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

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The Breast Tomography Project
University of California, Davis

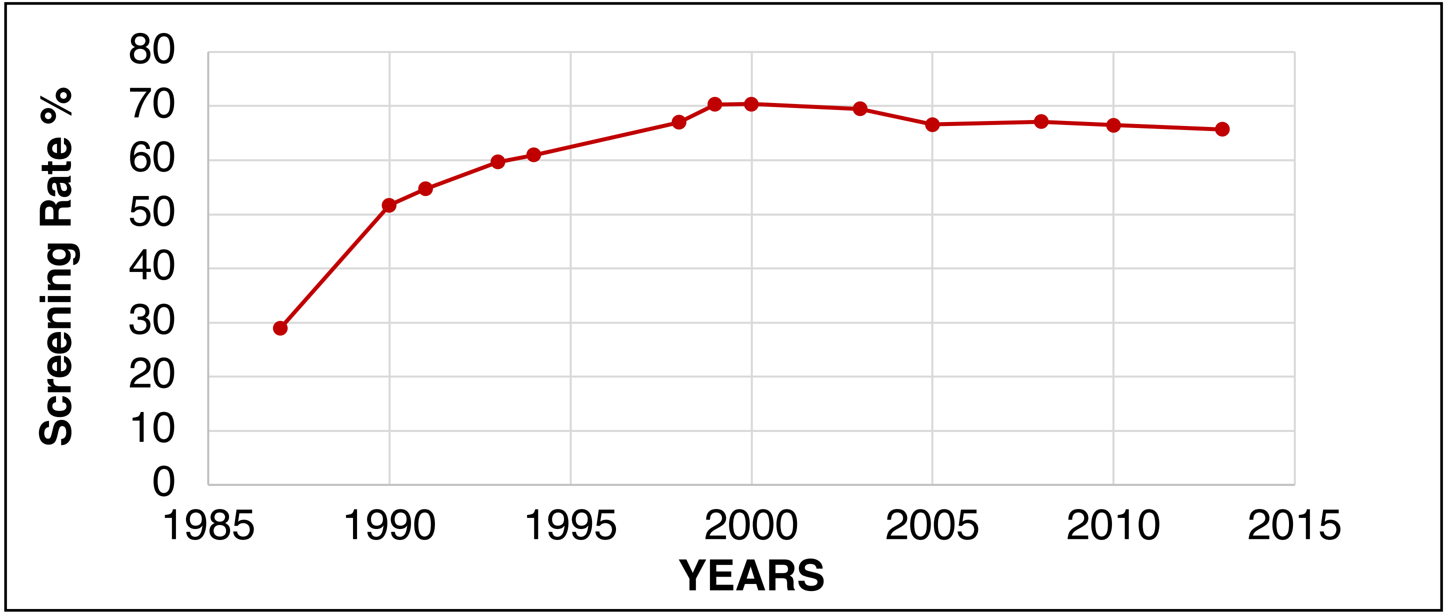
UCDAVIS
HEALTH

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?

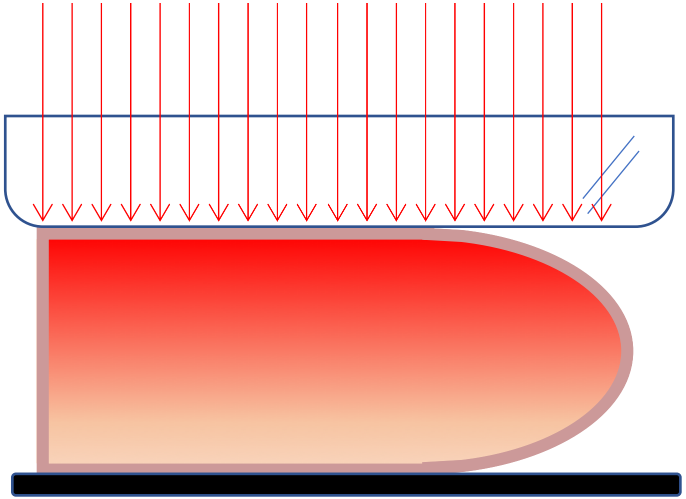
- Quality control
- Protocol optimization
- Evaluate risk to the patient (*benefit / risk* ratio)

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

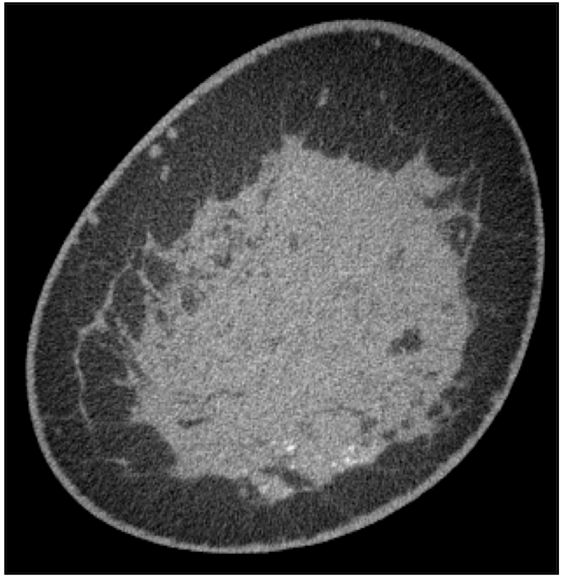
- Mid-breast dose

- Total energy imparted

Historical development of breast dosimetry

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

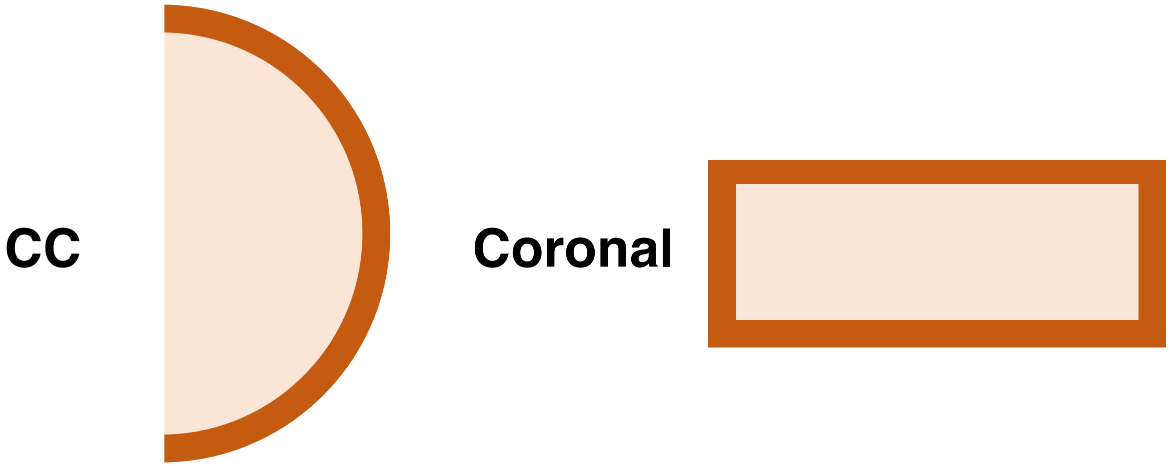
- Normalized glandular dose (DgN) relates a measurable quantity (entrance surface kerma) to MGD

$$DgN = \frac{MGD}{ESK}$$

Simple breast model

(Hammerstein *et al.* 1979)

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



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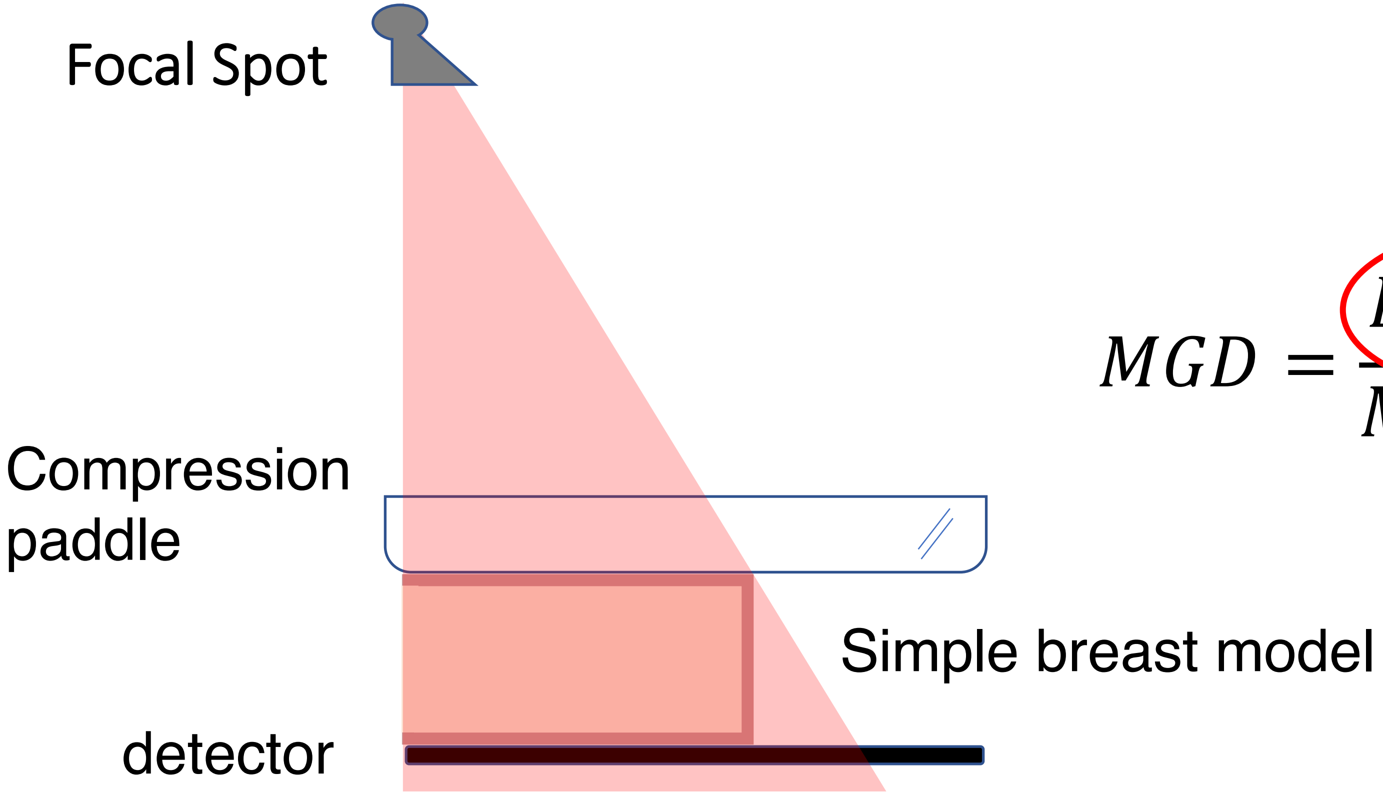
Factors affecting dose

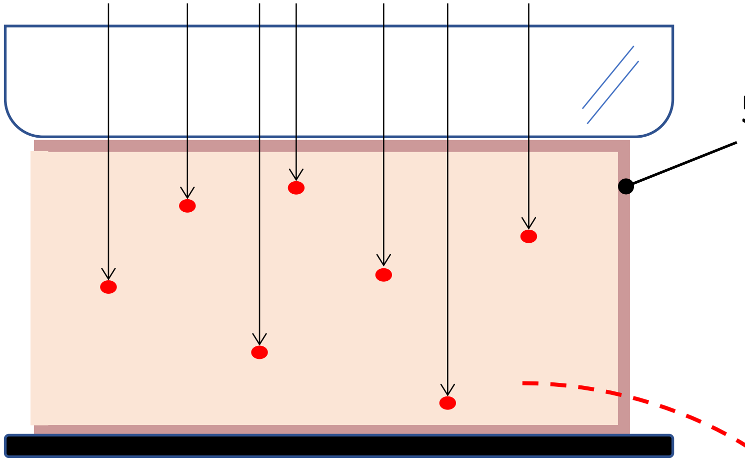
- Breast composition / thickness
- Target / filter, kV, and HVL

Monte Carlo modeling of dose



$$MGD = \frac{E_{glandular}}{M_{glandular}}$$

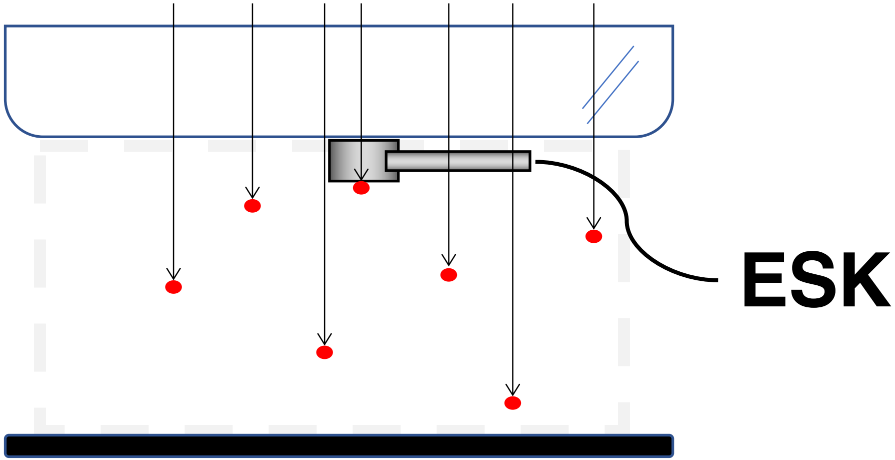
Mean Glandular Dose (MGD)



$$G(f_g) = \frac{f_g \left(\frac{\mu_{en}}{\rho}\right)_{glandular}}{f_g \left(\frac{\mu_{en}}{\rho}\right)_{glandular} + (1 - f_g)\left(\frac{\mu_{en}}{\rho}\right)_{adipose}}$$

$$MGD = \frac{E_{glandular}}{M_{gladnular}} = \frac{E_{tissue}^{deposit} \times G(f_g)}{f_g M_{tissue}}$$

