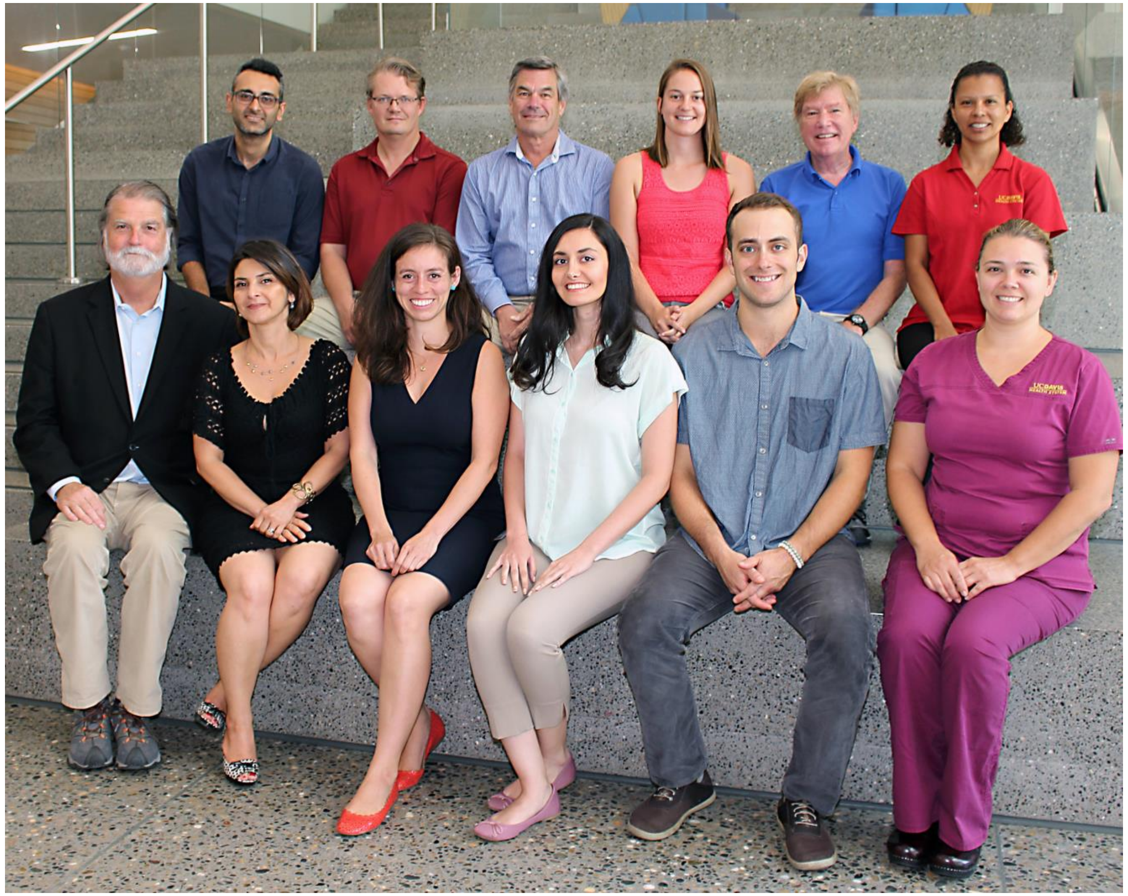
Breast CT: *Technology development and clinical potential*



The Breast Tomography Project

University of California, Davis

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Corporate Disclosures (required by UC Davis):

CONSULTANT
Jones Day (expert witness)
Arnold & Porter (expert witness)

RESEARCH FUNDING
National Cancer Institute (R01)
Stanford Research Institute (via NIH R01 subcontract)
UC Santa Barbara (via NIH R01 subcontract)

ROYALTIES
Lippincott Williams and Wilkins (book)

TRAVEL FUNDING
American Association of Physicists in Medicine (AAPM)
King Faisal Hospital ● Saudi Arabia

OTHER CONFLICTS
Patents Pending on various breast CT concepts
Izotropic Imaging, board member

Long Term Funding Acknowledgements:

R01 CA•89260 (Feasibility)
R01 EB•002138-10 (BRP)
R01 CA•129561 (RDB)
R01 CA●181081 (Current NIH)
P30 CA•093373 (Cancer Center)
California BCRP 7EB-0075
California BCRP 11I-0114
California BCRP 20IB-0125 (Merced)
Susan G. Komen Foundation
University of Pittsburgh
Varian Imaging Systems
UC Davis Bridge Funding

Breast CT: *Technology development and clinical potential*

- **Introduction**
- Technology Development
- Radiation Dose Assessment
- Image Quality Metrics
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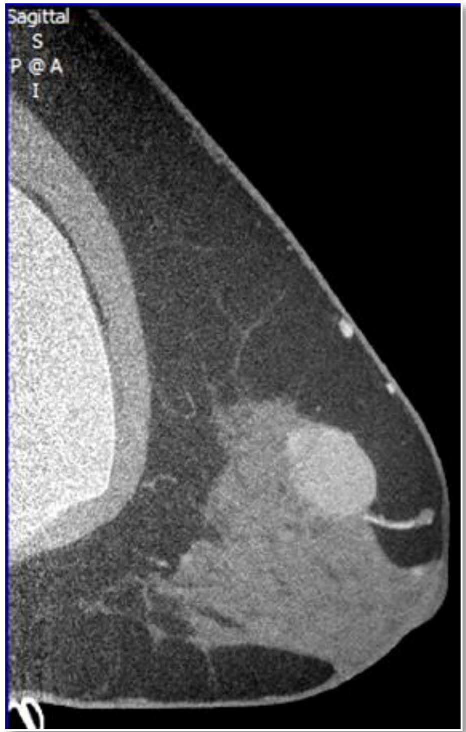
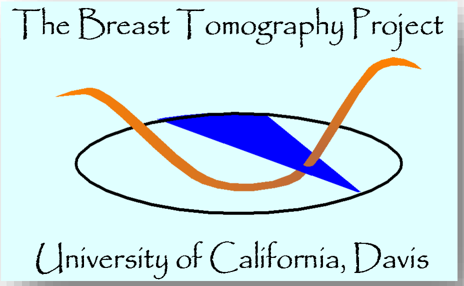
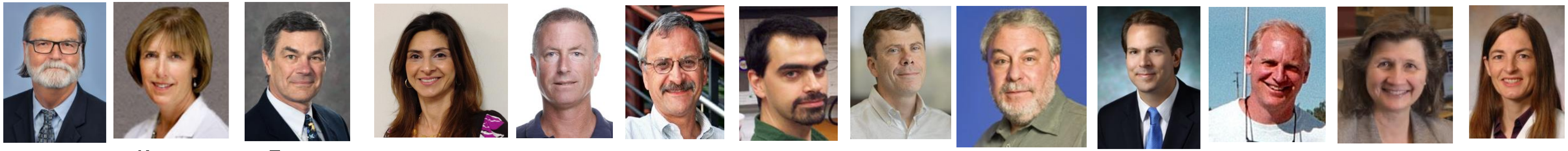
- Observer Performance
- Other Cool Spinoffs
- Summary







John Boone · Karen Lindfors · Tony Seibert · Shadi Shakeri · Craig Abbey · Norbert Pelc · Ramsey Badawi · Simon Cherry · Martin Yaffe · Jeff Siewerdsen · Loren Niklason · Maryellen Giger · Ingrid Reiser

Kai Yang · Orlando Velazquez · Clare Huang · Nathan Packard · Katie Metheany · Whit Miller · Dandan Zheng · Shonket Ray · Anita Nosratieh · Lin Chen · Sarah McKenny · Nicolas Prionas

Peymon Gazi · Andrew Hernandez · Amy Becker · Nilram Halat · Jessie Xia

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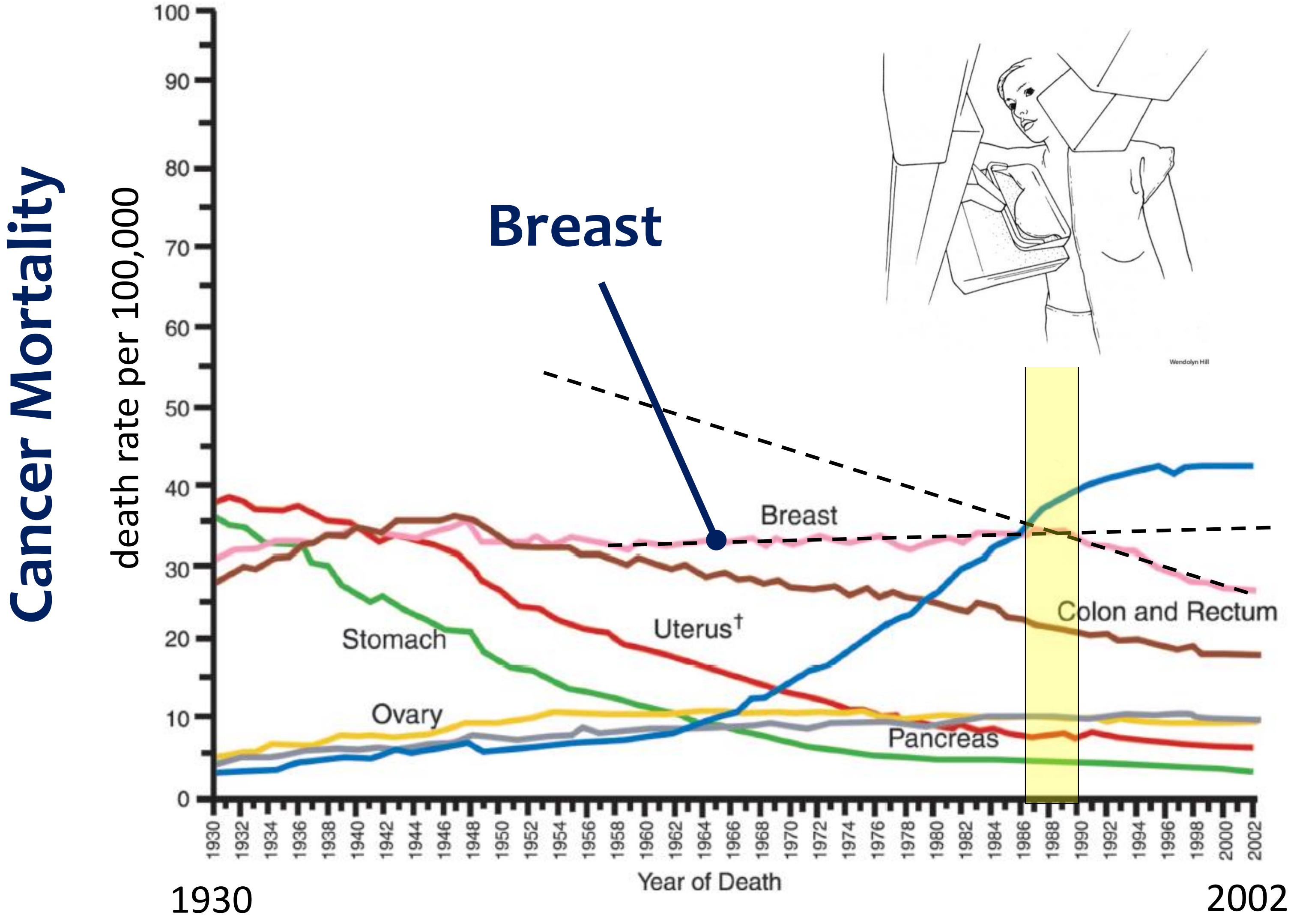
University of California, Davis

George Burkett · John Brock · Alex Kwan · Hong Zhou

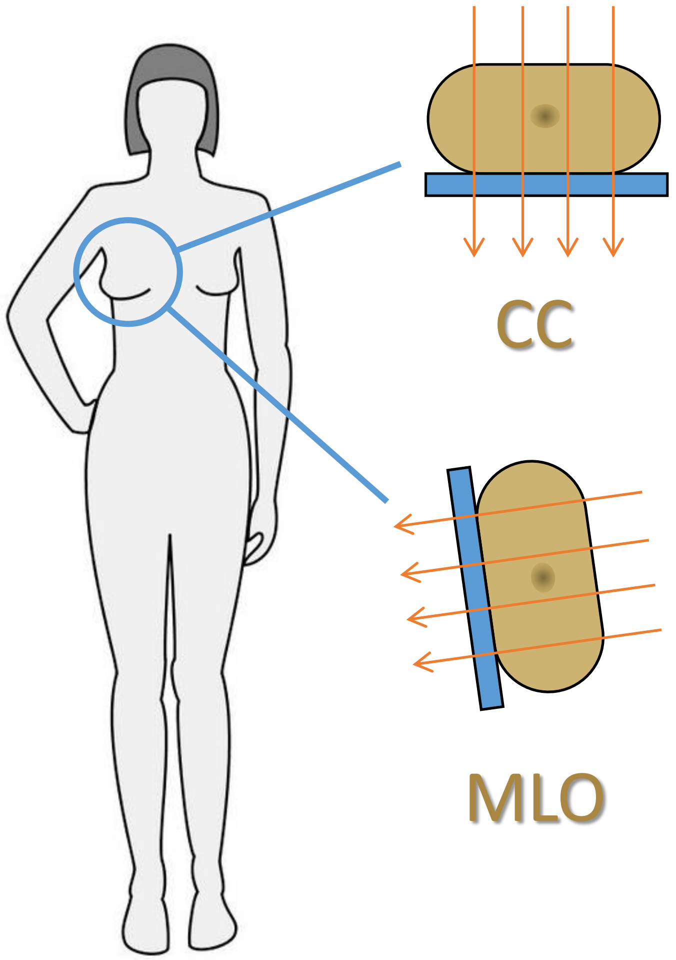
Laurie Boling · Desirée Lazo · Holly Murphy · Fareedah Simon · Linda Phelps · Heather Johnson · Elizabeth Lincoln · Tashina Hayduk · Tom Nelson · Elizabeth Krupinski · Carey Floyd · Bruce Hasegawa

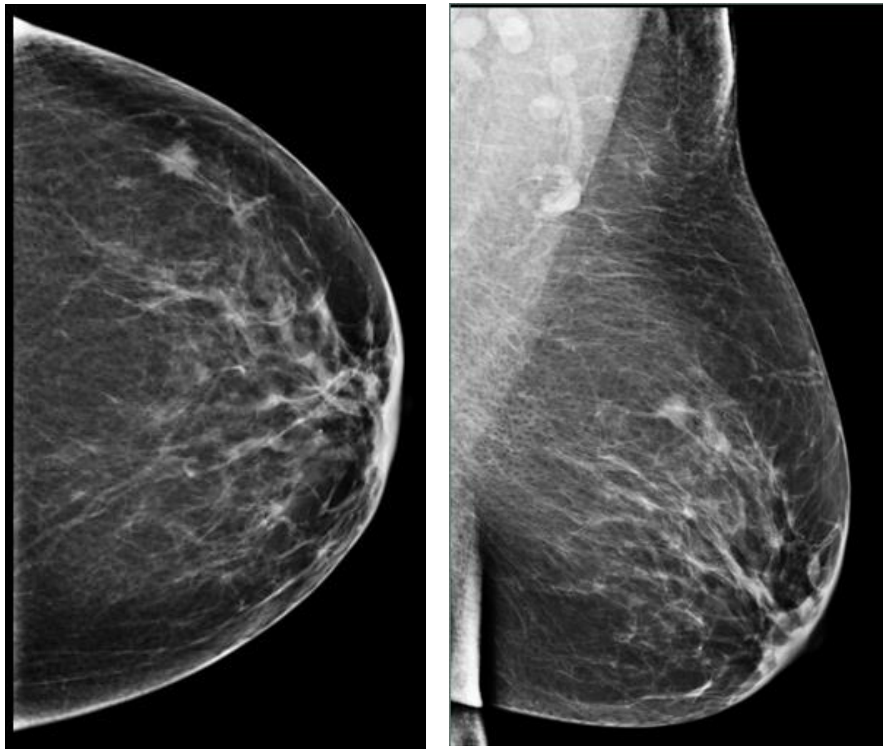
Cancer Mortality and Screening



Jemal A, *et al*., Cancer Statistics 2006

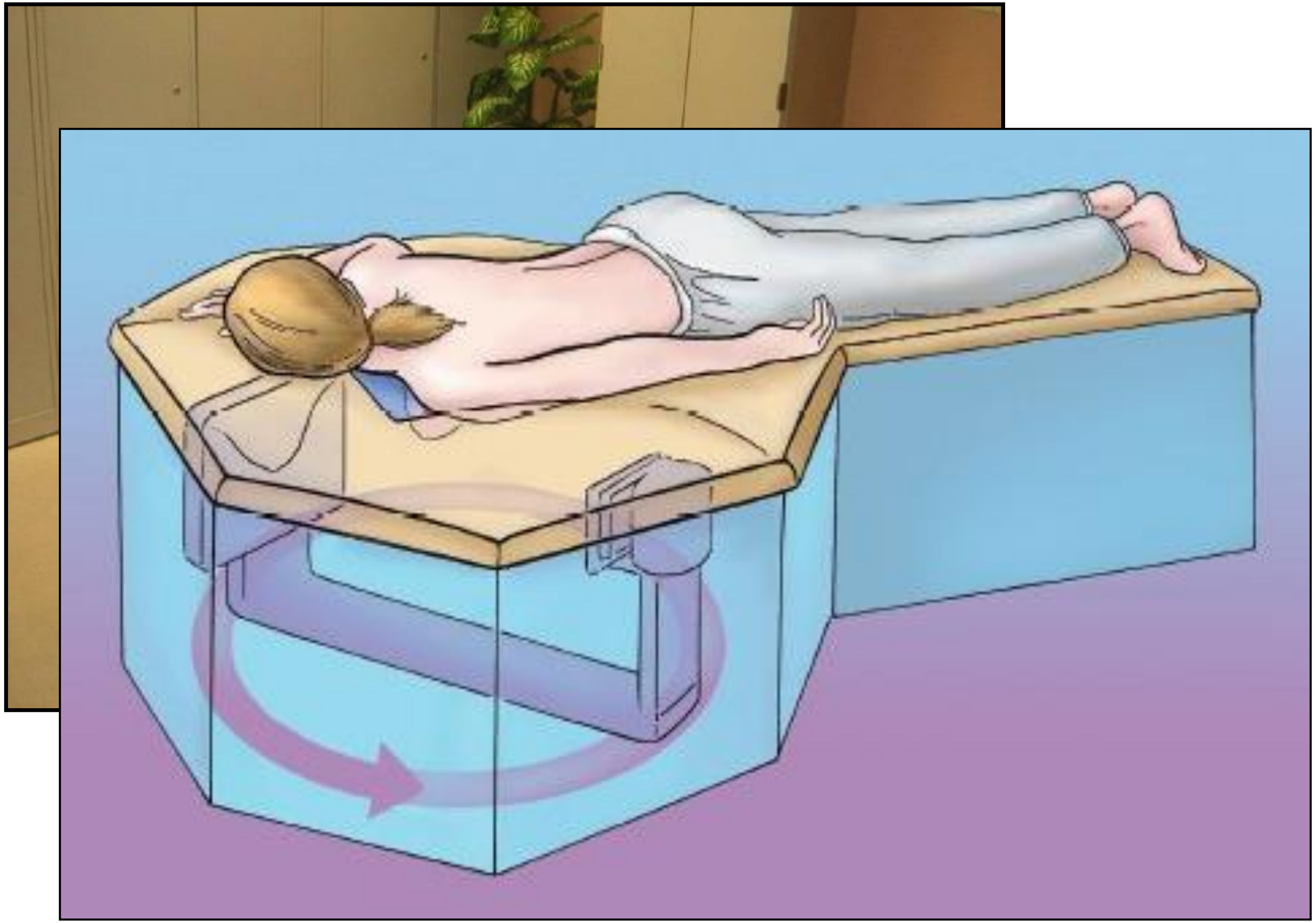
Mammography:
Standard of Care





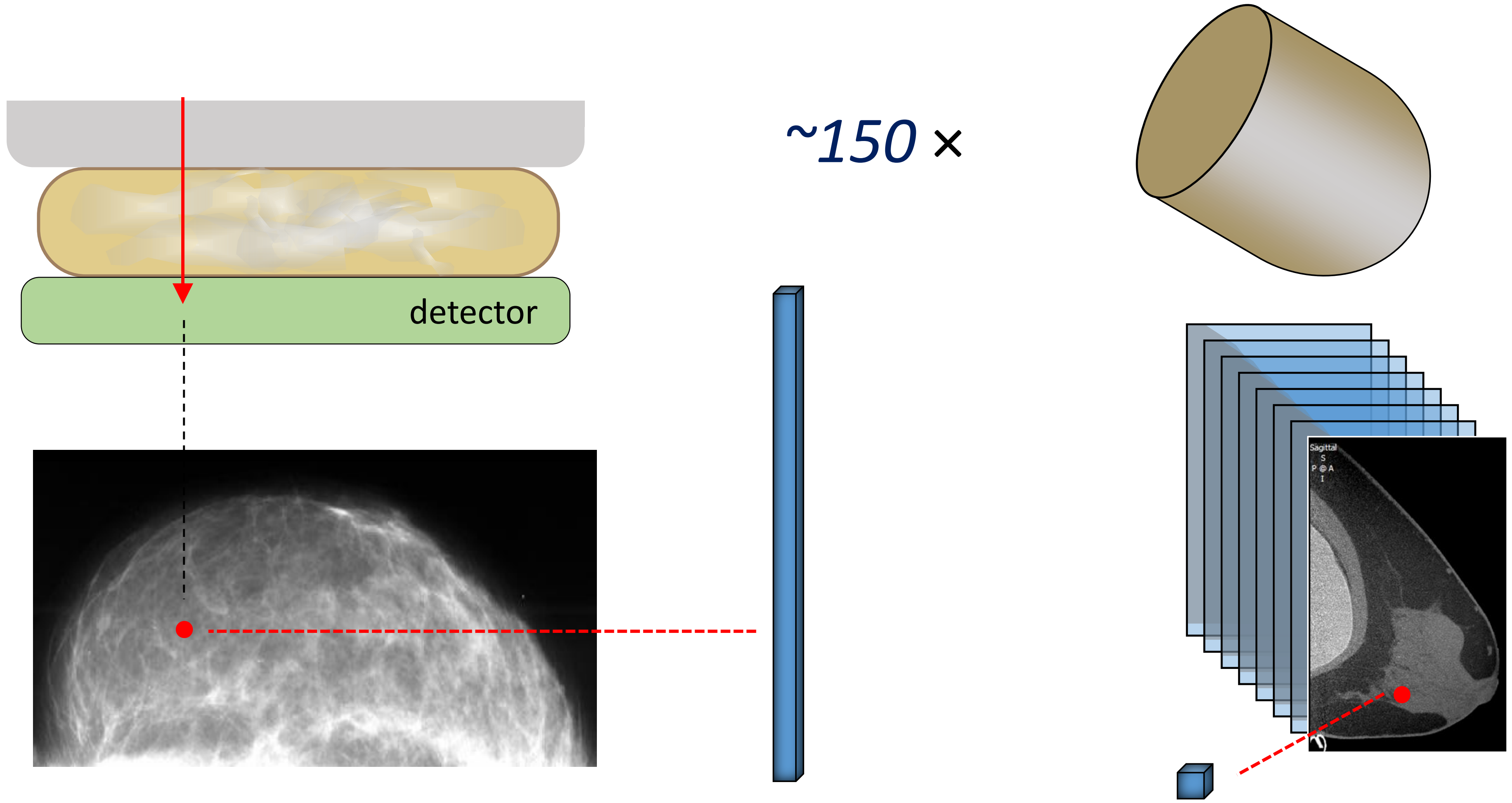
CC MLO

Dedicated Breast CT



Mammography

Dedicated Breast CT



0.10 × 0.10 × 50 mm

0.15 × 0.15 × 0.15 mm

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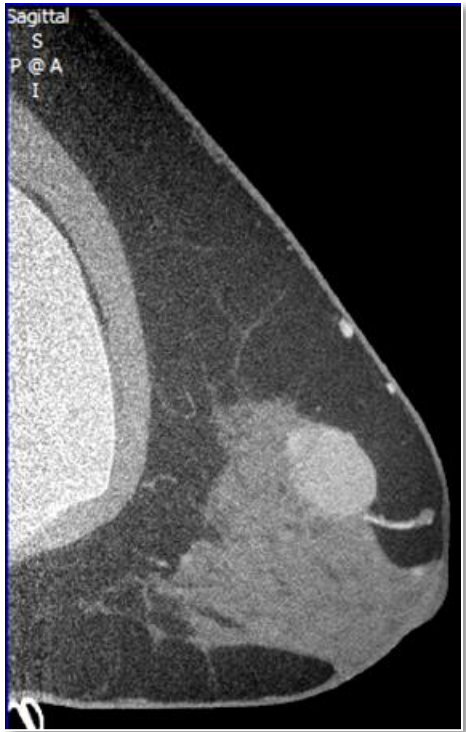
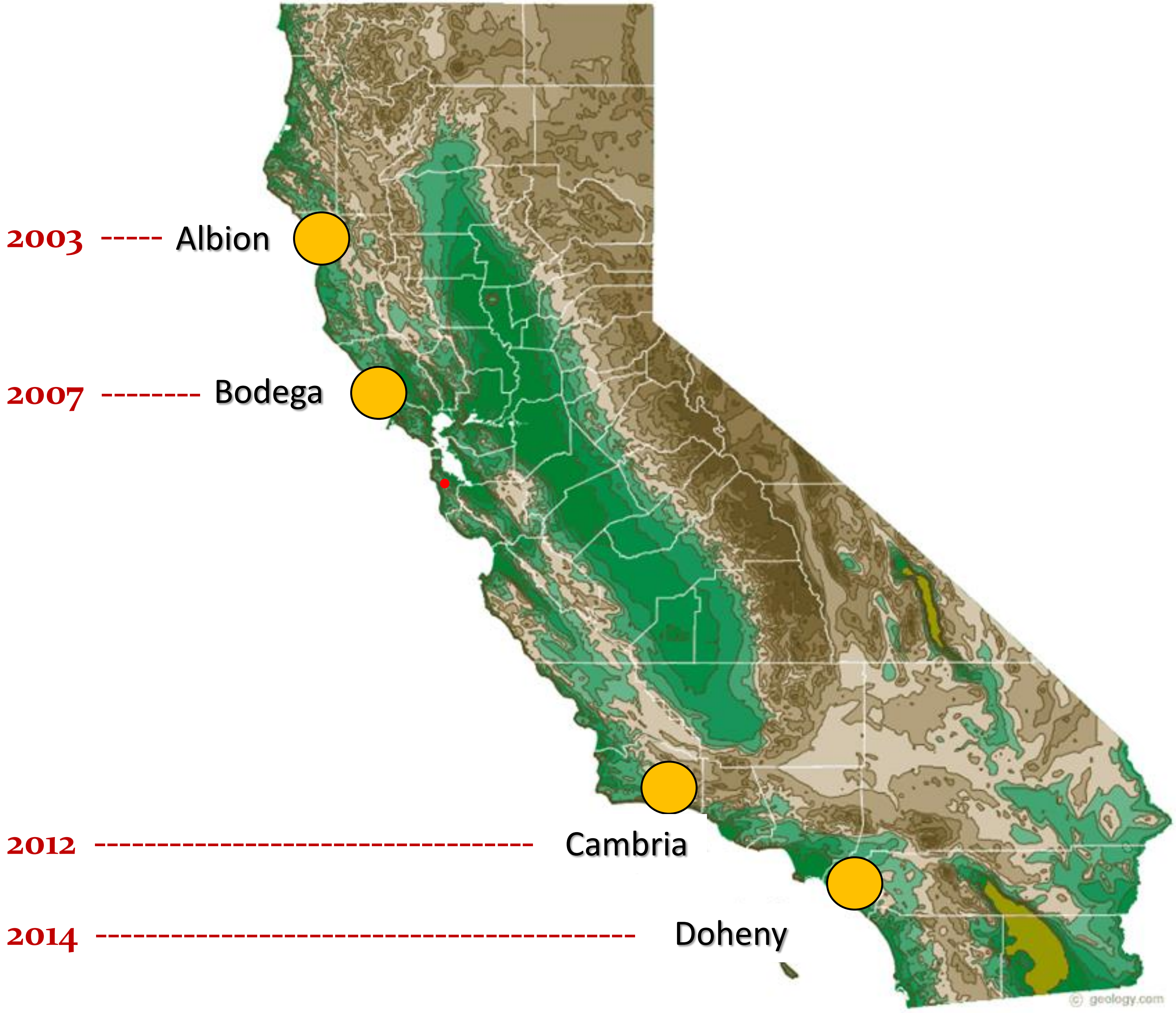


The Breast Tomography Project

University of California, Davis


2003 ----- Albion
2007 -------- Bodega
2012 ------------------------------------- Cambria
2014 -- Doheny
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Breast CT: *Technology development and clinical potential*

Introduction

Technology Development

Radiation Dose Assessment

Image Quality Metrics

Clinical Observations

Observer Performance

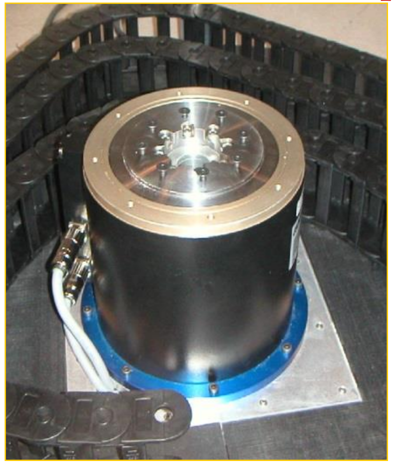
Other Cool Spinoffs

Summary

Hardware

Components

Motor / bearing / encoder

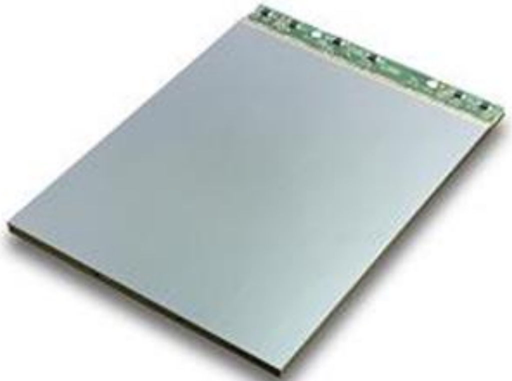


Kollmorgen

Yaskawa

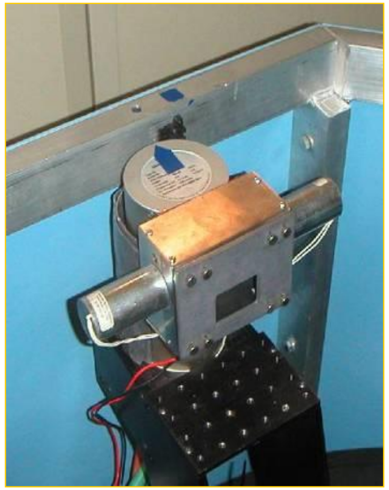
Detectors

Varian TFT



Dexela CMOS

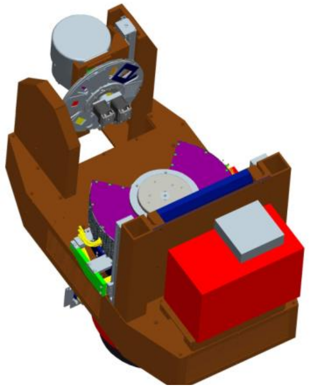
X-ray tubes

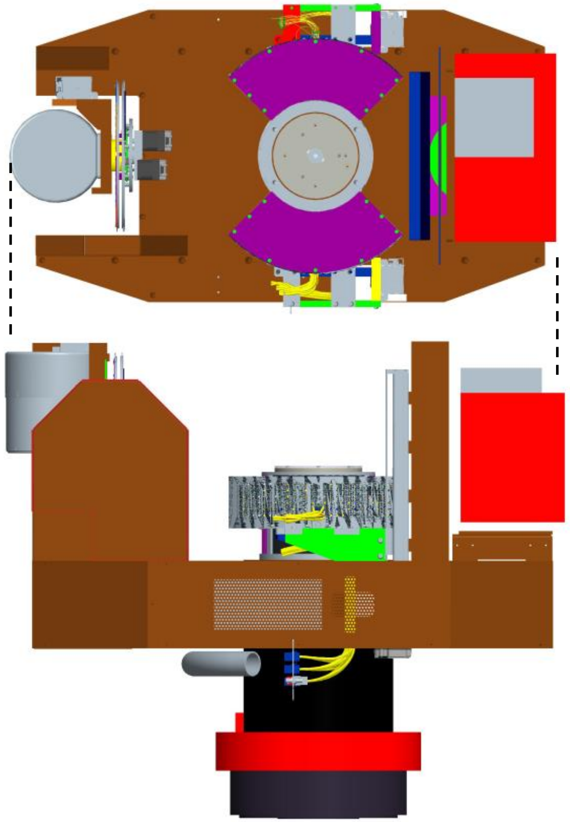


Comet X-ray

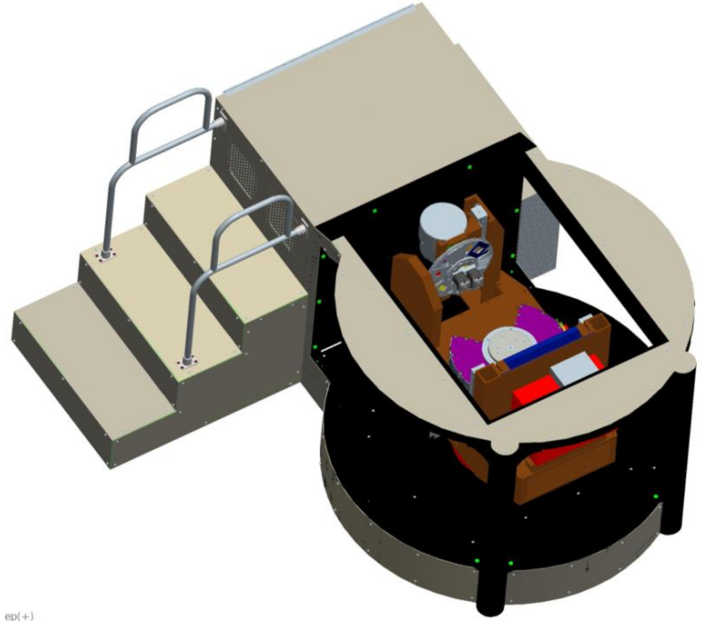
Varian 1501 X-ray

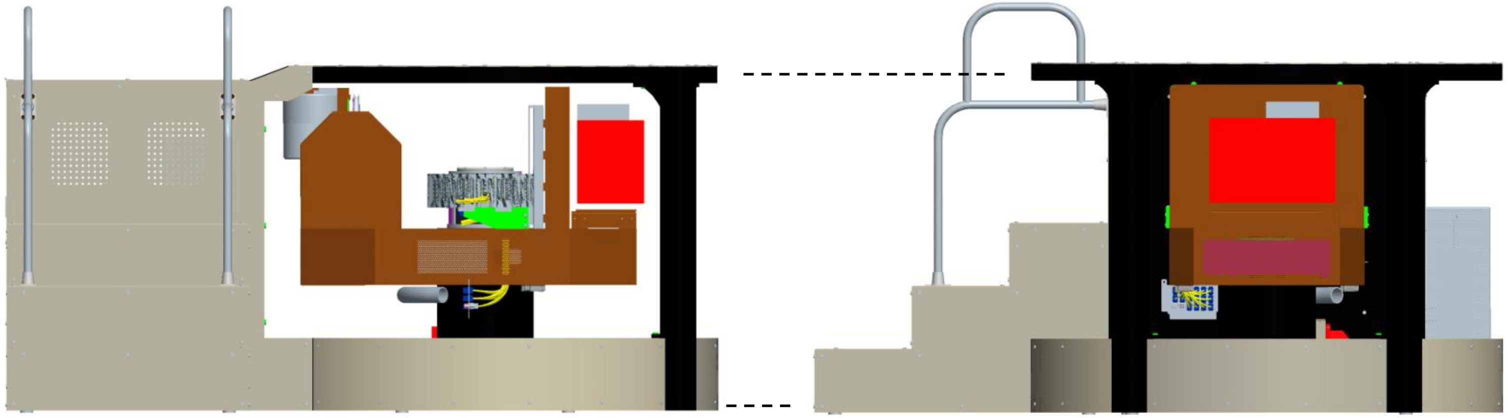
Doheny: Design





George
Burkett, M.S.

