The History, Current Practice, and Future of Breast Imaging Dosimetry

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Outline

• Why do we need breast dosimetry?
• Historical development of breast dosimetry
• Current dosimetry methodologies
• Limitations
• Future directions
Mammography Utilization
among women 40 years and older in U.S.

39.3 million annual mammography procedures reported
(as of April 1, 2018)

https://www.cdc.gov/nchs/hus/contents2015.htm#070
https://www.fda.gov/radiation-emittingproducts/mammographyqualitystandardsactandprogram/facilityscorecard/ucm113858.htm
Why do we need dosimetry?

• Quality control

• Protocol optimization

• Evaluate risk to the patient (benefit / risk ratio)
Outline

• Why do we need breast dosimetry?

• Historical development of breast dosimetry

• Current dosimetry methodologies

• Limitations

• Future directions
Historical development of breast dosimetry

- Entrance surface dose (ESD)
  - Dose decreases exponentially with breast thickness

Poor measure of breast dose!
Historical development of breast dosimetry

- Mid-breast dose
- Total energy imparted
Mean *Glandular Dose* (MGD)
(Karlsson *et al.* 1976)

- Glandular tissue at highest risk of carcinogenesis
- Recommended by ICRP in 1987
MGD cannot be measured directly

- Normalized glandular dose ($DgN$) relates a measurable quantity (entrance surface kerma) to MGD

$$DgN = \frac{MGD}{ESK}$$
Simple breast model
(Hammerstein et al. 1979)

1. 5 mm skin thickness
2. 50% glandular / 50% adipose
3. Homogeneous composition of adipose & glandular tissue
Outline

• Why do we need breast dosimetry?
• Historical development of dosimetry
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• Future directions
Factors affecting dose

• Breast composition / thickness

• Target / filter, kV, and HVL
Monte Carlo modeling of dose

\[ MGD = \frac{E_{\text{glandular}}}{M_{\text{glandular}}} \]
Mean Glandular Dose (MGD)

\[ MGD = \frac{E_{\text{glandular}}}{M_{\text{glandular}}} = E_{\text{tissue}} \times G(f_g) \]

\[ G(f_g) = \frac{f_g \left( \frac{\mu_{en}}{\rho} \right)_{\text{glandular}}}{f_g \left( \frac{\mu_{en}}{\rho} \right)_{\text{glandular}} + \left( 1 - f_g \right) \left( \frac{\mu_{en}}{\rho} \right)_{\text{adipose}}} \]
Entrance Surface Kerma (ESK)

• Relates a measurable quantity (ESK) to a Monte Carlo estimation of glandular dose (MGD)

• DgN look up tables are published for specific x-ray techniques and breast compositions
Previous ACR dosimetry method

Wu’s method

\[ MGD = X_{ESE} \times DgN \]

- DgN tables published for Mo/Mo, Mo/Rh, & Rh/Rh spectra (GE & SIEMENS only)
- Interpolated across different breast glandularities / thickness, HVL, and kV
- Required alternative tables for W anode systems

Wu et al. Radiology 1994
Monoenergetic MC simulation of DgN

Monoenergetic MC simulation of DgN

Monoenergetic MC simulation of DgN

\[ E = 5 \text{ keV} \]

50% glandularity
6 cm

Monoenergetic MC simulation of DgN

$E = 5\, \text{keV}$

$E = 30\, \text{keV}$

50% glandularity
6 cm

\[
pDgN = \frac{\sum_{E=E_{\text{min}}}^{E_{\text{min}}} \Phi(E) \delta(E) \cdot DgN(E)}{\sum_{E=E_{\text{min}}}^{E_{\text{min}}} \Phi(E) \delta(E)}
\]
2016 ACR dosimetry method