Entrance Surface Kerma (ESK)



$$DgN = \frac{MGD}{ESK}$$

- 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

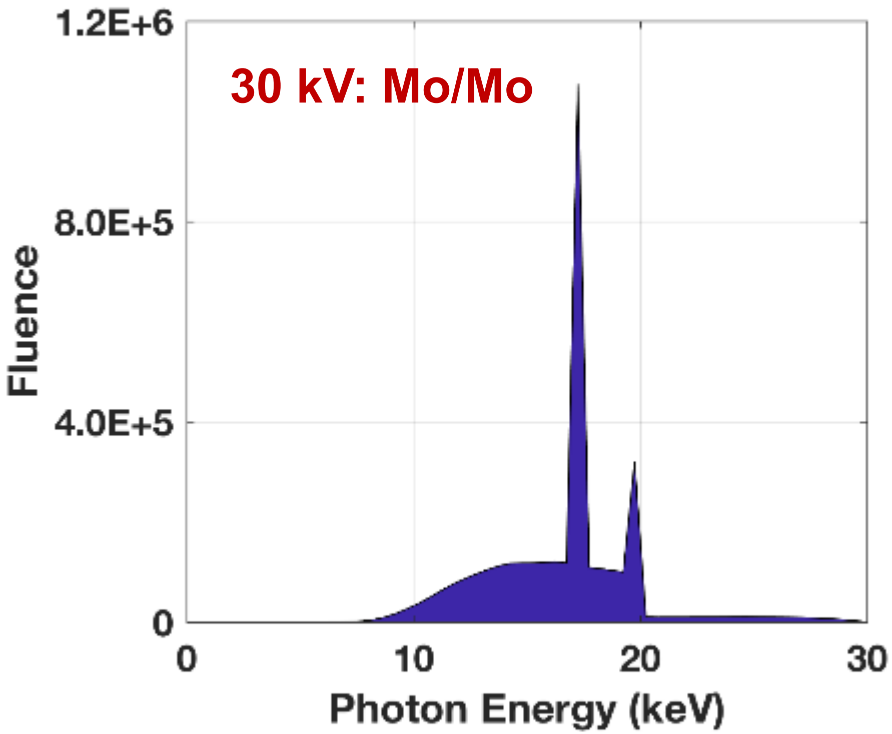
Wu's method

$$MGD = X_{ESE} \times DgN$$

- 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

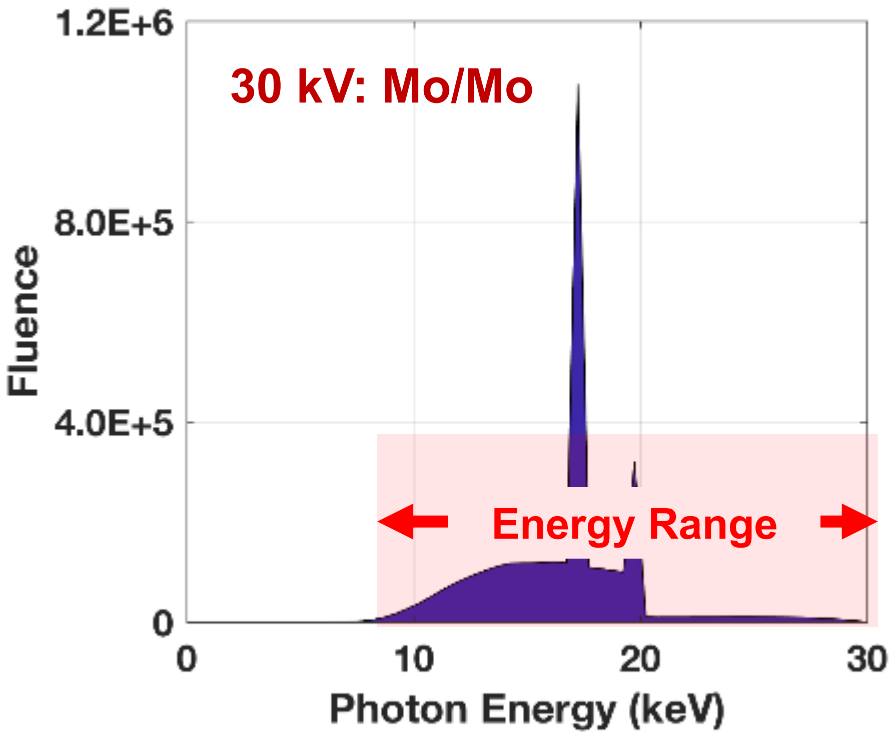
Wu *et al. Radiology* 1994

Monoenergetic MC simulation of DgN



Hernandez A.M. *et al. Med Phys.* 44(6) June 2017

Monoenergetic MC simulation of DgN



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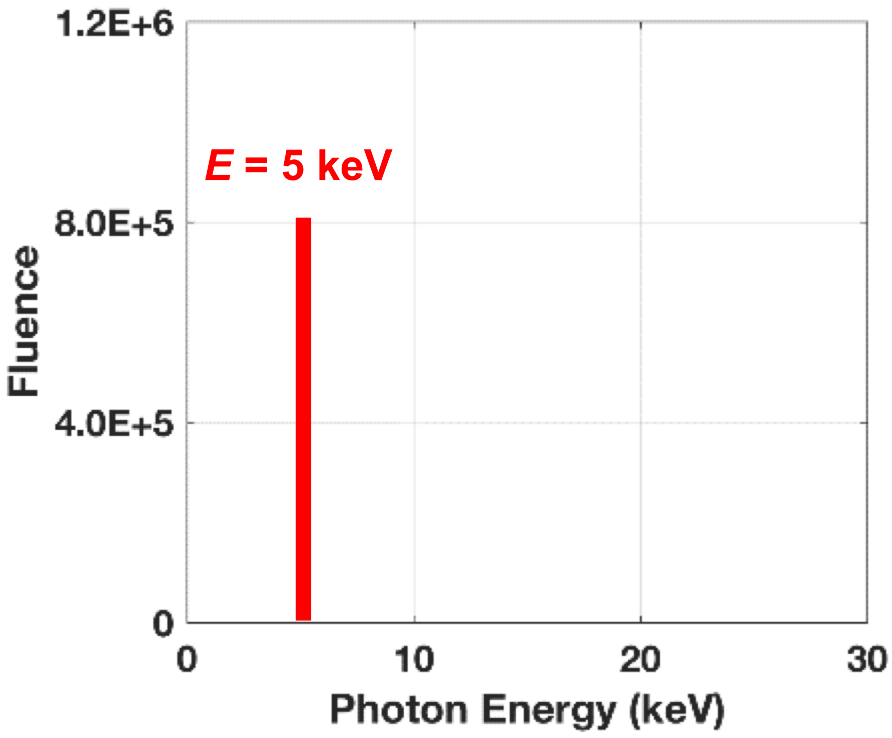
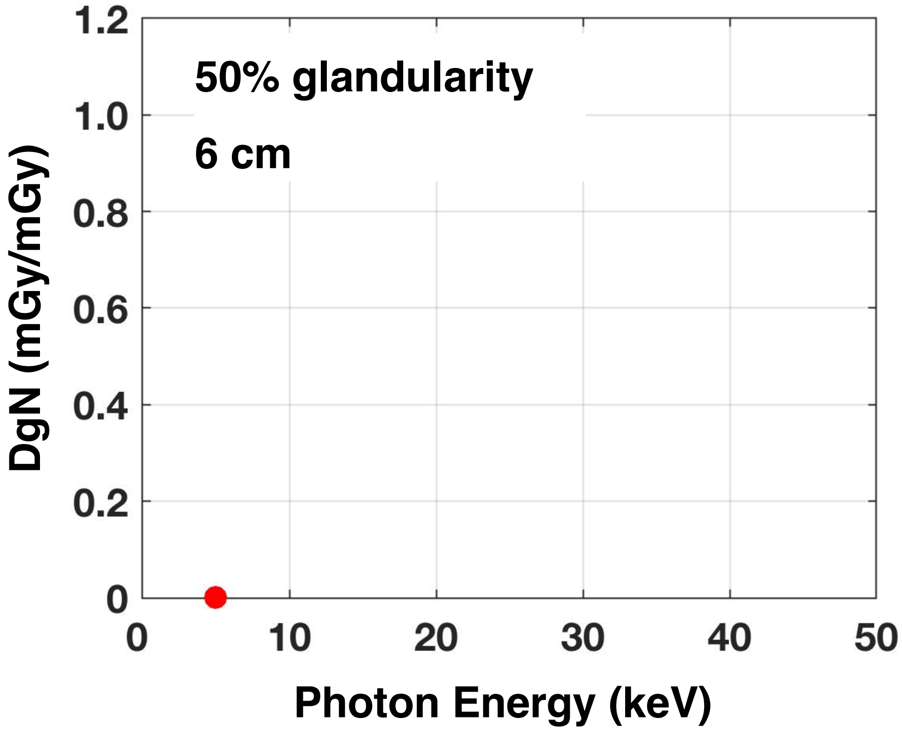
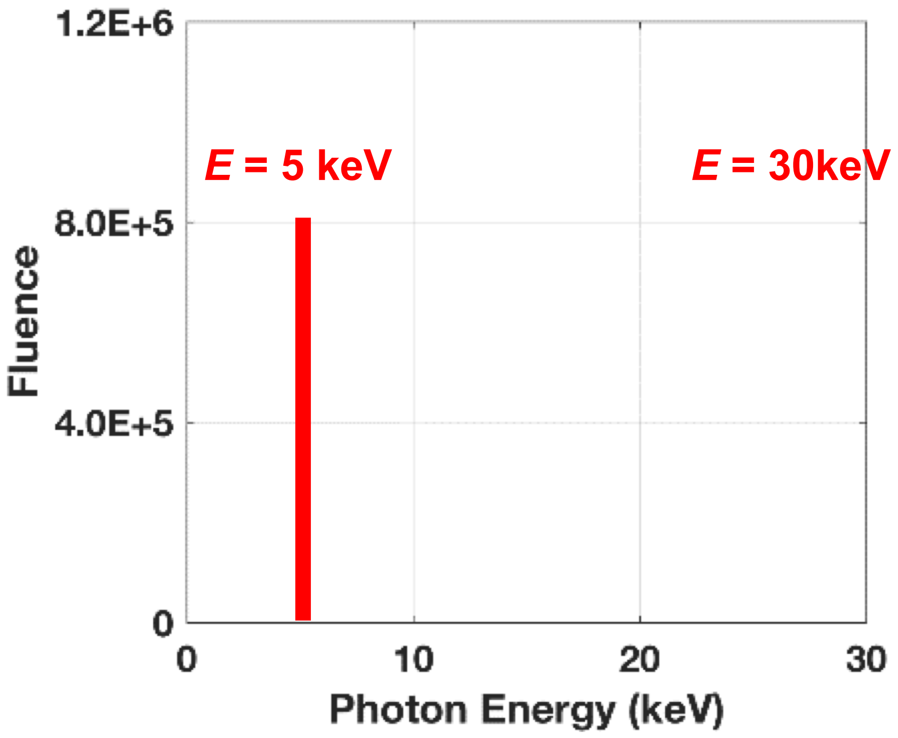
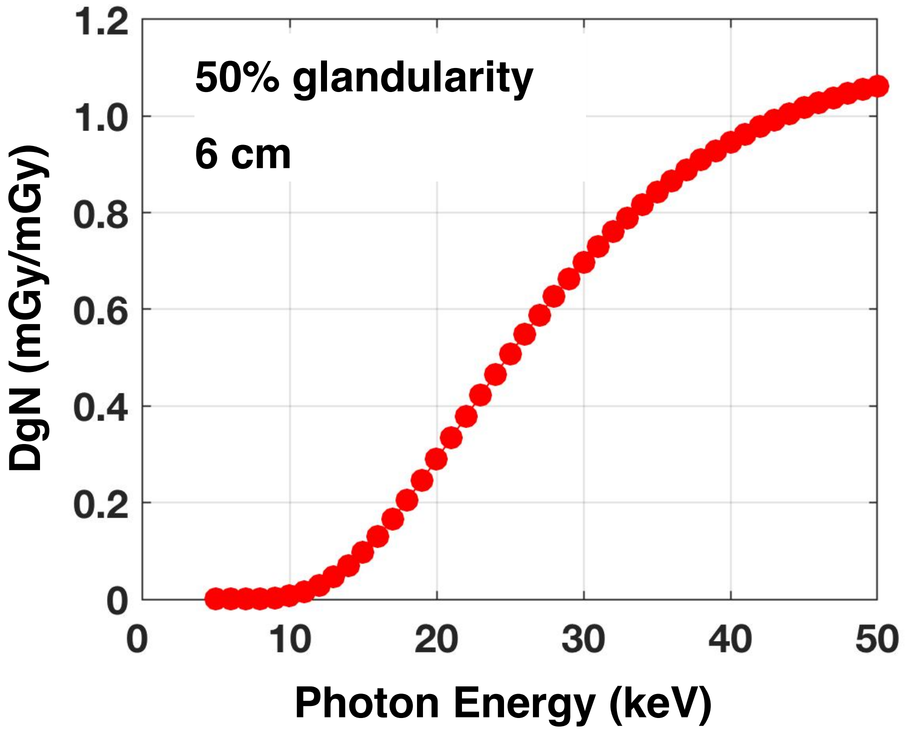