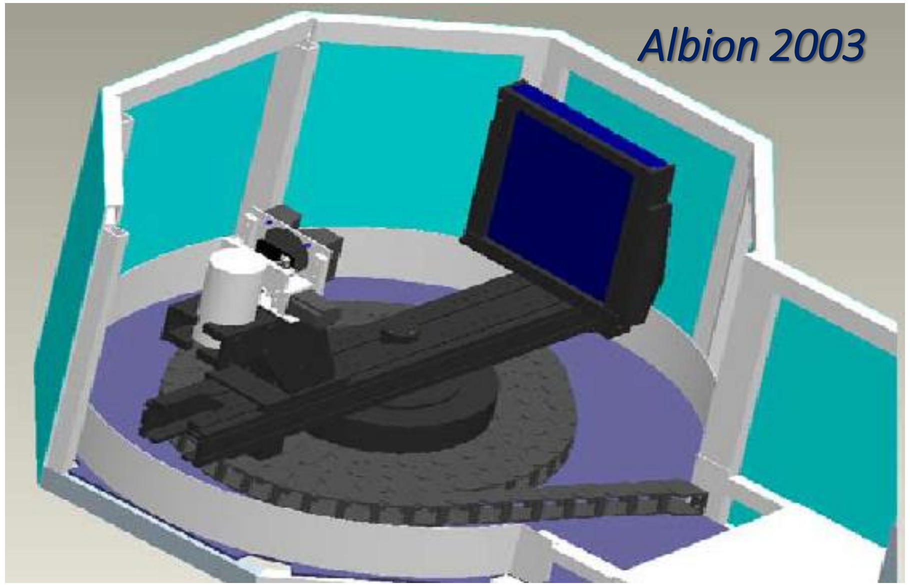


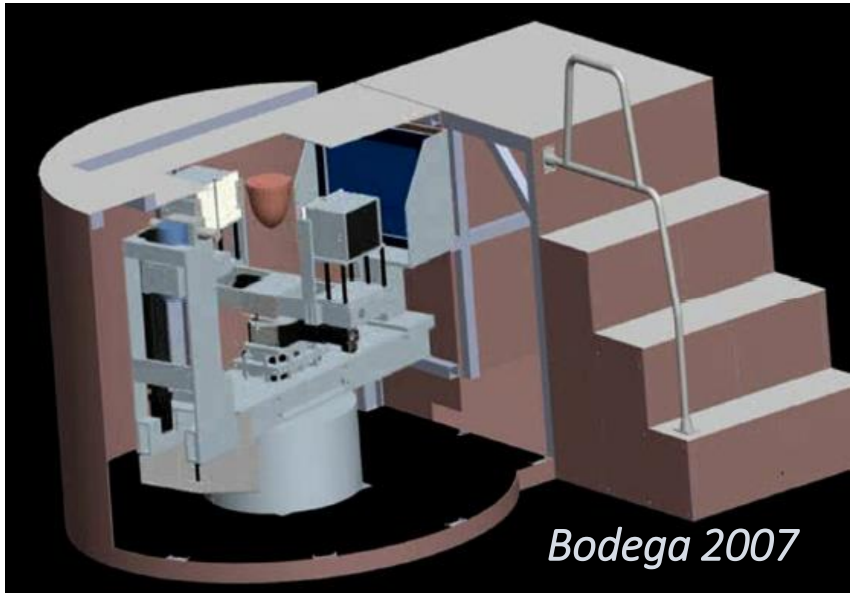


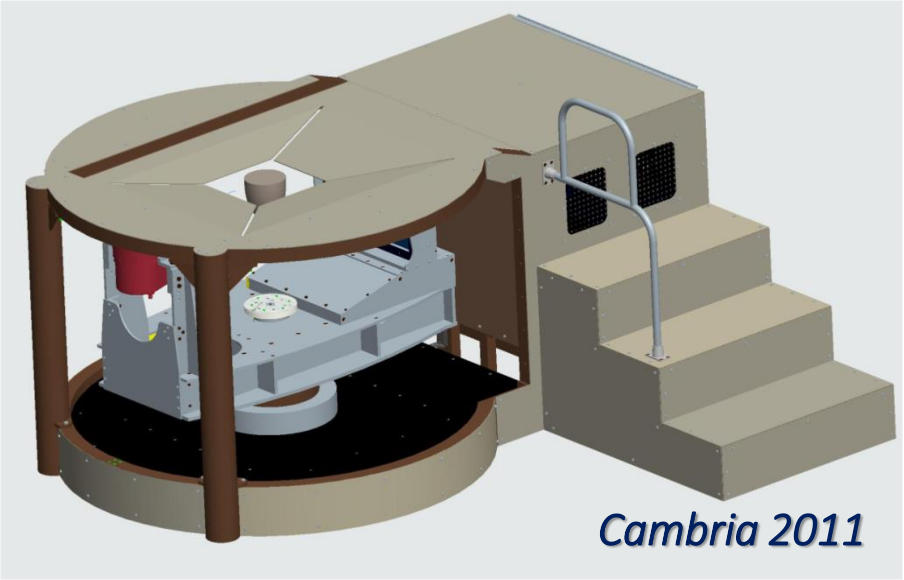
Gantry Views

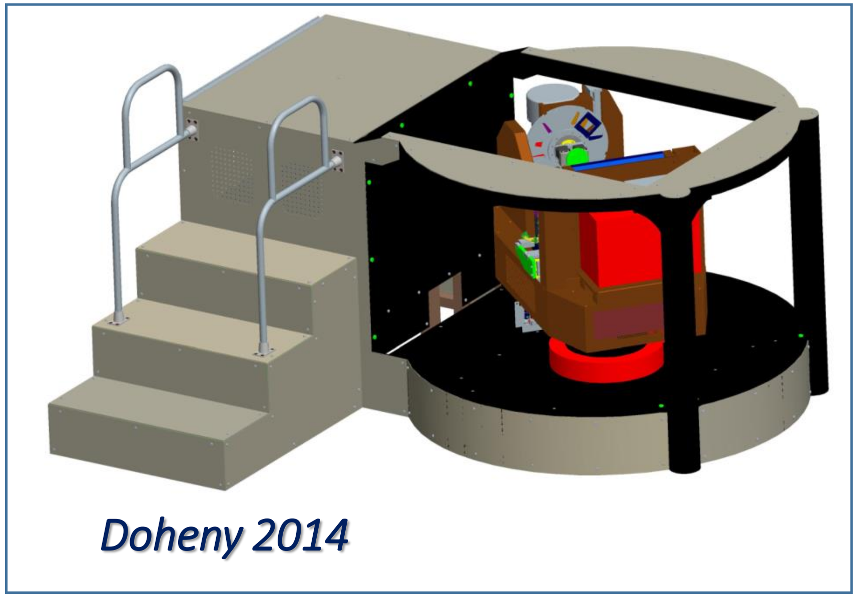
System views

Computer aided design / computer aided manufacture (CAD/CAM)





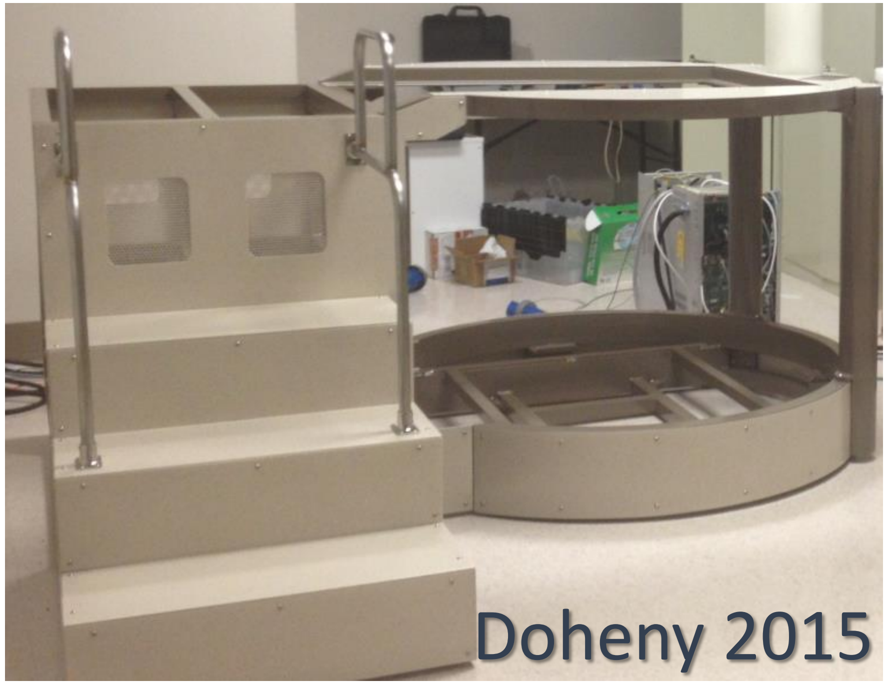




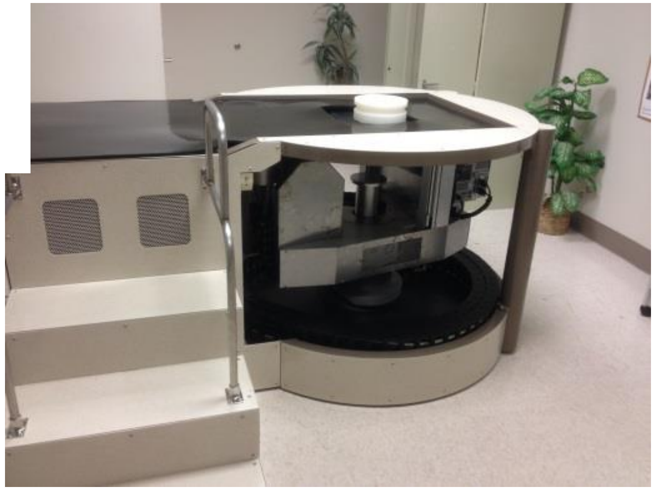

Albion 2004


Bodega 2007

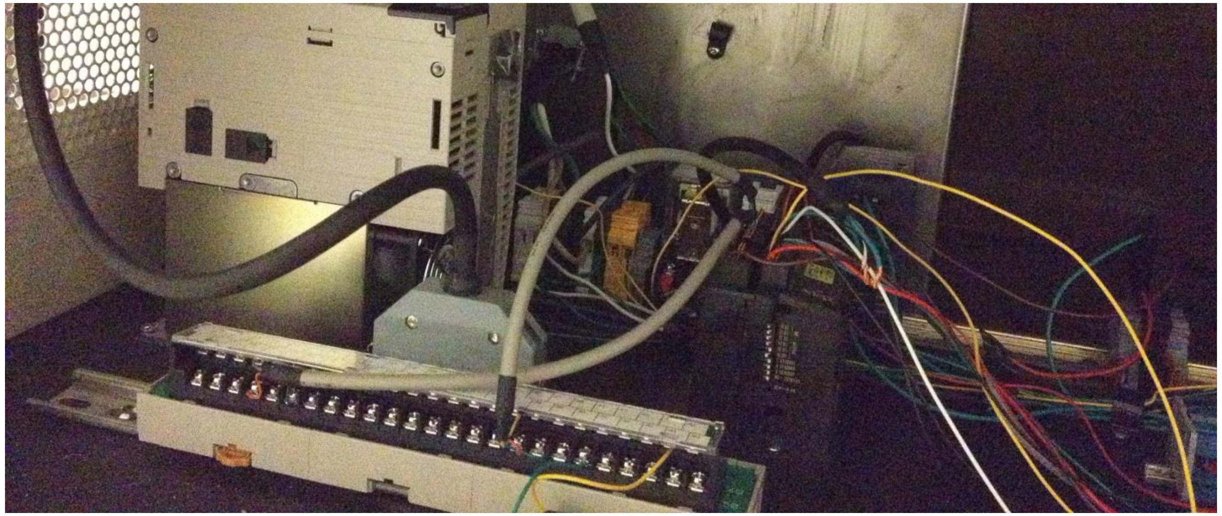

Cambria 2012


Doheny 2015

Doheny: Mechanical Fabrication



Doheny: Wiring



before

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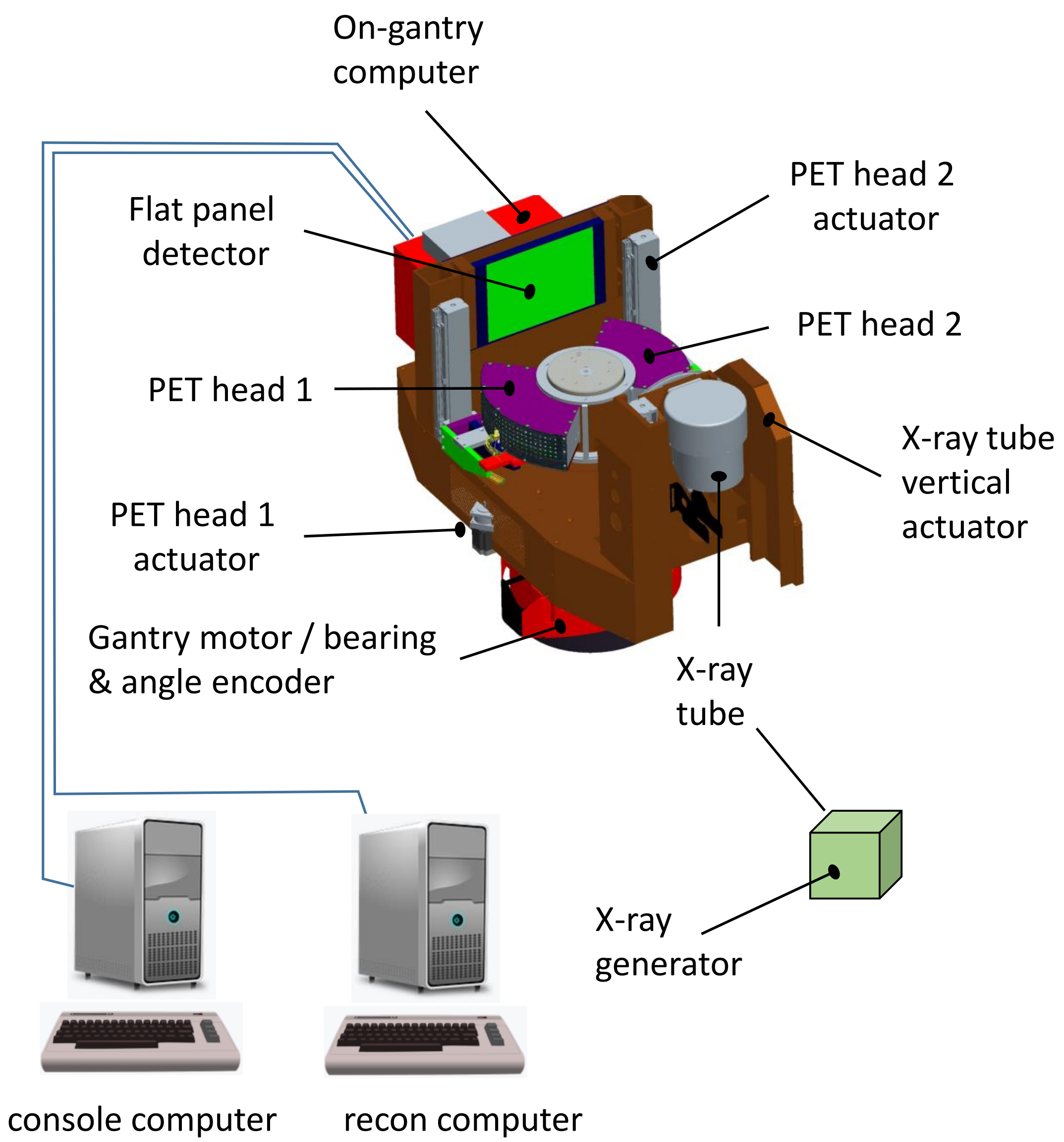
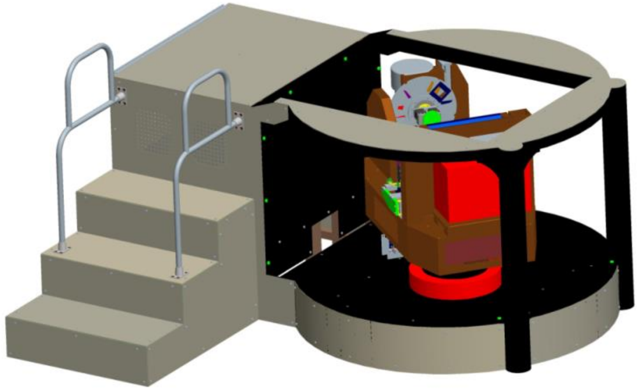
Software Integration

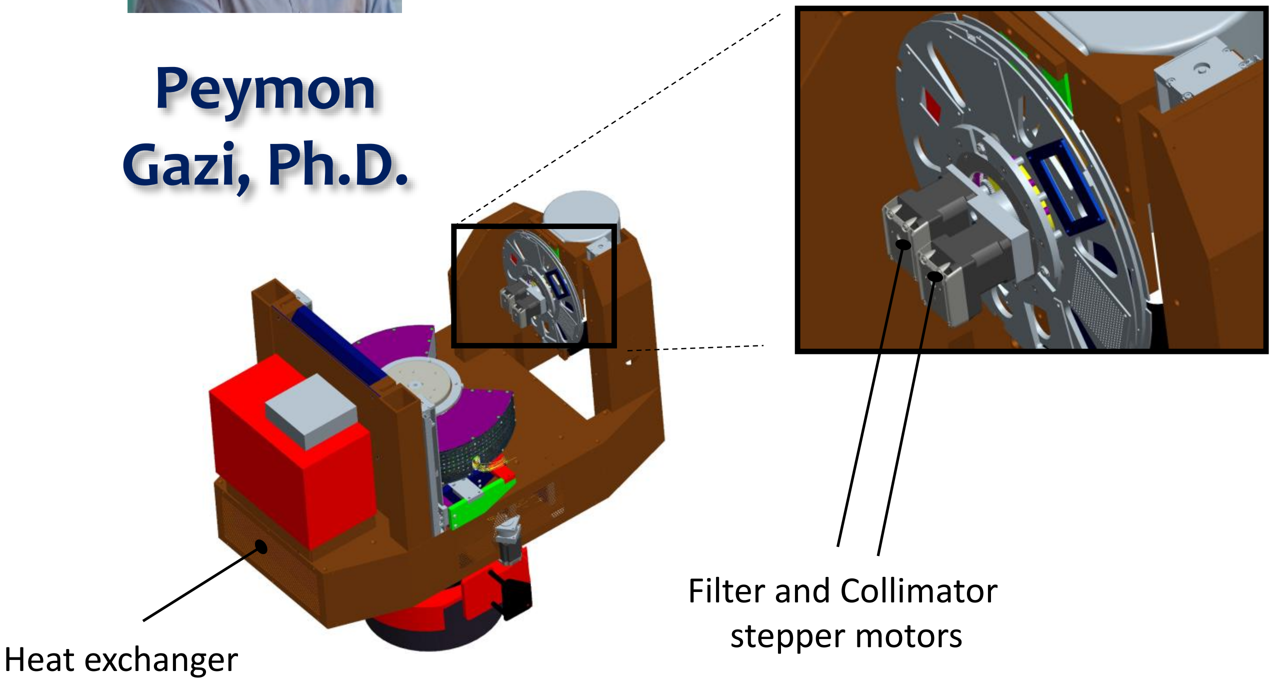
Software: Hardware Integration



Peymon Gazi, Ph.D.



DOHENY



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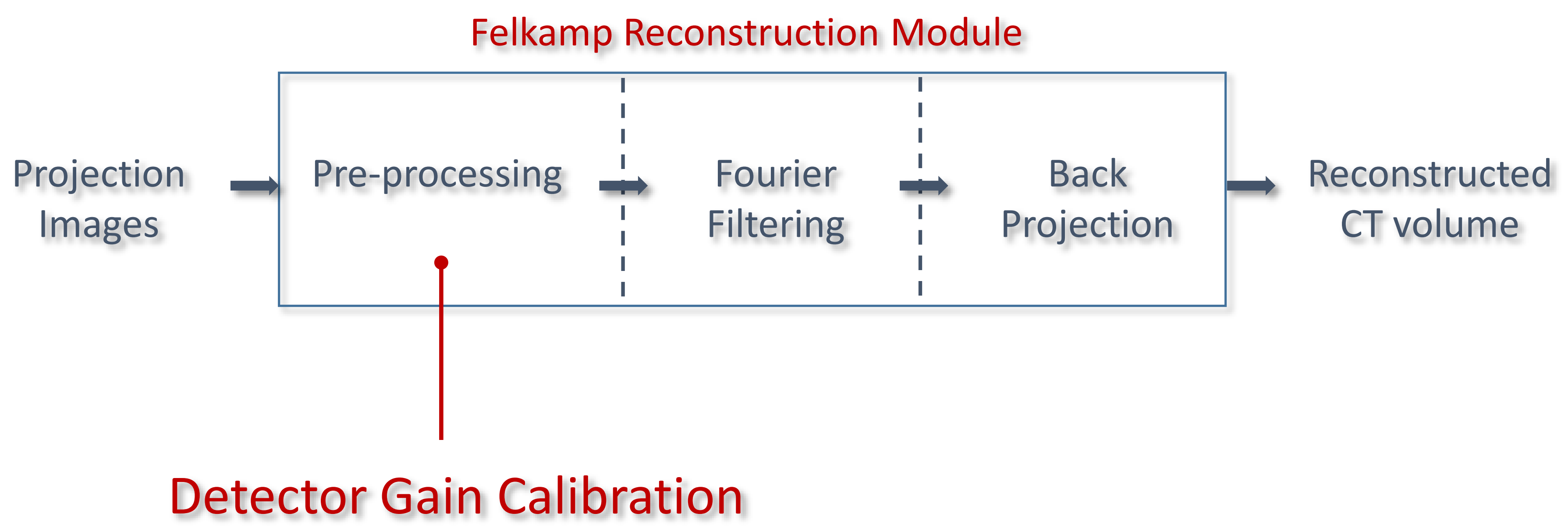
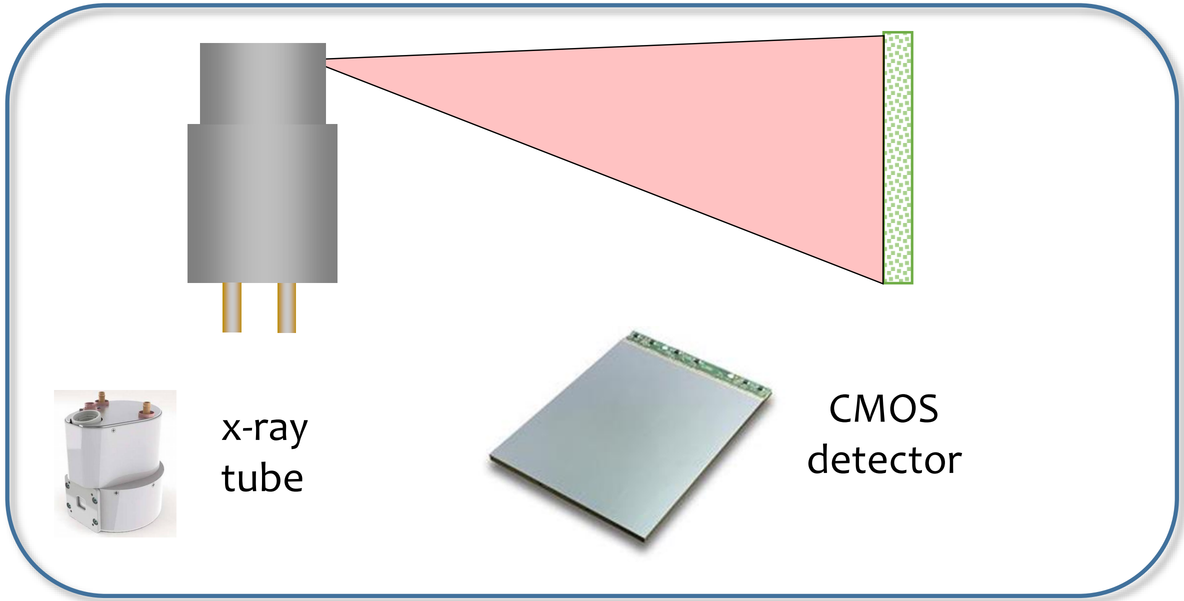
Calibration Software

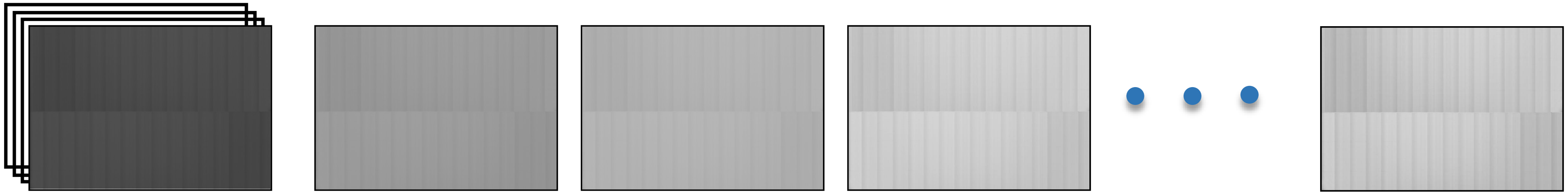
Calibration(s)



Detector calibration: Flat field correction

3.14 million detector elements





25 mA 35 mA 45 mA 100 mA 150 mA

Automatic acquisition (QC software) of 11 different exposure levels to detector (each with 100 averaged images)

Detector calibration: Flat field correction

Gain variation between dexels ≈ 48%

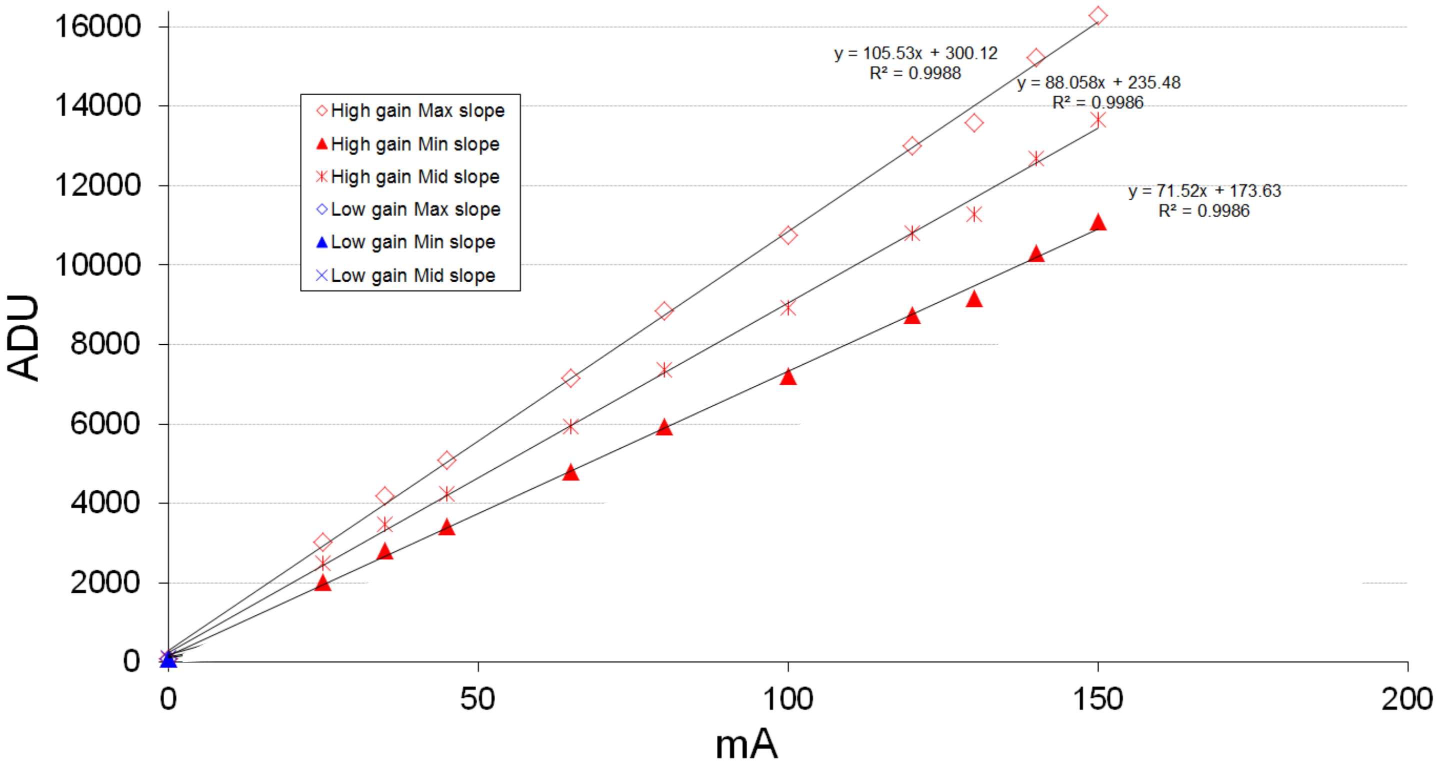
$$ADU(x,y) = \boldsymbol{A}(x,y) + \boldsymbol{B}(x,y) \times K$$

⬇ ⬇

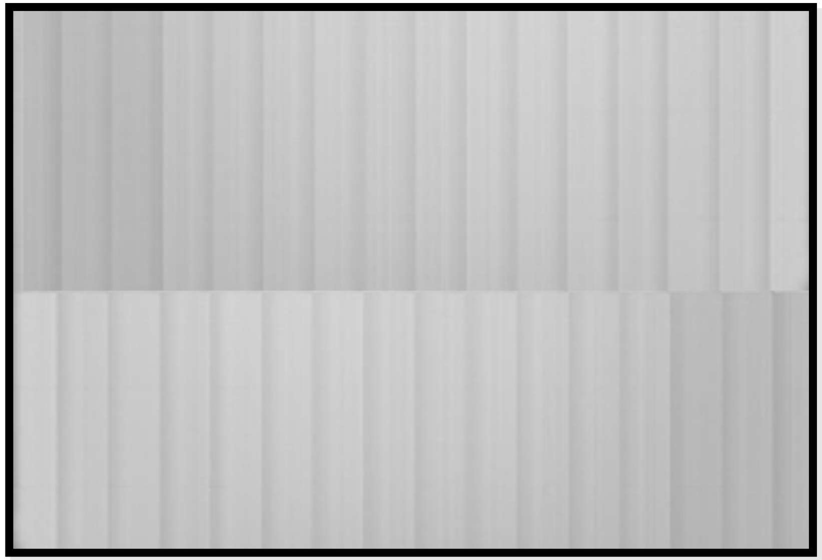
calibration data files

$x \times y = 11{,}800{,}000$

$x \times y = 3{,}145{,}728$



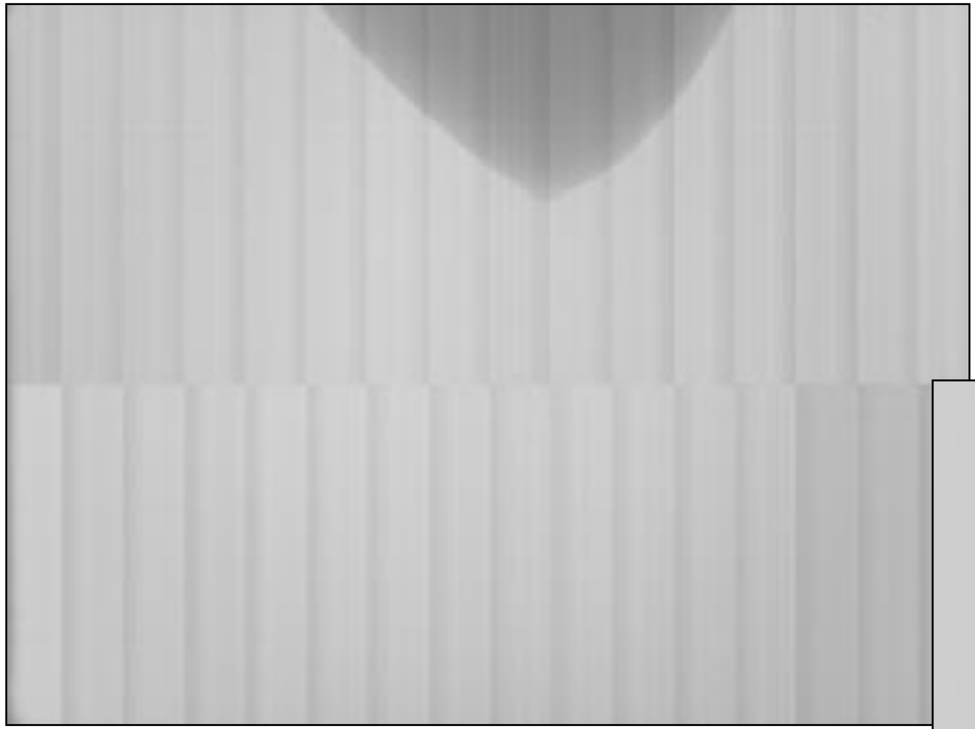
Detector calibration: Flat field correction



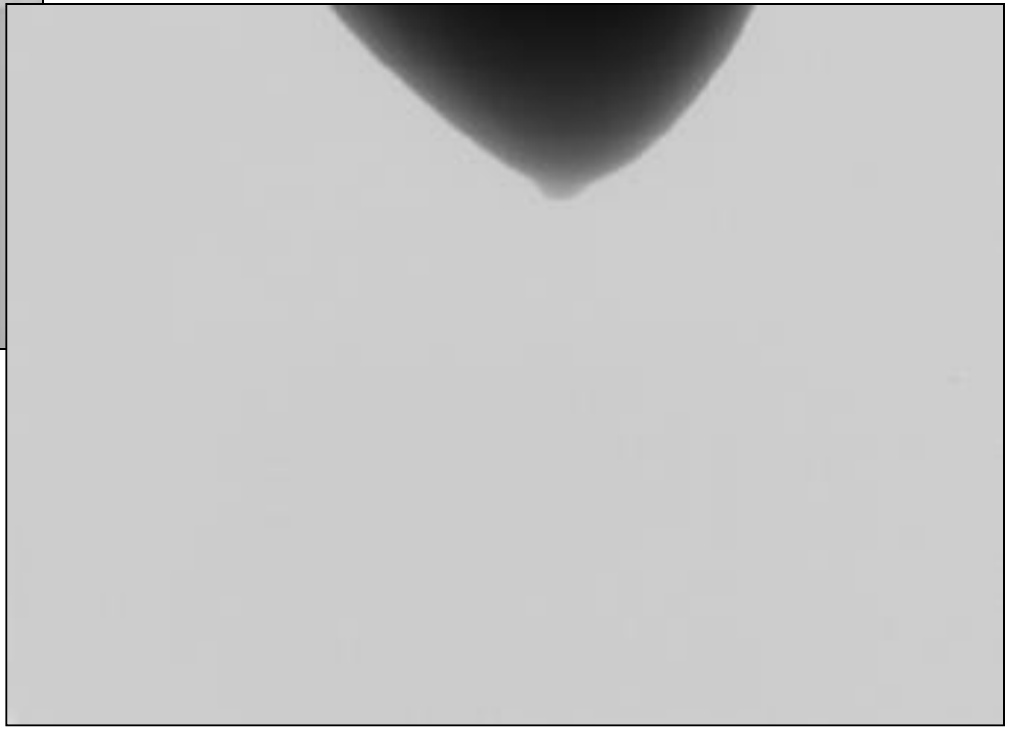
$$I(x,y)_{corr} = \bar{g}\,\frac{\left[I(x,y)_{raw} - A_{raw}(x,y)\right]}{\left[B(x,y) - A(x,y)\right]}$$

calibration data files

Detector calibration: Flat field correction

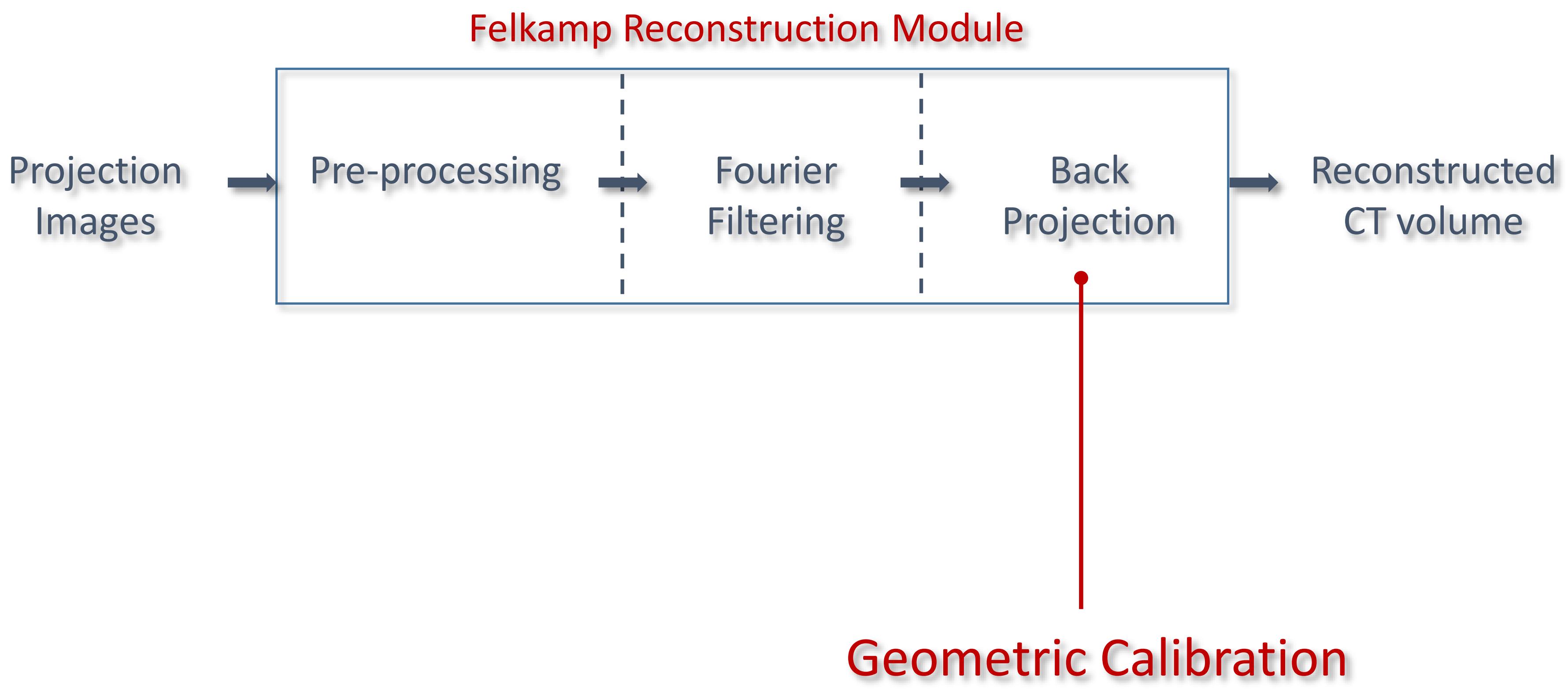


Raw Image

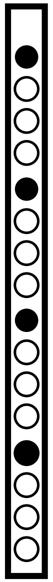


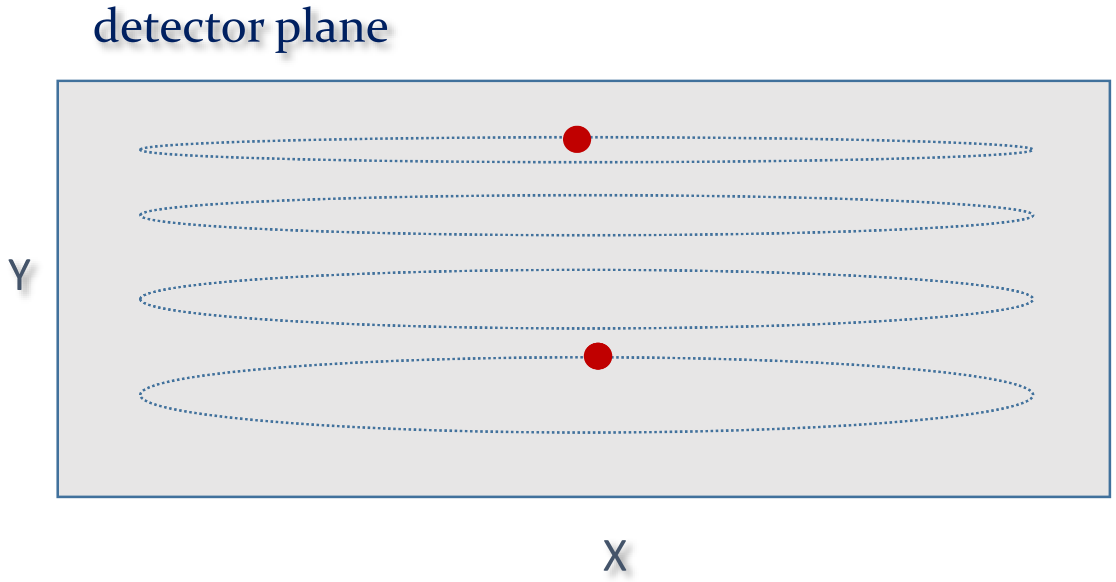
Corrected (flat fielded)