Dance’s Method

\[ D = Kgcs = K \times DgN \]

\[ D = \text{Average Glandular Dose (mGy)} \]
\[ K = \text{Entrance Exposure (mR)} \]
\[ g = \text{g-factor for breast simulated with acrylic or BR-12} \]
\[ c = \text{c-factor for breasts simulated with acrylic or BR-12} \]
\[ s = \text{s-factor for clinically used spectra} \]

Assumes a homogeneous breast model with 5 mm skin layer

\[ D = K g c s \]

- **g-factor** - dose conversion factor that assumes 50% glandularity

- **c-factor** - corrects for difference in glandularity
  
  \[ c = 1 \text{ for } 50\% \text{ glandularity} \]

Dependent on glandularity, thickness, and HVL.
50% Glandularity BR-12

- HVL = 0.3 mm Al
- HVL = 0.6 mm Al

Breast Thickness (cm)

<table>
<thead>
<tr>
<th>Thickness (cm)</th>
<th>HVL = 0.3 mm Al</th>
<th>HVL = 0.6 mm Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>5</td>
<td>2.5</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

c-factor * g-factor * 8.76 mGy/R
\[ D = Kgcs \]

Table 6. s-factors for Acrylic and BR-12

<table>
<thead>
<tr>
<th>Target/Filter</th>
<th>s-factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo/Mo</td>
<td>1.000</td>
</tr>
<tr>
<td>Mo/Rh</td>
<td>1.017</td>
</tr>
<tr>
<td>Rh/Rh</td>
<td>1.061</td>
</tr>
<tr>
<td>Rh/Al</td>
<td>1.044</td>
</tr>
<tr>
<td>W/Rh</td>
<td>1.042</td>
</tr>
<tr>
<td>W/Al</td>
<td>1.050</td>
</tr>
<tr>
<td>W/Ag</td>
<td>1.072</td>
</tr>
</tbody>
</table>

kV differences accounted for by g-factor dependence on HVL
Example: QC phantom dose

• 4.2 cm of 50% glandularity BR-12
• 32 kV W/Ag spectrum (HVL = 0.4 mm Al & $K = 1$ R)

1) Table 5 in ACR manual: $g \times c = 2.19 \text{ mGy/R}$

2) Table 6 in ACR manual: $s = 1.07$

\[
D = K \ g \ c \ s = 1 \ R \times \frac{2.19 \text{ mGy}}{R} \times 1.07 = 2.34 \text{ mGy}
\]
Example: “Patient” dose

- 6 cm compressed breast with 16% glandularity
- 32 kV W/Ag spectrum (HVL = 0.4 mm Al & K = 1 R)

**Table 2.** $g$-factors (mGy/mGy) for breast thicknesses of 2–11 cm and the HVL range 0.30–0.60 mm Al. The $g$-factors for breast thicknesses of 2–8 cm are taken from Dance (1990).

<table>
<thead>
<tr>
<th>Breast thickness (cm)</th>
<th>0.30</th>
<th>0.35</th>
<th>0.40</th>
<th>0.45</th>
<th>0.50</th>
<th>0.55</th>
<th>0.60</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.390</td>
<td>0.433</td>
<td>0.473</td>
<td>0.509</td>
<td>0.543</td>
<td>0.573</td>
<td>0.587</td>
</tr>
<tr>
<td>3</td>
<td>0.274</td>
<td>0.309</td>
<td>0.342</td>
<td>0.374</td>
<td>0.406</td>
<td>0.437</td>
<td>0.466</td>
</tr>
<tr>
<td>4</td>
<td>0.207</td>
<td>0.235</td>
<td>0.261</td>
<td>0.289</td>
<td>0.318</td>
<td>0.346</td>
<td>0.374</td>
</tr>
<tr>
<td>4.5</td>
<td>0.183</td>
<td>0.208</td>
<td>0.232</td>
<td>0.258</td>
<td>0.285</td>
<td>0.311</td>
<td>0.339</td>
</tr>
<tr>
<td>5</td>
<td>0.164</td>
<td>0.187</td>
<td>0.209</td>
<td>0.232</td>
<td>0.258</td>
<td>0.287</td>
<td>0.310</td>
</tr>
<tr>
<td>6</td>
<td>0.135</td>
<td>0.154</td>
<td>0.172</td>
<td>0.192</td>
<td>0.214</td>
<td>0.236</td>
<td>0.261</td>
</tr>
</tbody>
</table>