Boone J.M. *Med Phys.* 29(5) May 2002

Monoenergetic MC simulation of DgN





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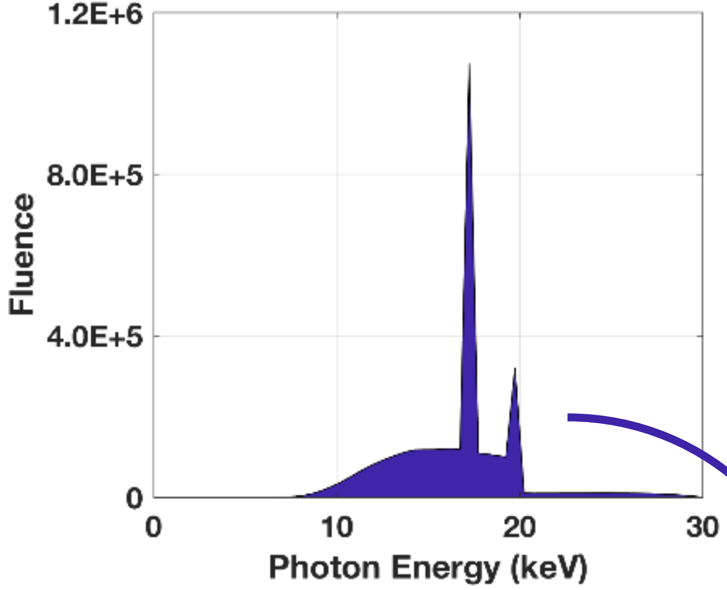
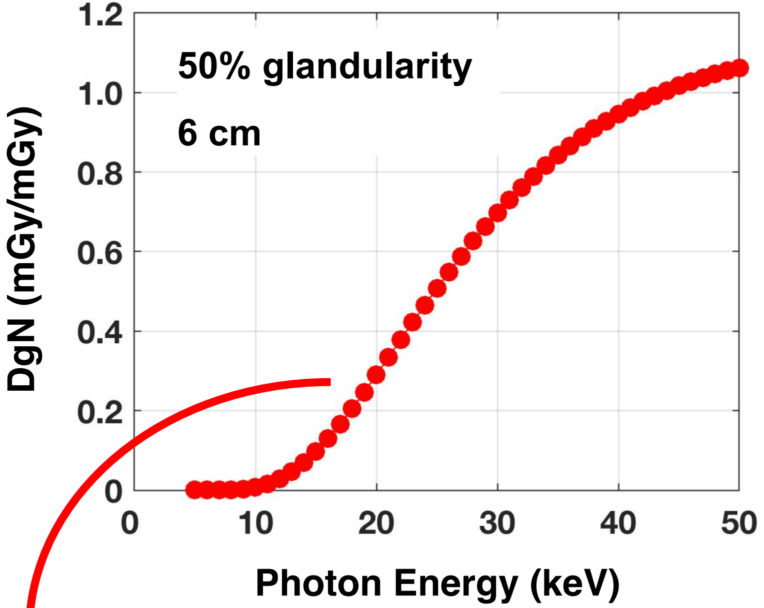




$$\mathrm{pDgN} = \frac{\sum_{E=E_{\min}}^{E_{\min}} \Phi(E)\,\vartheta(E)\,\mathrm{DgN}(E)}{\sum_{E=E_{\min}}^{E_{\min}} \Phi(E)\,\vartheta(E)}$$

Boone J.M. *Med Phys.* 29(5) May 2002

2016 ACR dosimetry method

Dance's Method

$$D = Kgcs = K \times DgN$$

D = Average Glandular Dose (mGy)

K = Entrance Exposure (mR)

g = g-factor for breast simulated with acrylic or BR-12

c = c-factor for breasts simulated with acrylic or BR-12

s = s-factor for clinically used spectra

Assumes a homogeneous breast model with 5 mm skin layer

Dance *et al. Phys. Med. Biol.* 2000

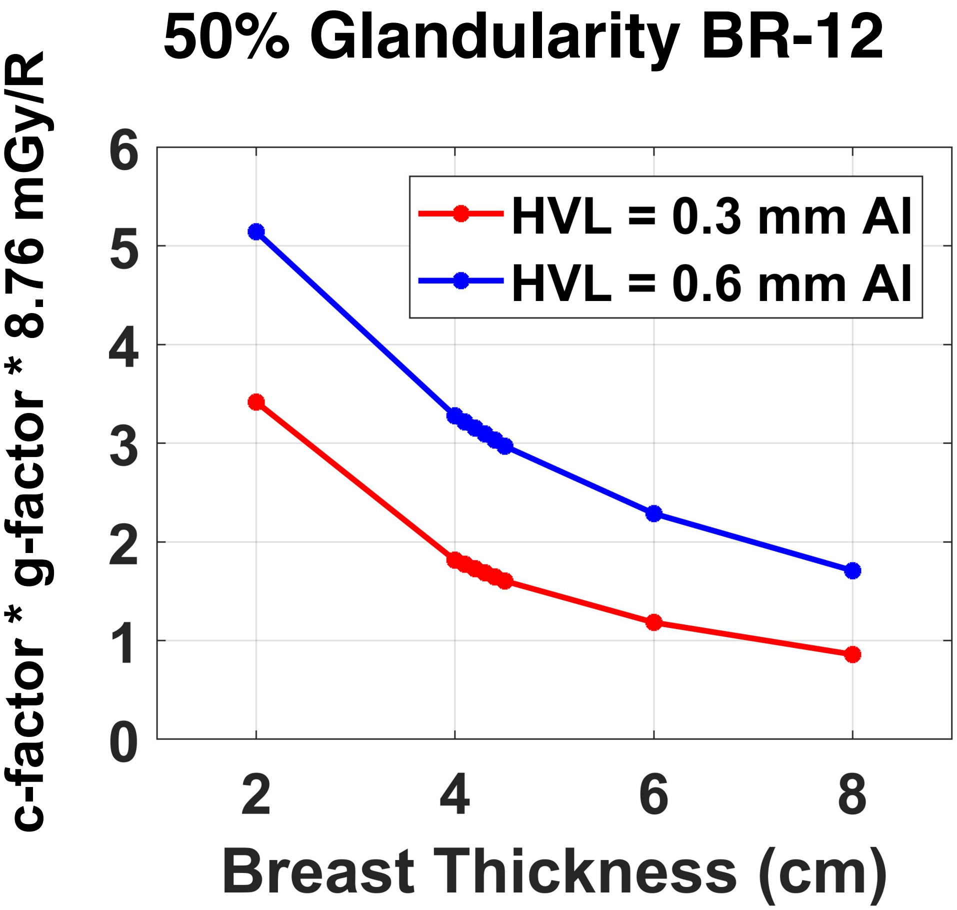
$$D = Kgcs$$

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

- **c-factor** - corrects for difference in glandularity

  =1 for 50% glandularity

Dependent on glandularity, thickness, and HVL


50% Glandularity BR-12
c-factor * g-factor * 8.76 mGy/R
0
1
2
3
4
5
6
2
4
6
8
Breast Thickness (cm)
HVL = 0.3 mm Al
HVL = 0.6 mm Al

$$D = Kgcs$$

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

s-factors for Acrylic and BR-12	
Target/Filter	**s-factor**
Mo/Mo	1.000
Mo/Rh	1.017
Rh/Rh	1.061
Rh/Al	1.044
W/Rh	1.042
W/Al	1.050
W/Ag	1.072

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: $\boldsymbol{g \times c = 2.19\ mGy/R}$

2) Table 6 in ACR manual: $\boldsymbol{s = 1.07}$

$$D = K\,g\,c\,s = 1\,R \times 2.19\frac{mGy}{R} \times 1.07 = \boldsymbol{2.34\ mGy}$$

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).

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

*Dance *et al. Phys. Med. Biol.* 2000

Example: “Patient” dose

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

Table 6. *c*-factors for glandularities of 0.1–100% in the central region of the breast, breast thicknesses of 2–11 cm and HVLs of 0.30–0.60 mm Al. Surface layers of 100% adipose tissue 0.5 cm thick are assumed.

HVL (mm Al)	Thickness (cm)	Breast glandularity 0.1%	25%	50%	75%	100%
0.40	5	1.258	1.120	1.000	0.899	0.810
0.40	6	1.276	1.125	1.000	0.890	0.798
0.40	7	1.292	1.132	1.000	0.887	0.793

*Dance *et al. Phys. Med. Biol.* 2000

Example: "Patient" dose

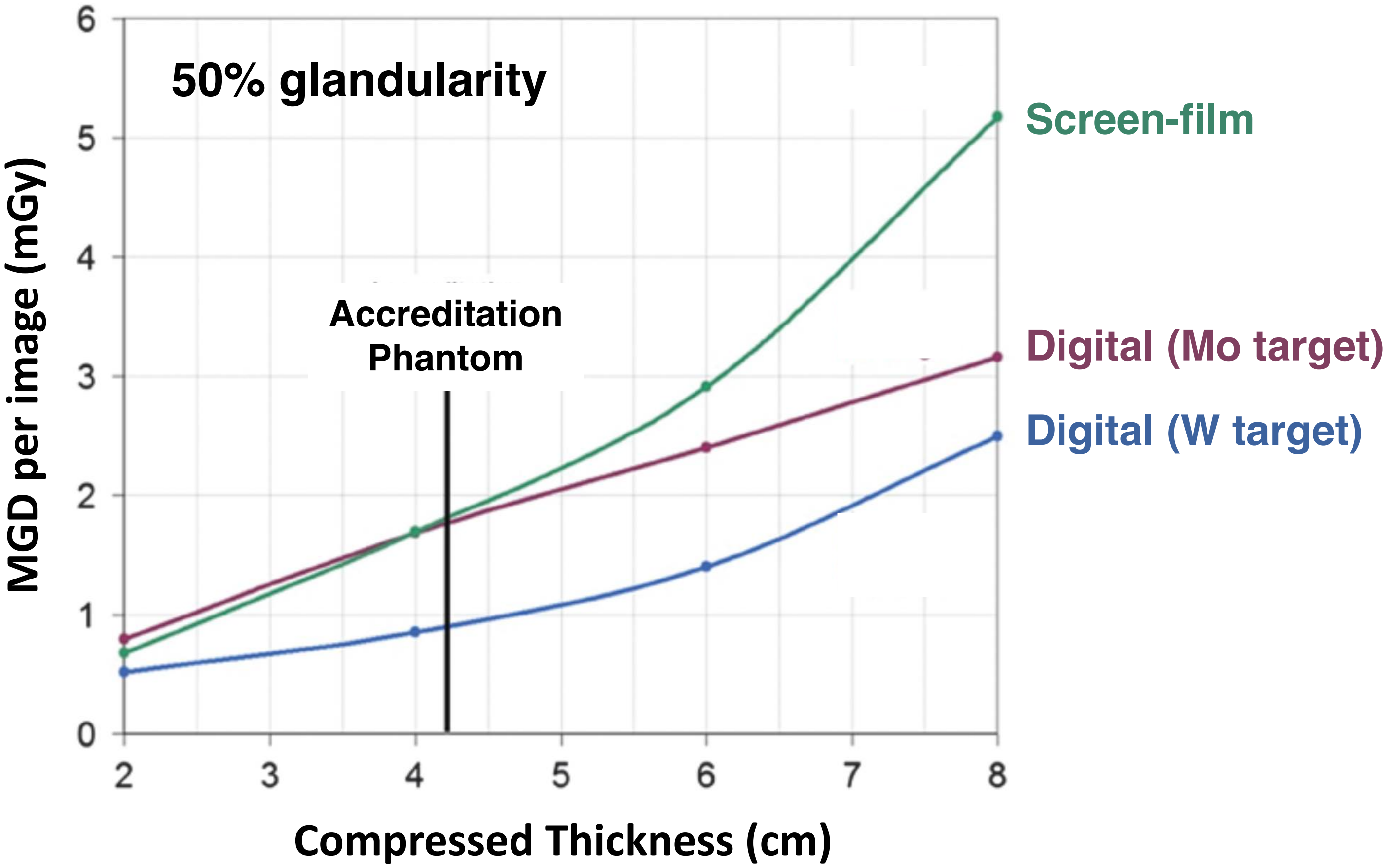
- 6 cm compressed breast with 16% glandularity
- 32 kV W/Ag spectrum (HVL = 0.4 mm Al & K = 1 R)

1) Interpolated from Table 2*: $\boldsymbol{g = 0.17\ mGy/mGy}$
2) Interpolated from Table 6*: $\boldsymbol{c = 1.18}$
3) Table 6 in ACR manual $\boldsymbol{s = 1.07}$

$$D = K\ g\ c\ s = 1\ R \times 0.17\frac{mGy}{mGy}\times 1.18 \times 1.07 \times 8.76\frac{mGy}{R} = \boldsymbol{1.88\ mGy}$$