Calibration(s)



Geometric calibration: System → software





$$u_{wr} = y_{obj} \cdot \frac{D + u_{wr} \cdot \sin\phi}{C + x_{obj}} \cdot \frac{1}{\cos\phi}, \quad v_{wr} = z_{obj} \cdot \frac{D + u_{wr} \cdot \sin\phi}{C + x_{obj}}.$$

Geometric calibration: System → software

$X_{center\ ray}$

$Y_{center\ ray}$

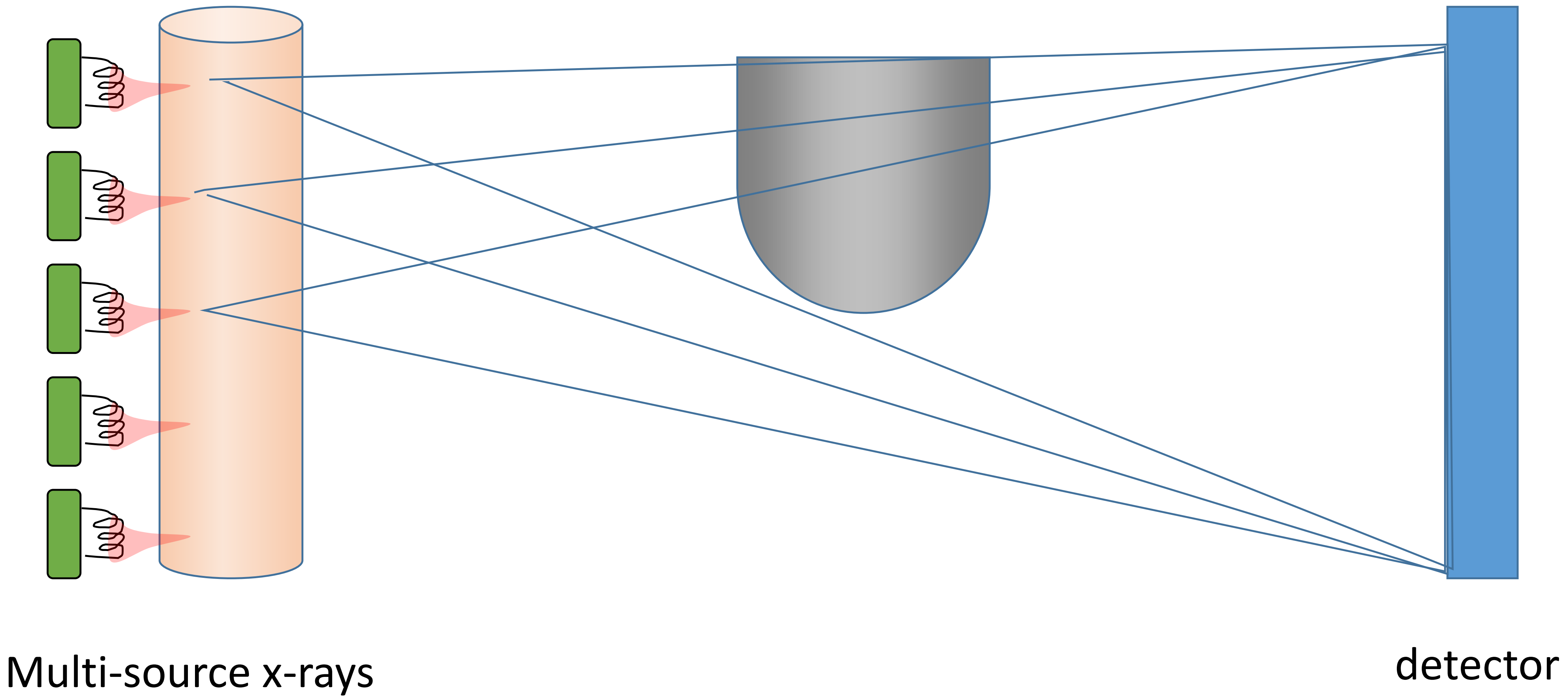
Δx

Δy

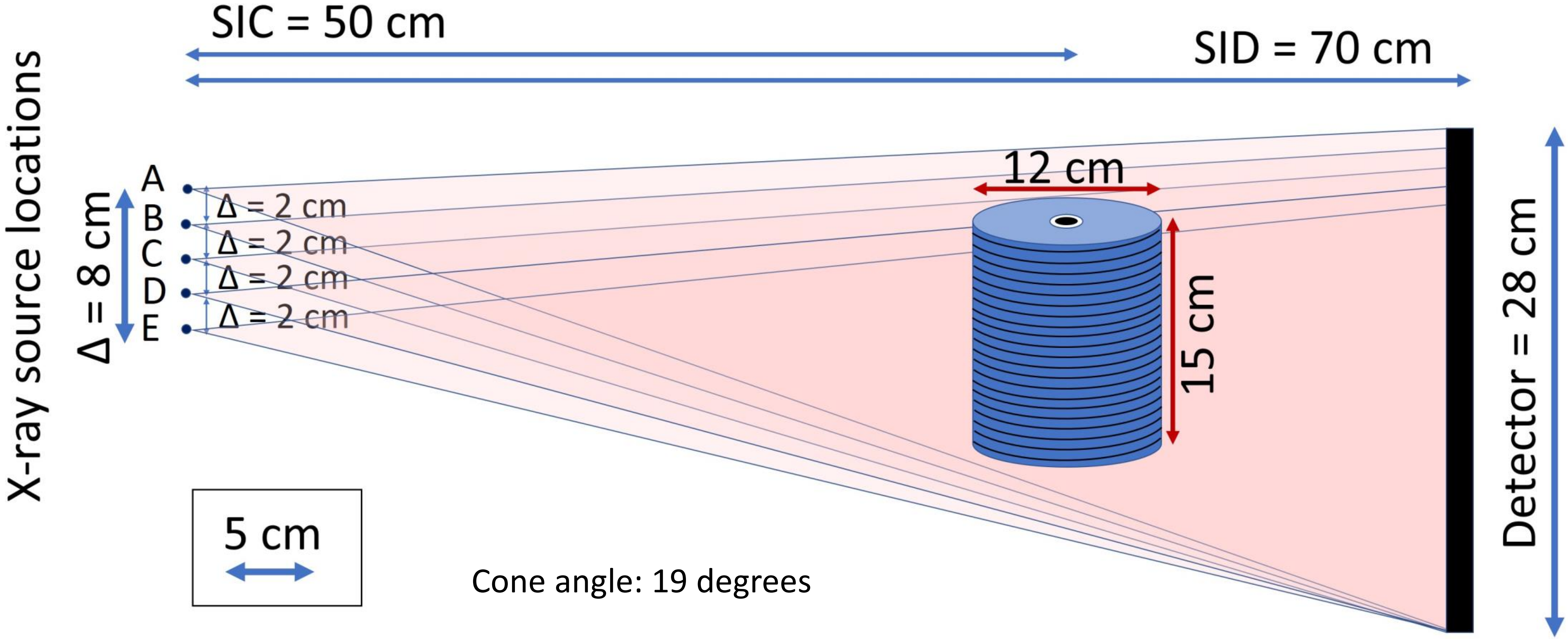
SIC

Physical scanner geometry ⟶ Reconstruction algorithm

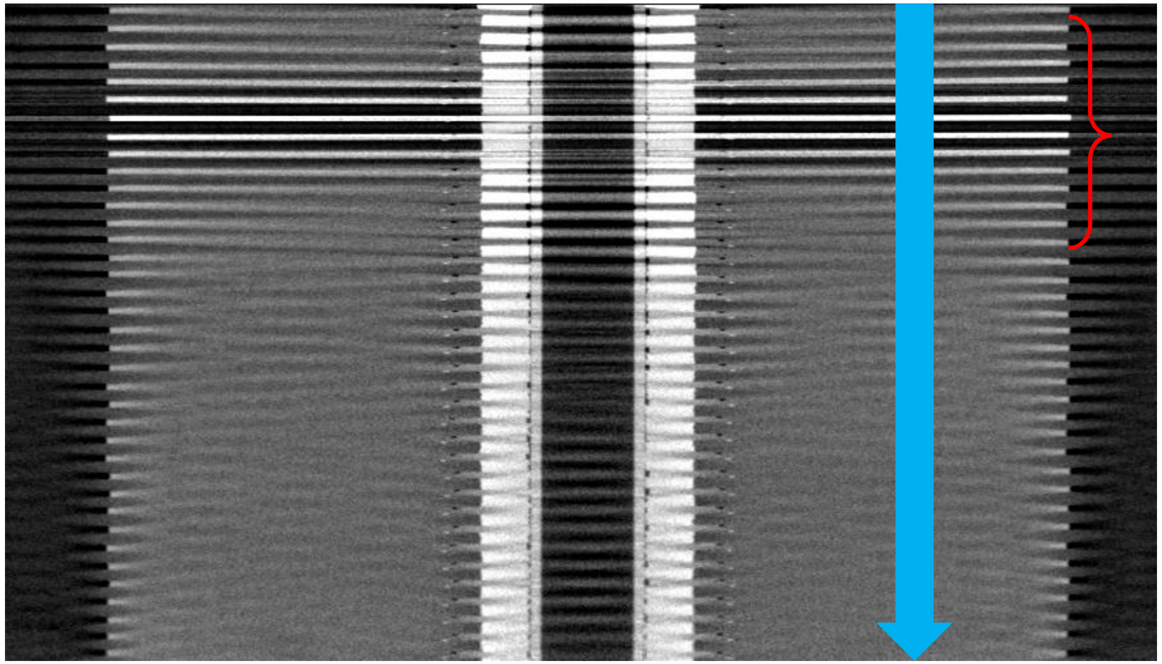
Multi-Source X-ray to reduce Cone Beam Artifacts

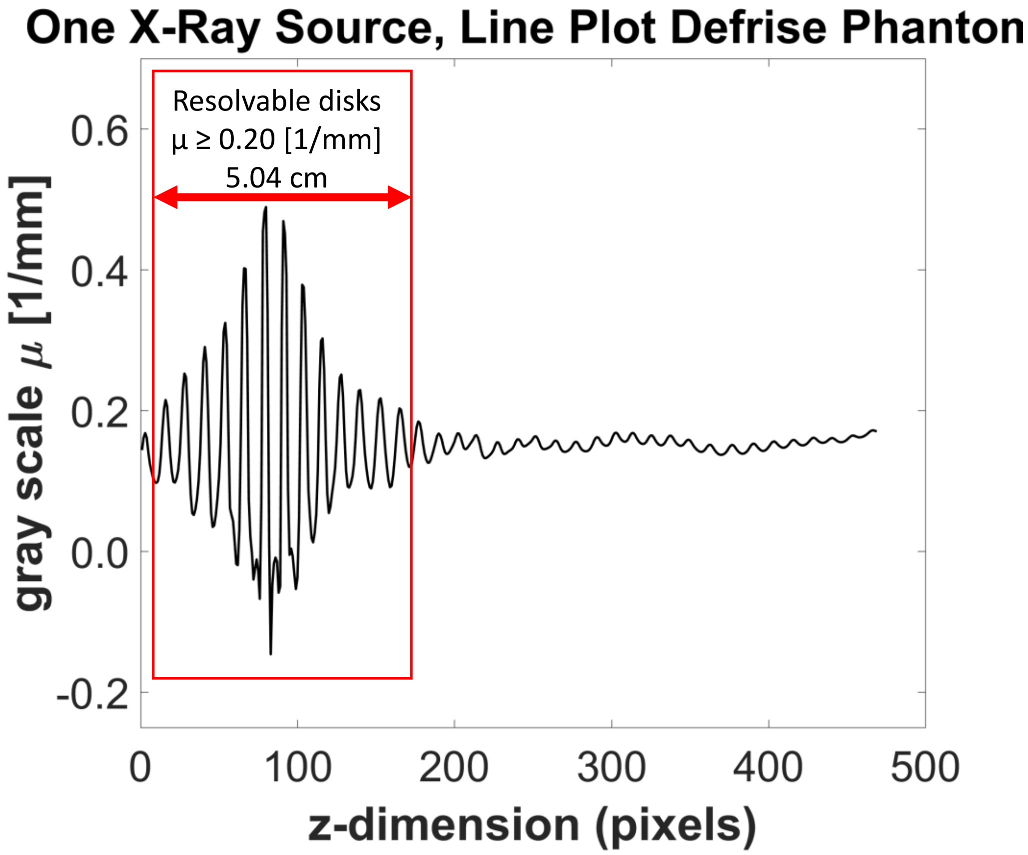


Multi-Source X-ray to reduce Cone Beam Artifacts

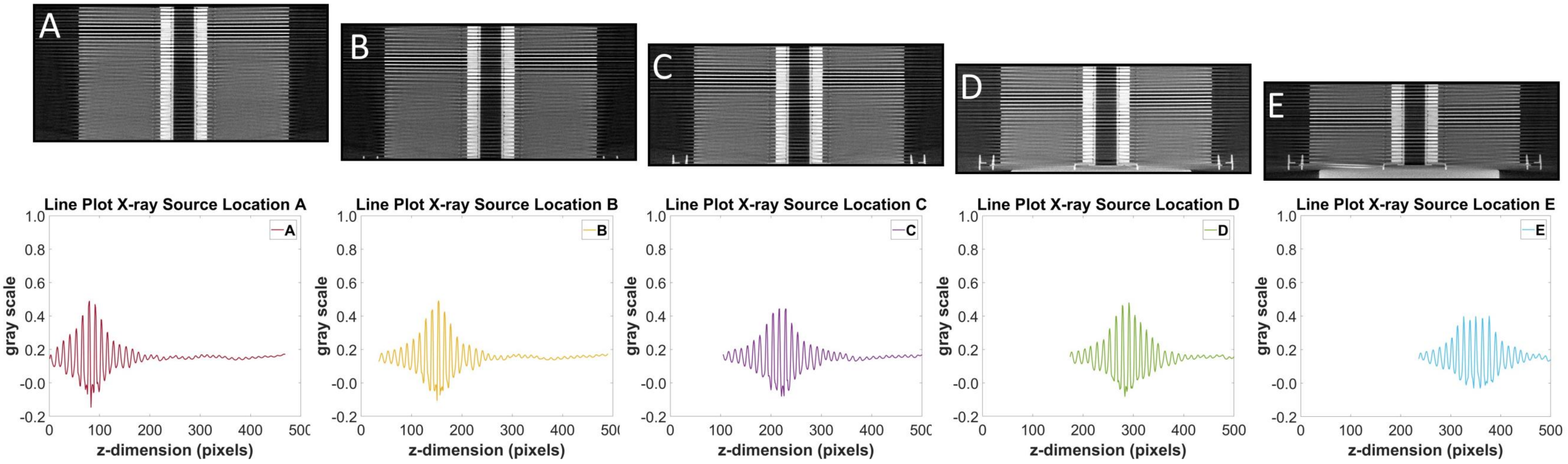


Defrise Phantom: One X-Ray Source



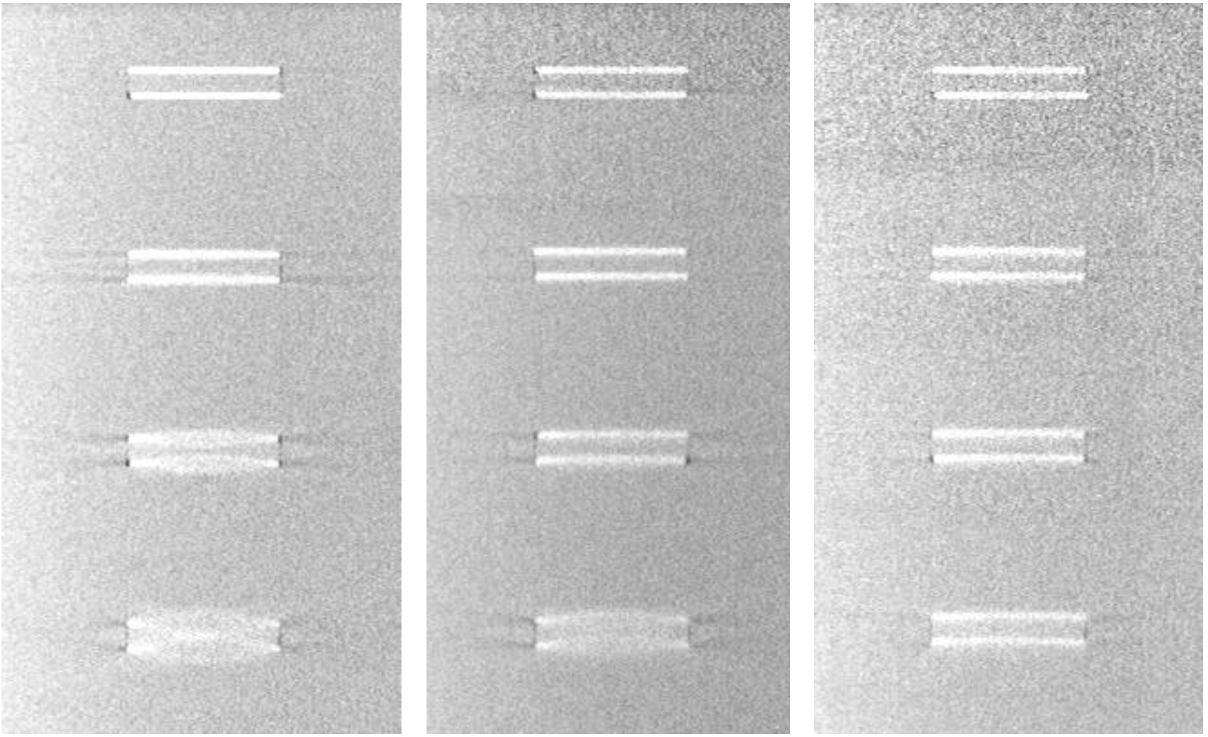


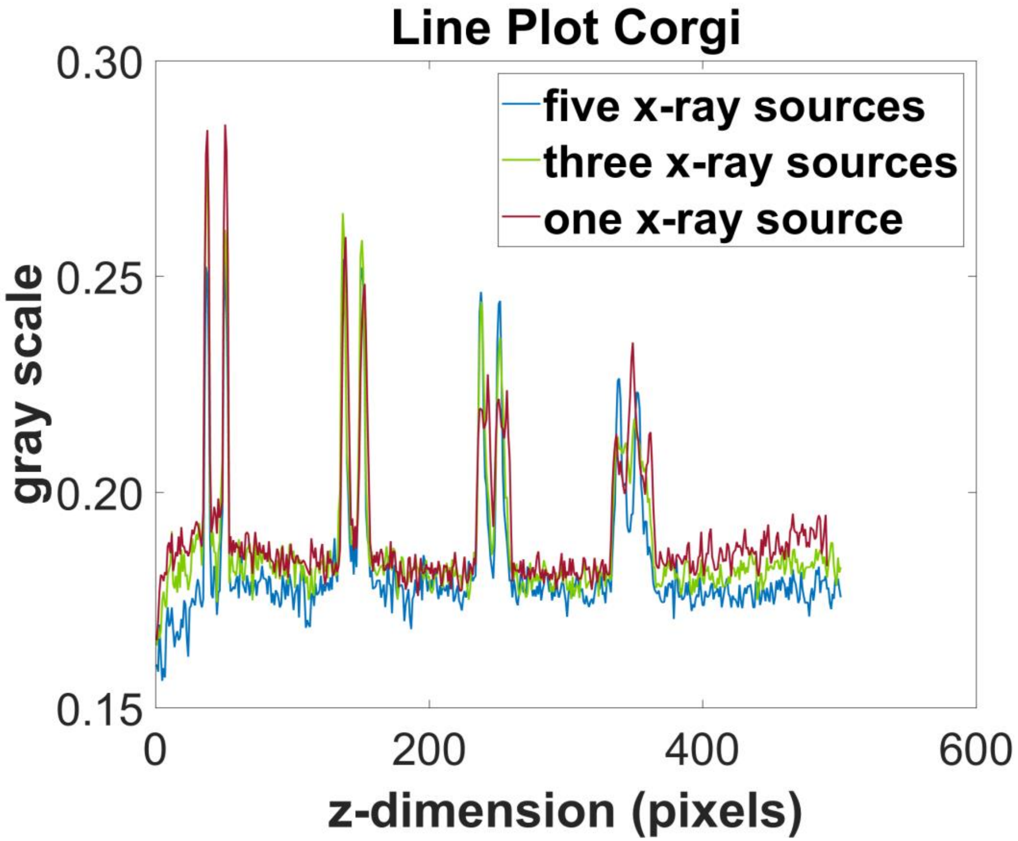
Individual source acquisitions



Corgi Phantom

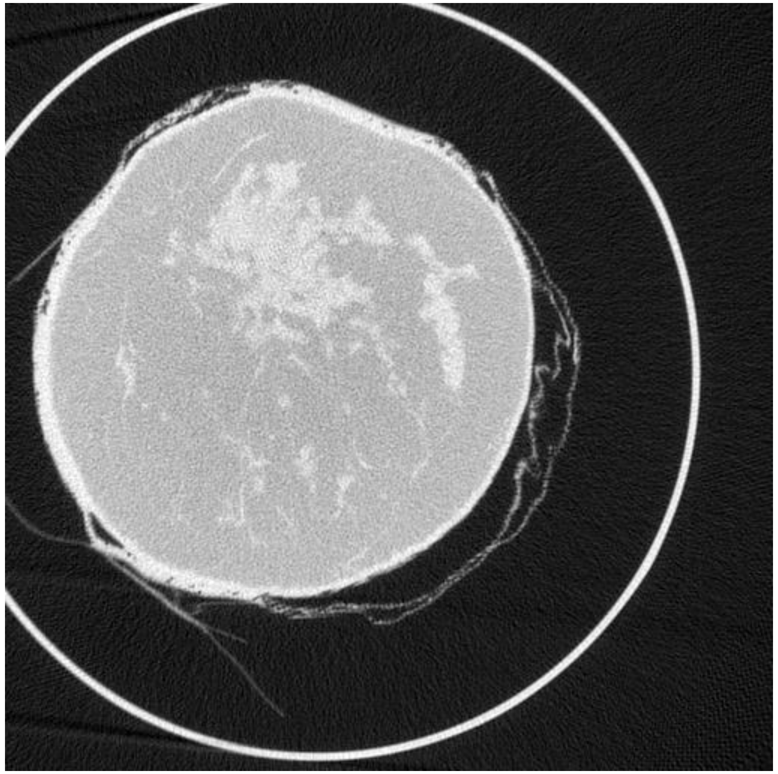
One Source Three Source Five Source



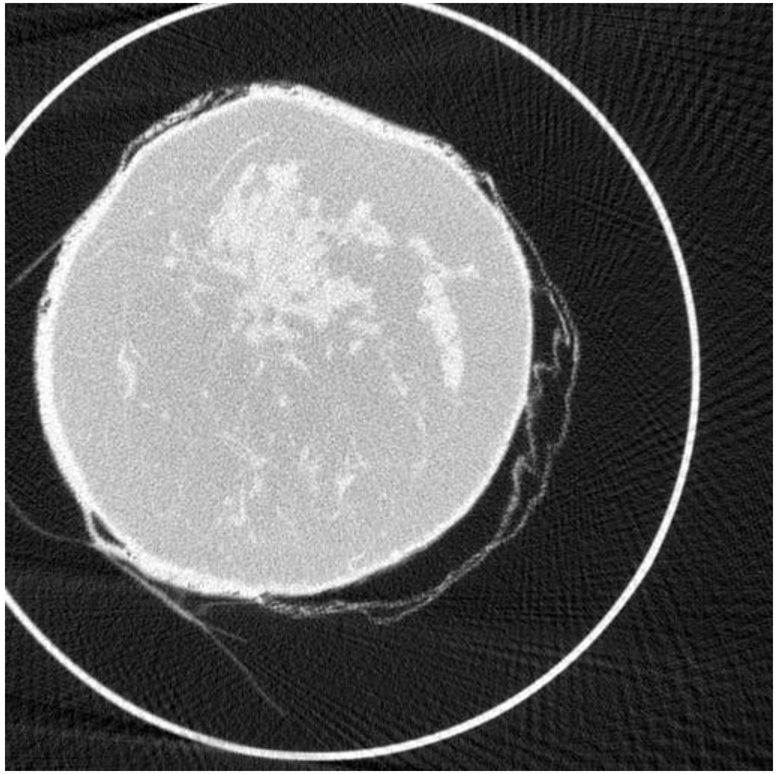


Cadaver Breast

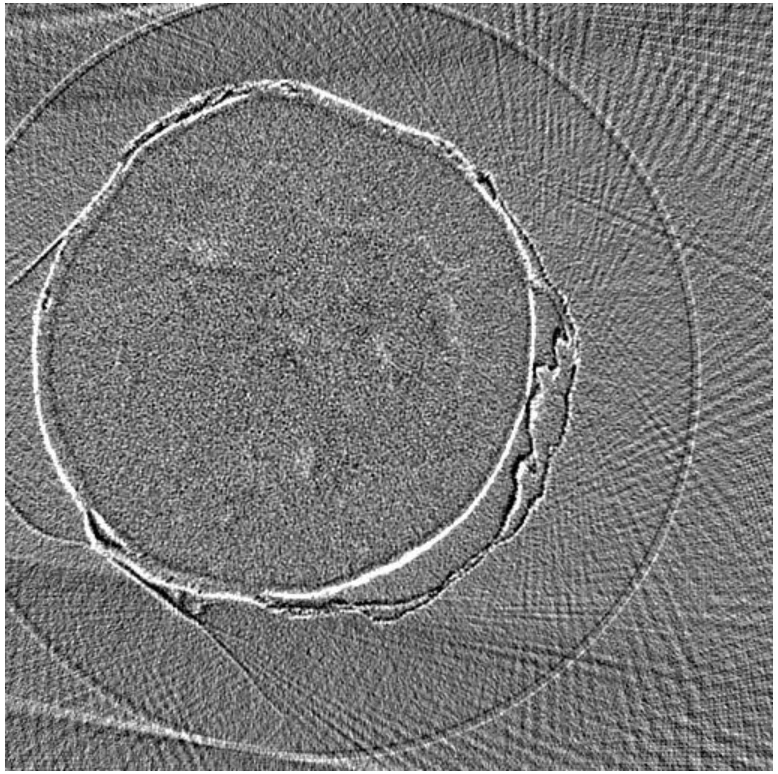
One Source



Three Source



Difference Image



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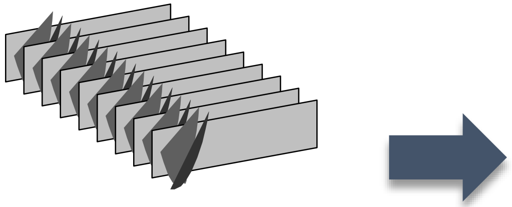
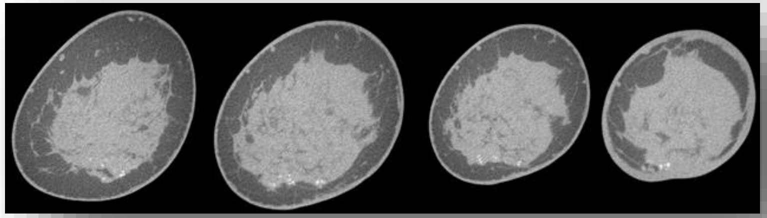
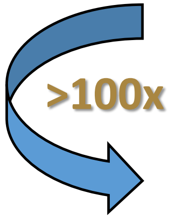
Reconstruction & Post-processing

FDK Reconstruction Code





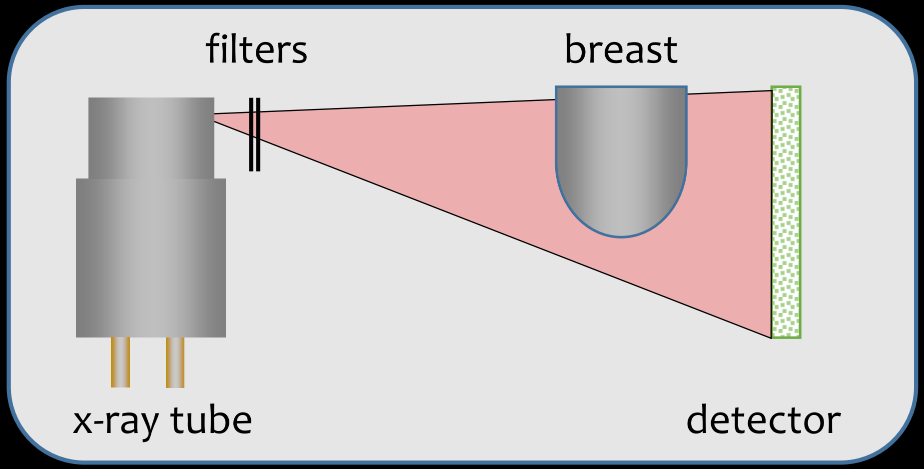
2003	~42 minutes
2008	~35 minutes
2010	~20 seconds

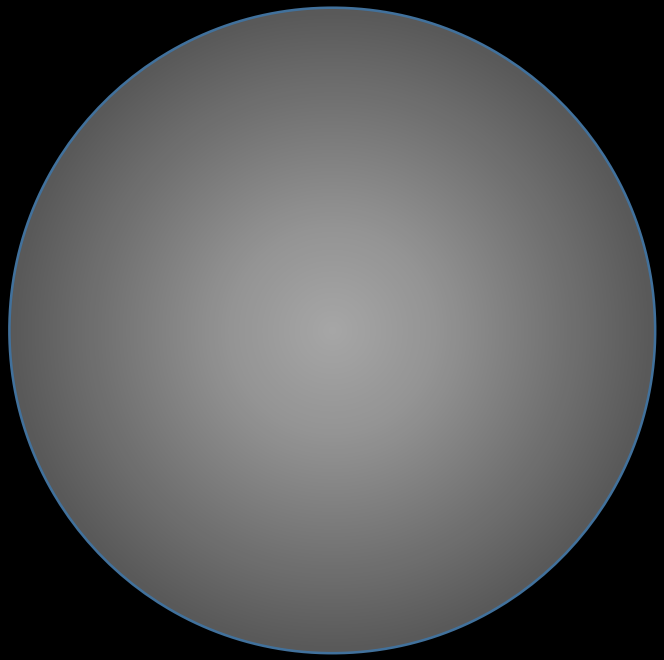


```
float tempi,tempr;
double theta,wi,wpi,wpr,wr,wtemp;

ntot=1;
for (idim=1;idim<=ndim;idim++)
        ntot *= nn[idim];
nprev=1;
for (idim=ndim;idim>=1;idim--) {
        n=nn[idim];
        nrem=ntot/(n*nprev);
        ip1=nprev << 1;
        ip2=ip1*n;
        ip3=ip2*nrem;
        i2rev=1;
        for (i2=1;i2<=ip2;i2+=ip1) {
                if (i2 < i2rev) {
                        for (i1=i2;i1<=i2+ip1-2;i1+=2) {
                                for (i3=i1;i3<=ip3;i3+=ip2) {
                                        i3rev=i2rev+i3-i2;
                                        SWAP(data[i3],data[i3rev]);
                                        SWAP(data[i3+1],data[i3rev+1]);
                                }
                        }
                }
                ibit=ip2 >> 1;
                while (ibit >= ip1 && i2rev > ibit) {
                        i2rev -= ibit;
                        ibit >>= 1;
                }
                i2rev += ibit;
        }
        ifp1=ip1;
        while (ifp1 < ip2) {
                ifp2=ifp1 << 1;
                theta=isign*6.28318530717959/(ifp2/ip1);
                wtemp=sin(0.5*theta);
                wpr = -2.0*wtemp*wtemp;
                wpi=sin(theta);
                wr=1.0;
                wi=0.0;
                for (i3=1;i3<=ifp1;i3+=ip1) {
                        for (i1=i3;i1<=i3+ip1-2;i1+=2) {
                                for (i2=i1;i2<=ip3;i2+=ifp2) {
                                        k1=i2;
                                        k2=k1+ifp1;
                                        tempr=wr*data[k2]-wi*data[k2+1];
                                        tempi=wr*data[k2+1]+wi*data[k2];
                                        data[k2]=data[k1]-tempr;
                                        data[k2+1]=data[k1+1]-tempi;
                                        data[k1] += tempr;
                                        data[k1+1] += tempi;
                                }
                        }
                        wr=(wtemp=wr)*wpr-wi*wpi+wr;
                        wi=wi*wpr+wtemp*wpi+wi;
                }
                ifp1=ifp2;
        }
        nprev *= n;
}
```

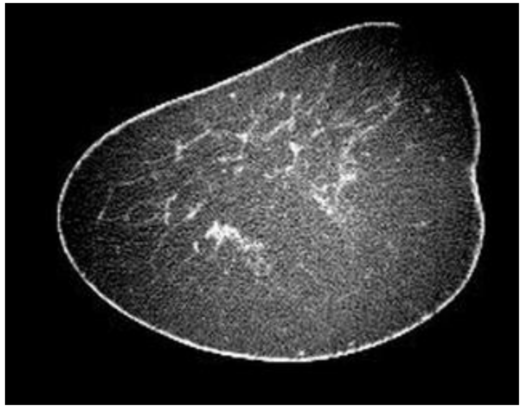
High Scatter environment



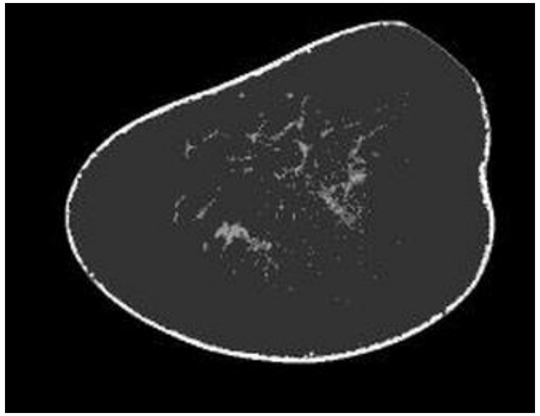


Cupping Artifact

Mathematical Flat Fielding of Breast CT images



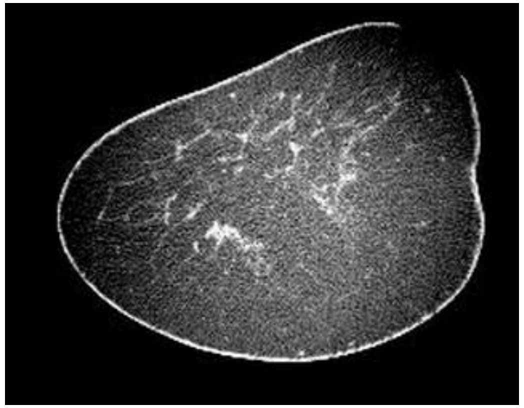
original image



segmented image

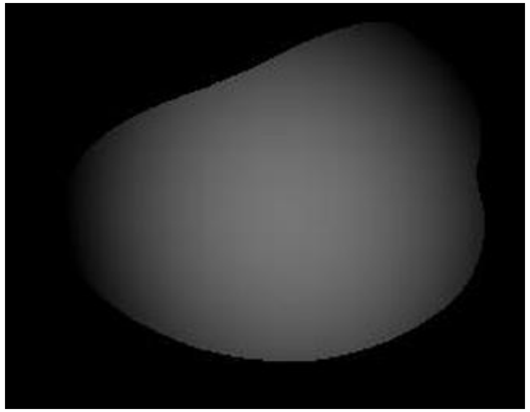
$$\mathbf{g}_A = \mathbf{Q}_A \boldsymbol{\beta} + \boldsymbol{\varepsilon}$$

$$\mathbf{Q}_A = \begin{bmatrix} \mathbf{1} & \mathbf{x}_A & \mathbf{y}_A & \mathbf{z}_A & \mathbf{x}_A\mathbf{y}_A & \mathbf{x}_A\mathbf{z}_A & \mathbf{y}_A\mathbf{z}_A & \mathbf{x}_A^2 & \mathbf{y}_A^2 & \mathbf{z}_A^2 \end{bmatrix}$$