Example: “Patient” dose

• 6 cm compressed breast with 16% glandularity
• 32 kV W/Ag spectrum (HVL = 0.4 mm Al & $K = 1$ R)

<table>
<thead>
<tr>
<th>HVL (mm Al)</th>
<th>Thickness (cm)</th>
<th>Breast glandularity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.1%</td>
</tr>
<tr>
<td>0.40</td>
<td>5</td>
<td>1.258</td>
</tr>
<tr>
<td>0.40</td>
<td>6</td>
<td>1.276</td>
</tr>
<tr>
<td>0.40</td>
<td>7</td>
<td>1.292</td>
</tr>
</tbody>
</table>

Example: “Patient” dose

• 6 cm compressed breast with 16% glandularity

• 32 kV W/Ag spectrum (HVL = 0.4 mm Al & K = 1 R)

1) Interpolated from Table 2*: \( g = 0.17 \text{ mGy/mGy} \)

2) Interpolated from Table 6*: \( c = 1.18 \)

3) Table 6 in ACR manual \( s = 1.07 \)

\[
D = K \cdot g \cdot c \cdot s = 1 \text{ R} \times 0.17 \frac{\text{mGy}}{\text{mGy}} \times 1.18 \times 1.07 \times 8.76 \frac{\text{mGy}}{R} = 1.88 \text{ mGy}
\]

Trends in mammography dose

- **50% glandularity**
- **Accreditation Phantom**
- **Screen-film**
- **Digital (Mo target)**
- **Digital (W target)**

Bushberg et al. 2011
Trends in mammography dose

UC Davis Hologic Selenia Dimensions (N = 262)
Tomosynthesis dosimetry

• Not included in ACR manual (appendix in progress)

\[ D_g N_{\text{TOMO}} = D_g N_{\text{MAMMO}} \sum_{\alpha_{\text{min}}}^{\alpha_{\text{max}}} \frac{\text{RGD}(\alpha)}{N_\alpha} \]
Tomosynthesis dosimetry

- Not included in ACR manual (appendix in progress)

\[ D_{\text{g}N_{\text{TOMO}}} = \frac{D_{\text{g}N_{\text{MAMMO}}}}{N_{\alpha}} \sum_{\alpha_{\text{min}}}^{\alpha_{\text{max}}} \text{RGD}(\alpha) \]

relative glandular dose at \( \alpha \) degrees

total # of projections

Tomosynthesis dosimetry

\[ D_g N_{TOMO} = D_g N_{MAMMO} \frac{\sum_{\alpha_{min}}^{\alpha_{max}} R GD(\alpha)}{N_\alpha} \]

- Uses existing DgN tables
- Parameterization of RGD dependence on only breast thickness, size, and \( \alpha \)

Tomosynthesis dosimetry

Tomosynthesis dosimetry

\[ DgN_{\text{TOMO}} = DgN_{\text{MAMMO}} \overline{\text{RGD}} \]

RGD can be used for “standard” acquisition:

- constant mAs for all projections & symmetric acquisition angles about 0°
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• Why do we need breast dosimetry?
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Assumptions of current breast models

1. 5 mm skin thickness
2. 50% glandular / 50% adipose
3. Homogeneous composition of adipose & glandular tissue
Assumptions of current breast models

1. 5 mm skin thickness
2. 50% glandular / 50% adipose
3. Homogeneous composition of adipose & glandular tissue
Observation from breast CT images: Skin is not 5 mm thick on the breast.
Skin thickness measurement