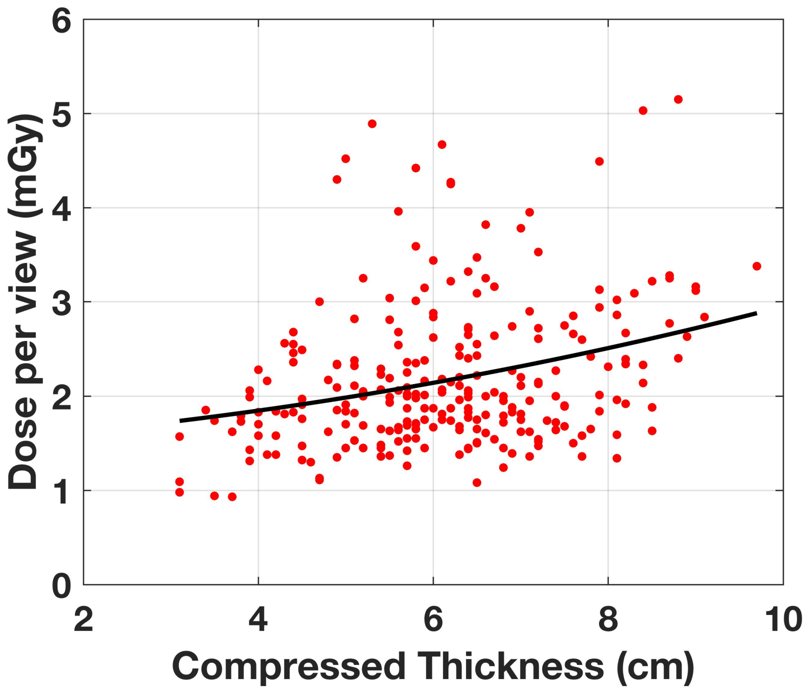
*Dance *et al.* *Phys. Med. Biol.* 2000

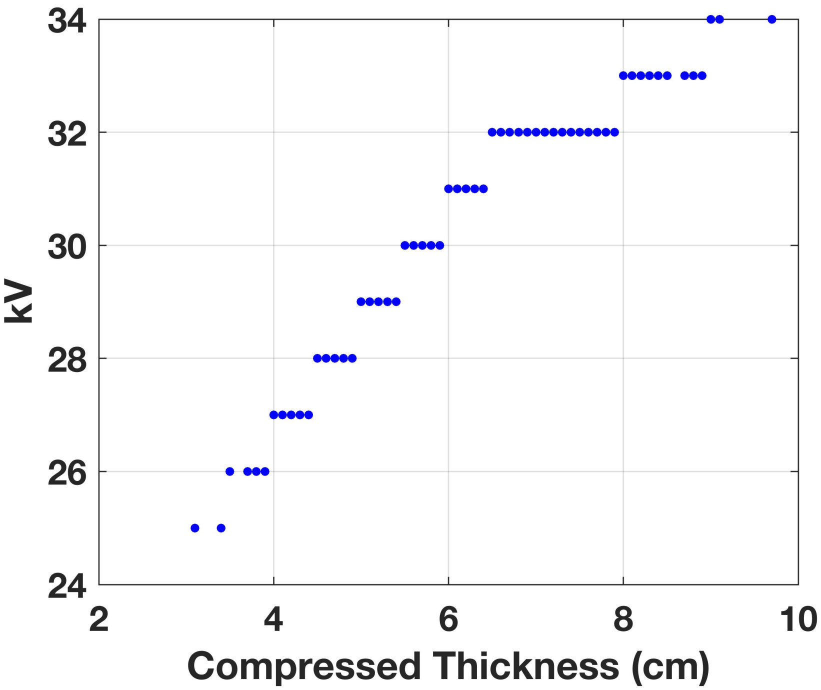
Trends in mammography dose



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)

$$DgN_{TOMO} = DgN_{MAMMO} \frac{\sum_{\alpha_{min}}^{\alpha_{max}} RGD(\alpha)}{N_\alpha}$$

Sechopoulos *et al. Med. Phys.* 41(9) Sept. 2014

Tomosynthesis dosimetry

- Not included in ACR manual (appendix in progress)

relative glandular dose at α degrees

$$DgN_{TOMO} = DgN_{MAMMO} \frac{\sum_{\alpha_{min}}^{\alpha_{max}} RGD(\alpha)}{N_\alpha}$$

total # of projections

Sechopoulos *et al. Med. Phys.* 41(9) Sept. 2014

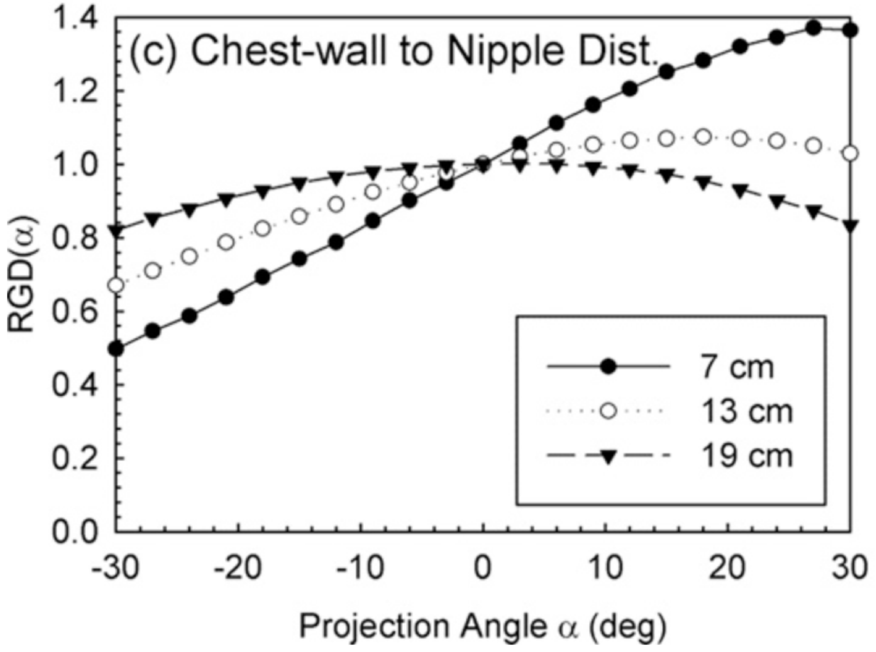
Tomosynthesis dosimetry

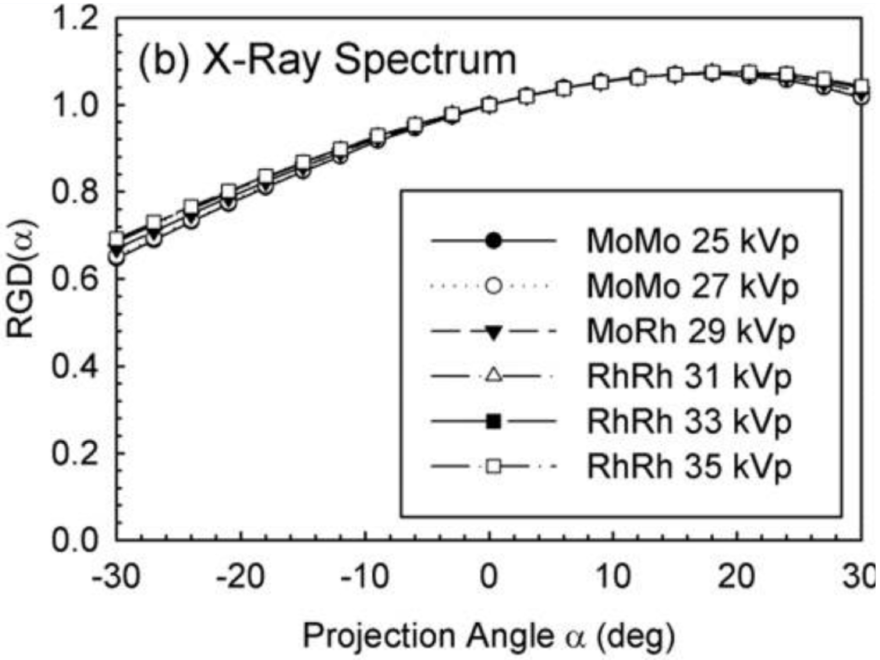
$$DgN_{TOMO} = DgN_{MAMMO} \frac{\sum_{\alpha_{min}}^{\alpha_{max}} RGD(\alpha)}{N_{\alpha}}$$

- Uses existing DgN tables
- Parameterization of RGD dependence on only breast thickness, size, and α

Sechopoulos *et al. Med. Phys.* 41(9) Sept. 2014

Tomosynthesis dosimetry





Sechopoulos *et al. Med. Phys.* 2007

Tomosynthesis dosimetry

$$DgN_{TOMO} = DgN_{MAMMO}\overline{RGD}$$

$\overline{\text{RGD}}$ can be used for “standard” acquisition:

- constant mAs for all projections & symmetric acquisition angles about 0°

Sechopoulos *et al. Med. Phys.* 41(9) Sept. 2014

Outline

- Why do we need breast dosimetry?
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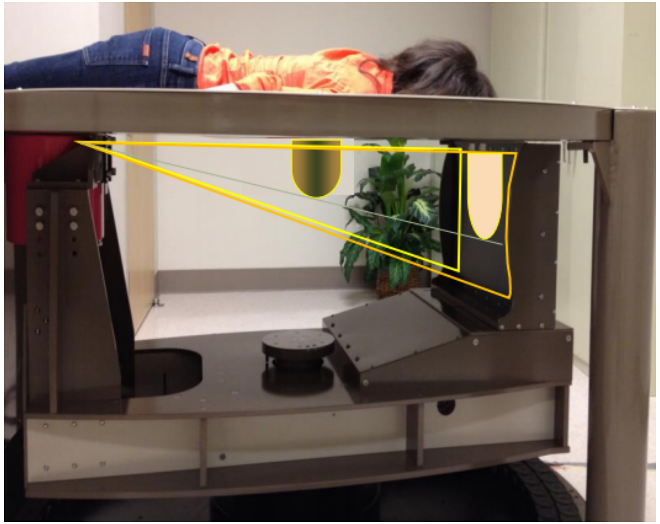
- Current dosimetry methodologies
- **Limitations**
- Future directions

Assumptions of current breast models

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



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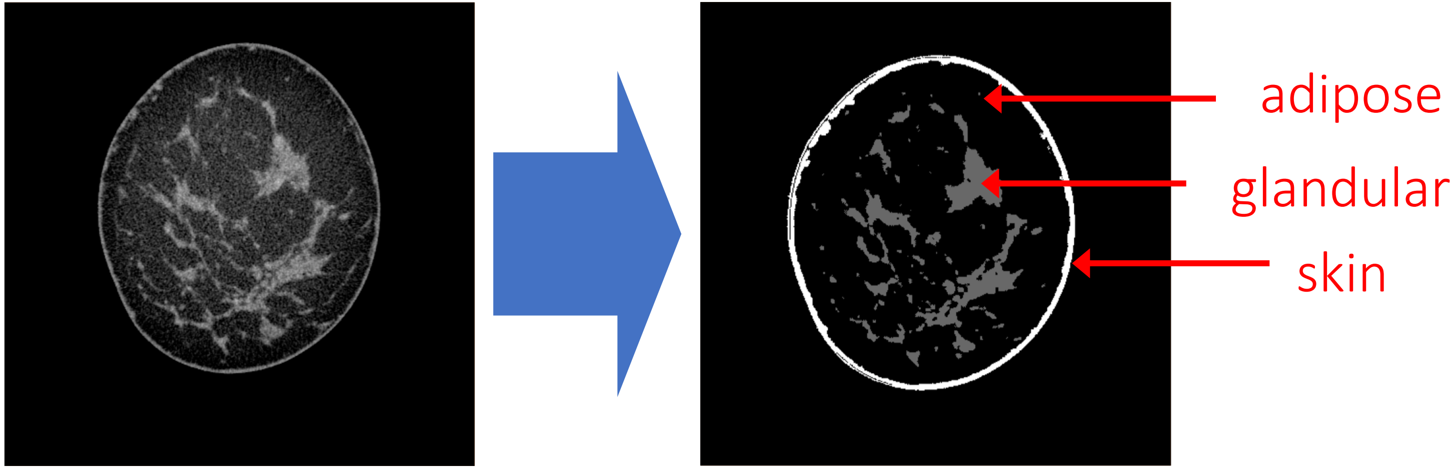
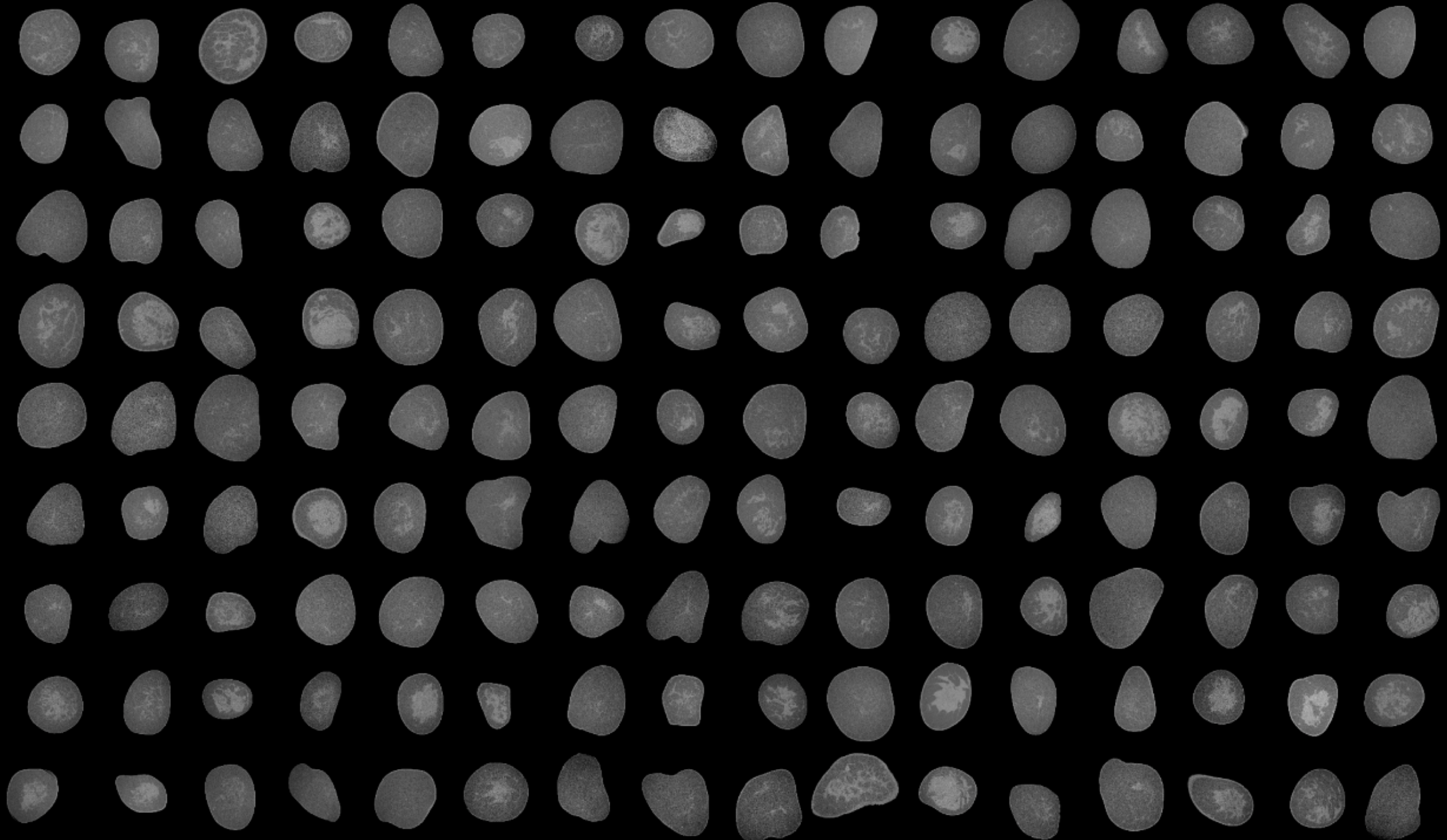
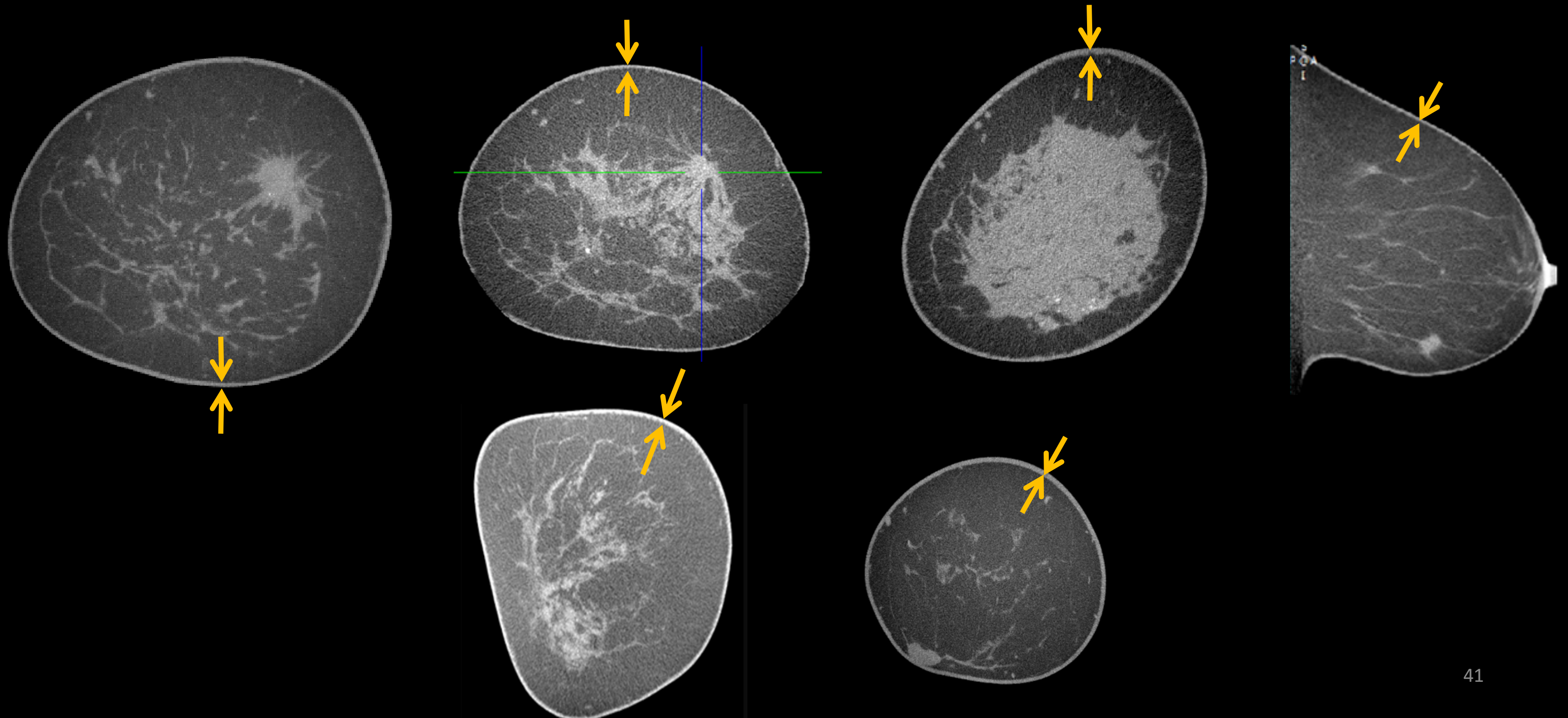