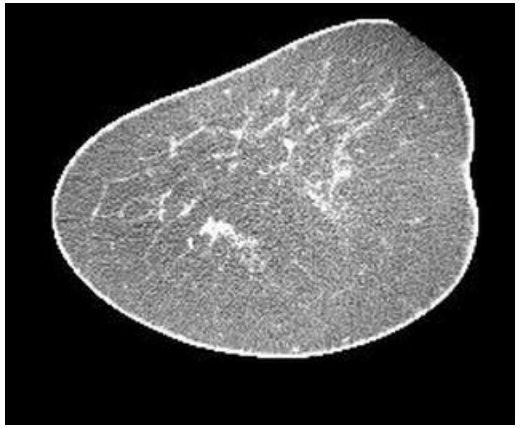
original image

–



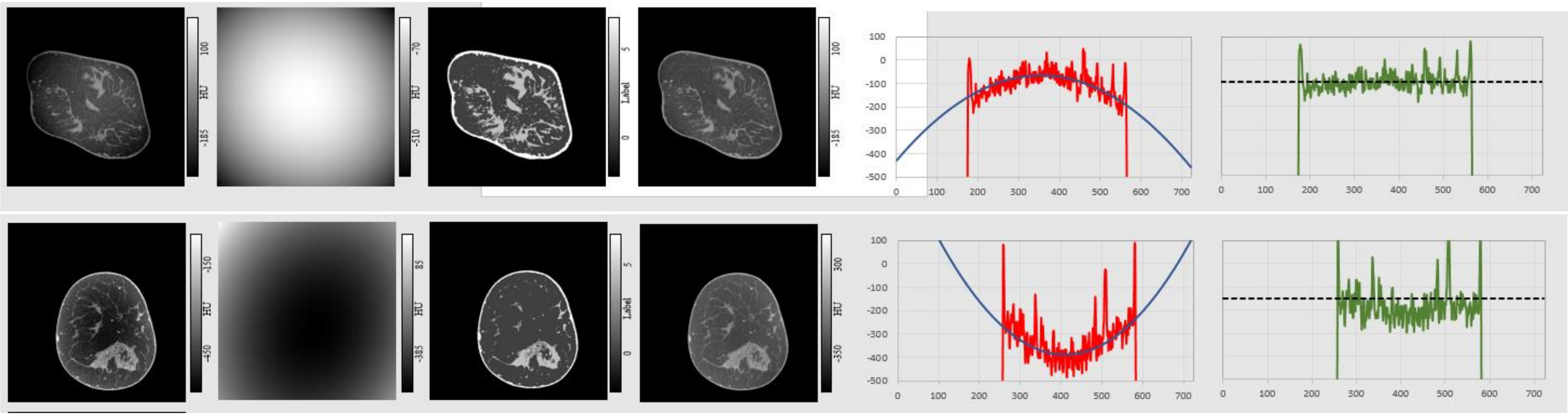
low order fit

=

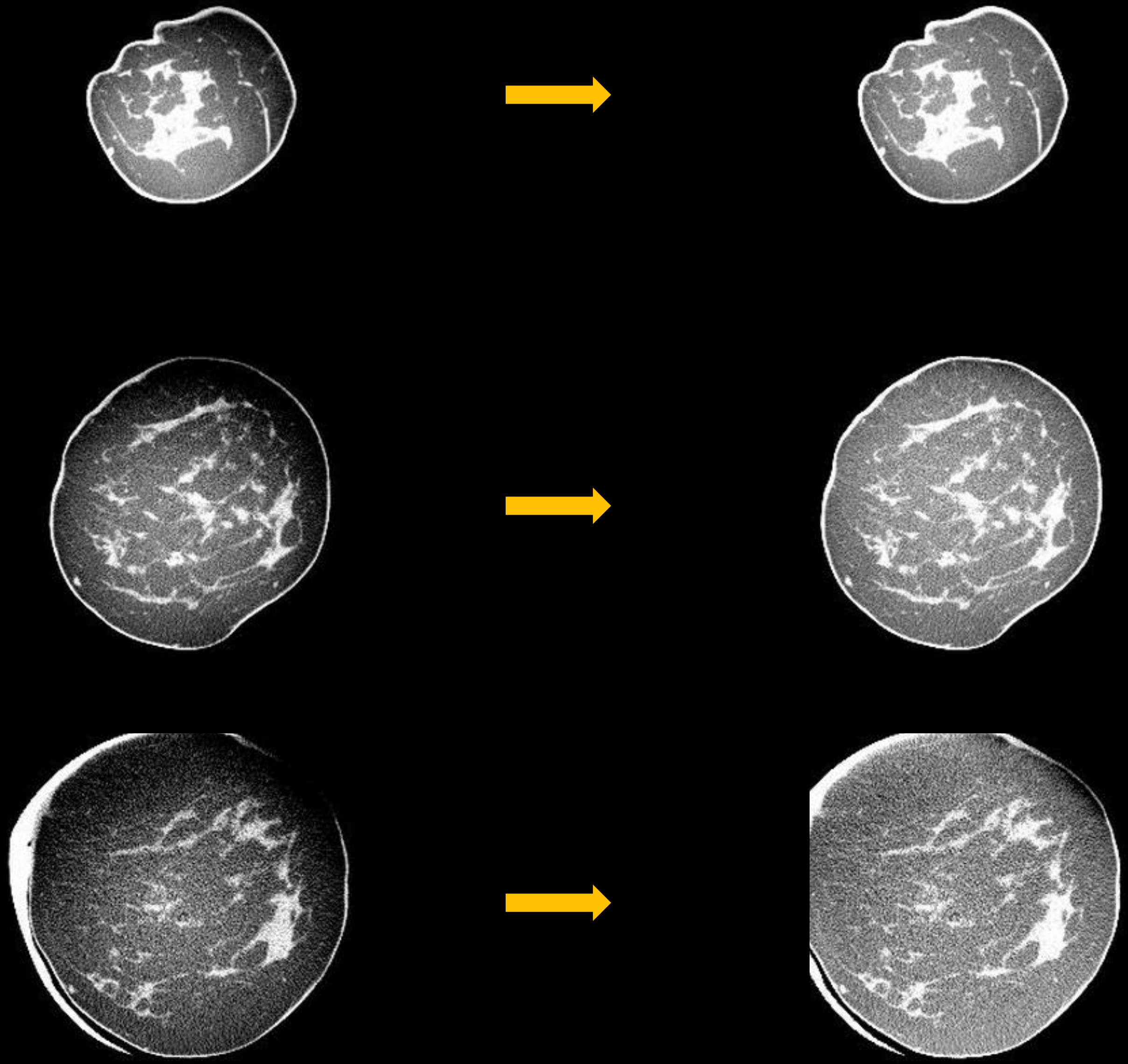


corrected image

capping



cupping



original corrected

Breast CT: *Technology development and clinical potential*

Introduction

Technology Development

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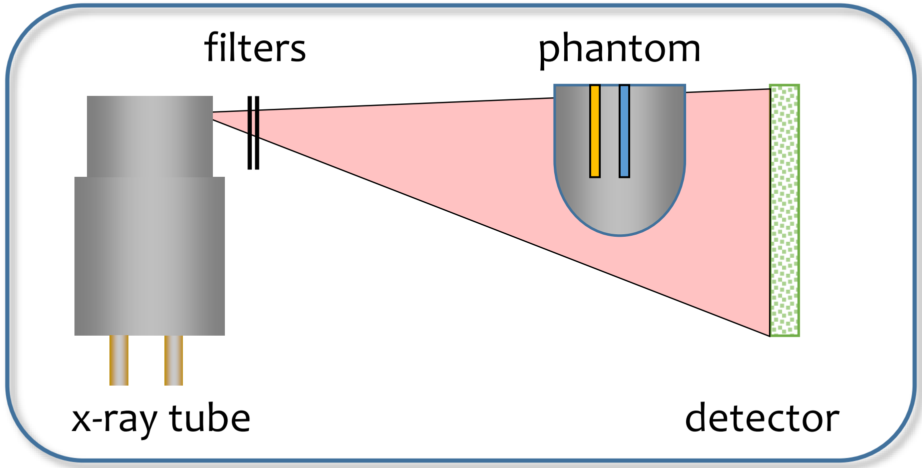
Summary

Spectral Optimization

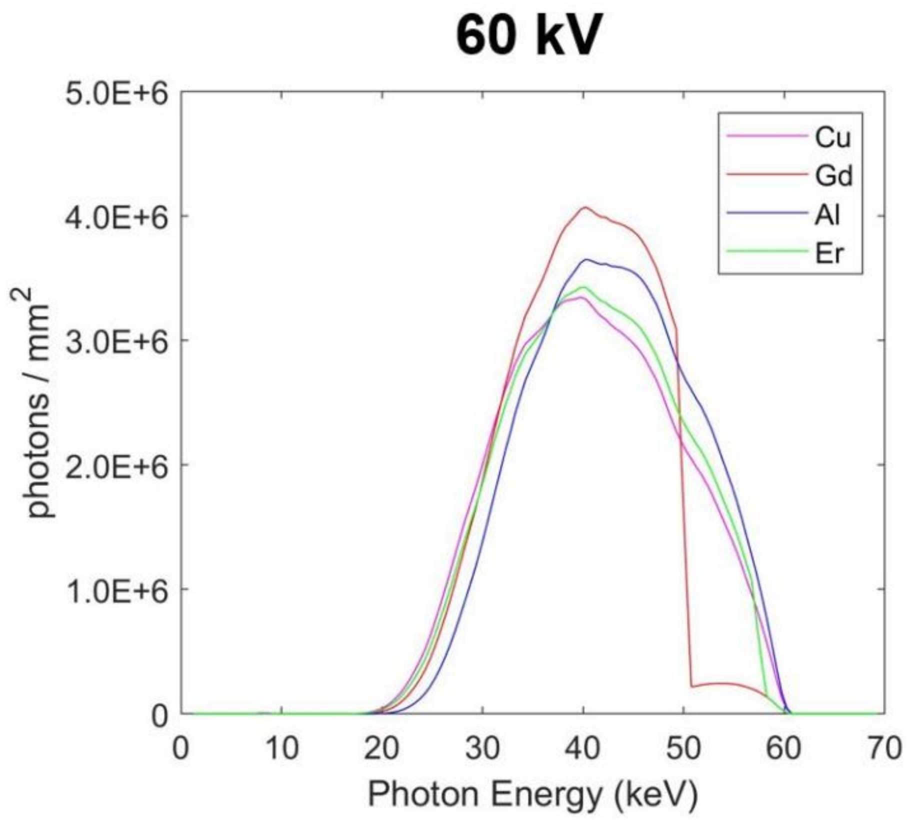


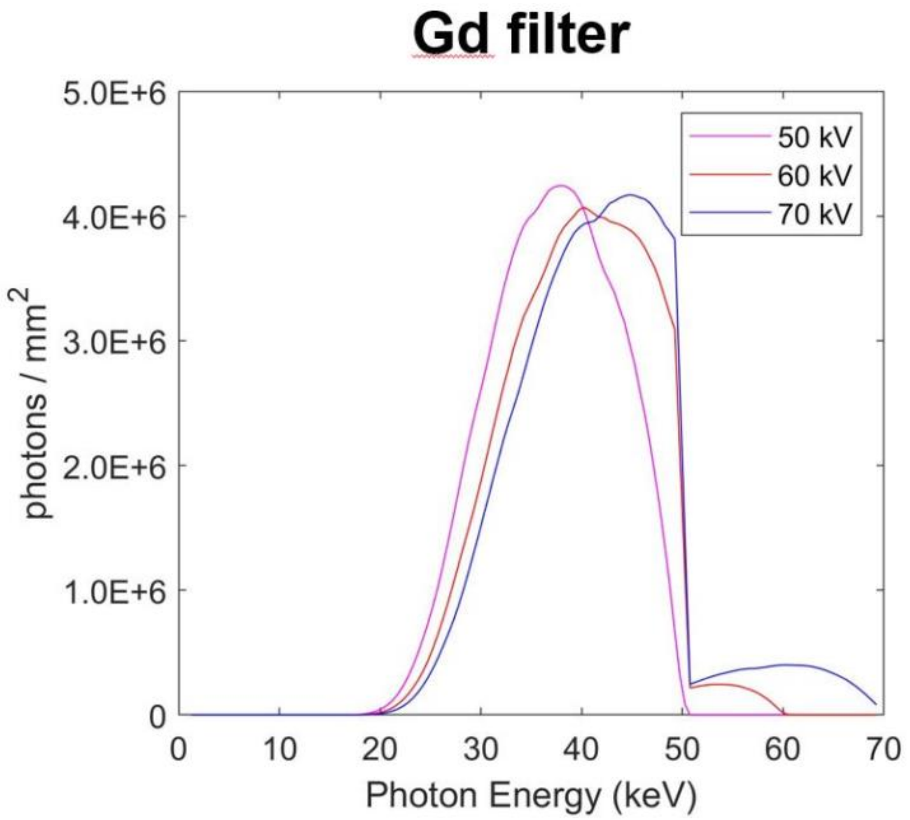
Spectral Optimization:

- Physical measurements
- Tube potential and filtration studies
- Soft tissue (adipose/glandular)
- Iodine contrast (iodine/adipose)

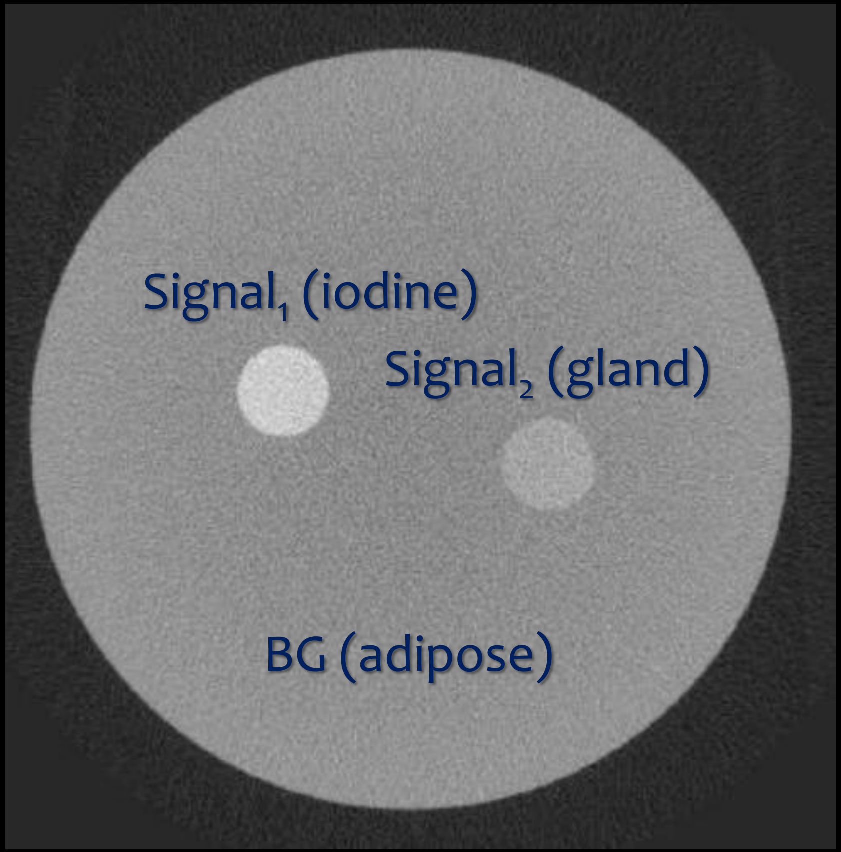
Spectral Optimization:

- Modeled spectra using TASMICS
- Dose calculated from Monte Carlo studies

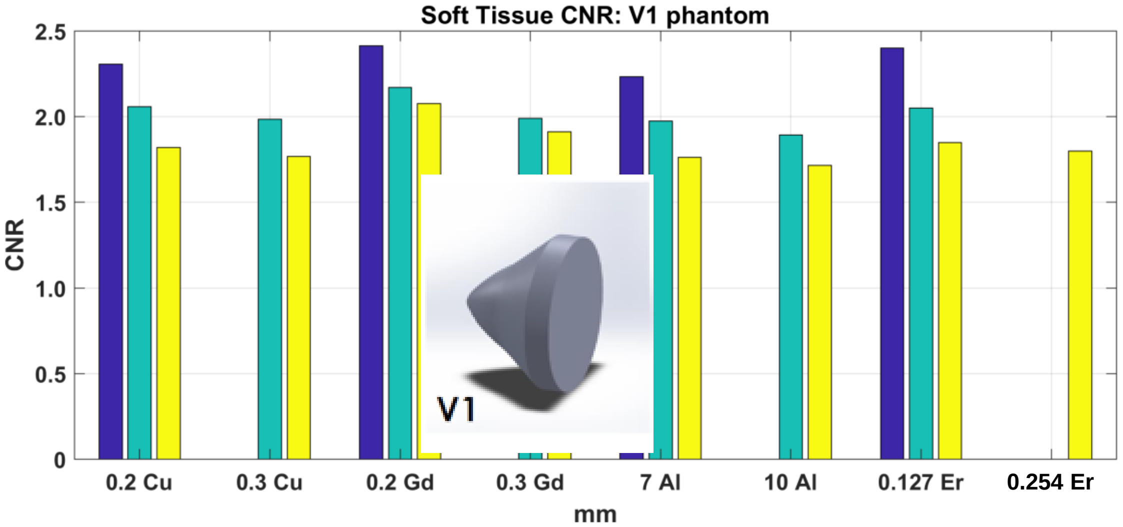


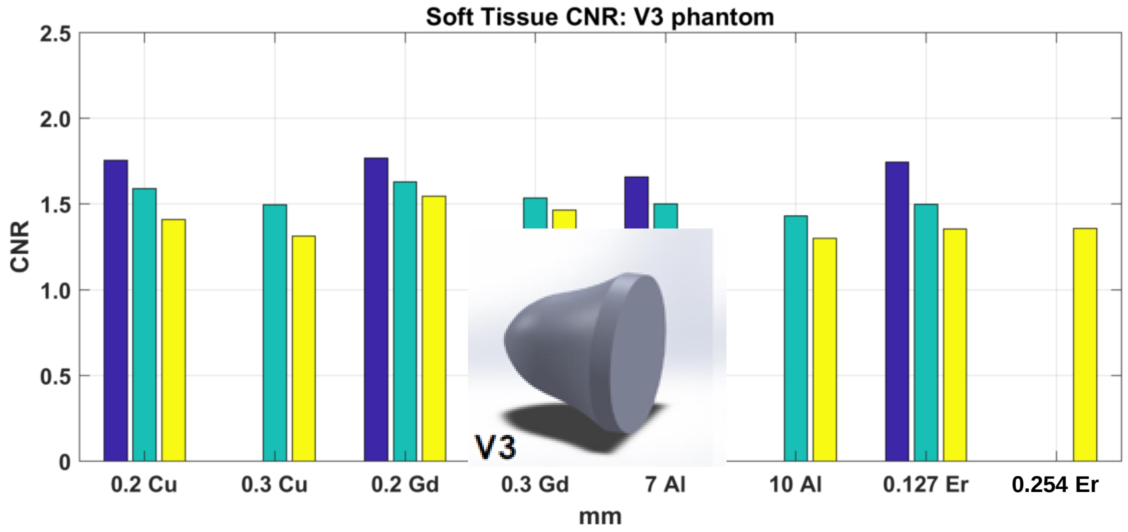


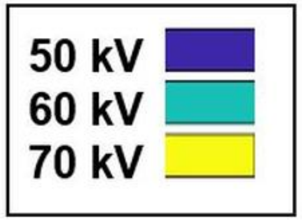
Contrast to Noise evaluation

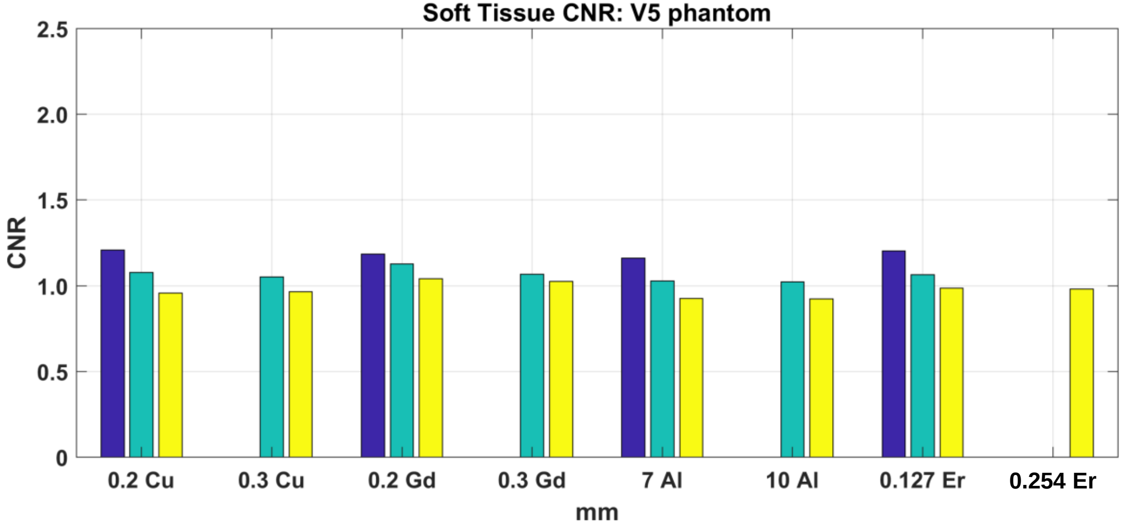


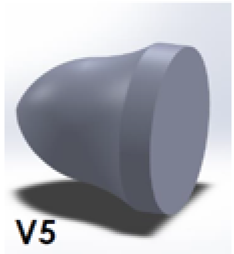
$$CNR = [M_{signal} - M_{bg}] / \sigma_{bg}$$



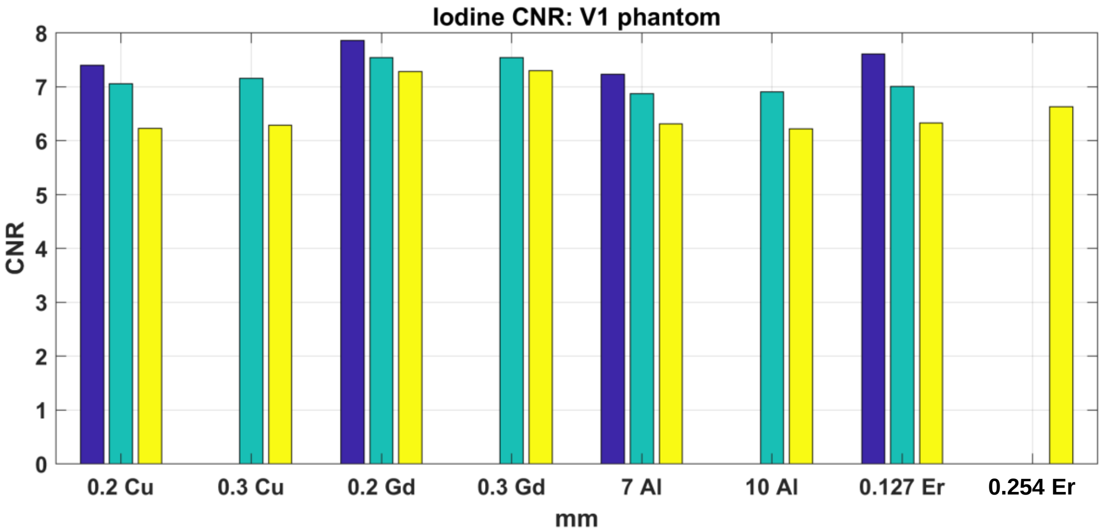


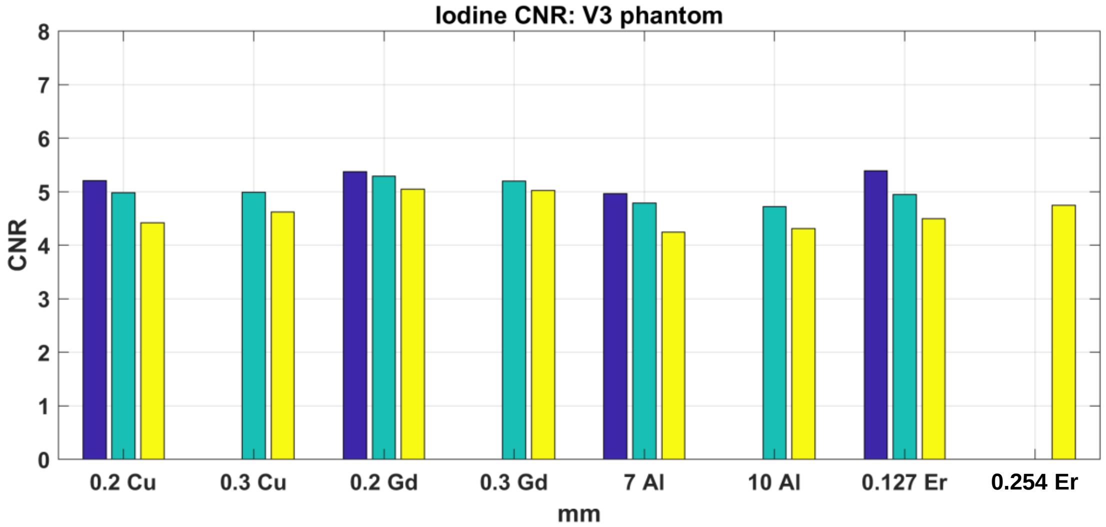


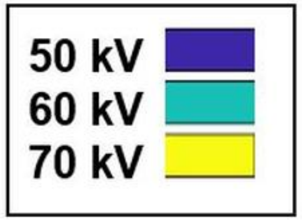


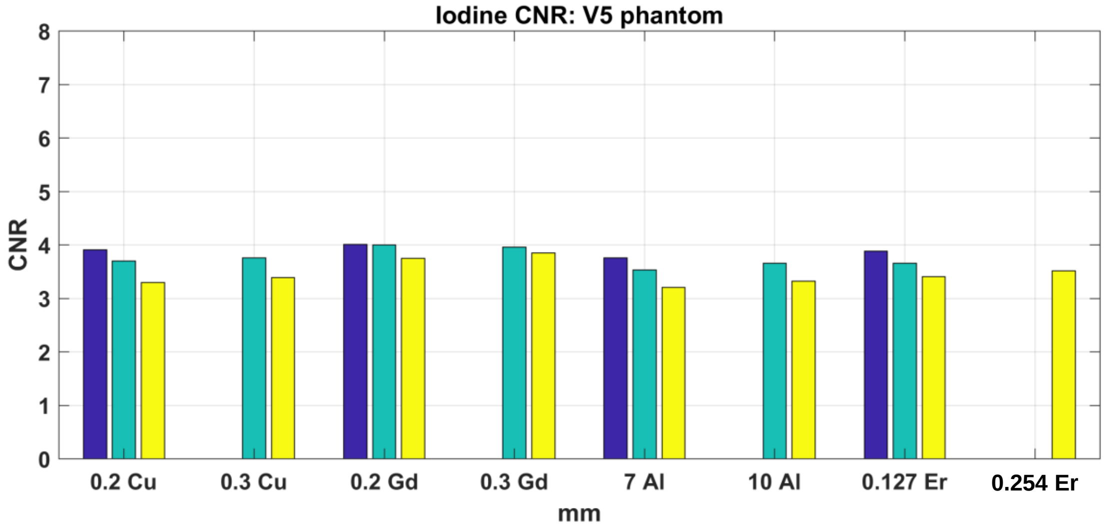


Soft Tissue CNR


Iodine CNR: V1 phantom
CNR
0
1
2
3
4
5
6
7
8
0.2 Cu
0.3 Cu
0.2 Gd
0.3 Gd
7 Al
10 Al
0.127 Er
0.254 Er
mm


Iodine CNR: V3 phantom
CNR
0
1
2
3
4
5
6
7
8
0.2 Cu
0.3 Cu
0.2 Gd
0.3 Gd
7 Al
10 Al
0.127 Er
0.254 Er
mm


50 kV
60 kV
70 kV


Iodine CNR: V5 phantom
CNR
0
1
2
3
4
5
6
7
8
0.2 Cu
0.3 Cu
0.2 Gd
0.3 Gd
7 Al
10 Al
0.127 Er
0.254 Er
mm

Iodine CNR

Breast CT: *Technology development and clinical potential*

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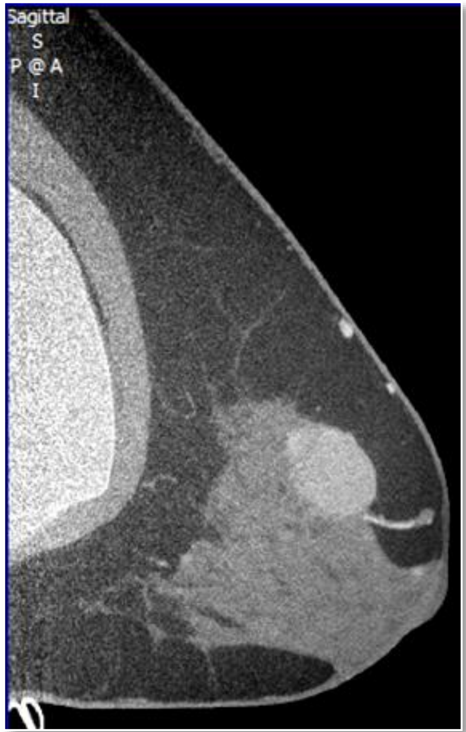

The Breast Tomography Project

University of California, Davis

Breast CT: *Technology development and clinical potential*

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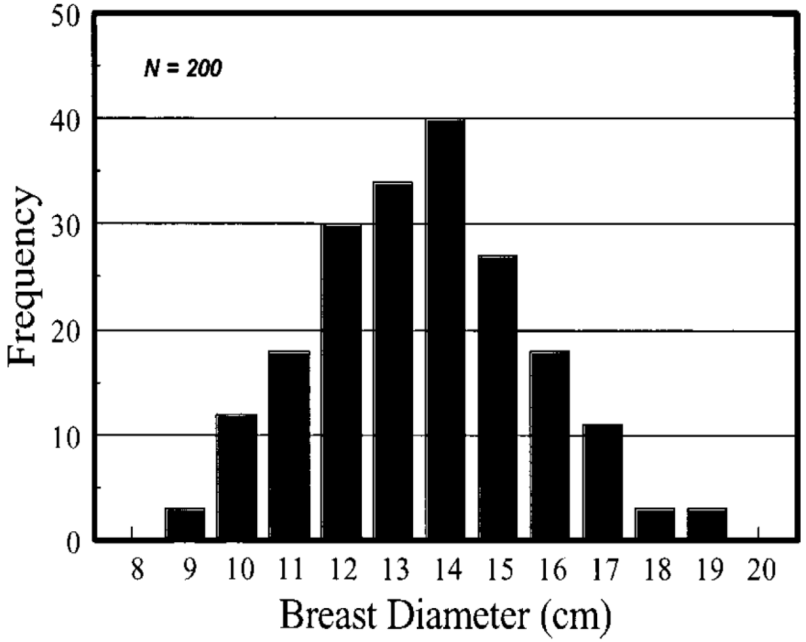
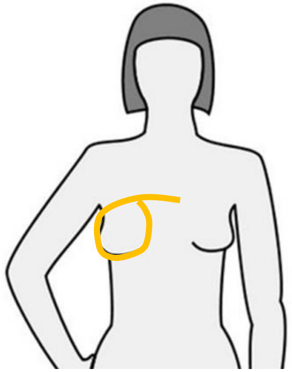
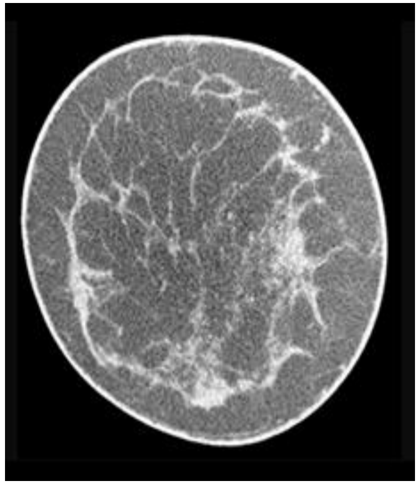
Phase 1: Cylinders

Radiation dose is size dependent!