Segmentation Algorithm

Measurements

Skin Thickness Results

Mean: ~1.5 mm [0.9 - 2.3]

N = 100 breasts
N = 51 women

Effect of skin thickness on glandular dose

![Diagram showing the effect of skin thickness on glandular dose.](image)

- **Effect:**
  - Relative Dose vs. Depth
  - MGD (Mean Glandular Dose)
  - 1.5 mm skin thickness

- **Explanation:**
  - The diagram illustrates how skin thickness affects the glandular dose at different depths.
  - The curve shows a decrease in glandular dose as depth increases.
  - Marked point at 1.5 mm skin thickness indicating the impact on MGD.
Effect of skin thickness on glandular dose

1.5 mm

3 mm

Relative Dose

Depth

MGD

3 mm
Effect of skin thickness on glandular dose

Relative Dose

Depth

MGD

5 mm

A

B

1.5 mm

3 mm

5 mm

A

B
Effect of skin thickness on glandular dose

~ 20% increase in glandular dose using 1.5 mm skin thickness compared against 5 mm!
Assumptions of current breast models

1. 4-5 mm skin thickness
2. 50% glandular / 50% adipose
3. Homogeneous composition of adipose & glandular tissue
Observation from breast CT:
no 100% glandular breast
Myth of the 50-50 breast

VGF_{SK} = \frac{\text{glandular}}{\text{glandular} + \text{adipose} + \text{skin}}
Myth of the 50-50 breast

- $N = 2831$
- Average $= 19.3\%$
Myth of the 50-50 breast

Median (~16% VGF)

Cumulative Prob.

$VGF_{SK} (%)$

3.5%
Assumptions of current breast models

1. 4-5 mm skin thickness
2. 50% glandular / 50% adipose
3. Homogeneous composition of adipose & glandular tissue
Consequences of glandular heterogeneity on breast dose in mammography

Homogeneous (VGF = 16%)

Heterogeneous (VGF = 16%)
Consequences of glandular heterogeneity on breast dose in mammography

Homogeneous
(VGF = 16%)

Heterogeneous
(VGF = 16%)
Simple breast model overestimates glandular dose

Breast-CT derived glandular distributions

Homogeneous vs. heterogeneous

small ($f_g = 17.0\%$)

medium ($f_g = 12.6\%$)

large ($f_g = 7.0\%$)

Size Dependence


-34% Mo

-23% W
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• Why do we need breast dosimetry?
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• Provide a consensus on techniques necessary for the clinical assessment of MGD in breast imaging modalities including:
  • Digital mammography
  • Breast tomosynthesis
  • Magnification view mammography with partial breast irradiation

• Joint project with ICRU & EFOMP
Addressing the dose overestimation

BCT images acquired at:
Radboud (~80 cases)
UC Davis (~200 cases)

Classification

Image Segmentation:
Caballo M. et al. 2018

Compression

Finite Element Compression

slide courtesy of Sechopoulos et al. & TG 282
New breast dosimetry model

- Heterogenous dense breast model with binary classification of adipose and glandular tissue
- Monte Carlo simulations have to be validated for local dose deposition
MC Validation

Homogenous phantom / monoenergetic beam

- TLD
- MOSFET
- GafChromic™
- Monte Carlo

Fedon et al. Med Phys. 2018
MC Validation

Homogenous phantom / monoenergetic beam

All experimental values in good agreement (< 5%) with Monte Carlo simulations

Fedon et al. Med Phys. 2018
Mammography diagnostic views

• Spot compression and magnification
• Partial breast irradiation

• Should glandular dose include:
  all glandular tissue OR only glandular tissue irradiated?

No clear consensus on the dose metric!
Summary

• Breast dose is impacted by changes in target/filter, kV, and breast thickness/composition

• The homogeneous model overestimates glandular dose by ~30%

• Heterogeneous breast models represent the next generation in dosimetry

• Current efforts are focused on harmonizing international breast dosimetry protocols
Questions?

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