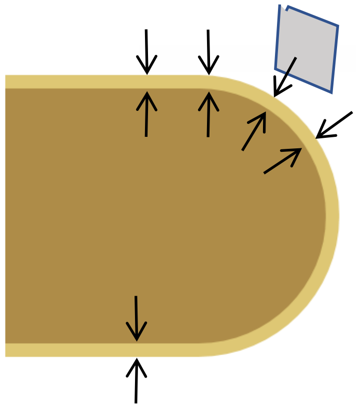
bCT coronal image   segmented image



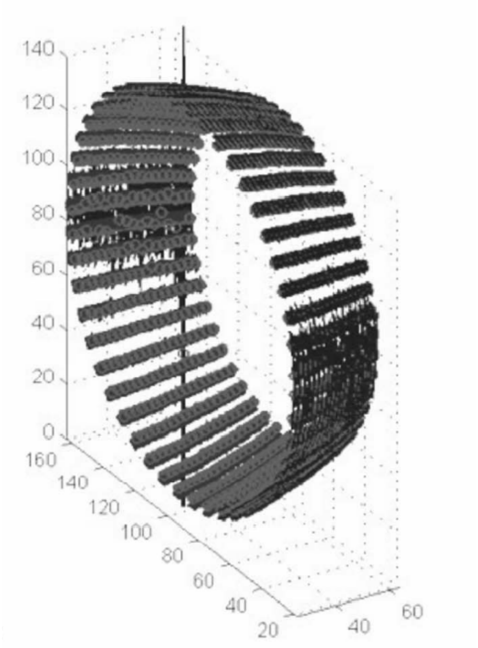
Observation from breast CT images: Skin is not 5 mm thick on the breast



Skin thickness measurement

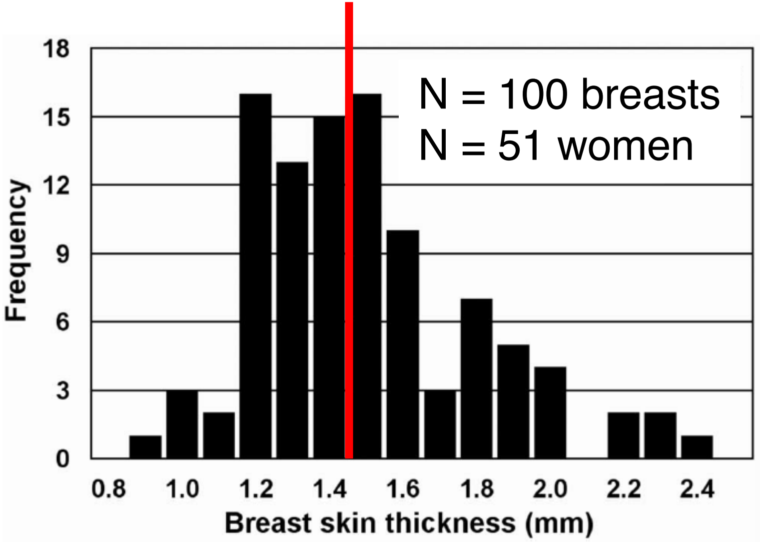


Segmentation Algorithm



Measurements

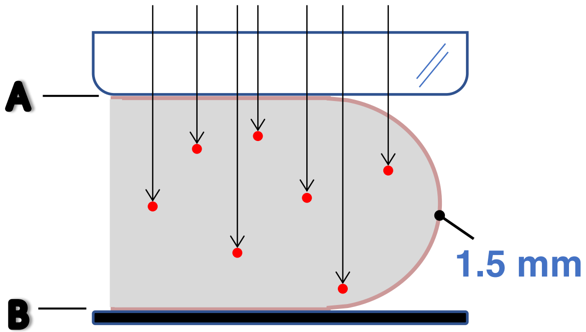
Mean: ~1.5 mm [0.9 - 2.3]

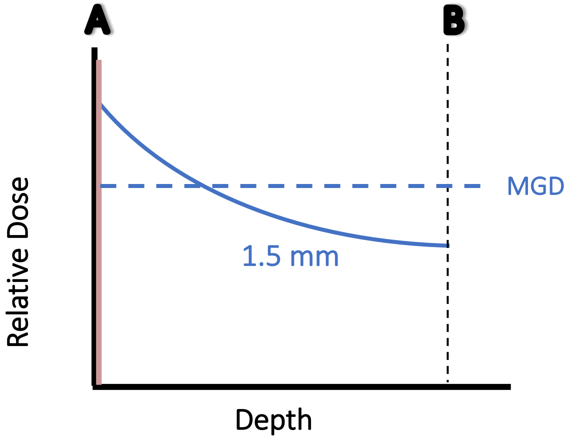


Skin Thickness Results

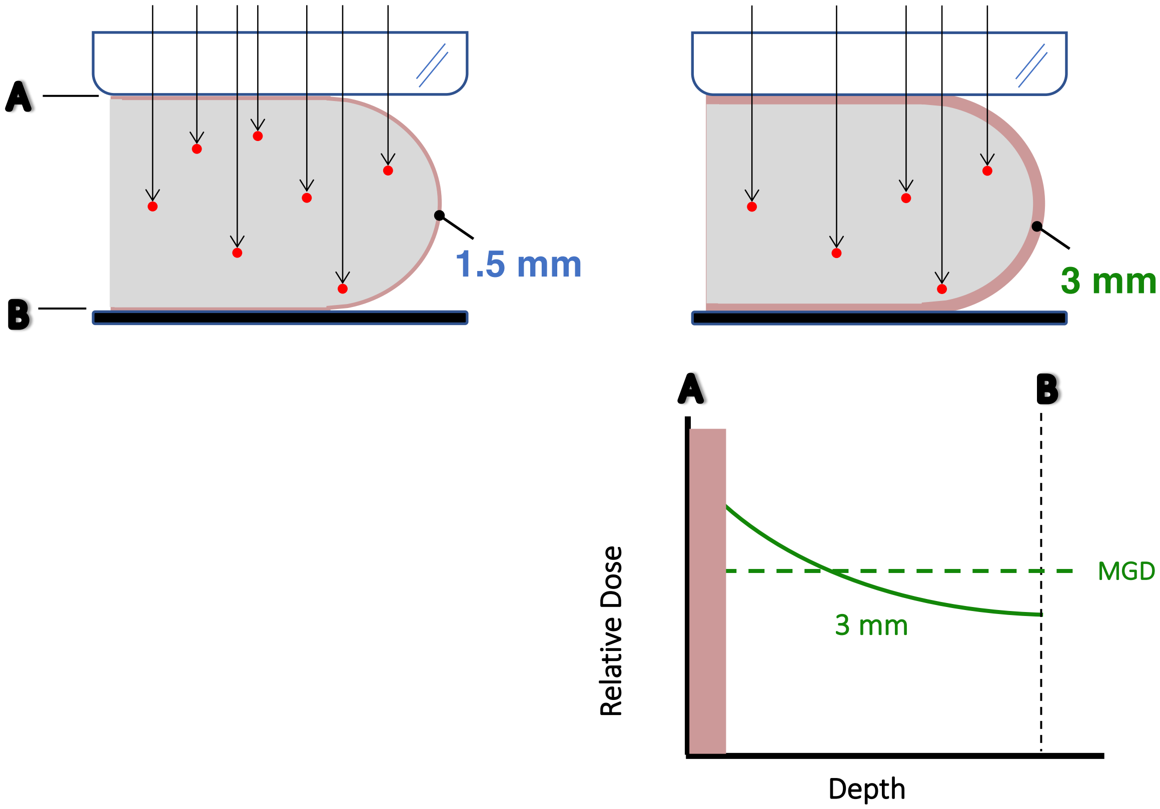
Huang S.Y. *et al. Med. Phys. 35*(4) April 2008

Effect of skin thickness on glandular dose





Effect of skin thickness on glandular dose



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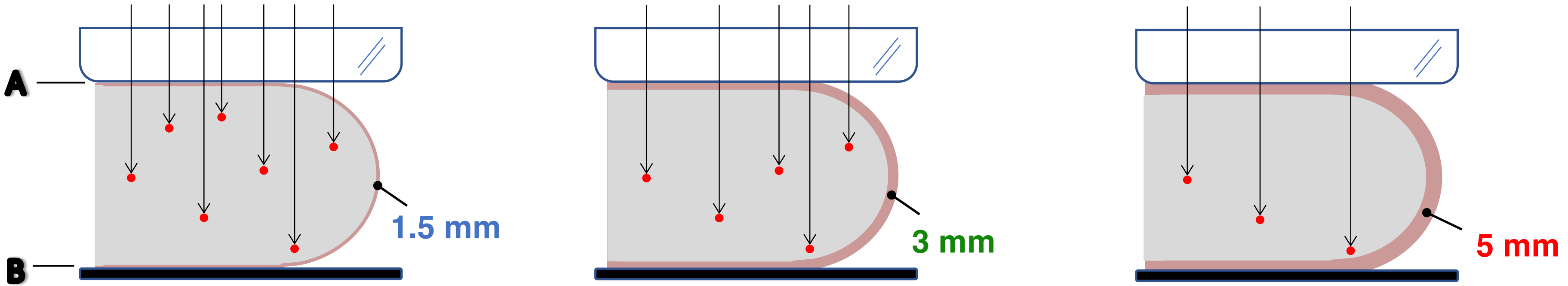
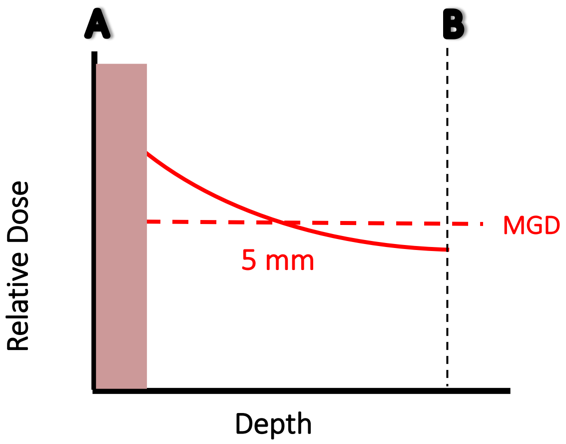
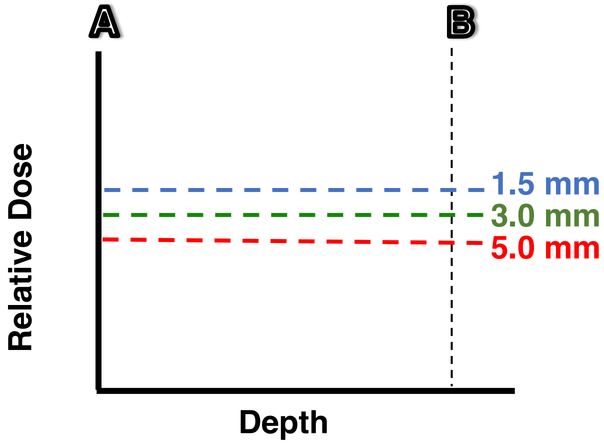




Effect of skin thickness on glandular dose

~ 20% increase in glandular dose using 1.5 mm skin thickness compared against 5 mm !