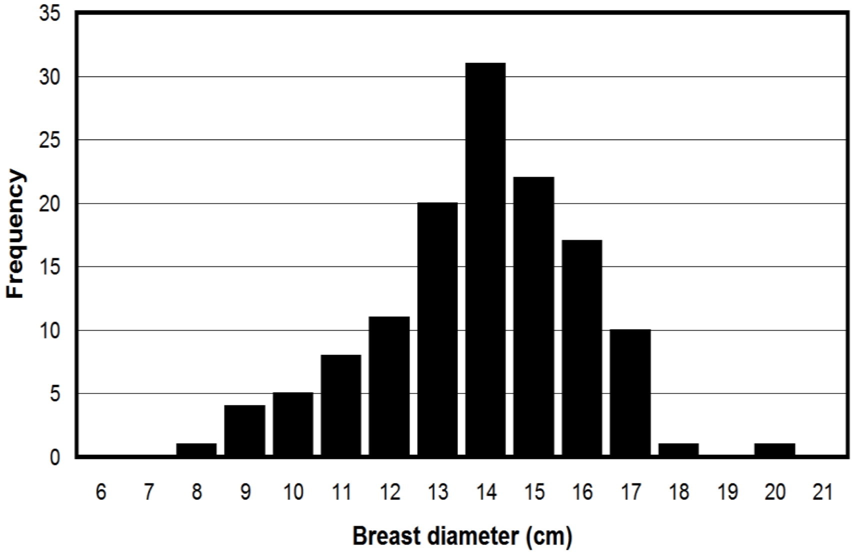
2001 tape measure results (N = 200)



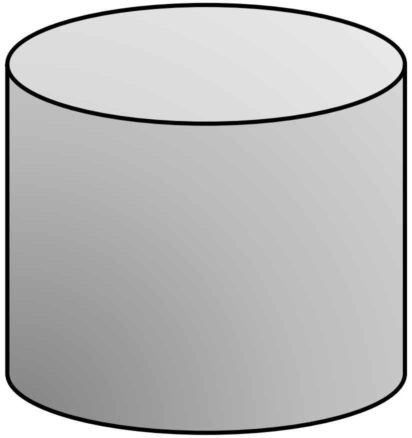


X = 13.4 cm
σ= 2.0 cm
Median = 13.6 cm

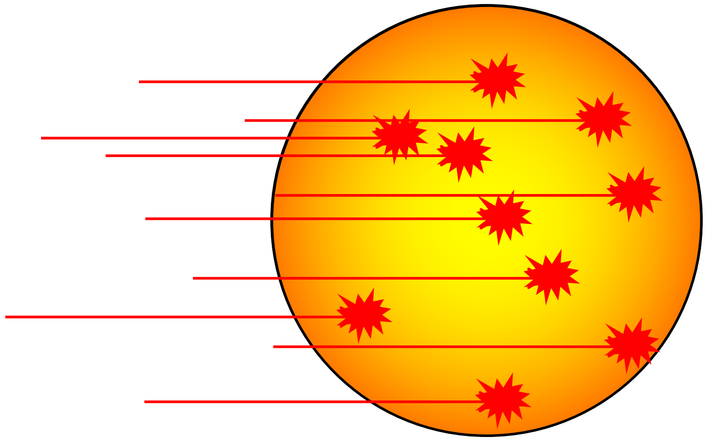
2008 assessment on bCT images (N = 137)



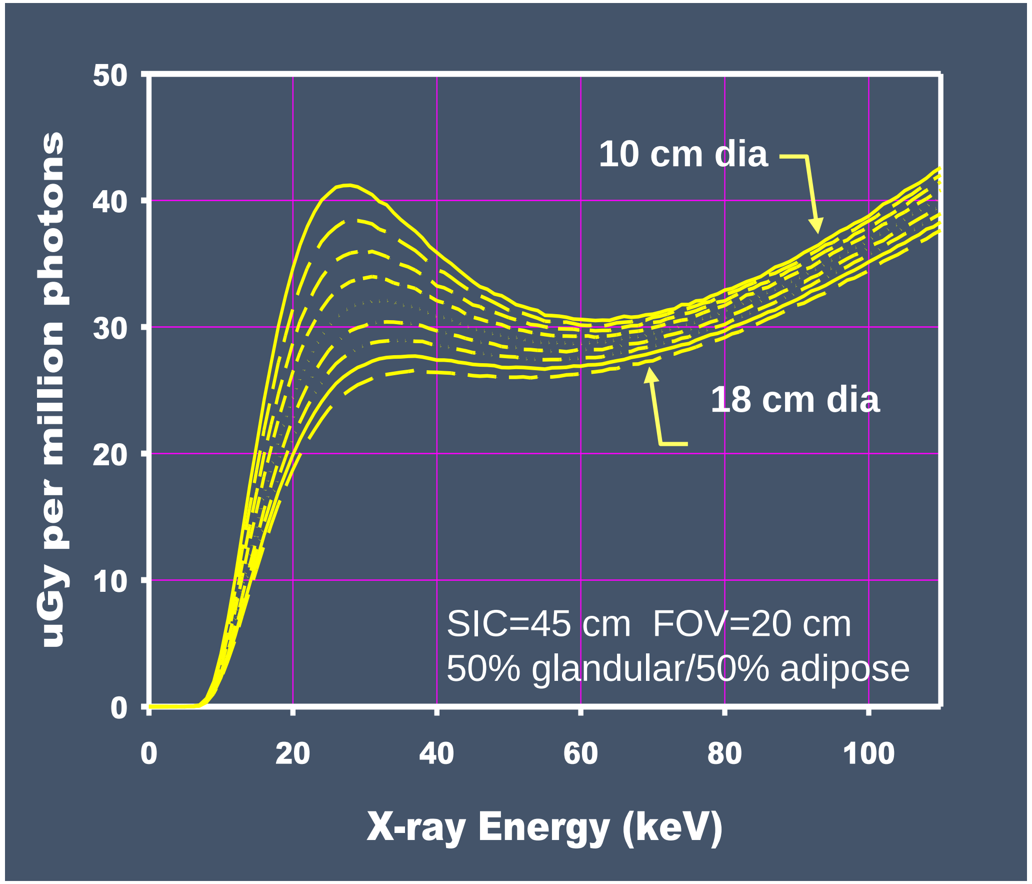
Monte Carlo Assessment of Dose Deposition



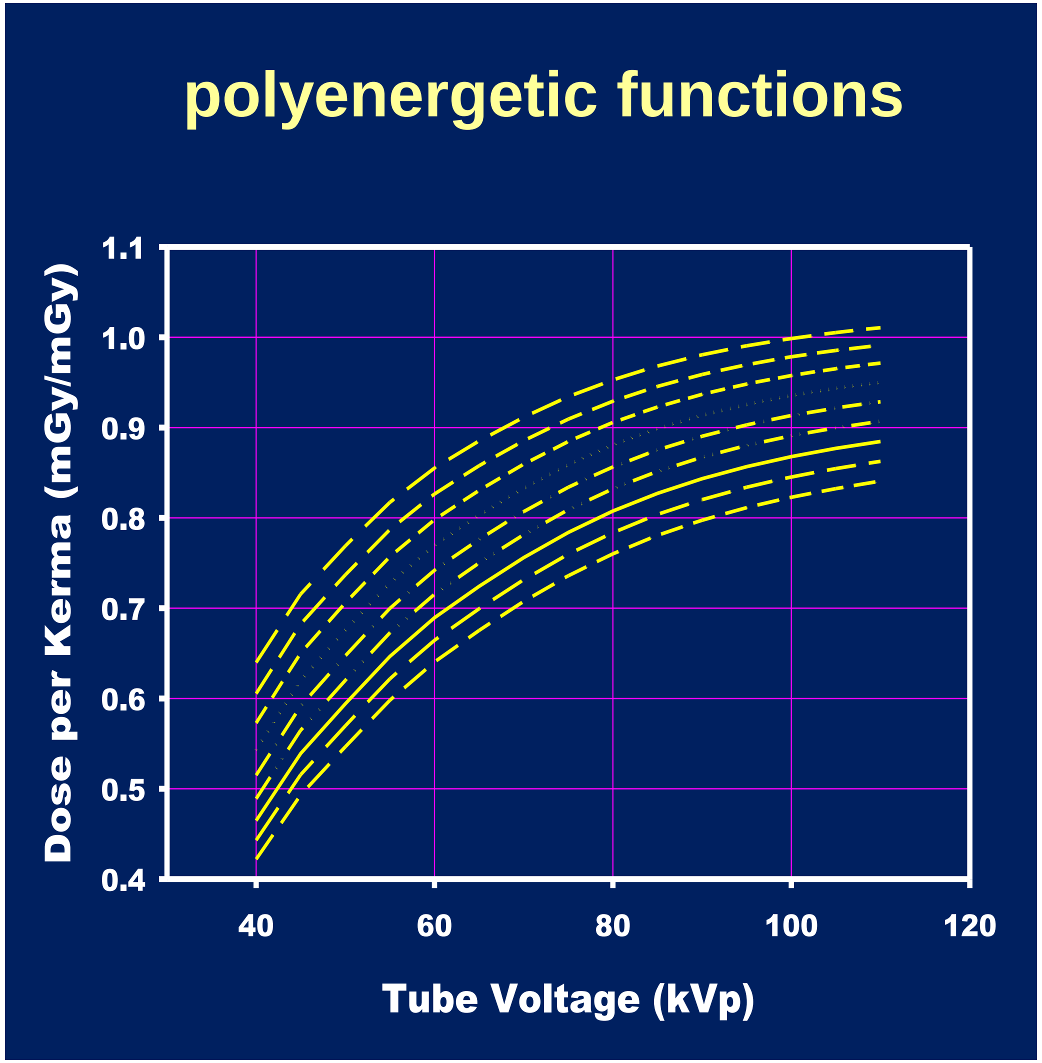
breast modeled as a cylinder



monoenergetic functions



Breast CT Dose (UCD) equivalent to 2-view mammography



Radiation Dose (2003)

A comprehensive analysis of DgN_{CT} coefficients for pendant-geometry cone-beam breast computed tomography

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N. Shah
Department of Radiology, U.C. Davis Medical Center, 4701 X Street, X-ray Imaging Laboratory, Sacramento, California 95817

T. R. Nelson
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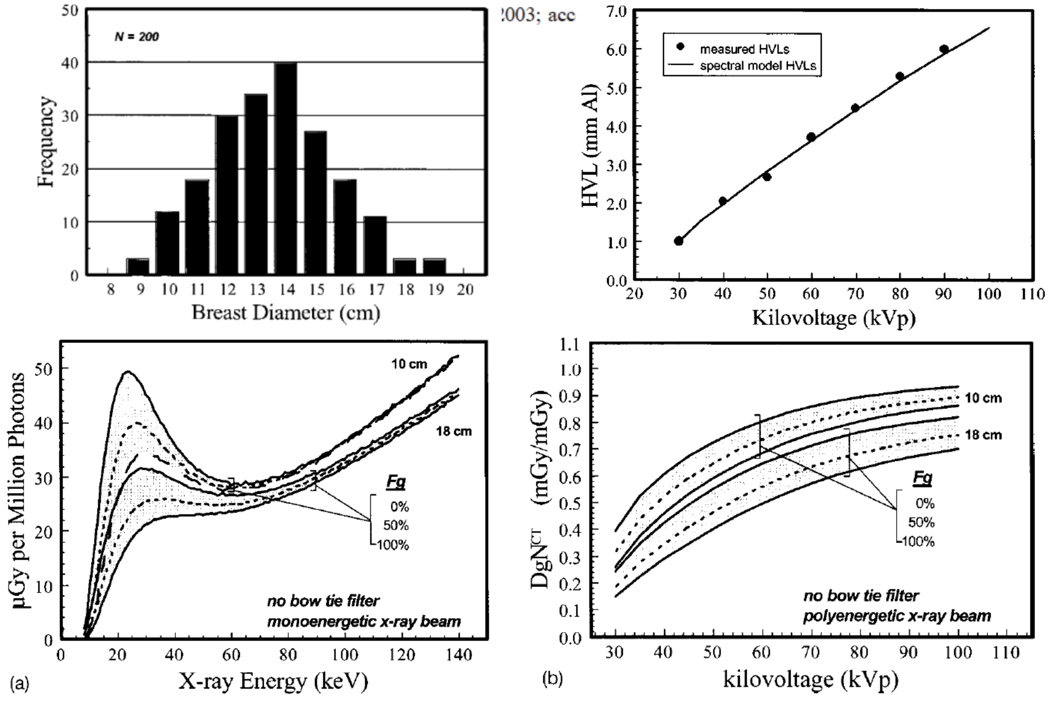

Breast CT: *Technology development and clinical potential*

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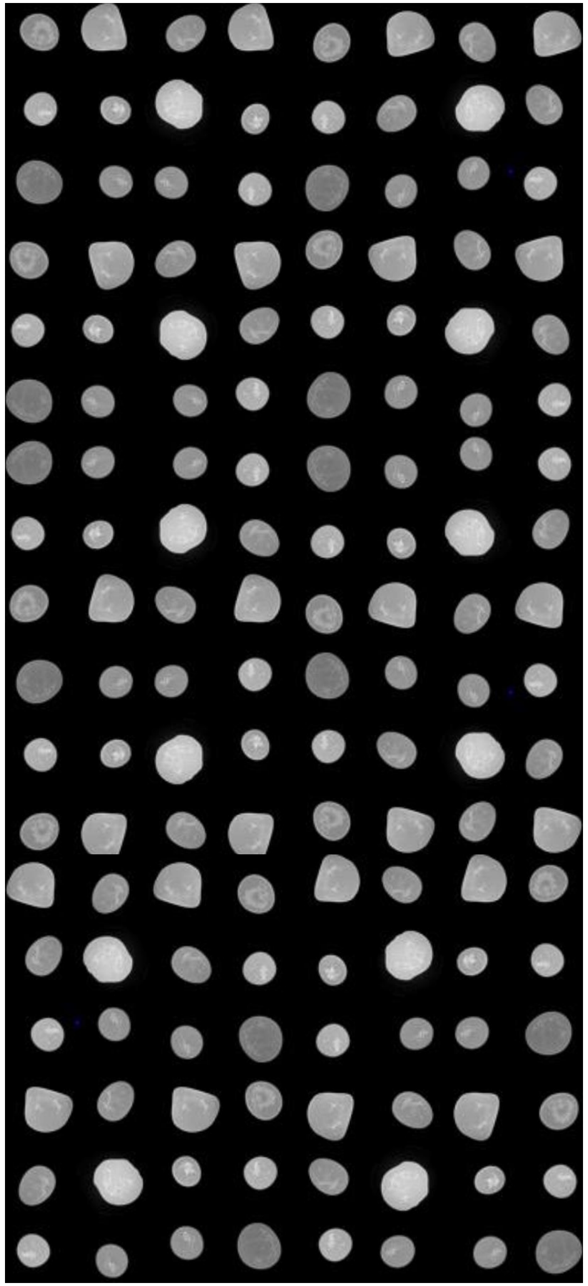
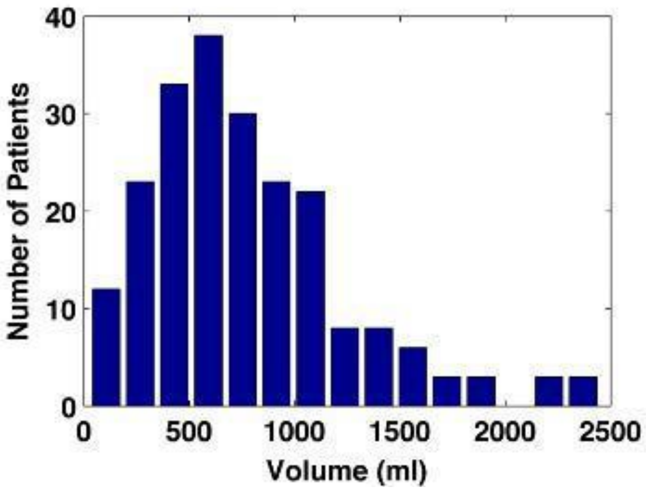
Phase 2: Breast Shapes

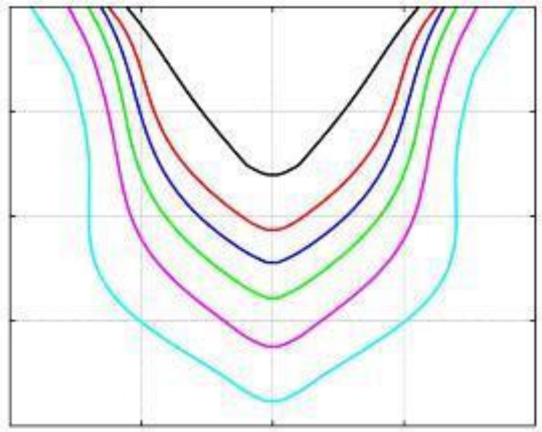
219 Breast CT data sets



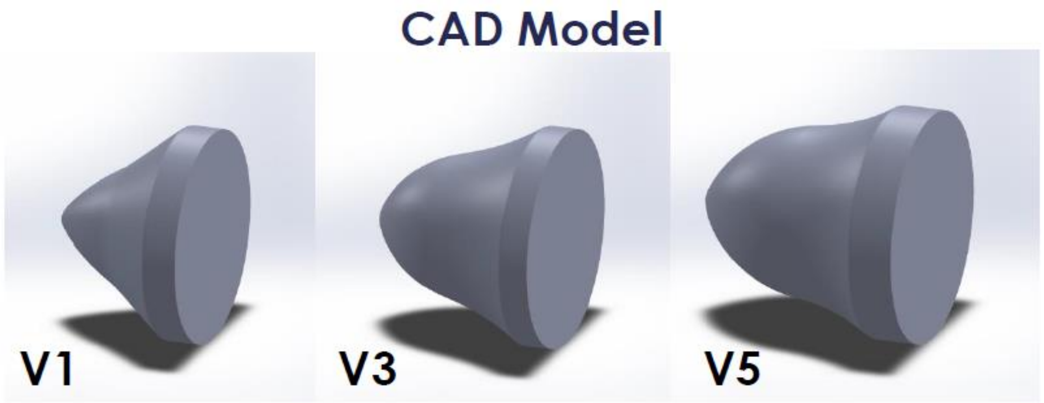
categorized by breast volume placed into 5 groups (43 per)



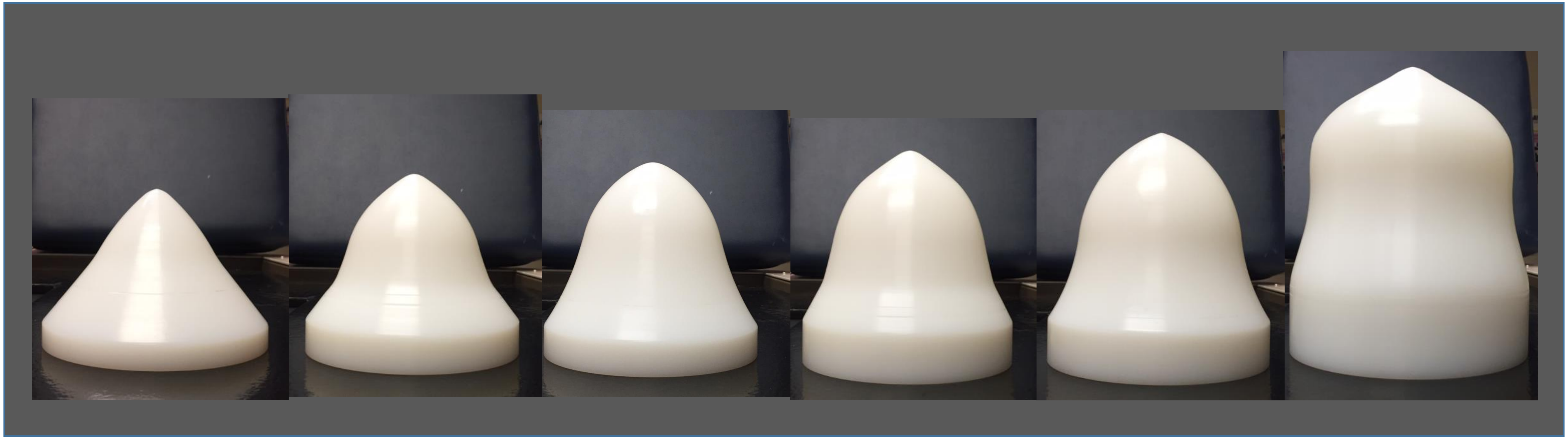
Each group used to compute median shape



V1 – V2 – V3 – V4 – V5



Six phantoms (V1-V6)



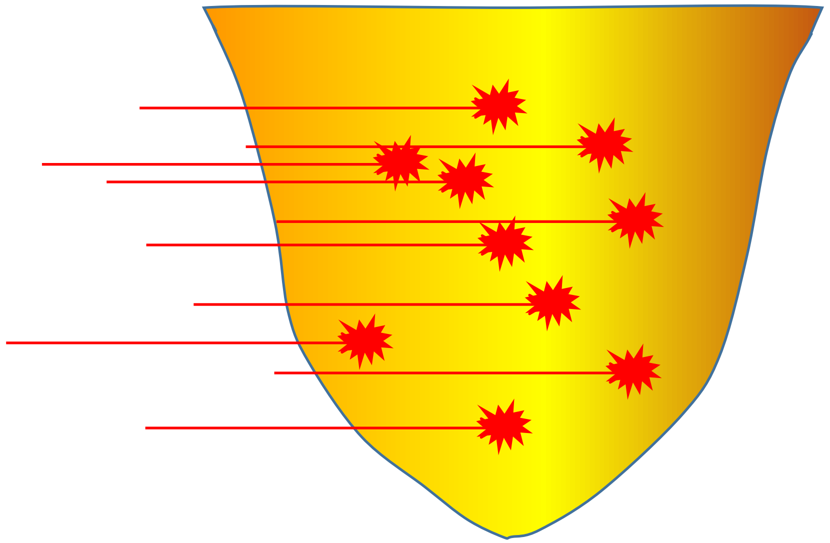
1st | 2nd | 3rd | 4th | 5th | Largest 5 breasts

N = 219 : ~ 5 sets of 43

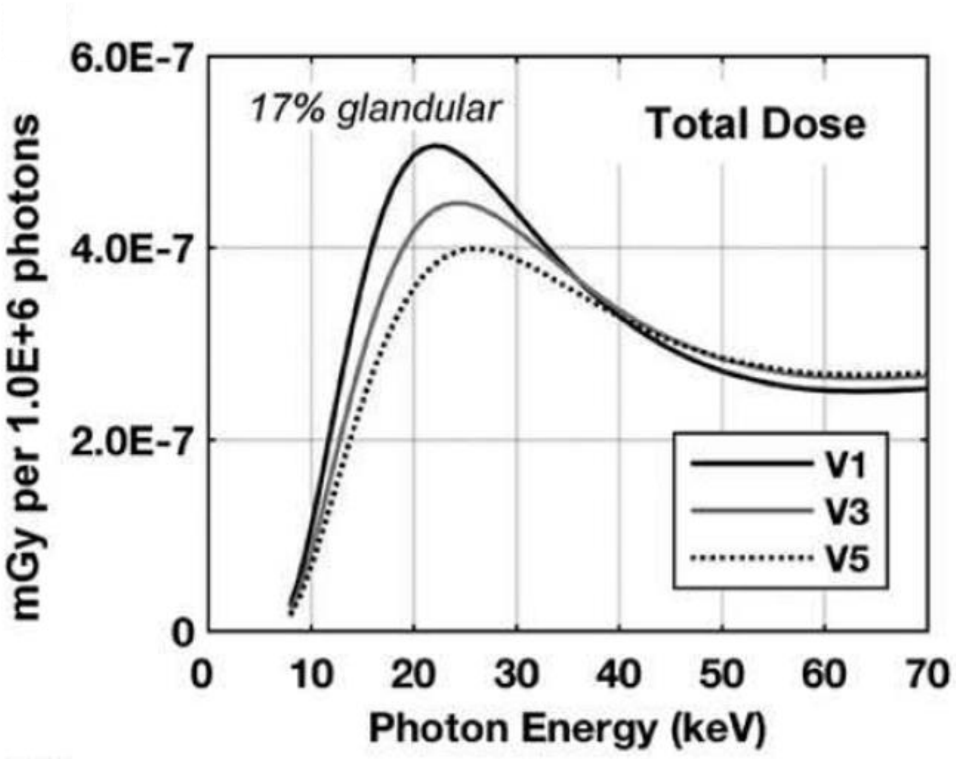
Mean volume and shape in each quintile

Monte Carlo Assessment of Dose Deposition

realistic breast shaped modeled



monoenergetic functions



Average glandular dose coefficients for pendant-geometry breast CT using realistic breast phantoms

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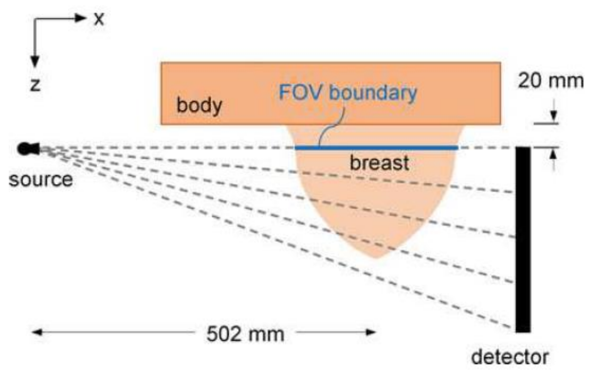
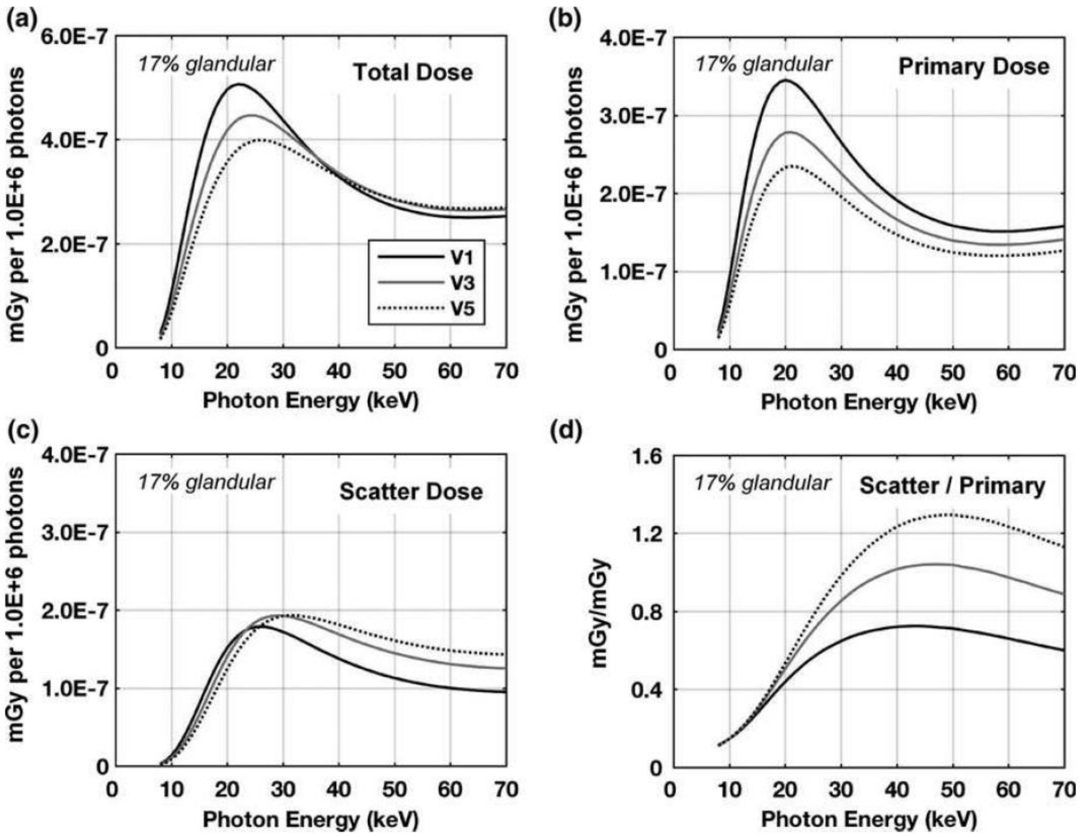
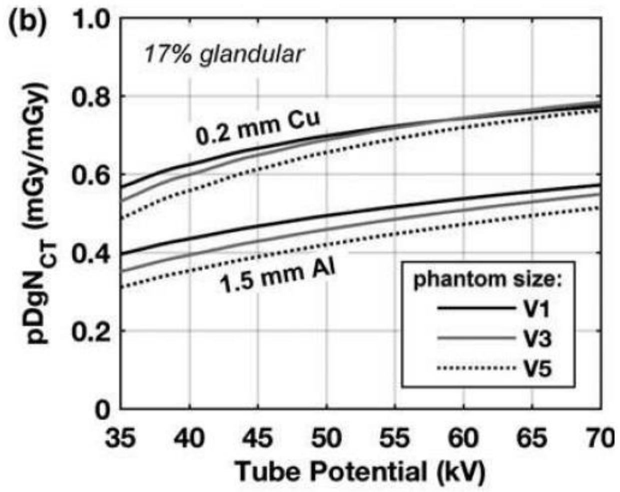
(Received 17 March 2017; revised 6 June 2017; accepted for publication 26 June 2017; published 20 August 2017)



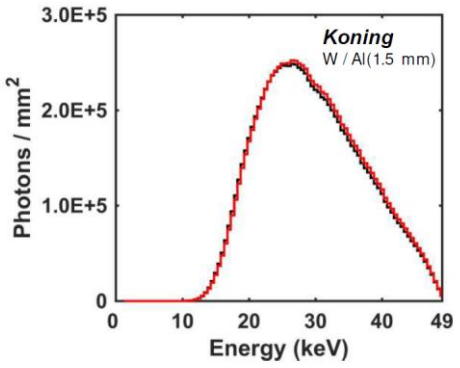
geometric model



MC-derived monoenergetic DgN_{CT} values



Polyenergetic DgN_{CT} values



spectral model(s)

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Phase 3: Skin & density distributions

The effect of skin thickness determined using breast CT on mammographic dosimetry

Shih-Ying Huang, John M. Boone,[a] and Kai Yang
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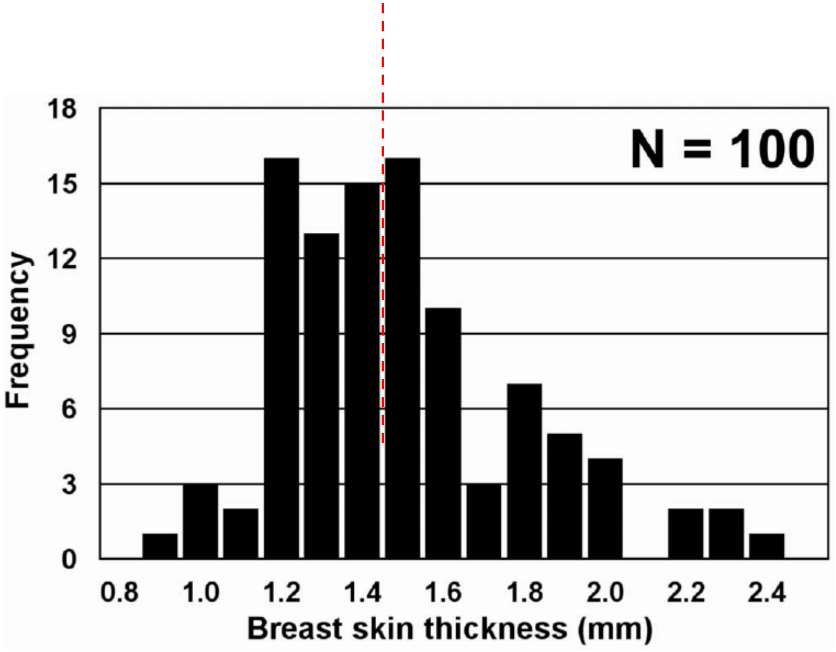
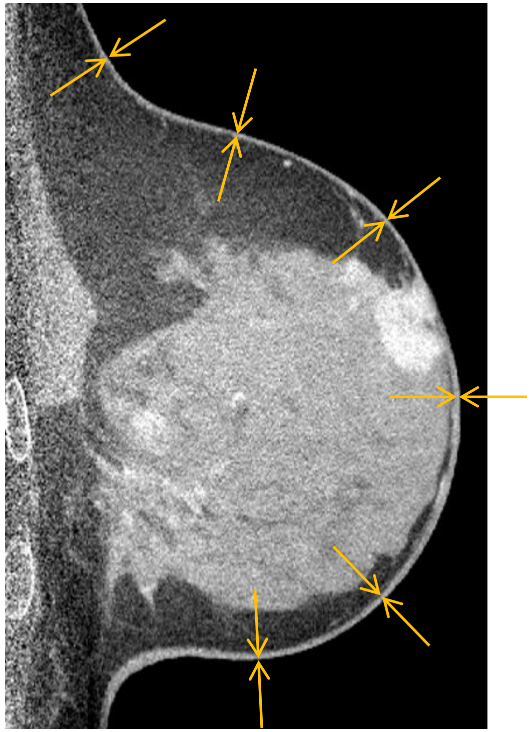
(Received 24 October 2007; revised 15 January 2008; accepted for publication 17 January 2008; published 6 March 2008)





Computed skin thickness for 100 women

Skin thickness ~ 1.5 mm

The characterization of breast anatomical metrics using dedicated breast CT

Shih-Ying Huang[a] and John M. Boone[b]
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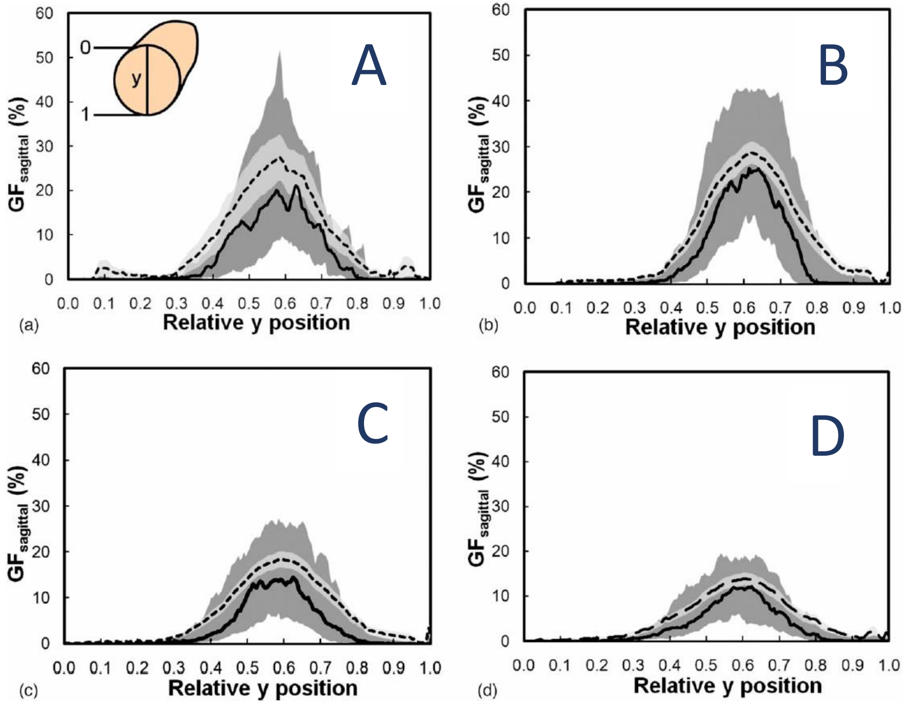
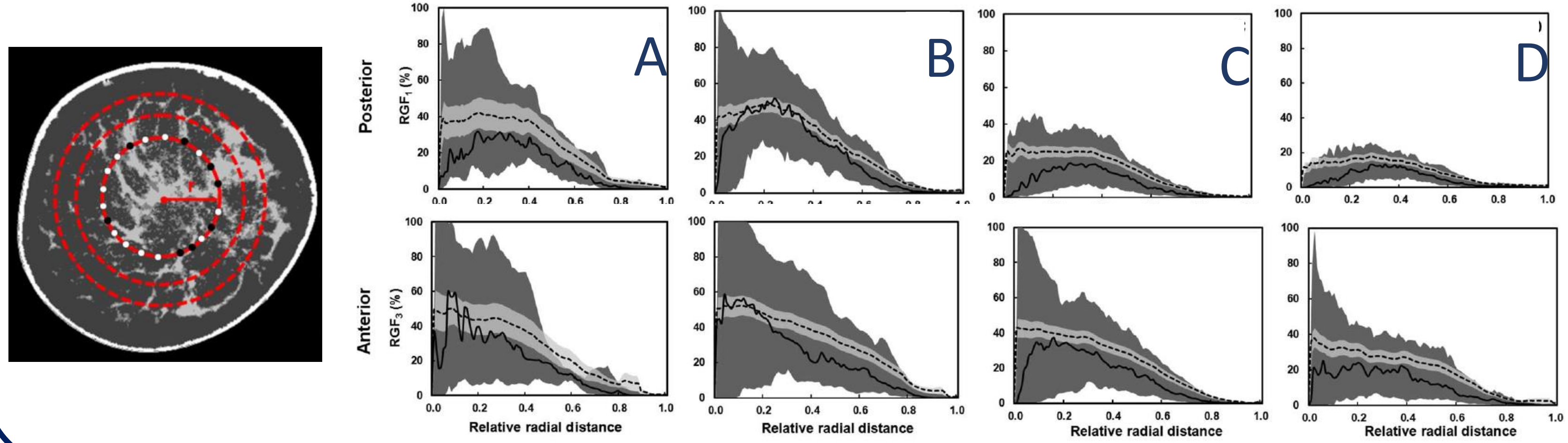
(Received 17 September 2010; revised 23 February 2011; accepted for publication 24 February 2011; published 28 March 2011)

Glandular tissue distributions (coronal plane)

