$DgN(E)_{hetero}$ (mGy/mGy)
Changing Perceptions and Updated Methods for Mammography Dosimetry

Clinical Implications
DgN(E): heterogeneous vs. homogeneous

- **SMALL**
  - VGF = 17.0%

- **MEDIUM**
  - VGF = 12.6%

- **LARGE**
  - VGF = 7.0%

Graphs showing DgN(E) for different photon energies and fluences, comparing homogeneous and heterogeneous conditions.
pDgN: heterogeneous vs. homogeneous

Size Dependence

-29%  -36%  -38%
-34%  Mo
-23%  W

Density Dependence

-35%  -36%  -39%
-37%  Mo
-26%  W
Asymmetric shifts in glandular distributions

Asymmetric shifts in glandular distributions
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- New Mammography Spectra
- Density Heterogeneity

Summary
Changing Perceptions and Updated Methods for Mammography Dosimetry

• The only breast density metric that matters in breast dosimetry is volume glandular fraction
• A new understanding of breast geometry along with updating anode/filter/kV parameters will make clinical breast dosimetry more accurate
• Skin thickness would be important with homogeneous breast tissue, but less so with heterogeneous models
The mammography spectra presented here will be made available in spreadsheet format (after it’s published) by request.

The DgN values described in a PMB publication (200 pages) will be provided by request.

Heterogeneous breast models represent the next generation in breast dosimetry.
Future Directions

• Generate more realistic breast shapes under compression for Monte Carlo studies
• Model MLO projection different from CC
• With some tomosynthesis systems going to much wider angles, a full angled-beam MC analysis will be necessary
• The cycle of CAP ➔ Research ➔ CAP ➔ Research ➔ CAP continues
Future Directions

New AAPM Task Group on Breast Dosimetry

- Ioannis Sechopolous
- David Dance
- Ken Young
- R. Vanegen
- John Boone
Changing Perceptions and Updated Methods for Mammography Dosimetry

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