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1. 4-5 mm skin thickness
2. **50% glandular / 50% adipose**
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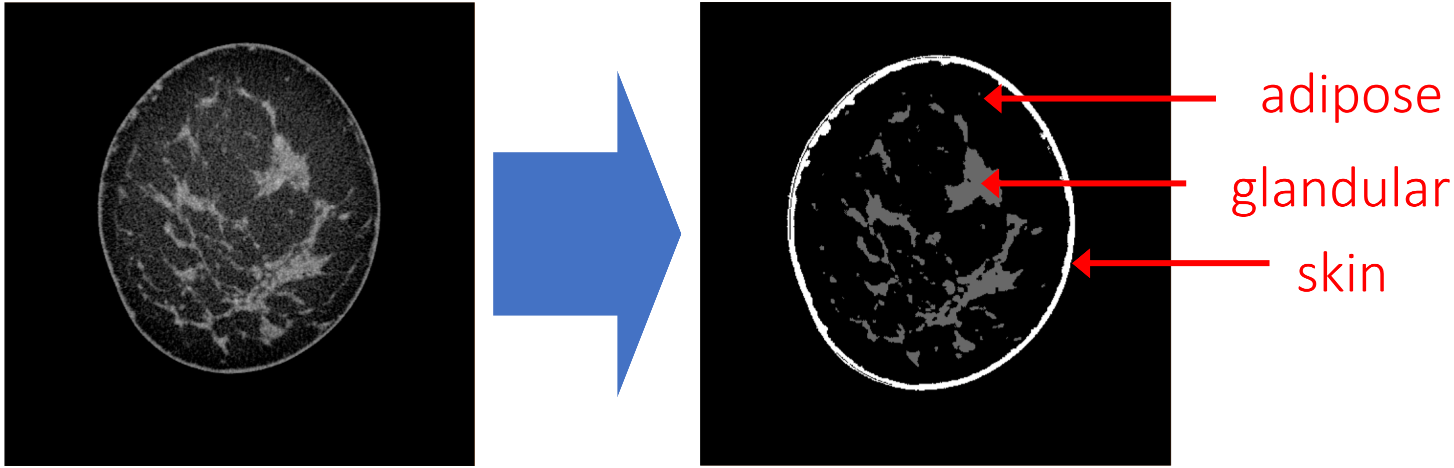
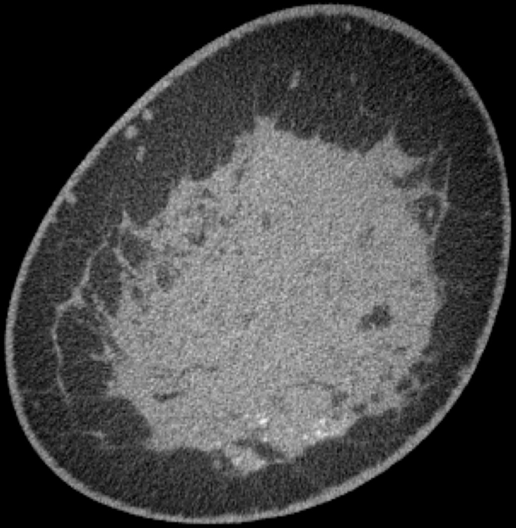


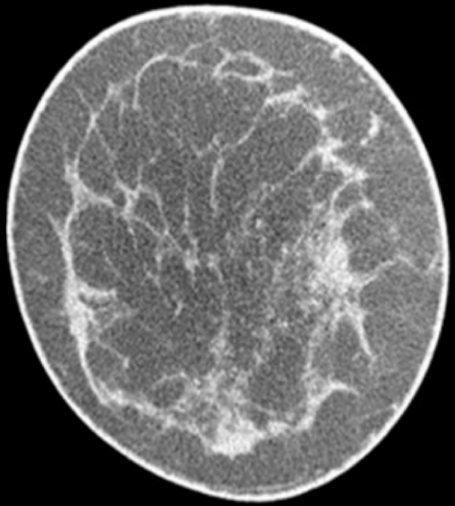
bCT coronal image

segmented image

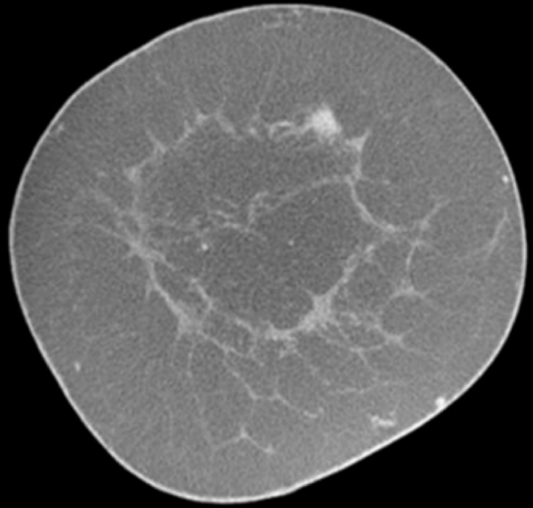
Observation from breast CT:
no 100% glandular breast



High



Medium



Low

Myth of the 50-50 breast

The myth of the 50-50 breast

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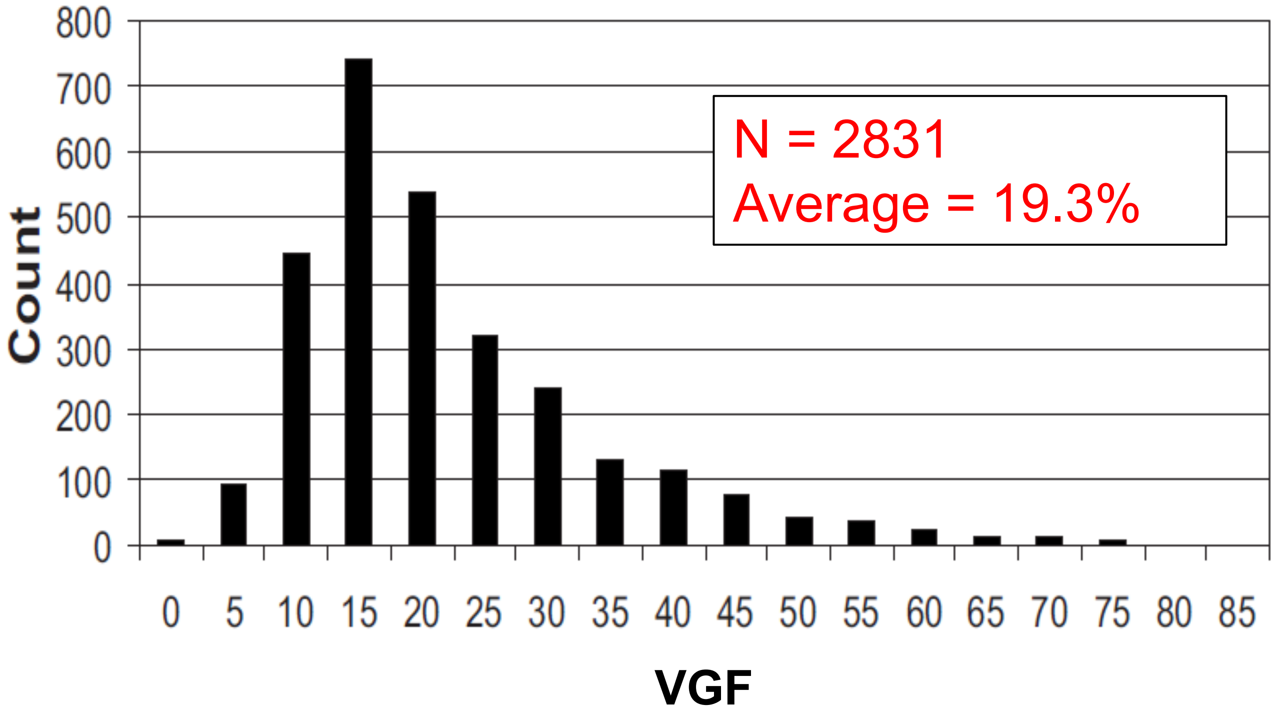
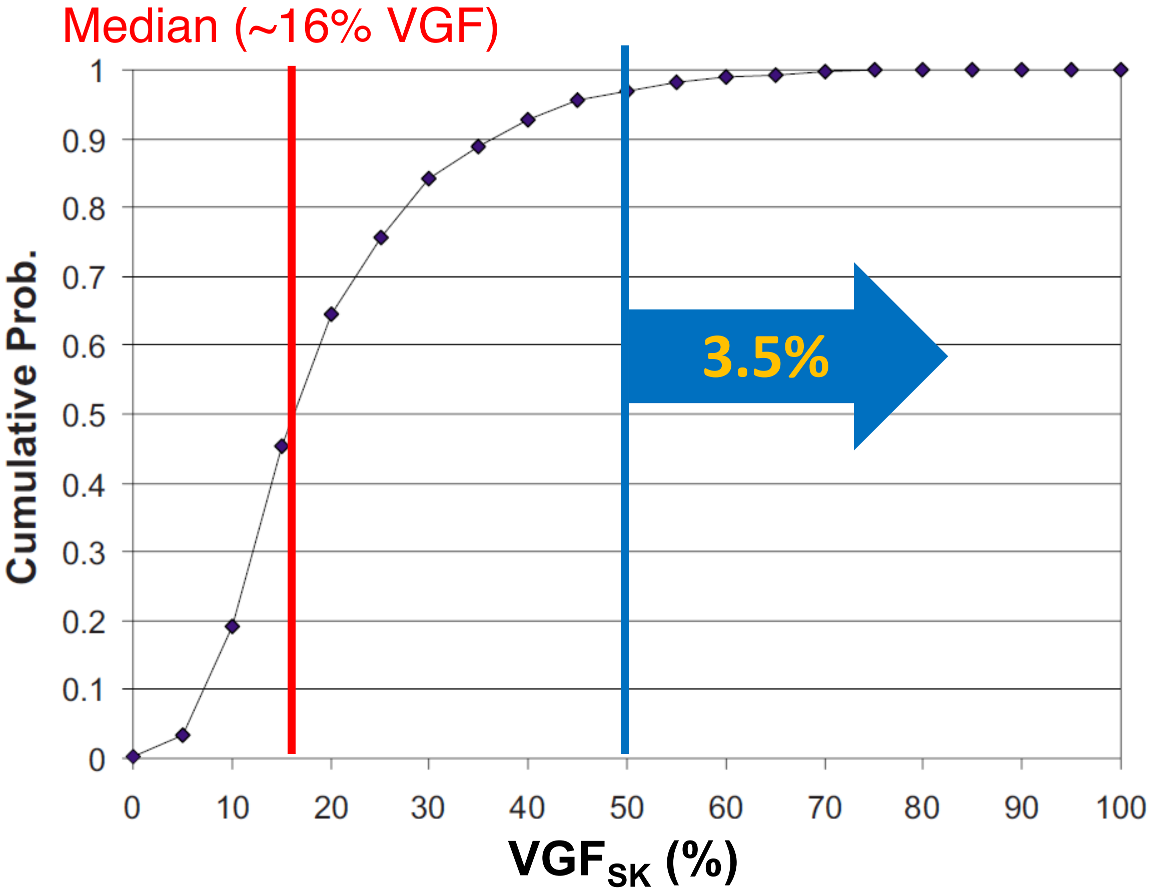
$$\mathrm{VGF_{SK}} = \frac{\text{glandular}}{\text{glandular} + \text{adipose} + \text{skin}}$$