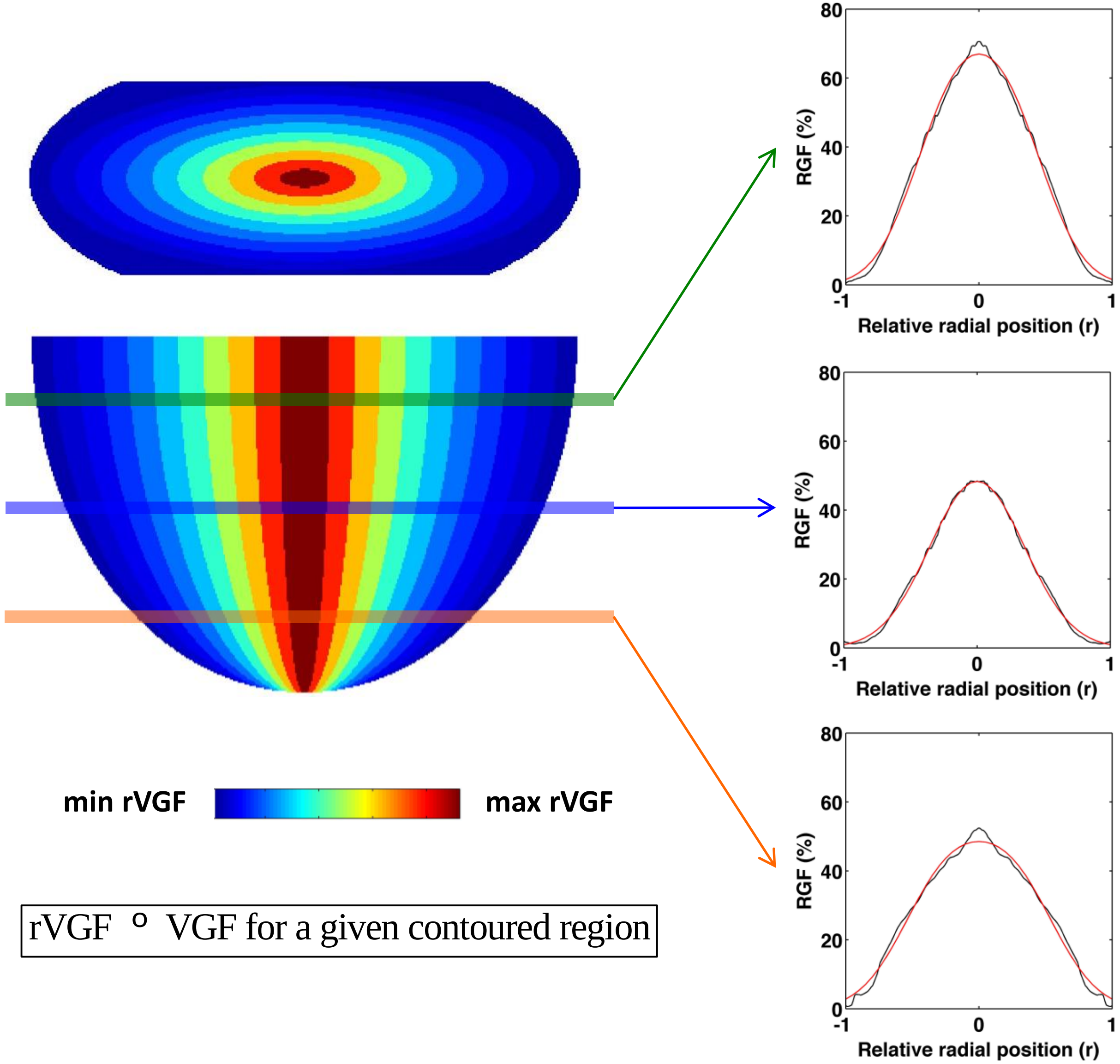


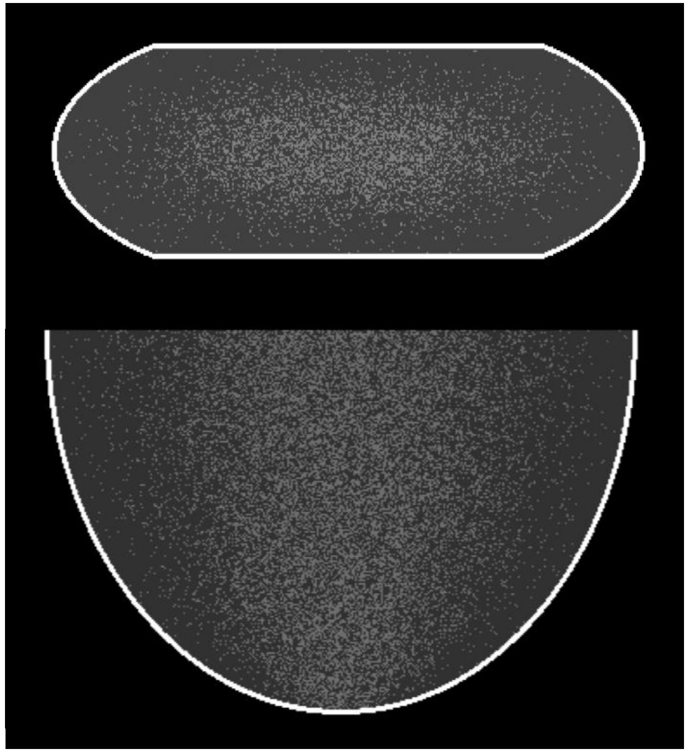
Glandular tissue distributions (sagittal plane)



bra cup size:
A,B,C,D

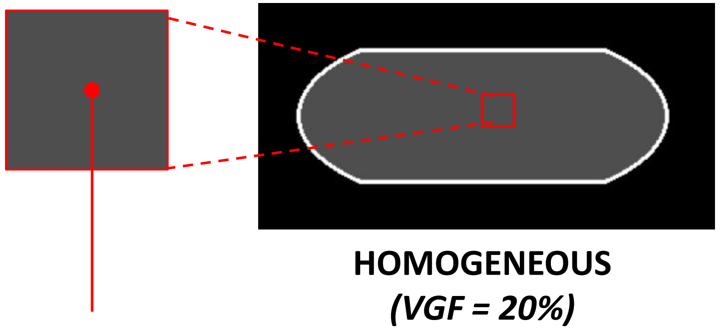
Modeled Radial Glandular Fractions in compressed phantoms → Mammography Dosimetry



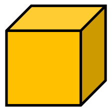


rVGF ° VGF for a given contoured region

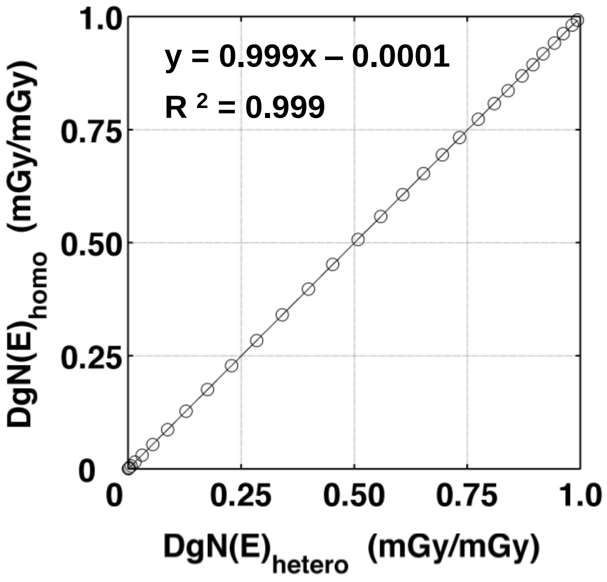
Validating Methodology

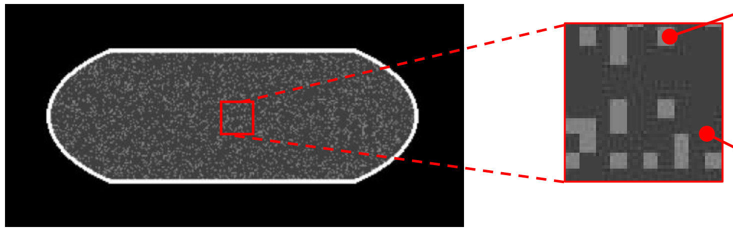


HOMOGENEOUS
(VGF = 20%)

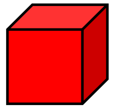


mix of glandular and adipose tissue

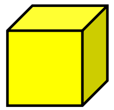




SPATIALLY-INDEPENDENT HETEROGENEOUS
(VGF = 20%)

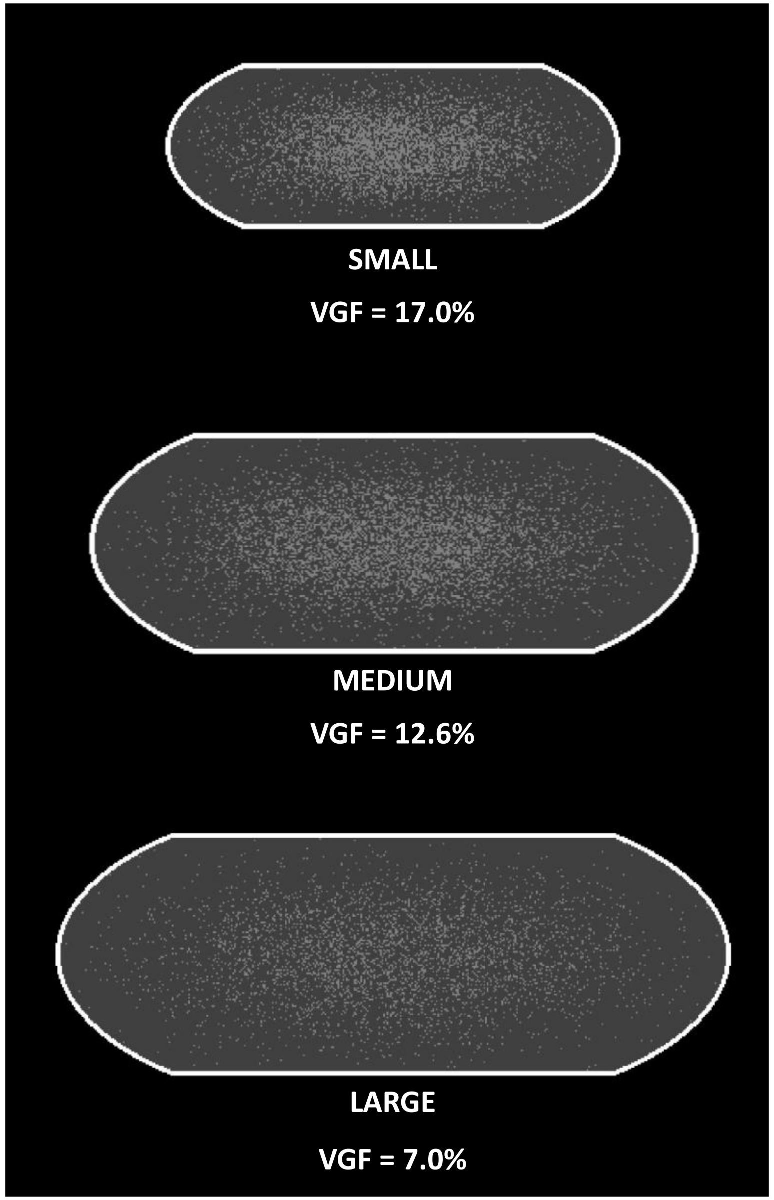


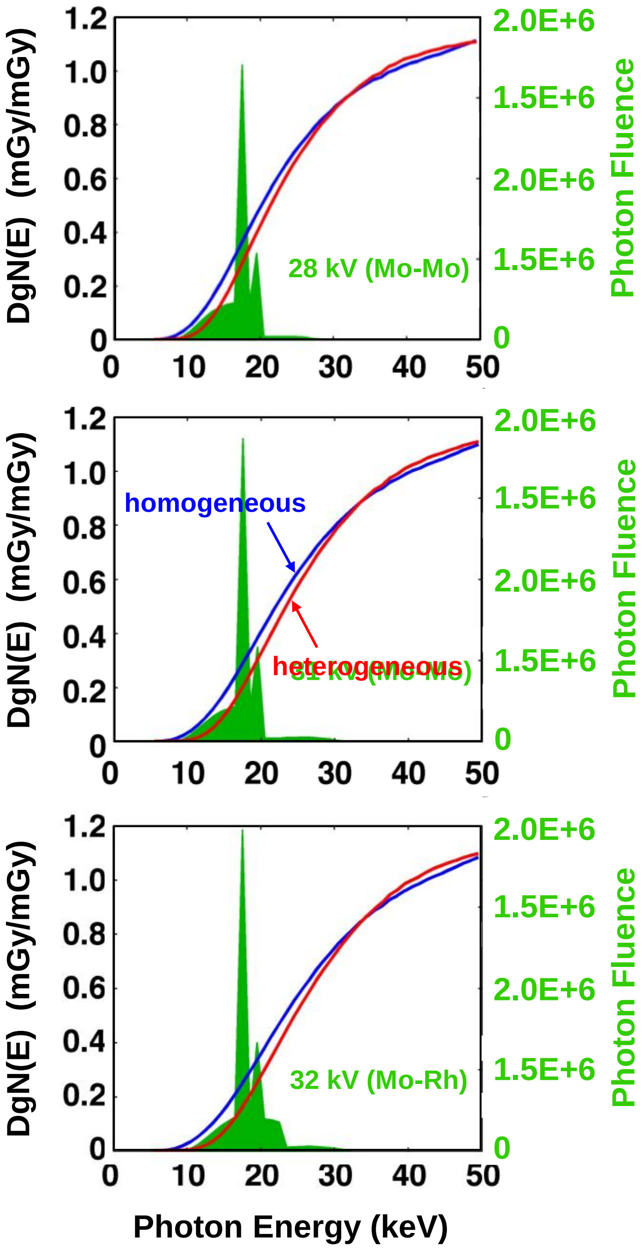
all glandular tissue



all adipose tissue

DgN(E): homogeneous vs. heterogeneous





Breast dose in mammography is about 30% lower when realistic heterogeneous glandular distributions are considered

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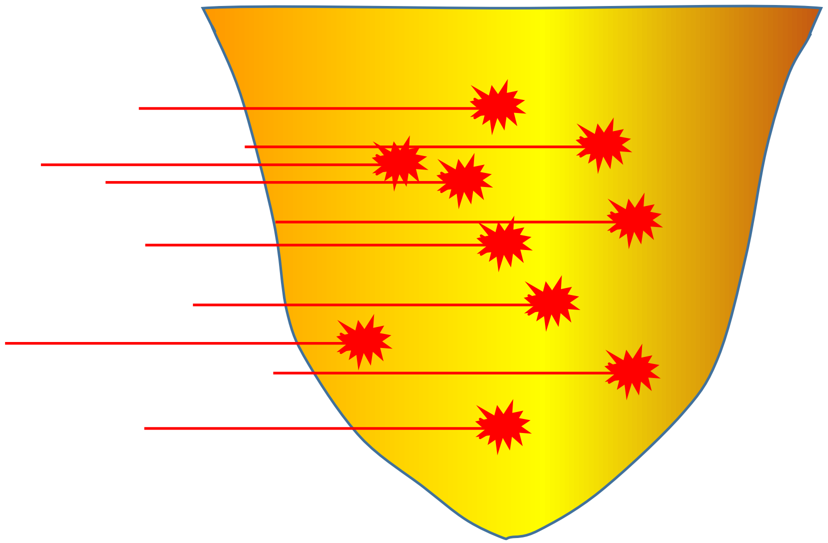
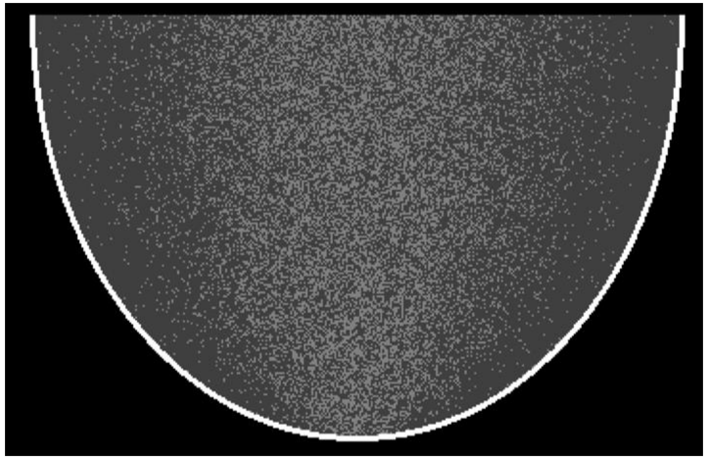
(Received 22 April 2015; revised 11 August 2015; accepted for publication 15 September 2015; published 9 October 2015)

Back to Breast CT Dosimetry

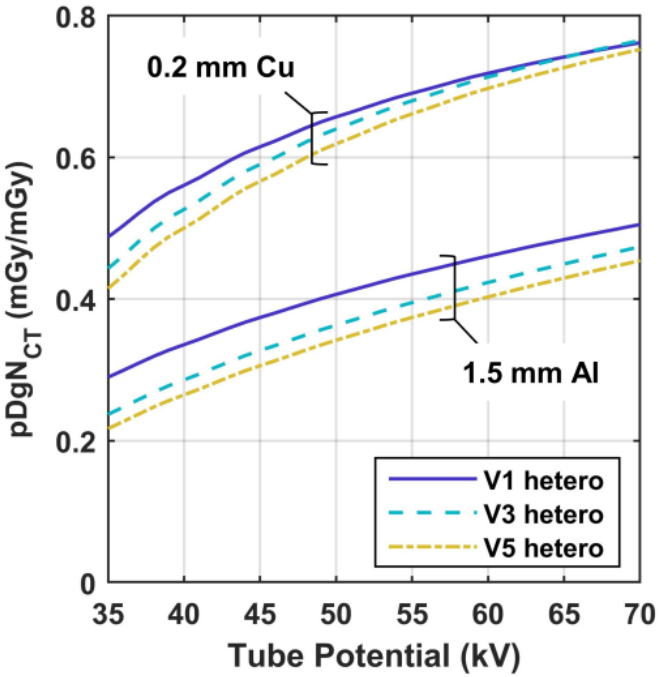
realistic breast shaped modeled

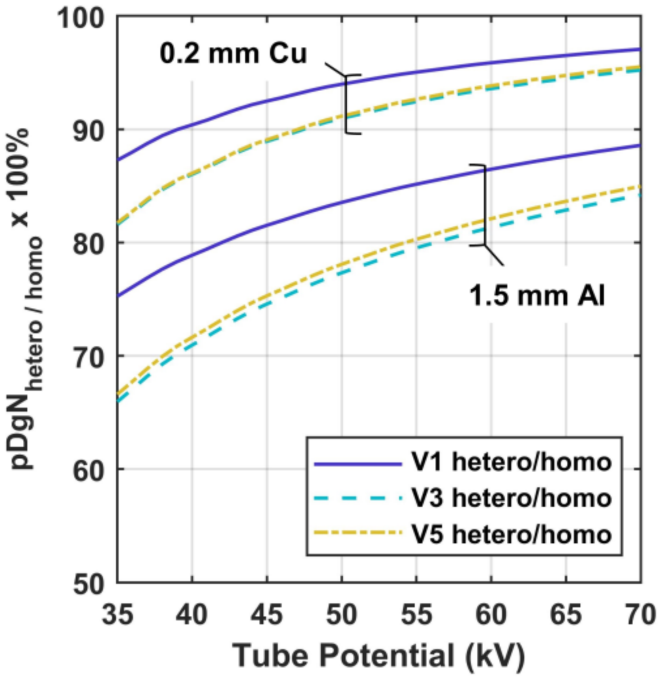




Updated breast CT dose coefficients (DgNCT) using patient-derived breast shapes and fibroglandular distributions

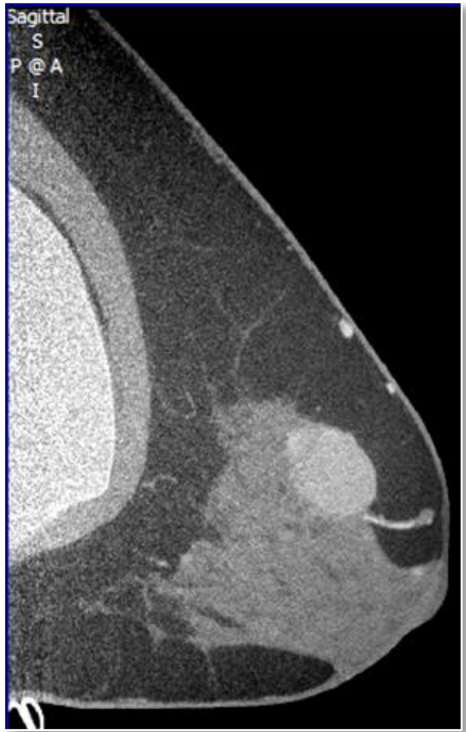
Submitted to Medical Physics Sept 2018





Breast CT: *Technology development and clinical potential*

- Introduction
- Technology Development
- Radiation Dose Assessment
- **Image Quality Metrics**
- Clinical Observations
- Observer Performance
- Other Cool Spinoffs
- Summary



The Breast Tomography Project

University of California, Davis

Breast CT: *Technology development and clinical potential*

Introduction

Technology Development

Radiation Dose Assessment

- Image Quality Metrics

Clinical Observations

Observer Performance

Other Cool Spinoffs

Summary

Spatial Resolution

Performance Metrics

Spatial Resolution

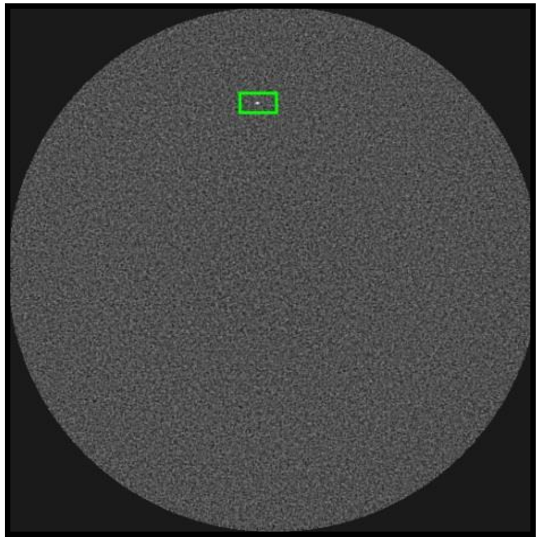
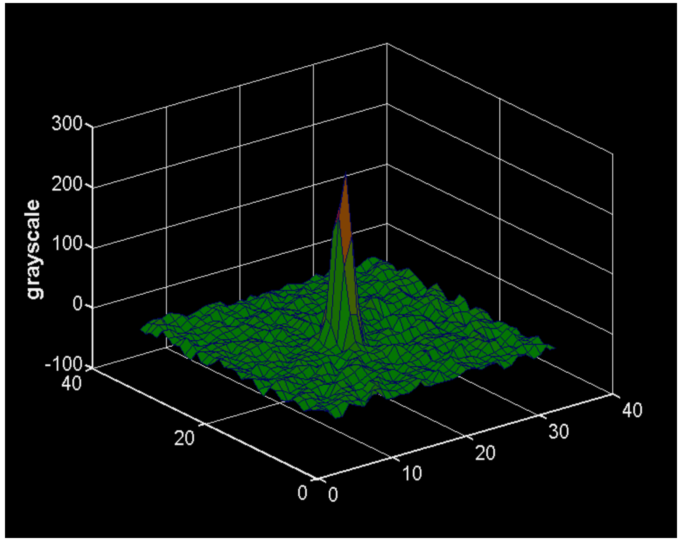
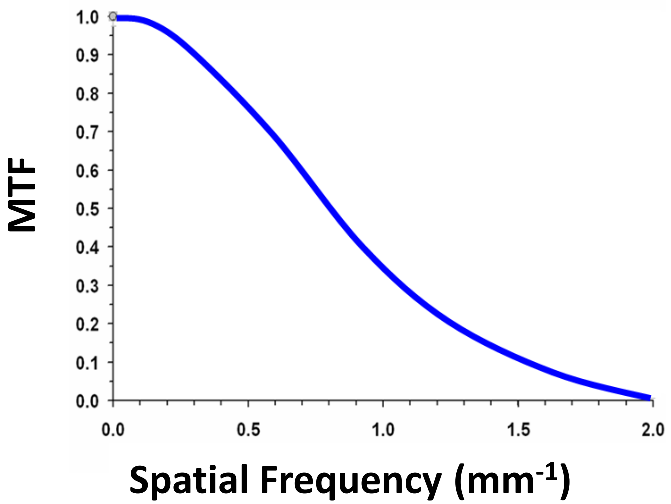


Image a 70 μm wire



PSF(x,y)

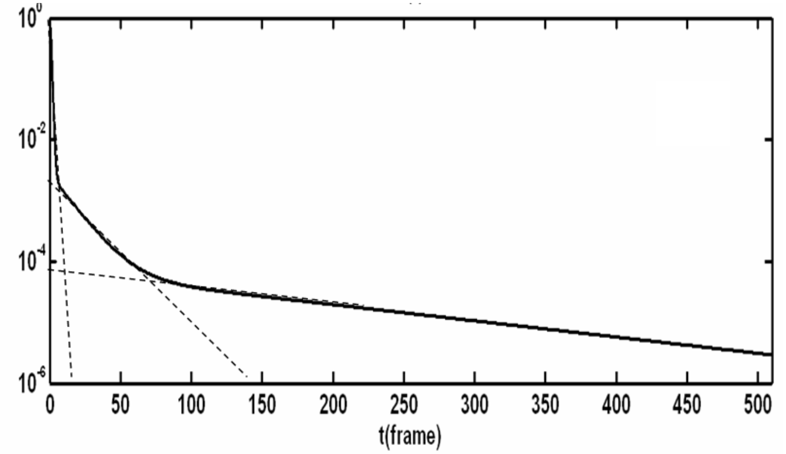


$$LSF(x) = \int PSF(x,y)dy$$

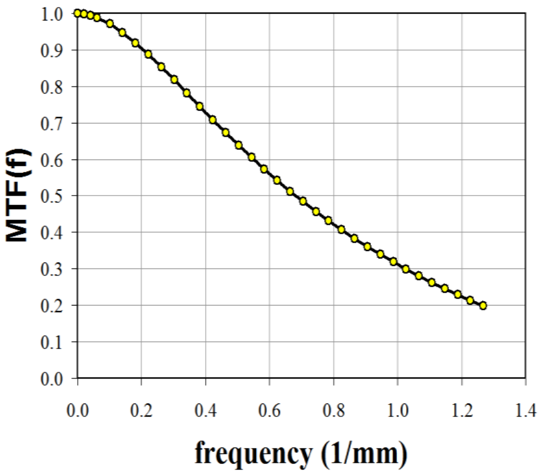
$$MTF(f) = \int dx\, LSF(x)\, e^{-2\pi i f x}$$

spatial resolution modeling

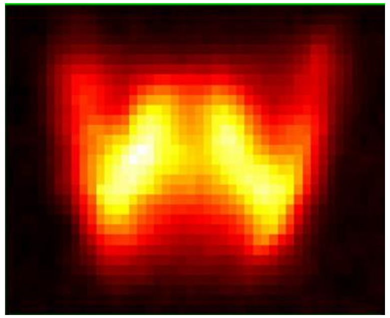
$$g(t) = f \cdot A \cdot \left[a_1 \cdot (1-\exp(-t/T_1)) + a_2 \cdot (1-\exp(-t/T_2)) + a_3 \cdot (1-\exp(-t/T_3))\right]$$



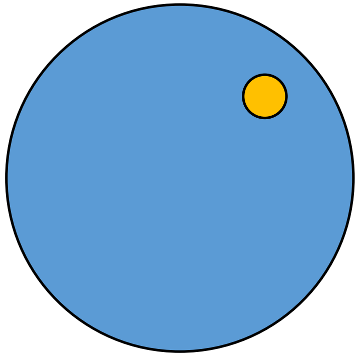
detector lag



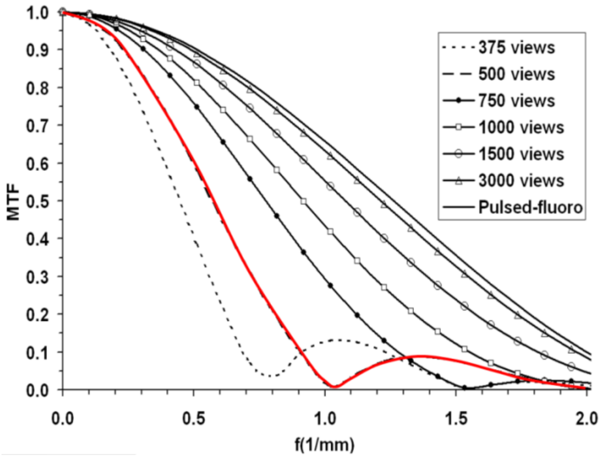
detector MTF



focal spot size



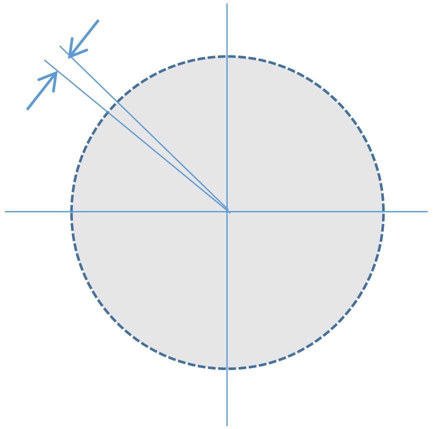
gantry rotation

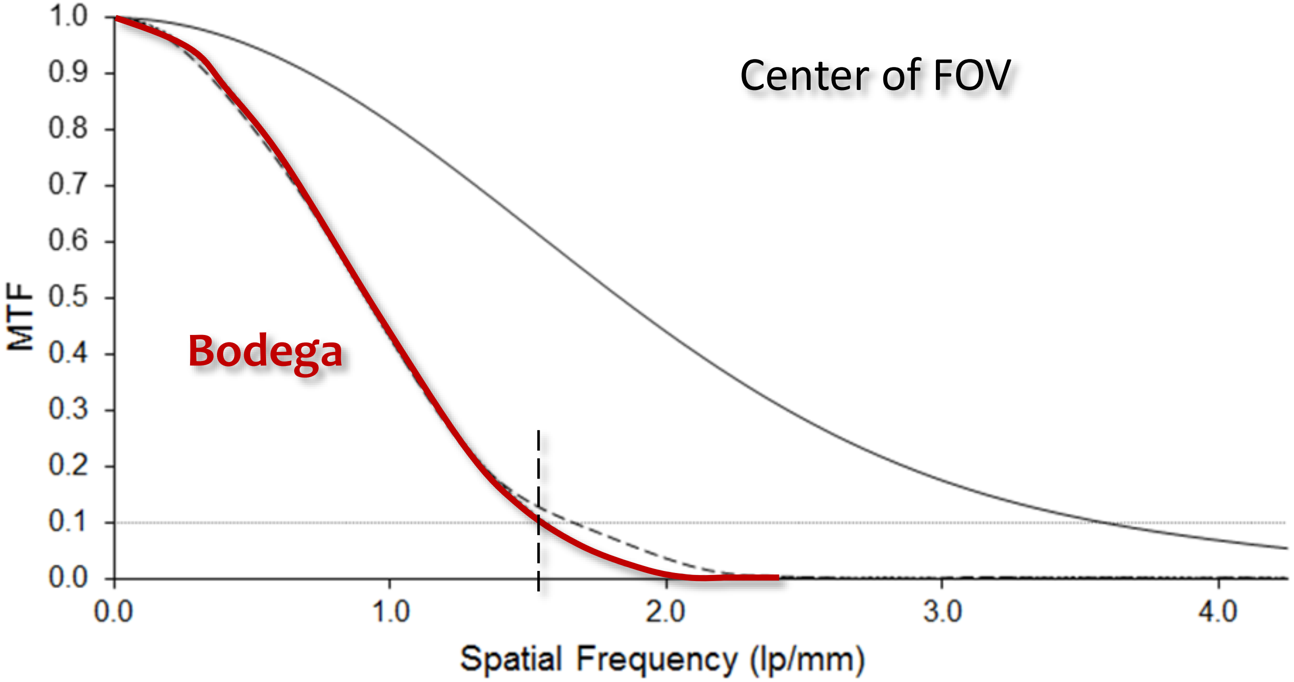


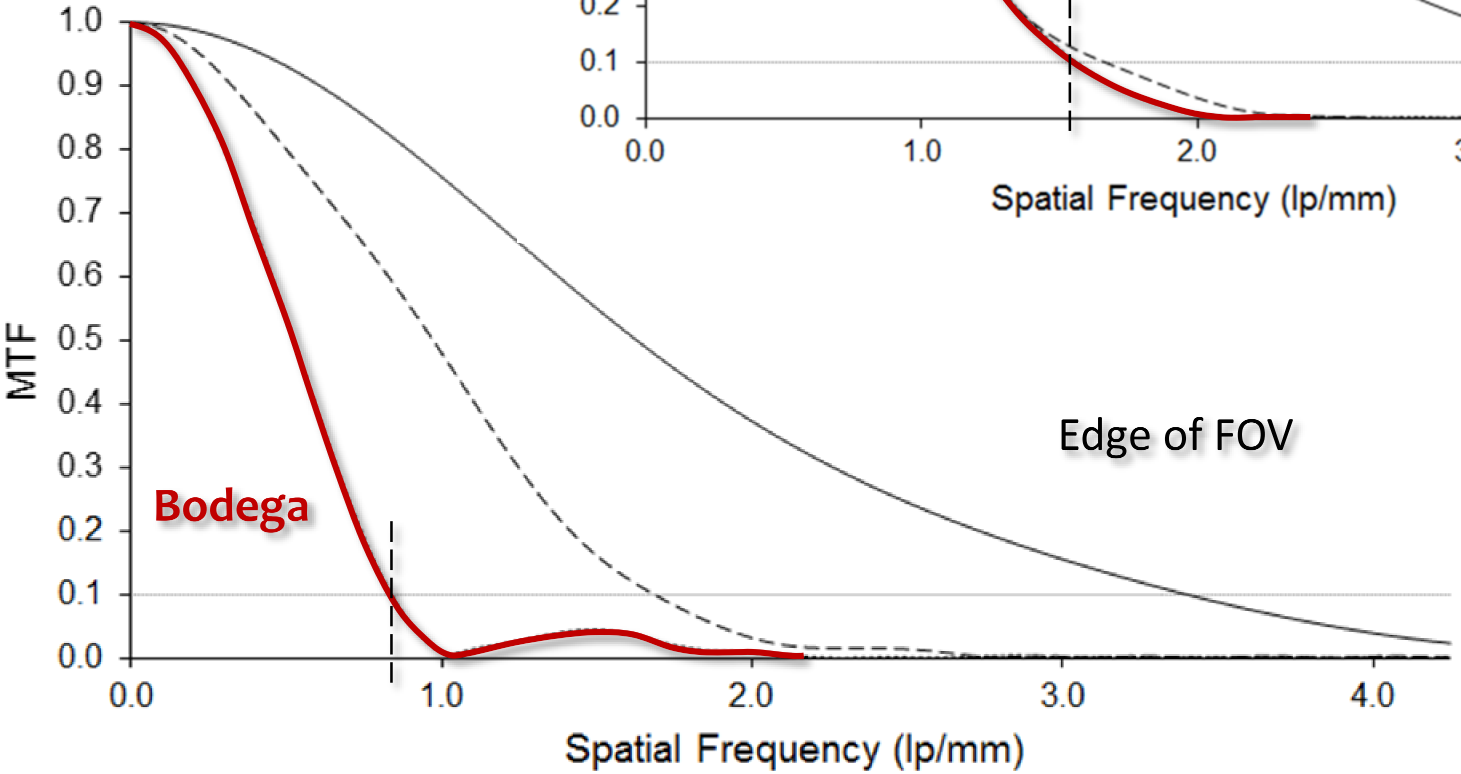
number of views

Yang et al., Computer modeling of the spatial resolution properties of a dedicated breast CT system, Med Phys 2008

Engineering impacts resolution

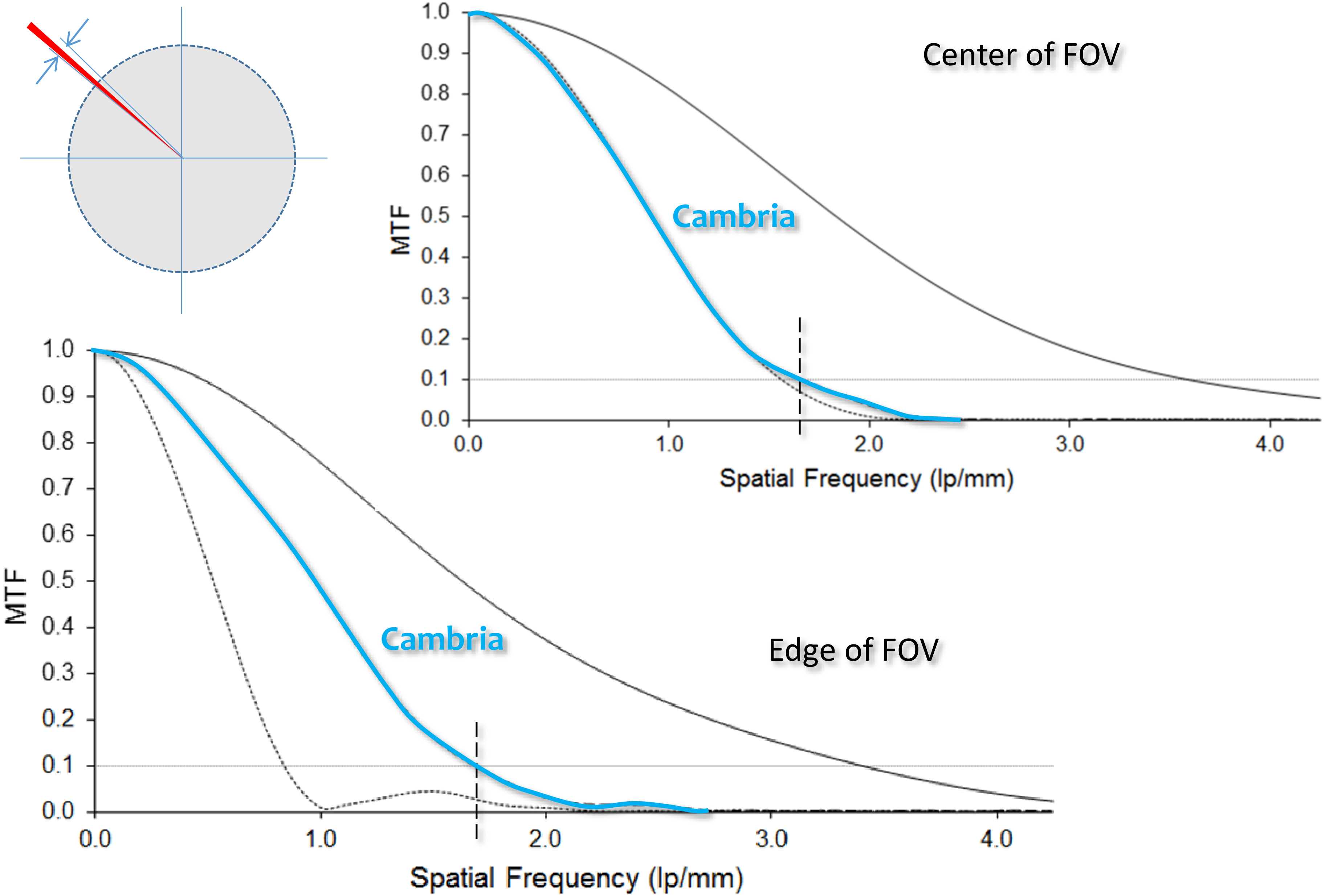






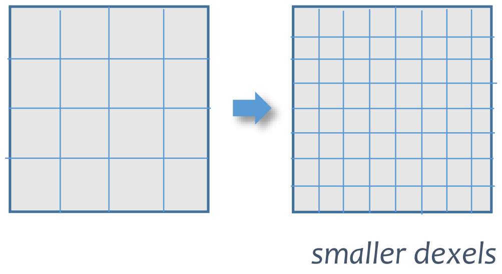
Engineering impacts resolution

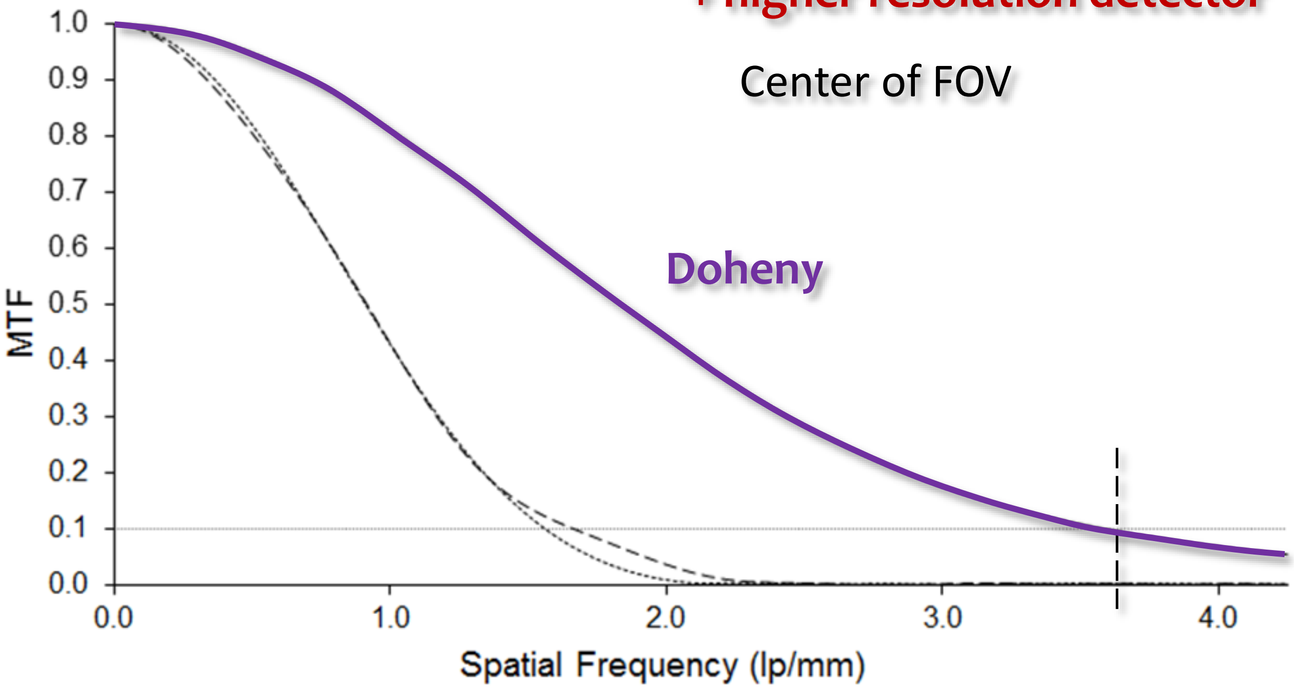
pulsed acquisition (4 ms)