Myth of the 50-50 breast



Myth of the 50-50 breast



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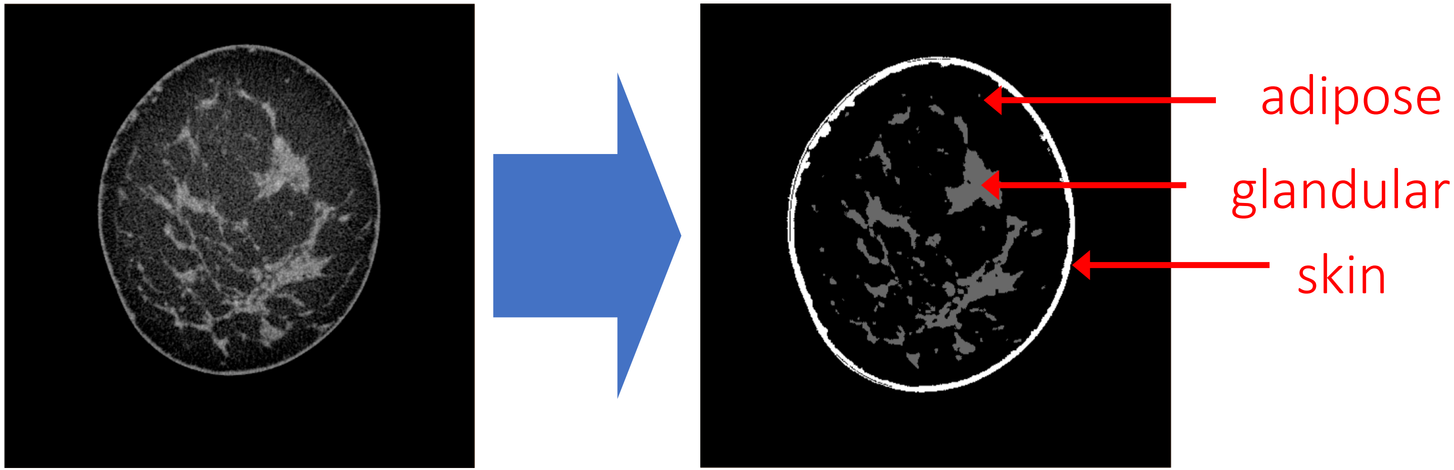
3. **Homogeneous composition of adipose & glandular tissue**



bCT coronal image | segmented image

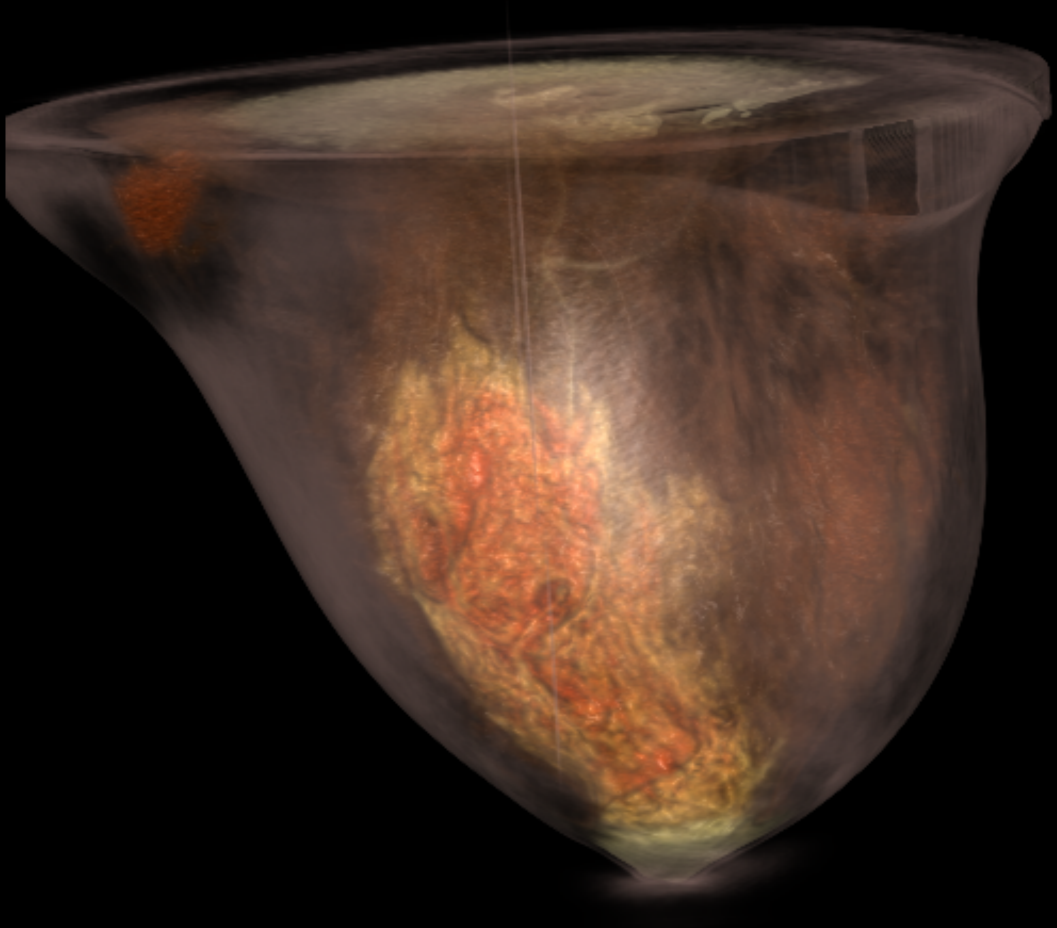
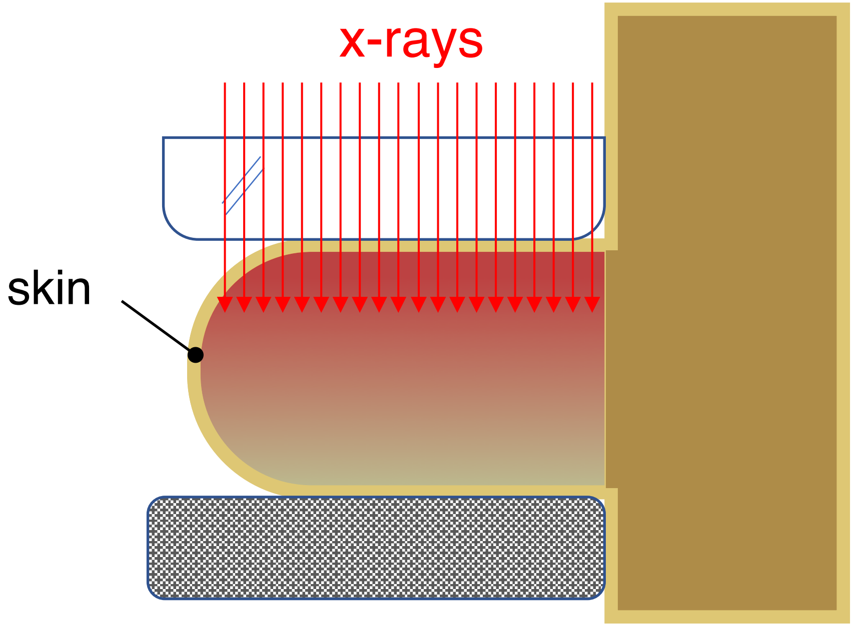


Image courtesy of Kwan Liu Ma, PhD, UC Davis Dept. of Computer Science

Consequences of glandular heterogeneity on breast dose in mammography

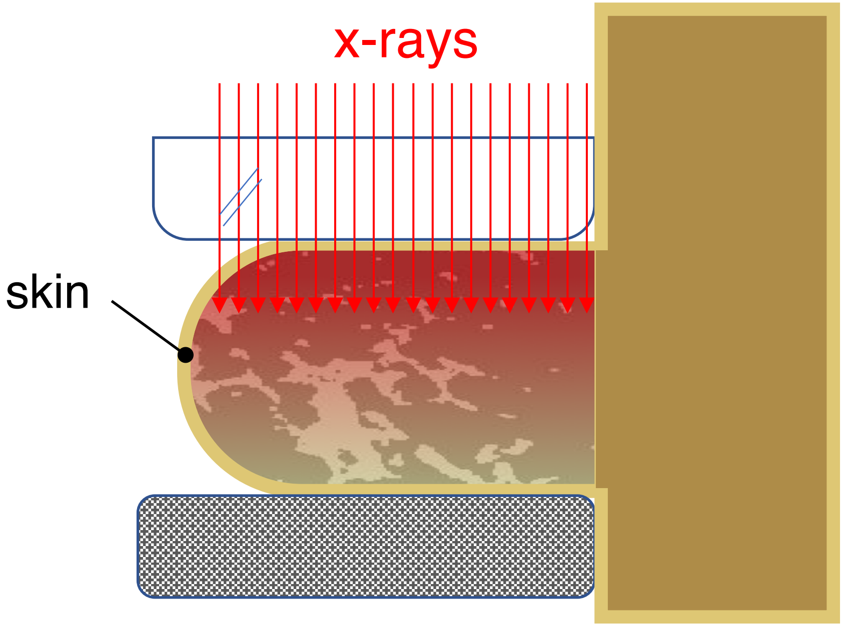
Homogeneous

(VGF = 16%)



Heterogeneous

(VGF = 16%)

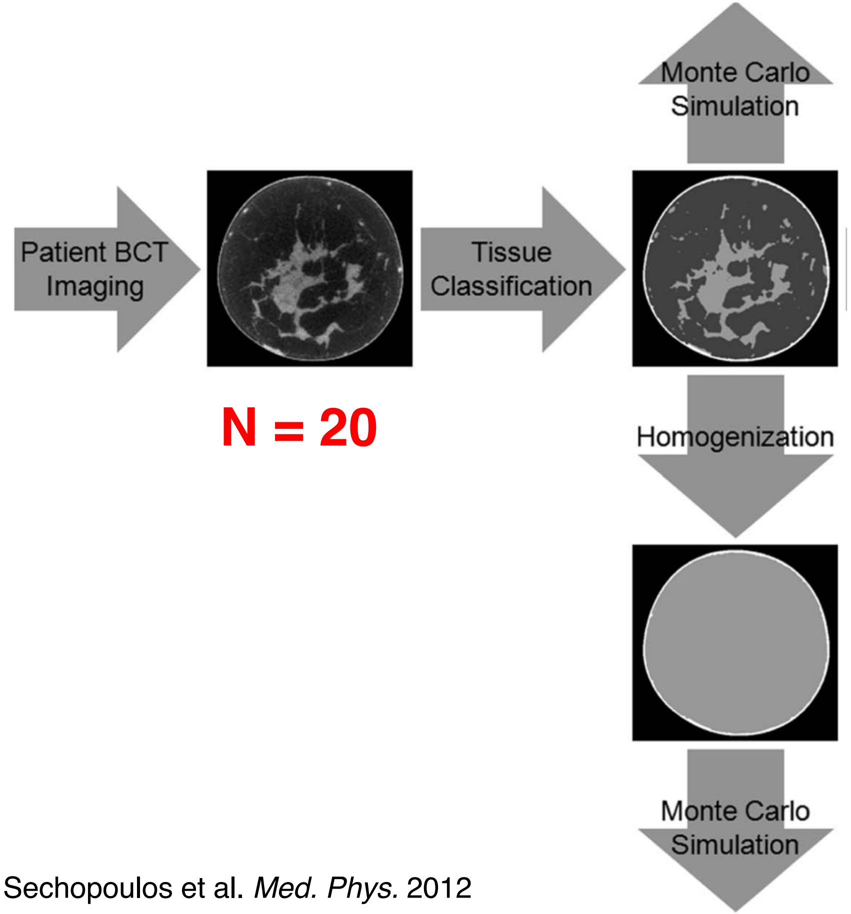


Consequences of glandular heterogeneity on breast dose in mammography

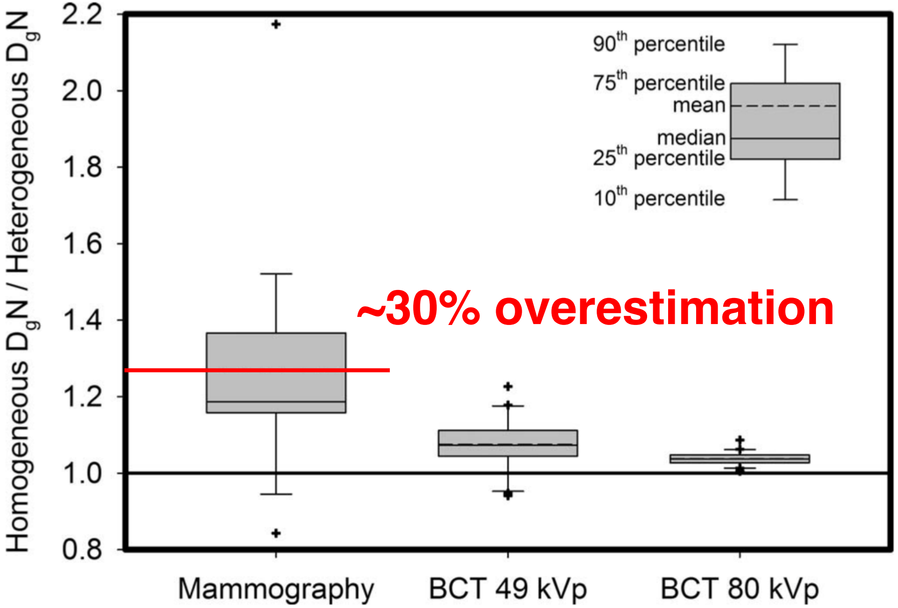
Homogeneous
(VGF = 16%)

Heterogeneous
(VGF = 16%)