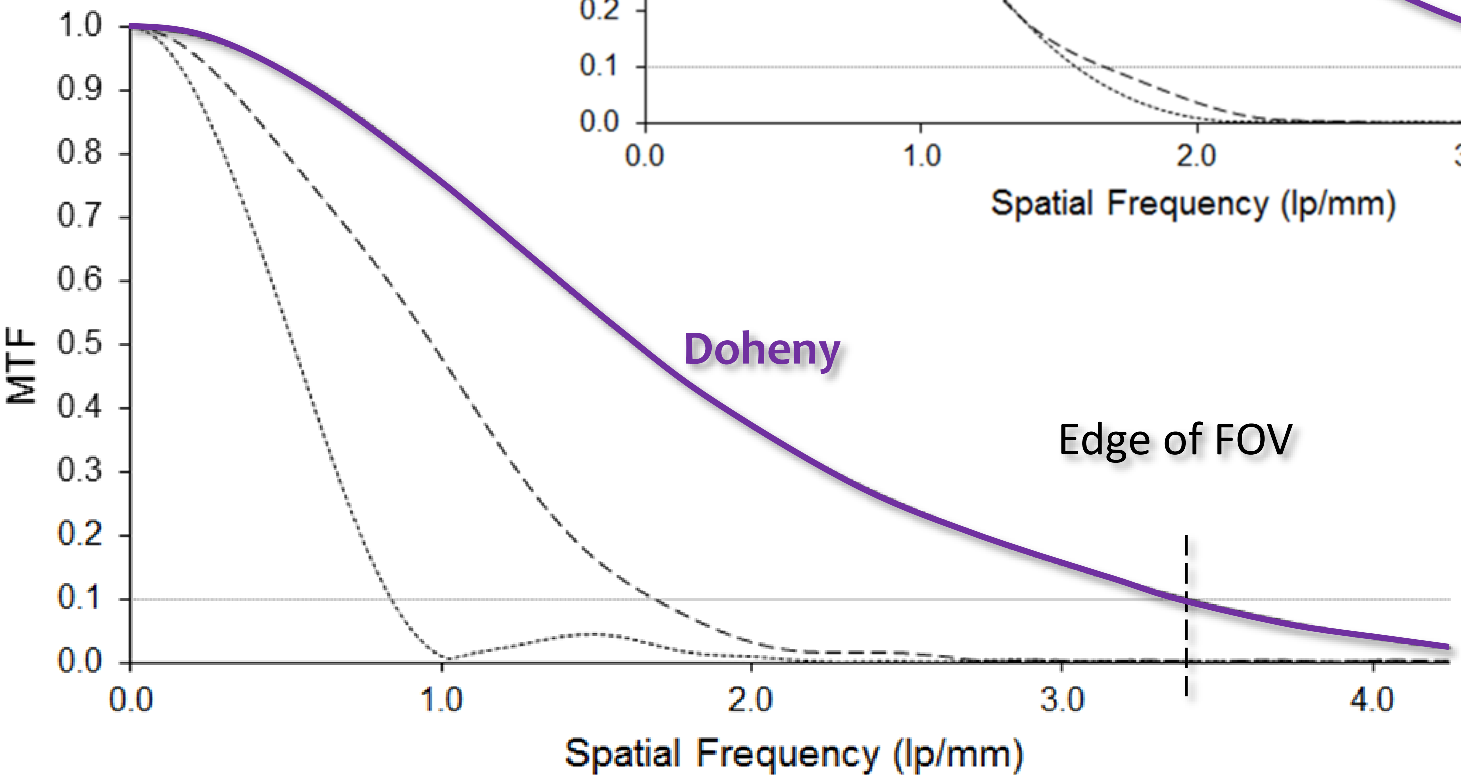


Engineering impacts resolution

pulsed acquisition (4 ms)
+ higher resolution detector

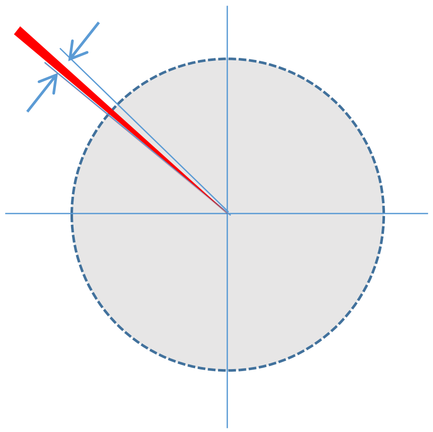


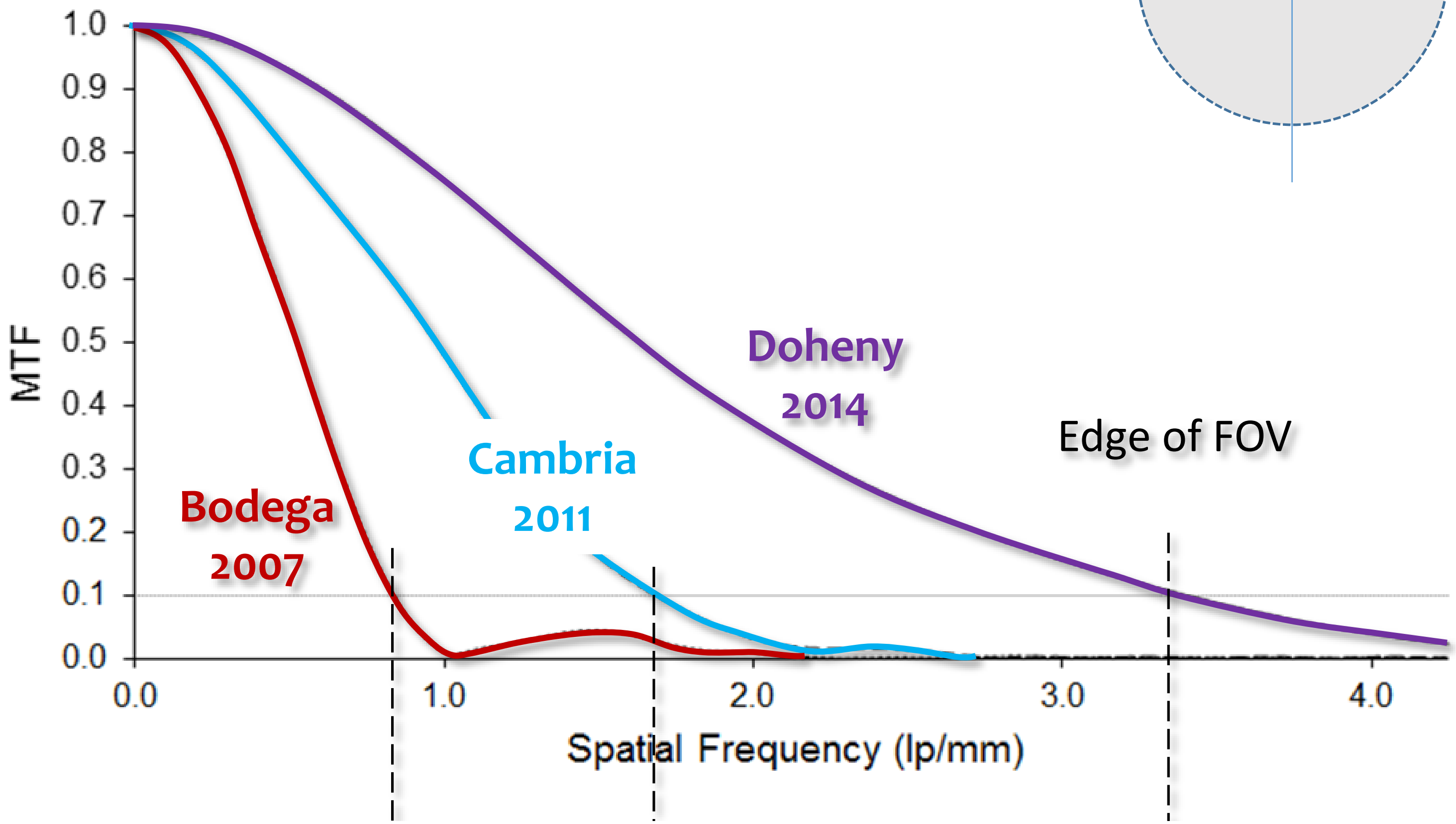




Engineering impacts resolution

pulsed acquisition (4 ms)





$0.8\ mm^{-1}$ $1.8\ mm^{-1}$ $3.4\ mm^{-1}$

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Noise Power Spectra

Performance Metrics

Contrast Resolution

total noise
(variance)

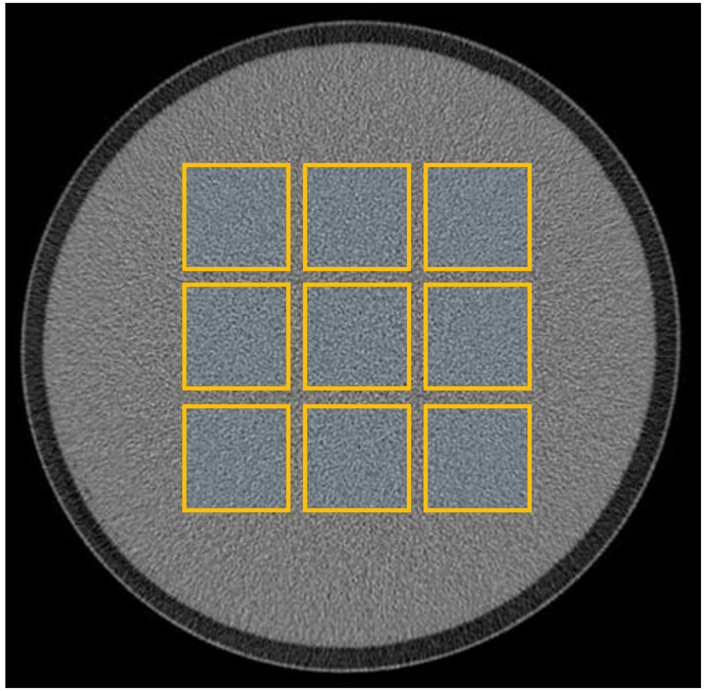
anatomical noise

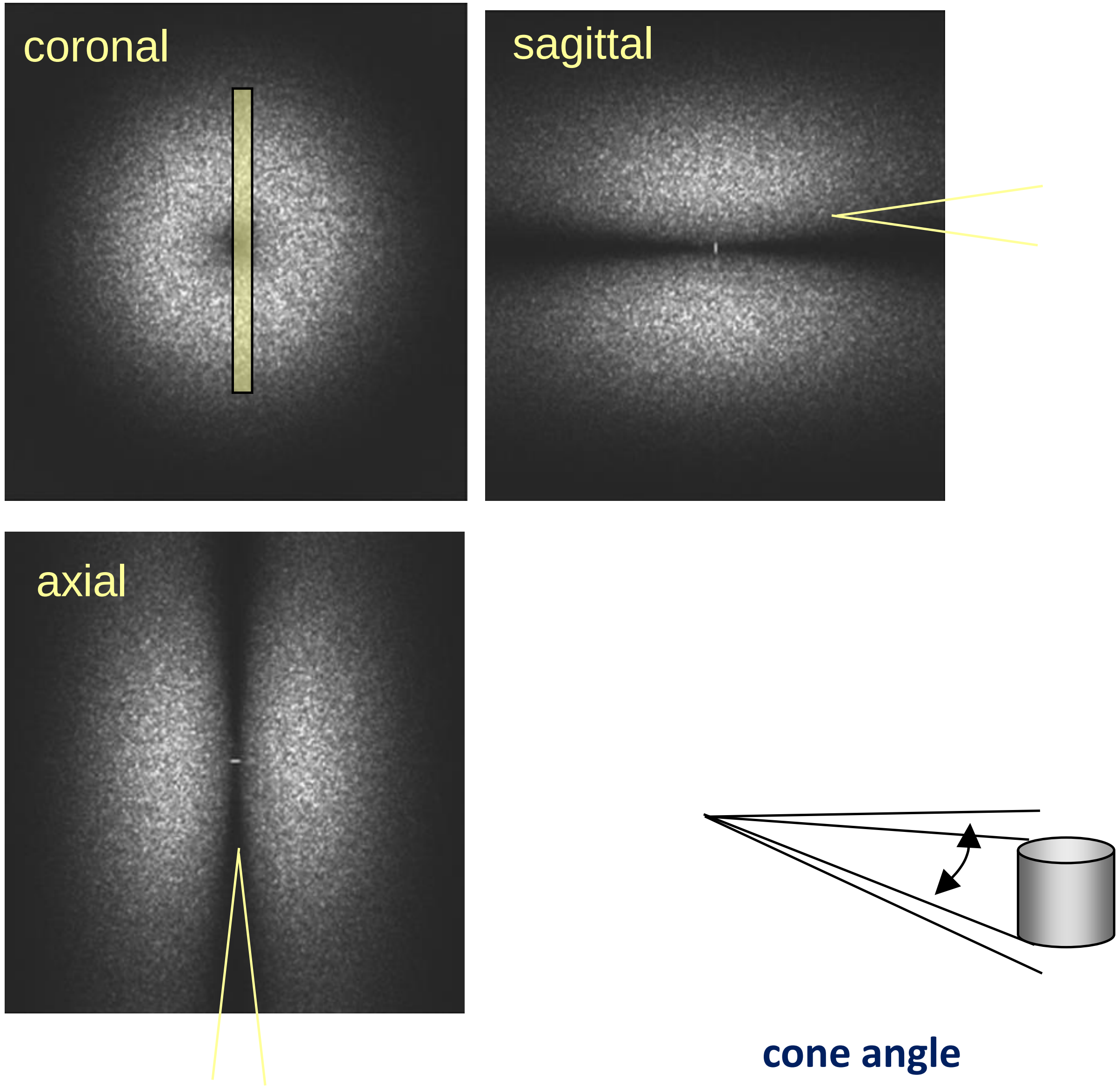
quantum noise

$$NPS(f) = NPS_a(f) + NPS_q(f)$$

Contrast Resolution: NPS measurements

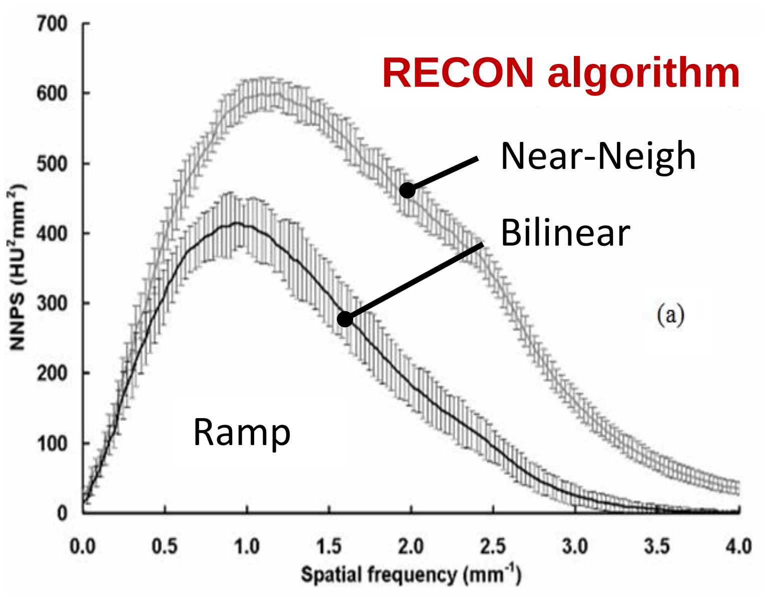
$$NPS(u,v) = \frac{|F(u,v)|^2}{N_X N_Y} \Delta_X \Delta_Y$$

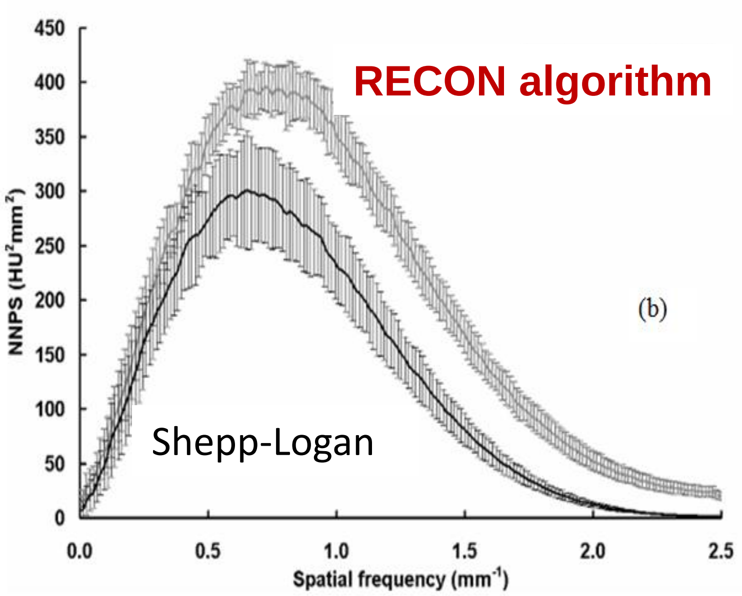


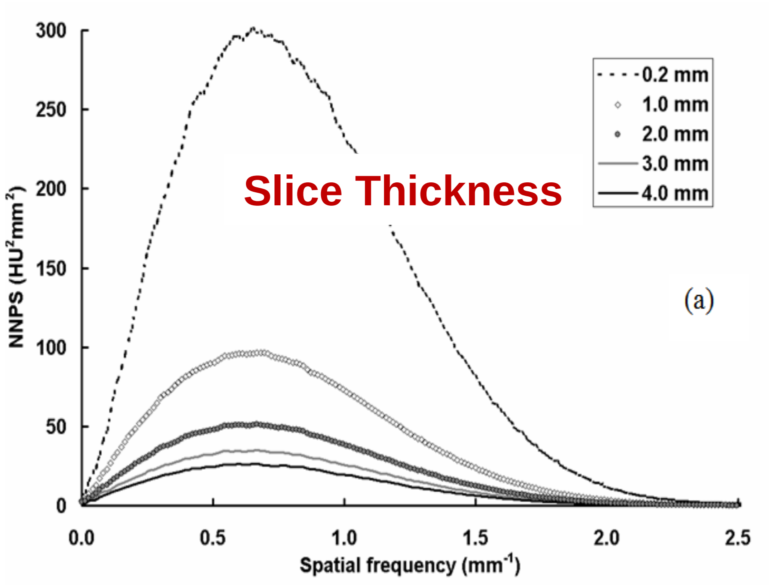


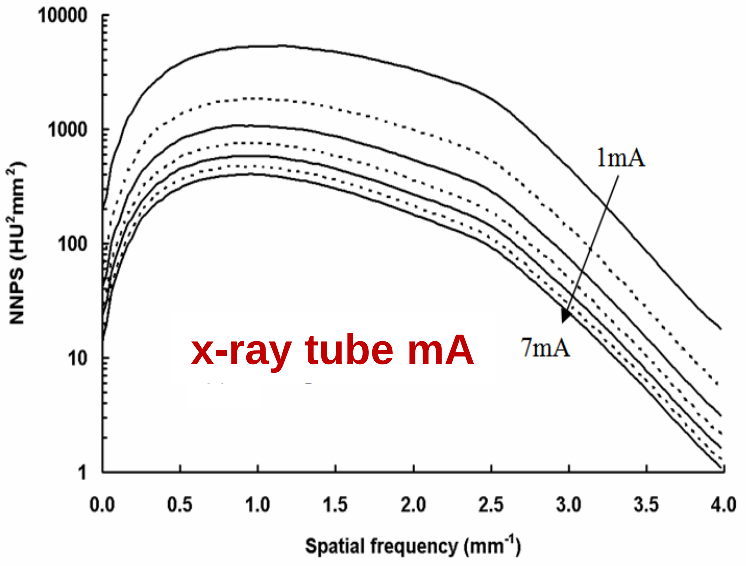
cone angle

Noise Power Spectrum (NPS) measurements (Bodega)







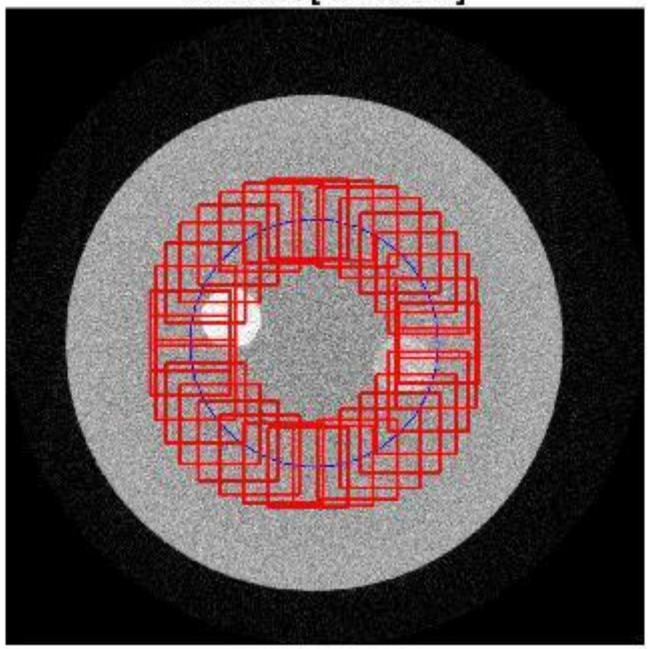


Yang *et al*., Noise power properties of a cone beam CT system for breast cancer detection, Med Phys. 2008

Noise Power Spectrum (NPS) Analysis

- Detrending using image subtraction with identical parameters

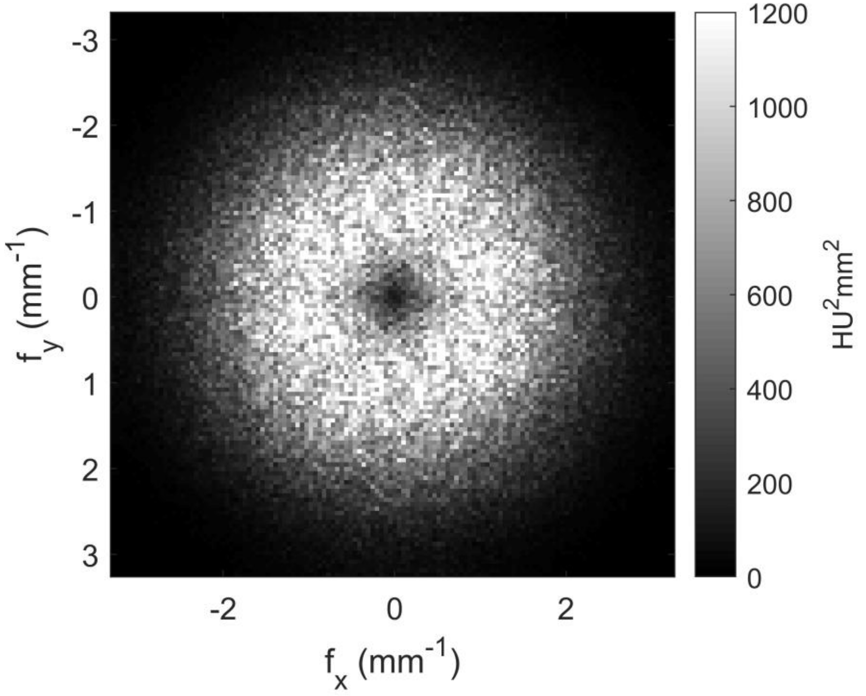
$$K(x,y) = I_{\mathrm{A}}(x,y) - I_{\mathrm{B}}(x,y)$$

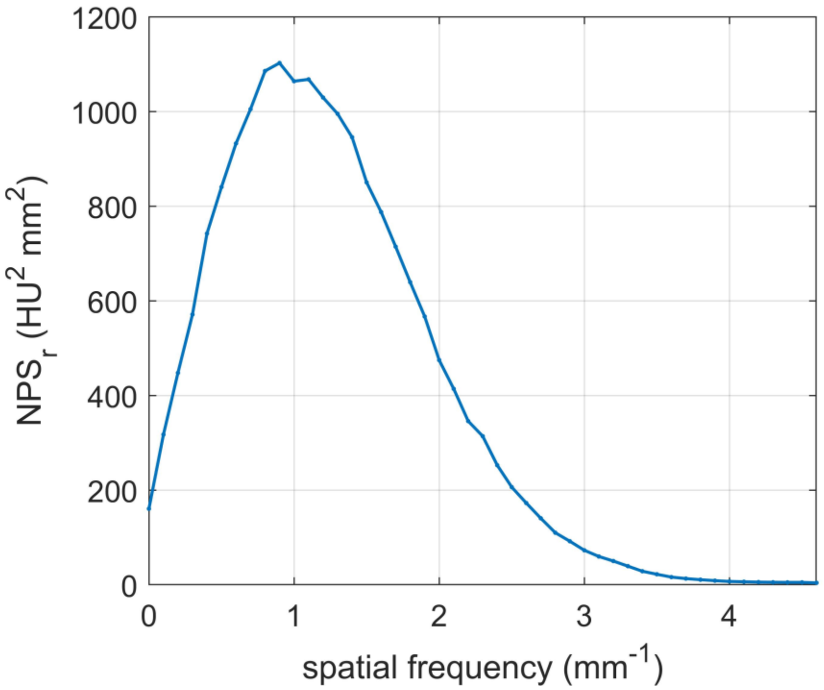


- $$NPS(f_{\mathrm{x}},f_{\mathrm{y}}) = \frac{1}{N}\frac{\sum_{i=1}^{N}\left|\mathrm{DFT}_{\mathrm{2D}}[K_{\mathrm{i}}(x,y) - \overline{K}_{\mathrm{i}}]\right|^2}{2}\;\frac{\Delta_{\mathrm{x}}\Delta_{\mathrm{y}}}{N_{\mathrm{x}}N_{\mathrm{y}}}$$

$$\sigma^2 = \iiint NPS\left(f_x, f_y\right)\, df_x\, df_y$$

Noise Power Spectrum (NPS) Analysis





Breast CT: *Technology development and clinical potential*

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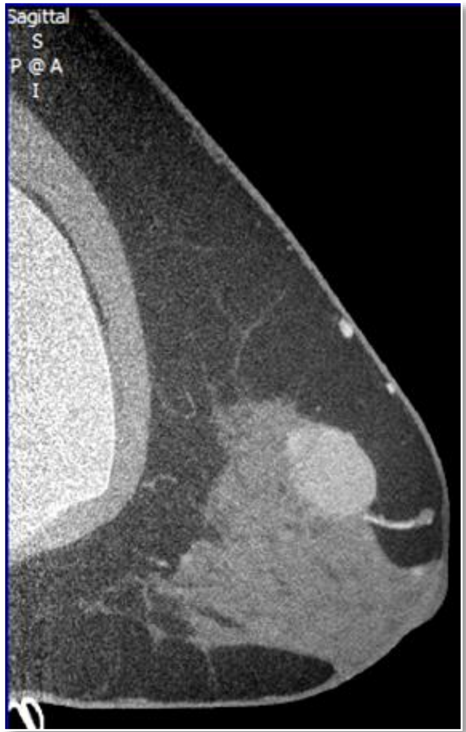

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University of California, Davis

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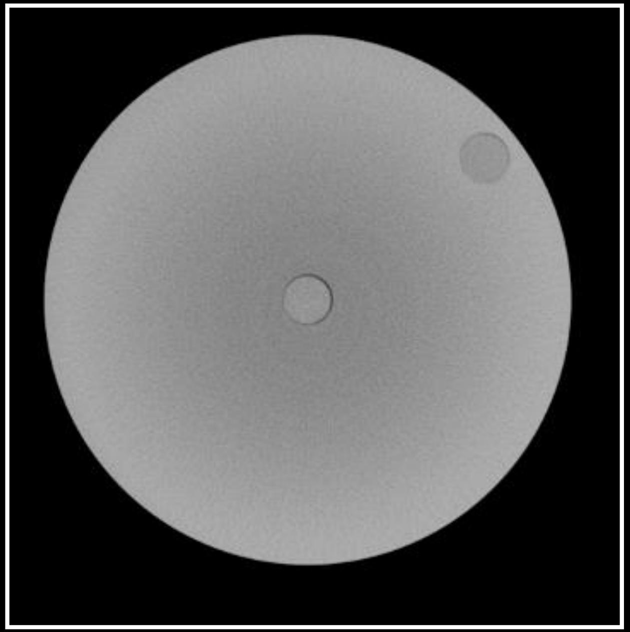
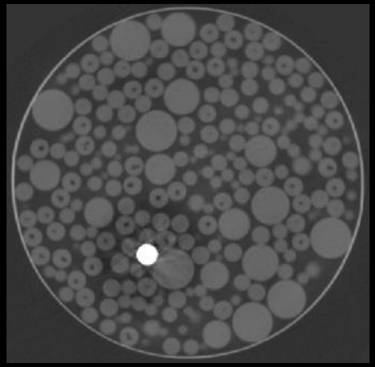
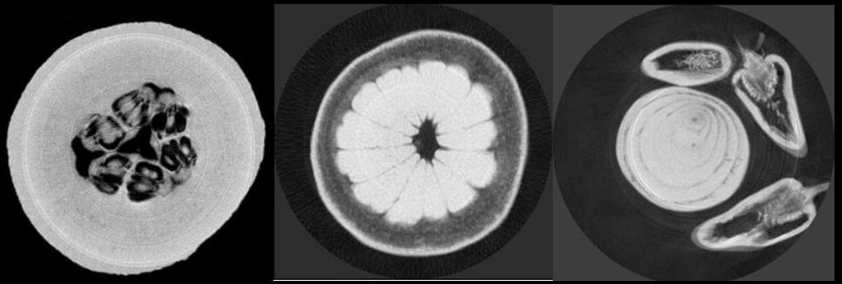
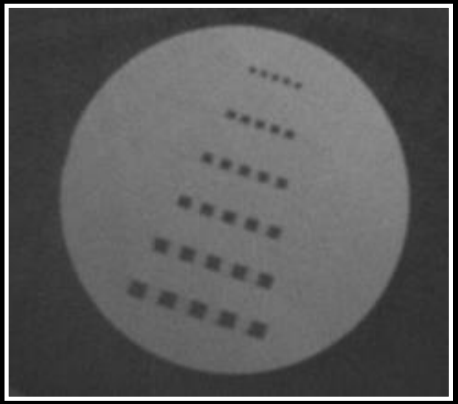
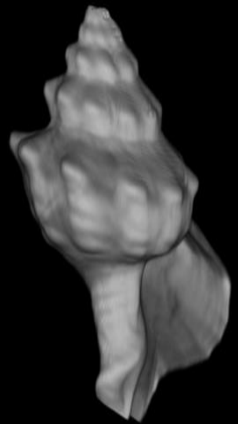
Preliminaries

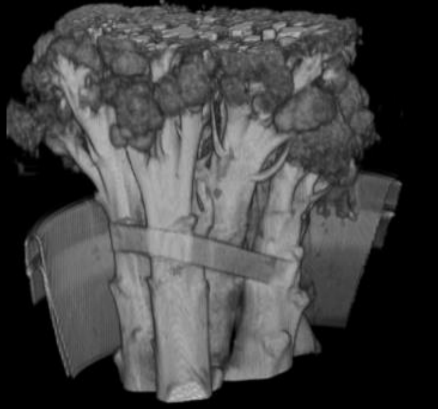
Before Patient Imaging



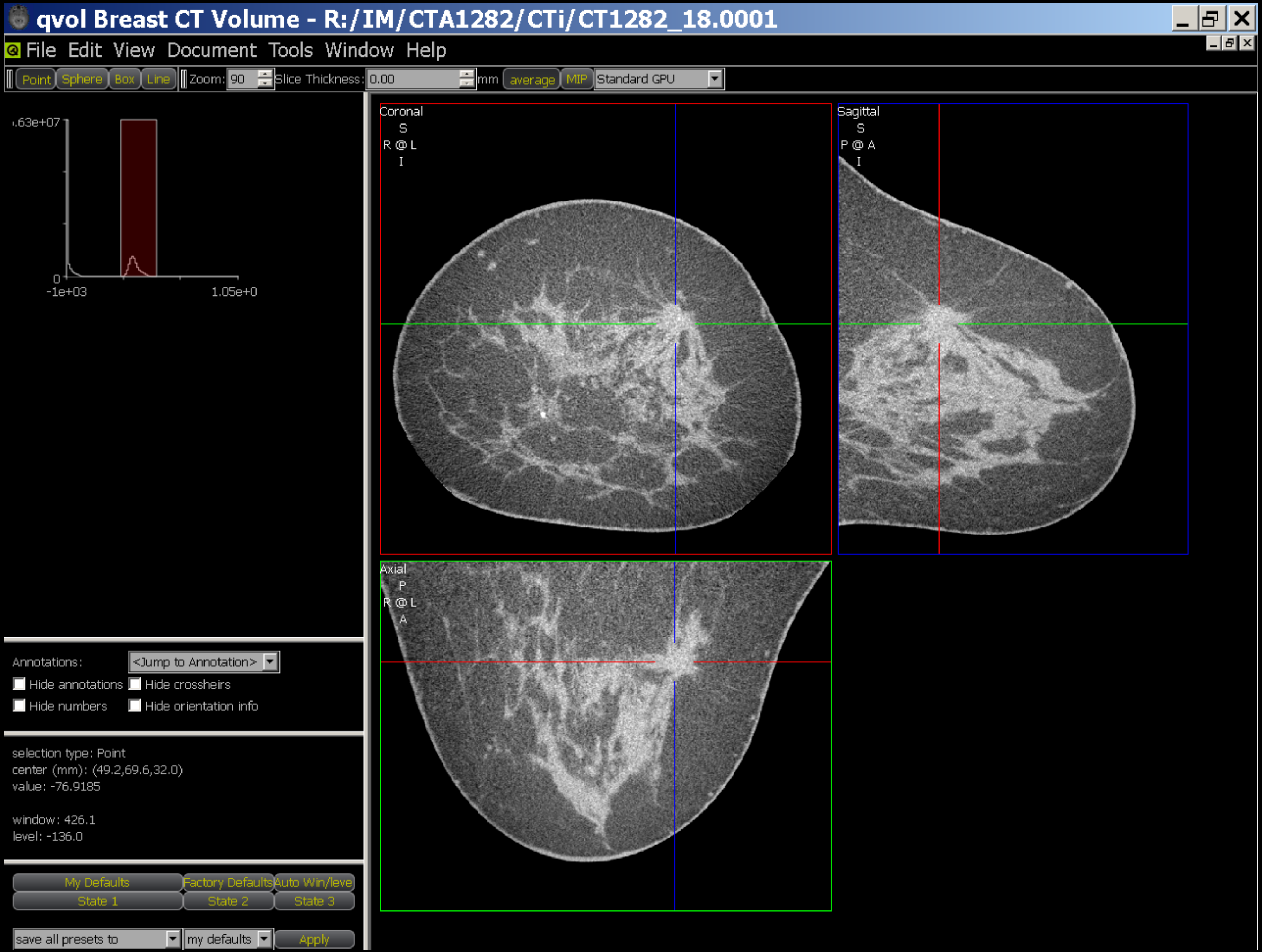






Nathan Packard

True 3D Display !