Simple breast model overestimates glandular dose

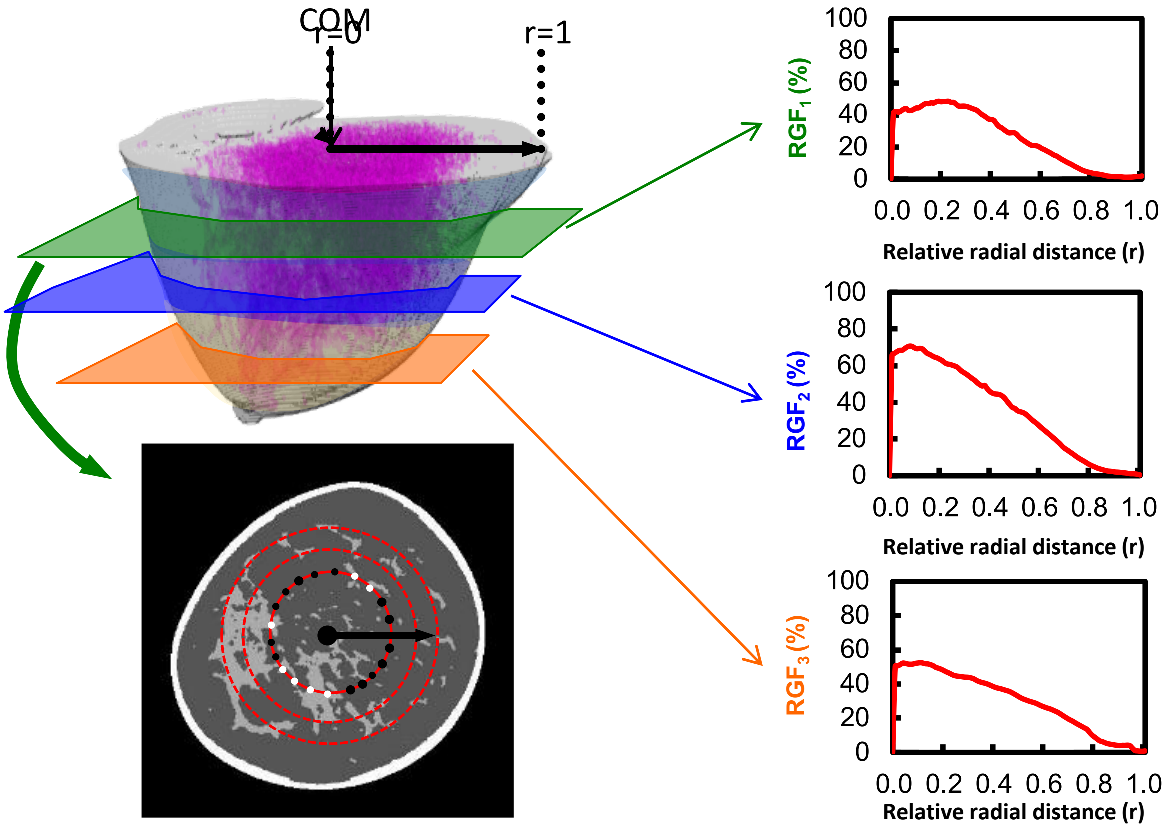


N = 20



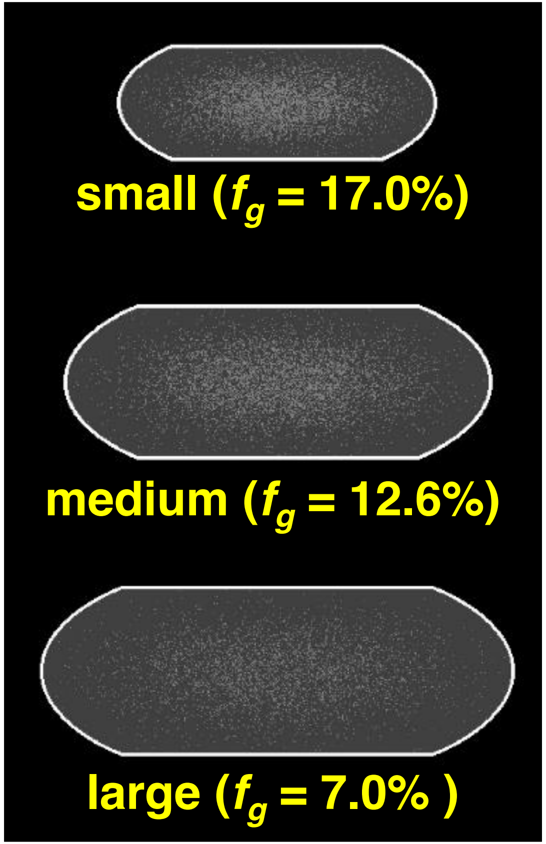
Sechopoulos et al. *Med. Phys.* 2012

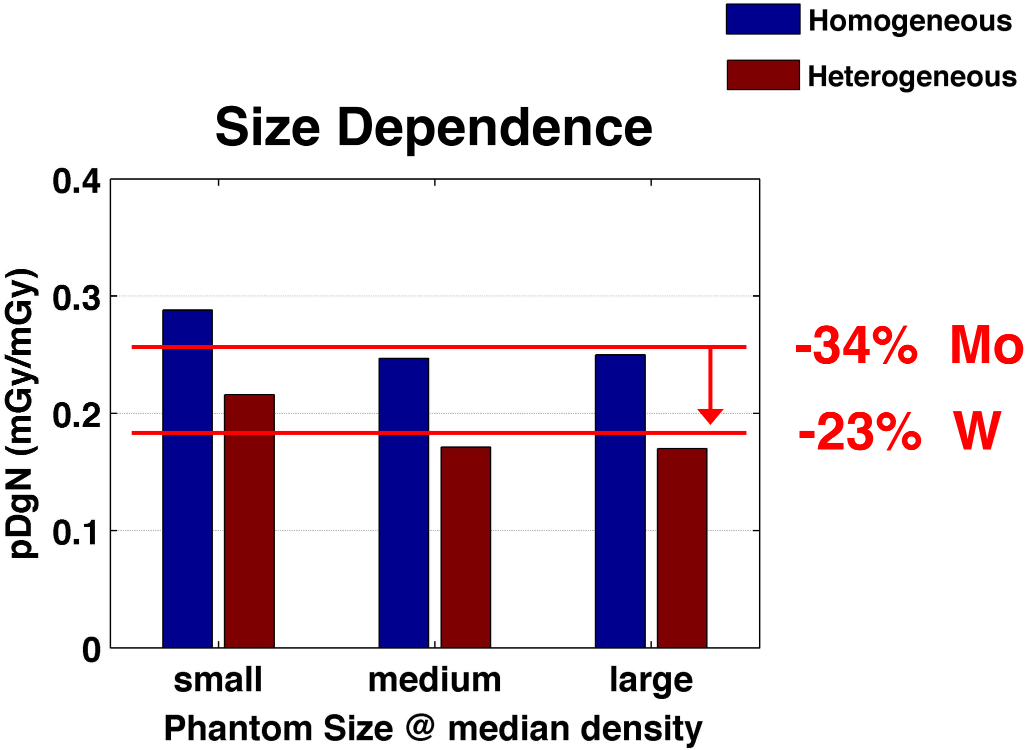
Breast-CT derived glandular distributions



Huang S.-Y., Boone J.M. *et al. Med Phys.* 38 (4) April 2011

Homogeneous vs. heterogeneous





Hernandez A.M. *et al. Med. Phys.* 42(11) Nov. 2015

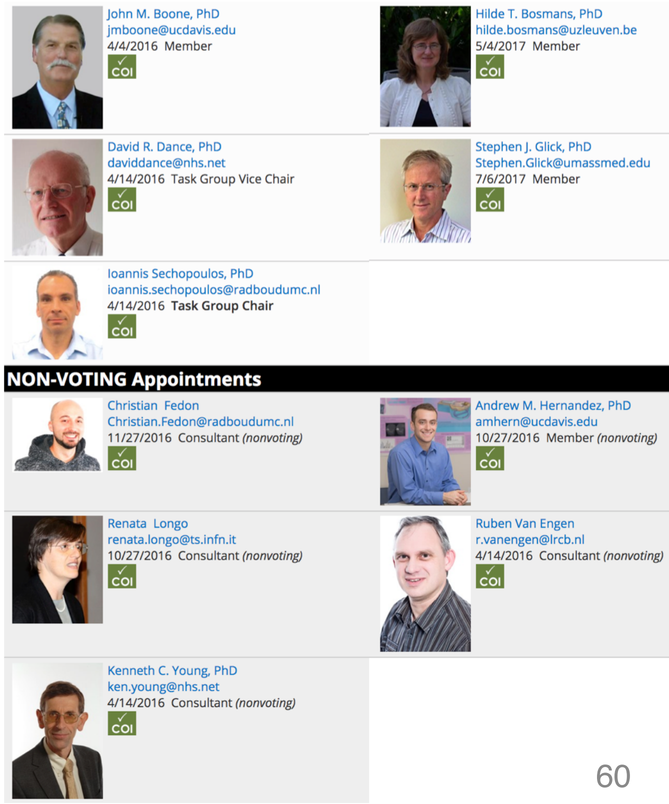
Outline

- Why do we need breast dosimetry?
- Historical development of dosimetry
- Current dosimetry methodologies
- Limitations
- **Future directions**

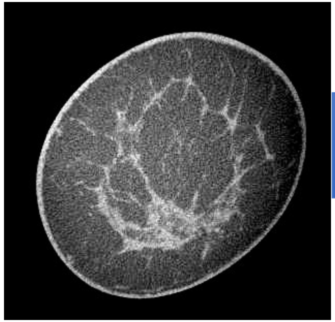
AAPM TG 282: Development of a new universal breast dosimetry method

- 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

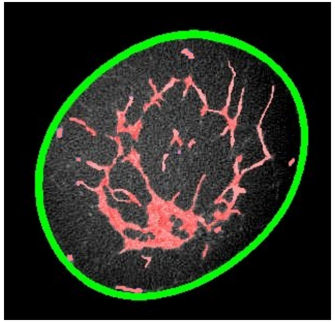
- Joint project with ICRU & EFOMP



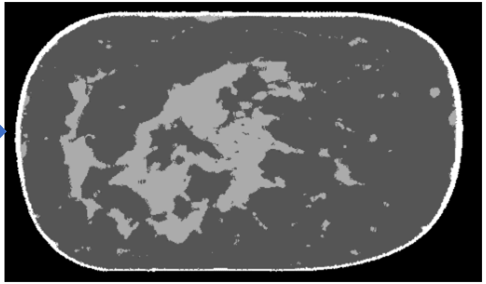
Addressing the dose overestimation



Classification



Compression



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

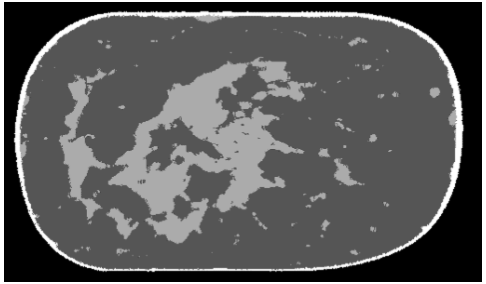
Image Segmentation:
Caballo M. et al . 2018

Finite Element Compression

slide courtesy of Sechopoulos *et al.* & TG 282

New breast dosimetry model

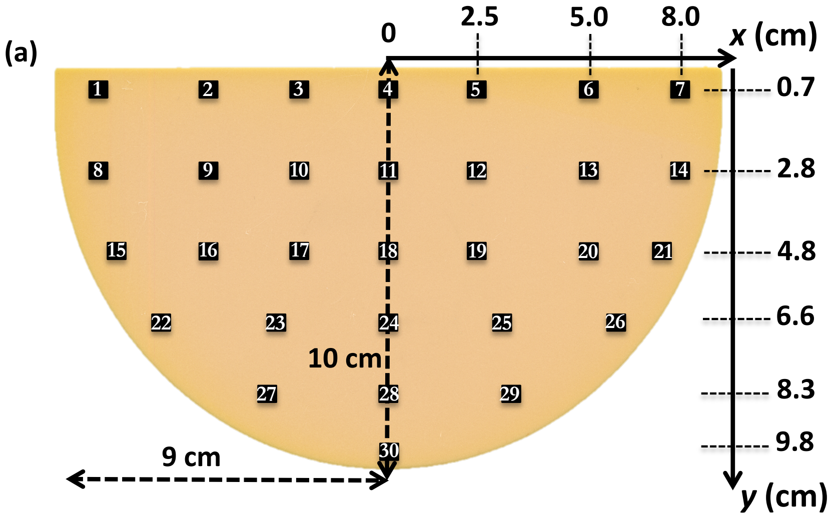
- Heterogenous dense breast model with binary classification of adipose and glandular tissue



- Monte Carlo simulations have to be validated for local dose deposition

MC Validation

Homogenous phantom / monoenergetic beam

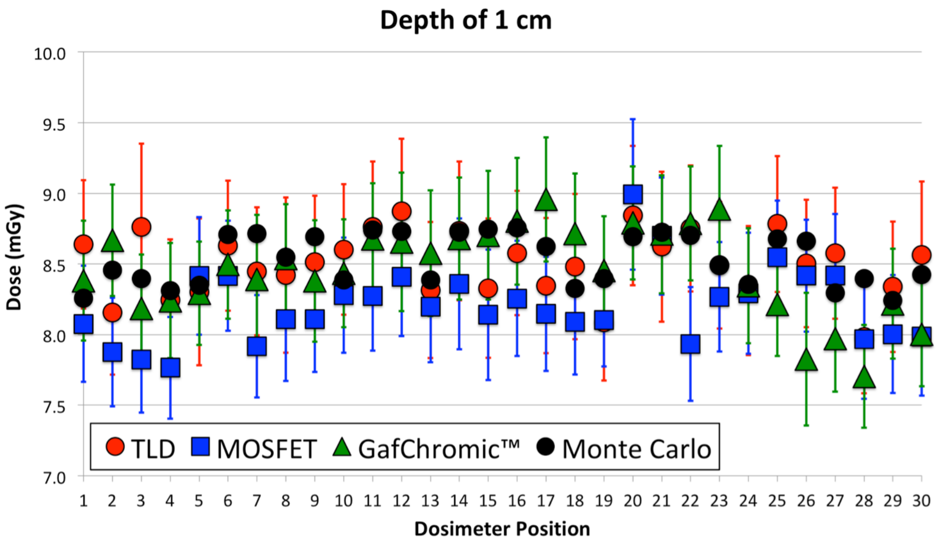


- TLD
- MOSFET
- GafChromic™
- Monte Carlo

Fedon *et al. Med Phys.* 2018

MC Validation

Homogenous phantom / monoenergetic beam



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

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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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