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Breast CT images

Breast CT: *Technology development and clinical potential*

Clinical Studies

BIRADS 4 and 5 women (headed to biopsy)

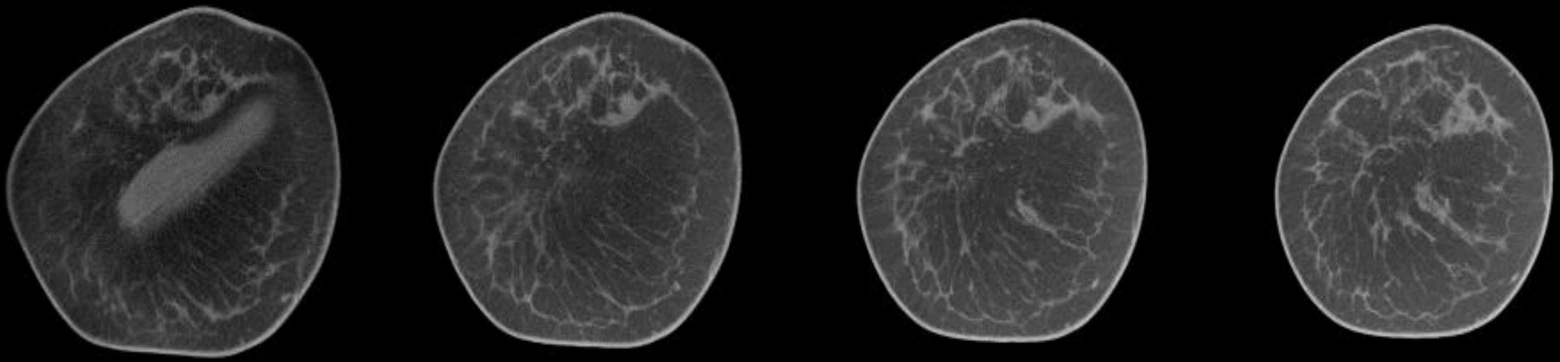
>600 patients imaged over several clinical trials

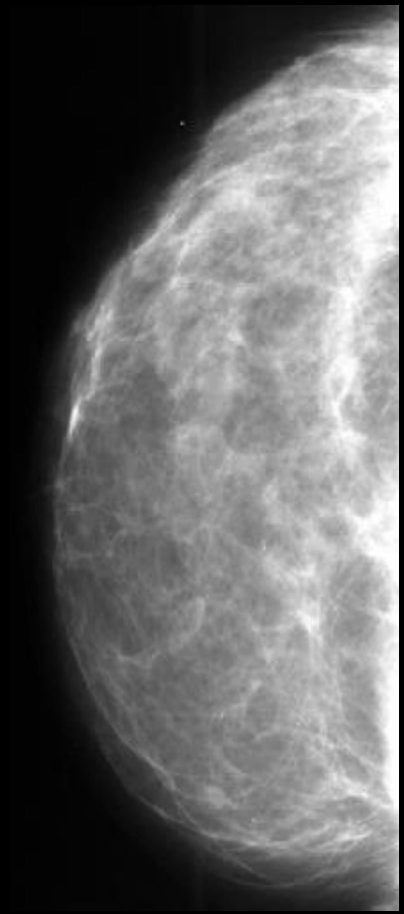
~275 patients with iodine contrast

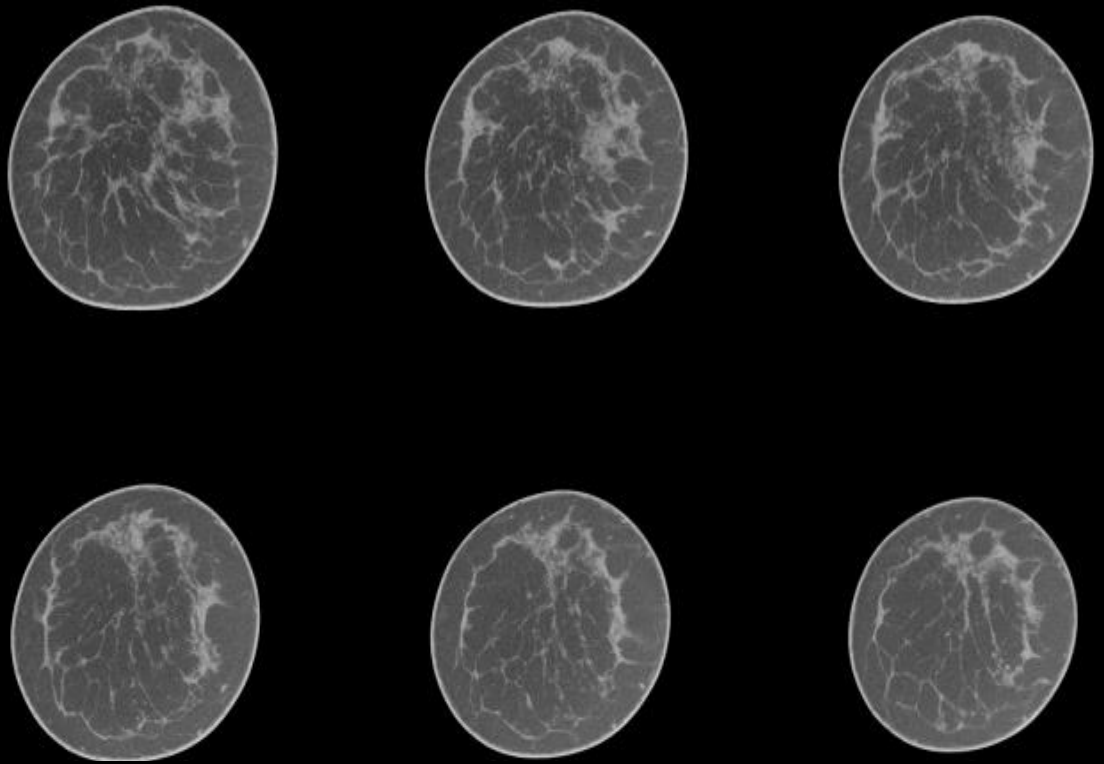
Past: (1024 x 768) 500 views over 360° 512 x 512 x N reconstruction

Now: (2048 x 1536) 500 views over 360° 1024 x 1024 x N reconstruction

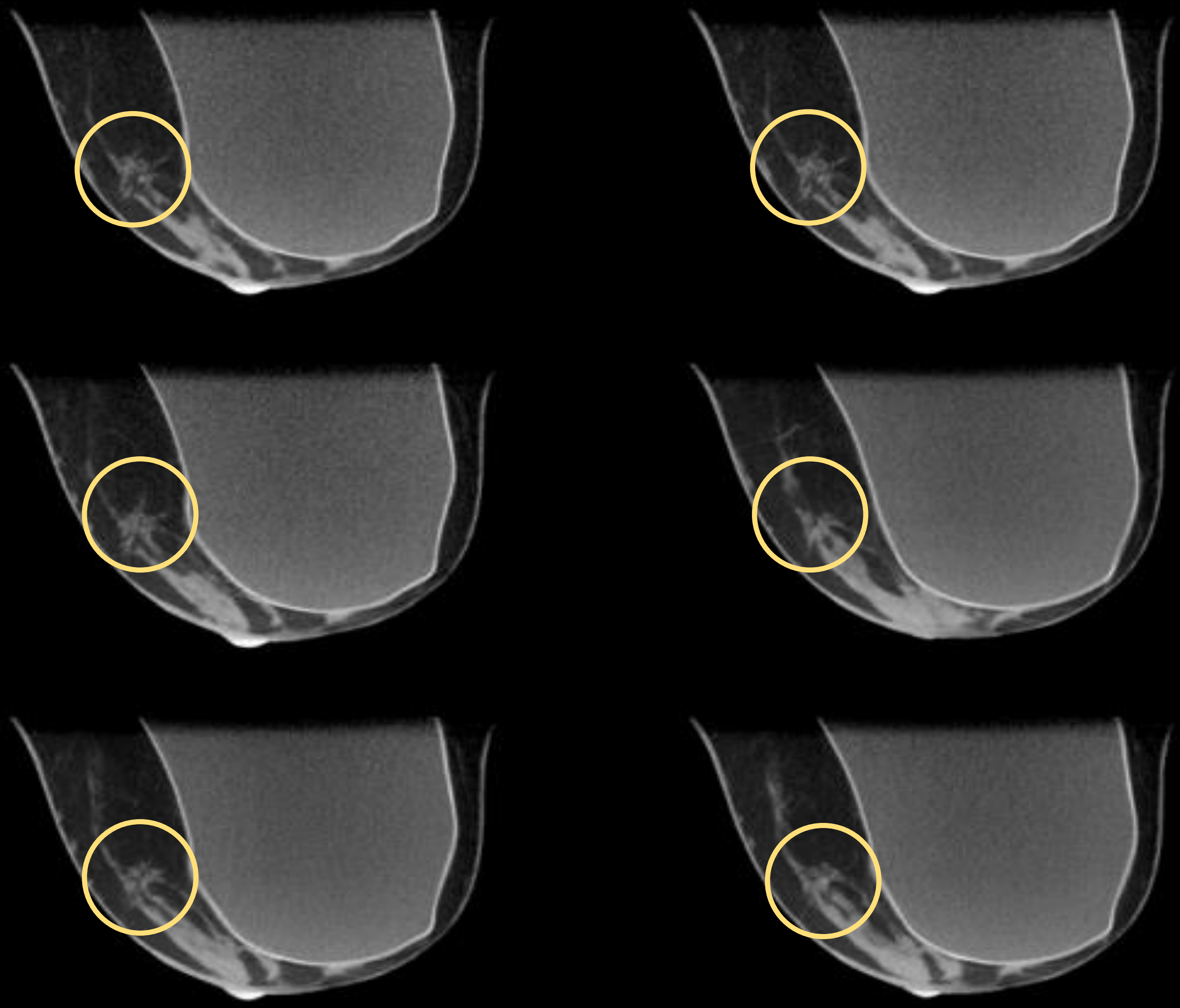
150 um isotropic voxels





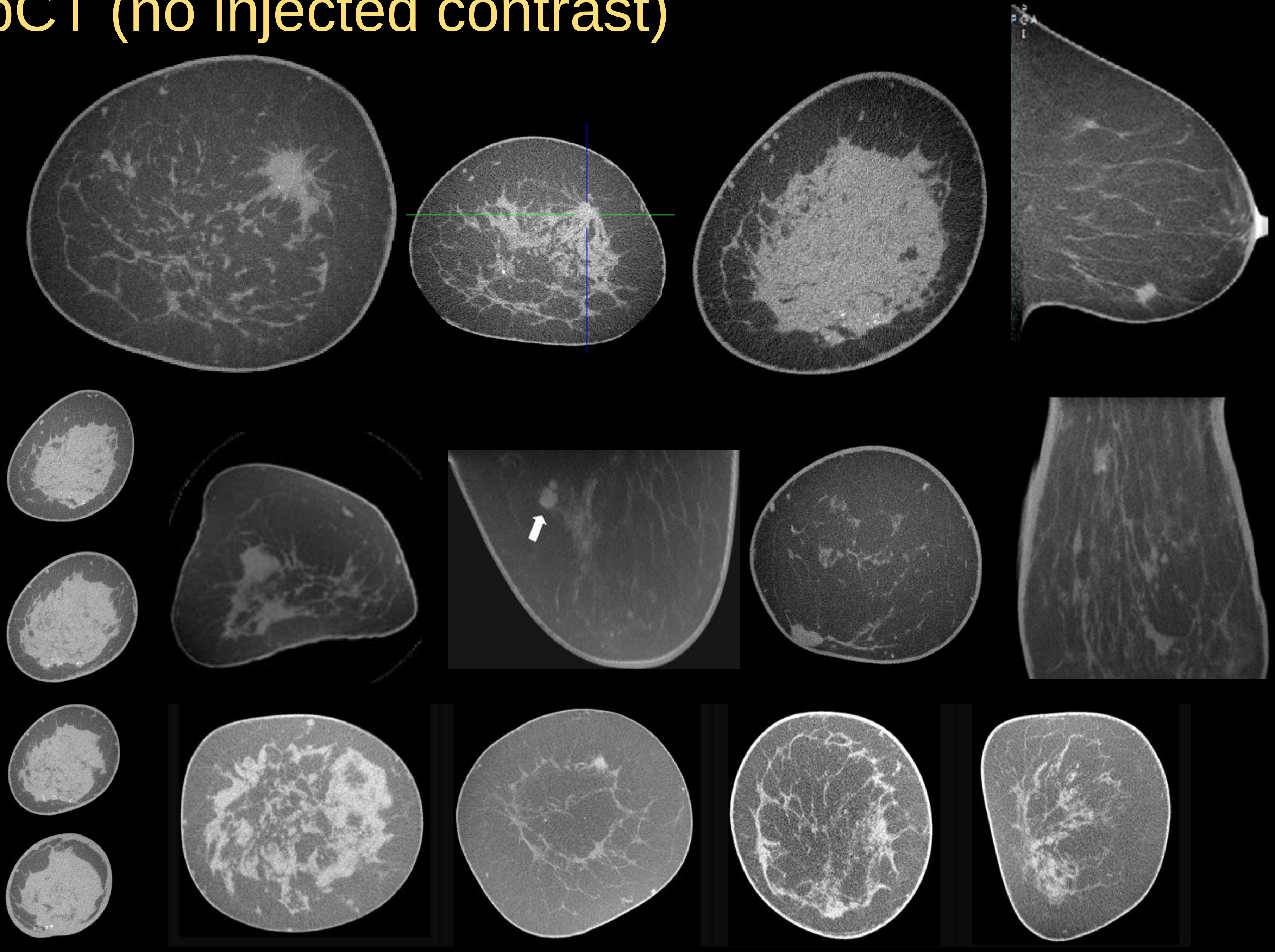


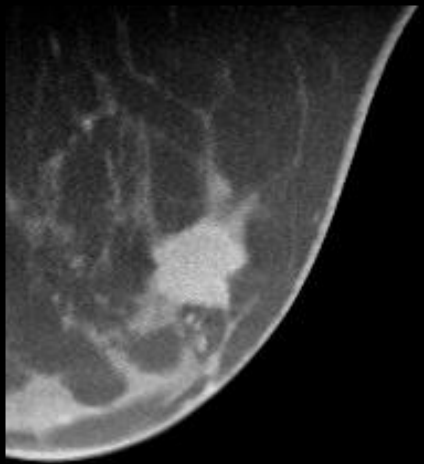
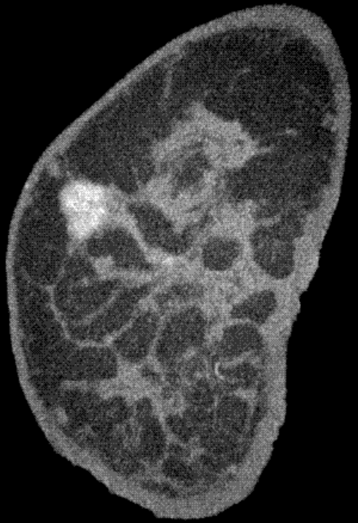
second volunteer imaged: January 2005

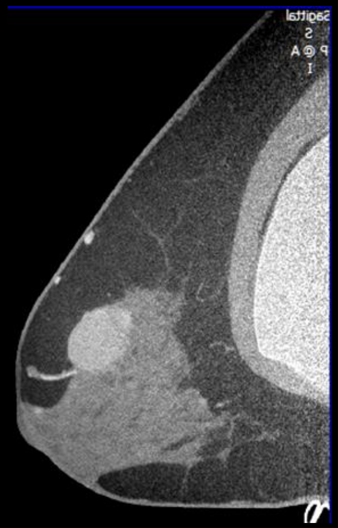


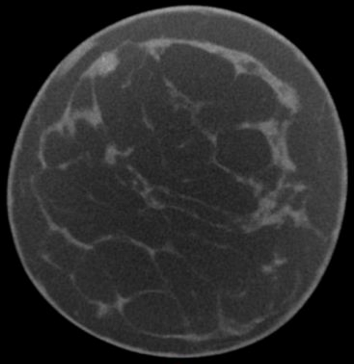
first breast cancer imaged: January 2005

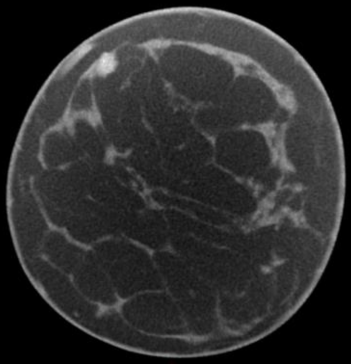
bCT (no injected contrast)



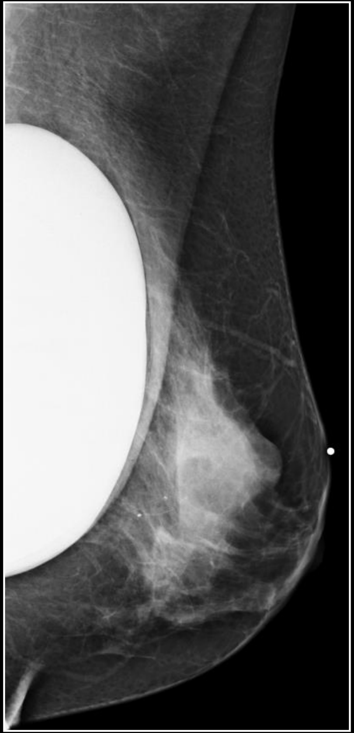


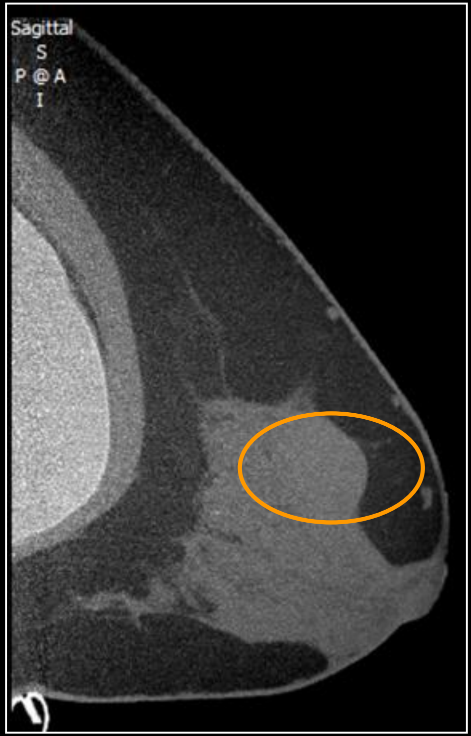

PRE CONTRAST


POST CONTRAST

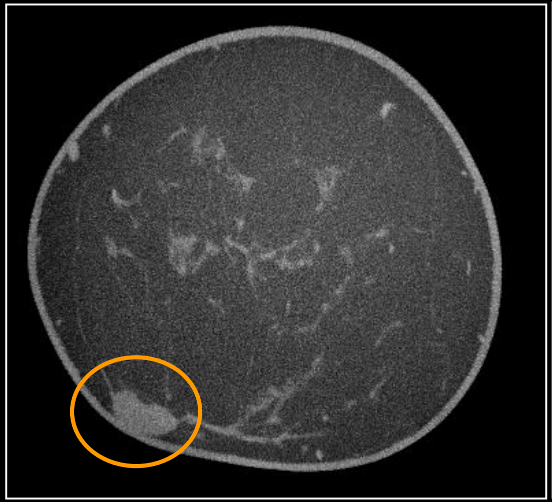
bCT (with contrast)

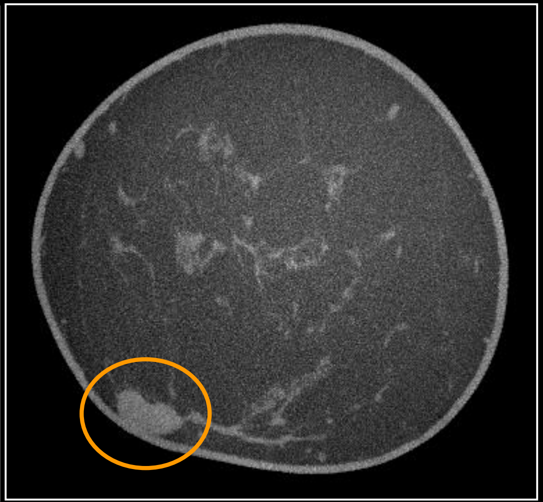
Contrasted Enhanced breast CT





Malignant





benign

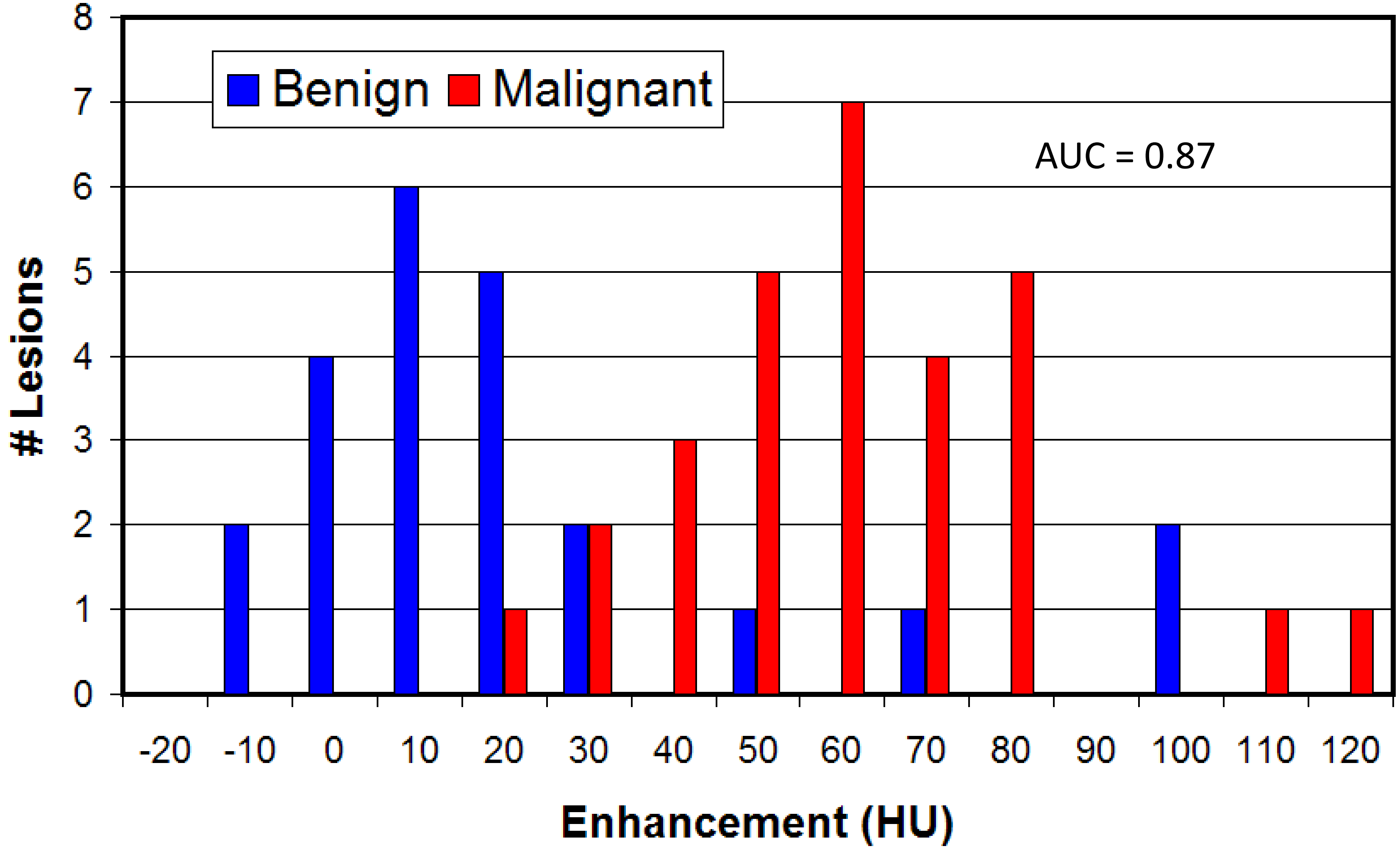
Pt 160

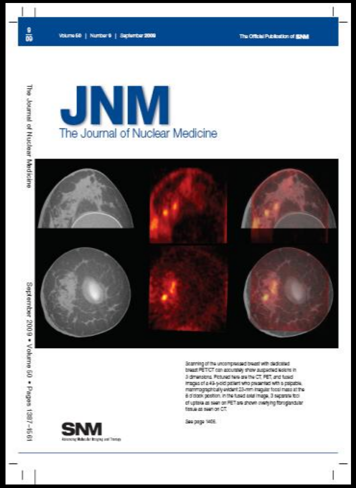
Radiology

2010

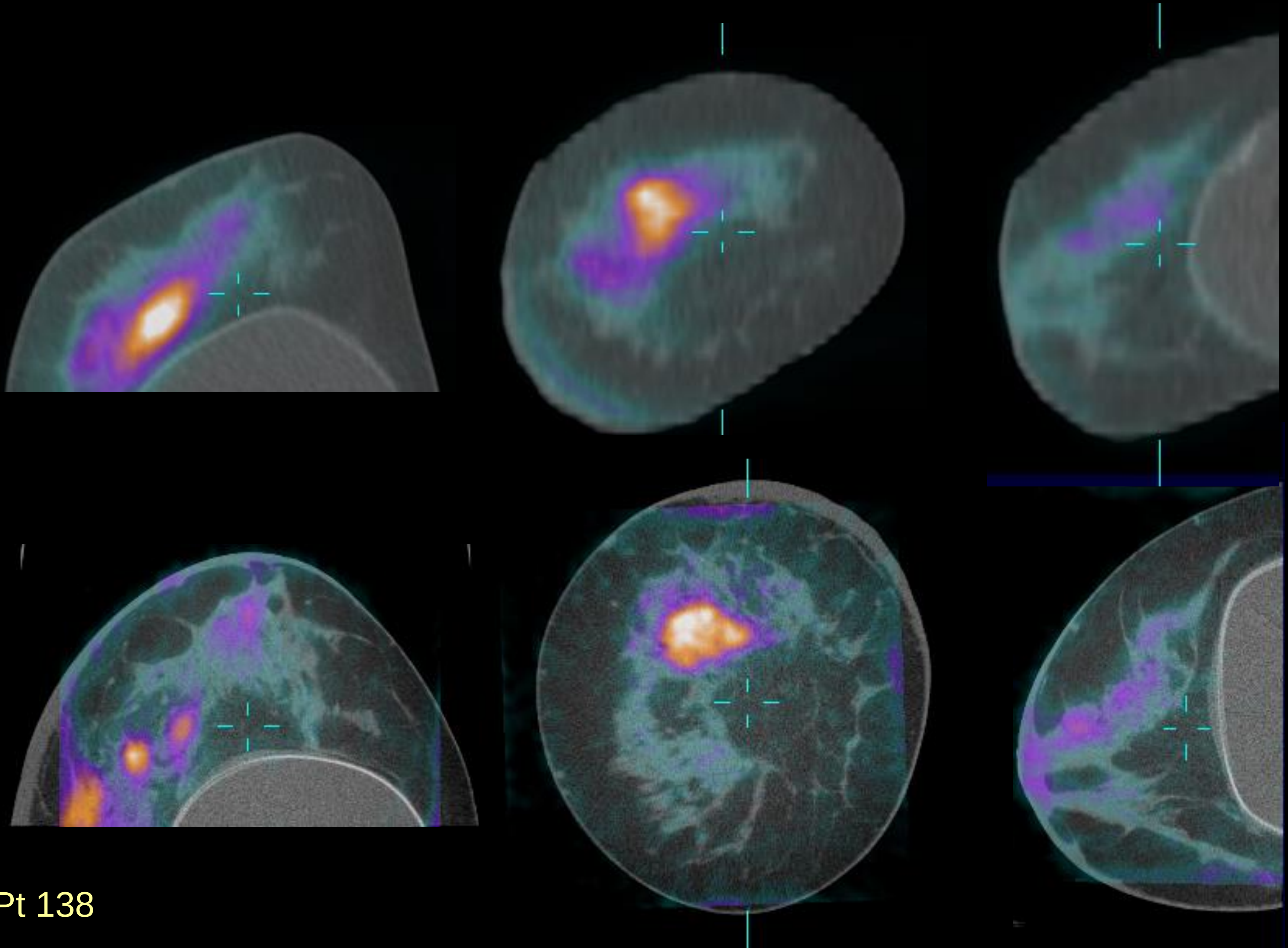
Contrast-enhanced Dedicated Breast CT: Initial Clinical Experience[1]

Nicola
Karen
Shonk
Shih-Y
Laurel
Wayne
John





Invasive Mammary Carcinoma



Pt 138

Breast CT: *Technology development and clinical potential*

- Introduction
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- **Clinical Observations** (current section)
- Observer Performance
- Other Cool Spinoffs
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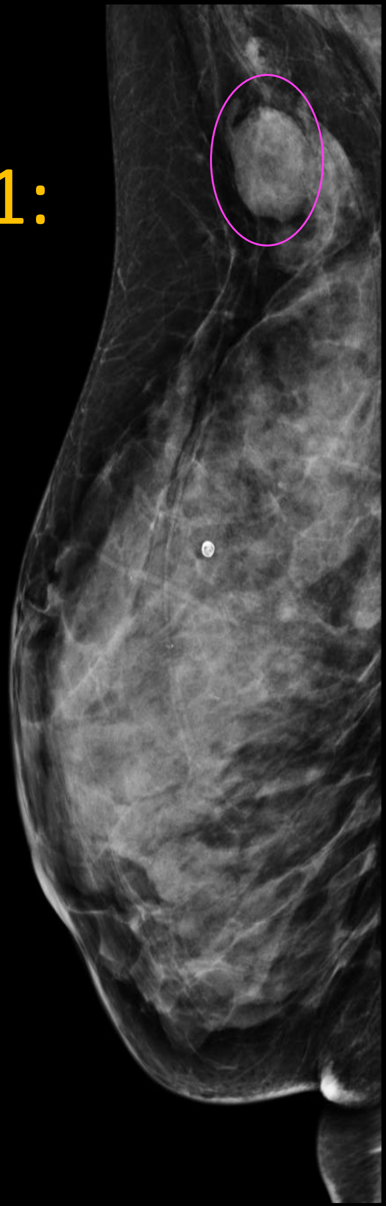
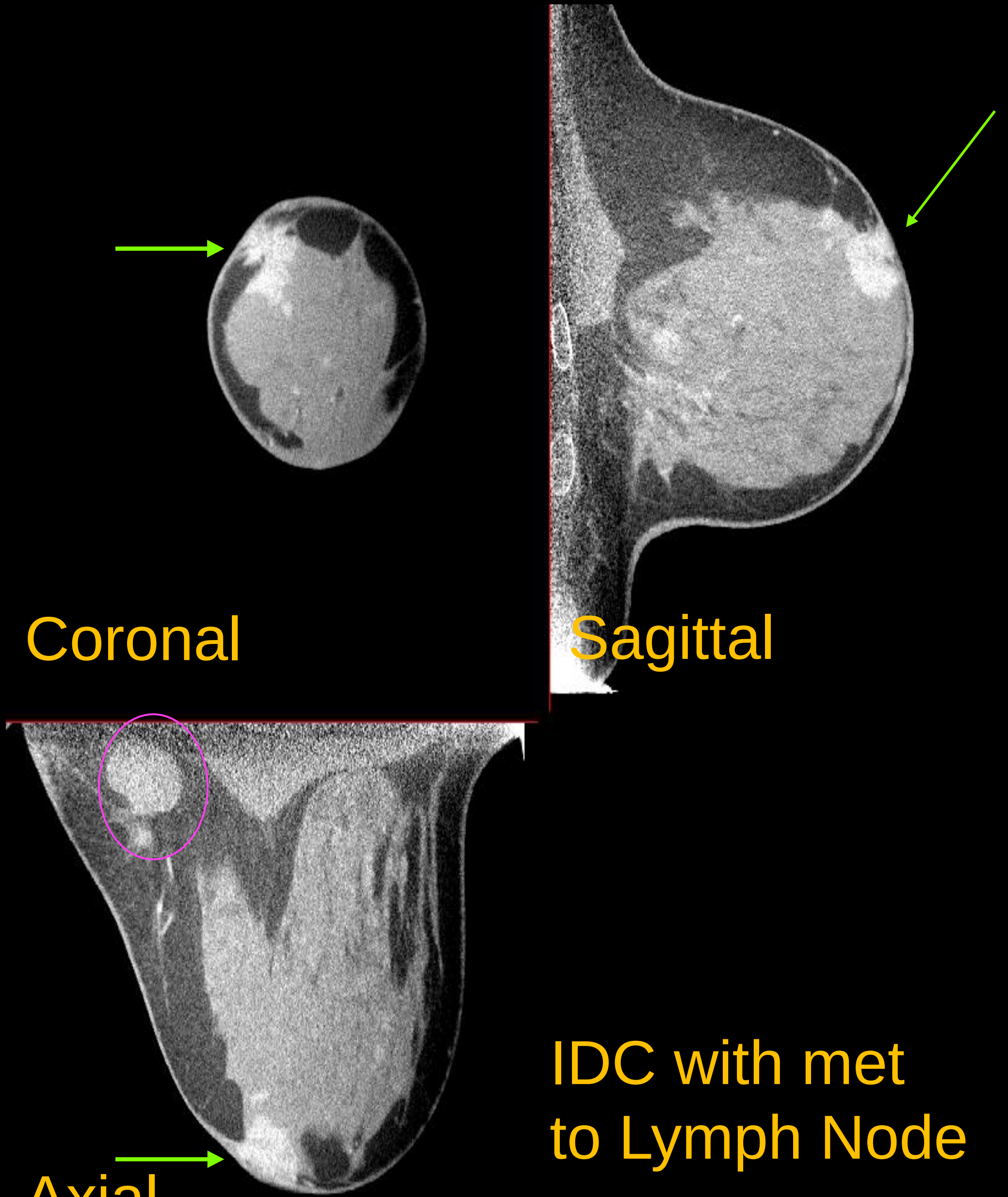
clinical comparisons

Clinical Example 1: Masses



R MLO
DM

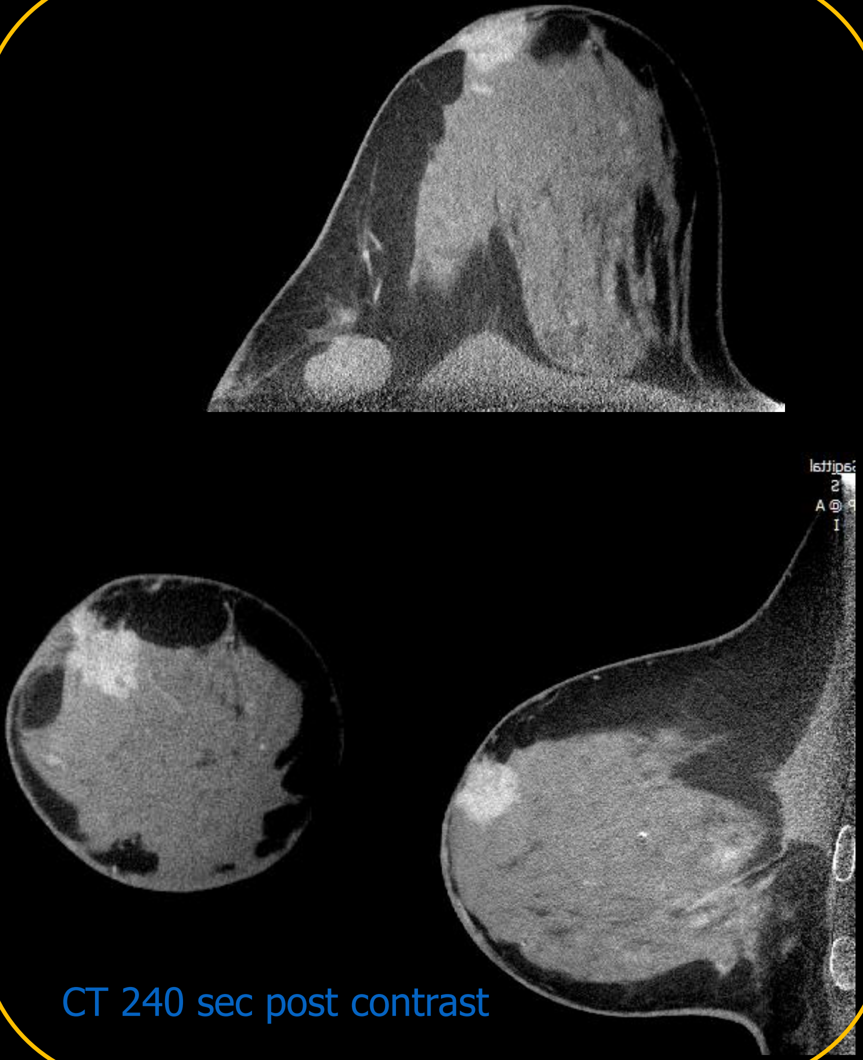
R MLO
DBT



IDC with met to Lymph Node

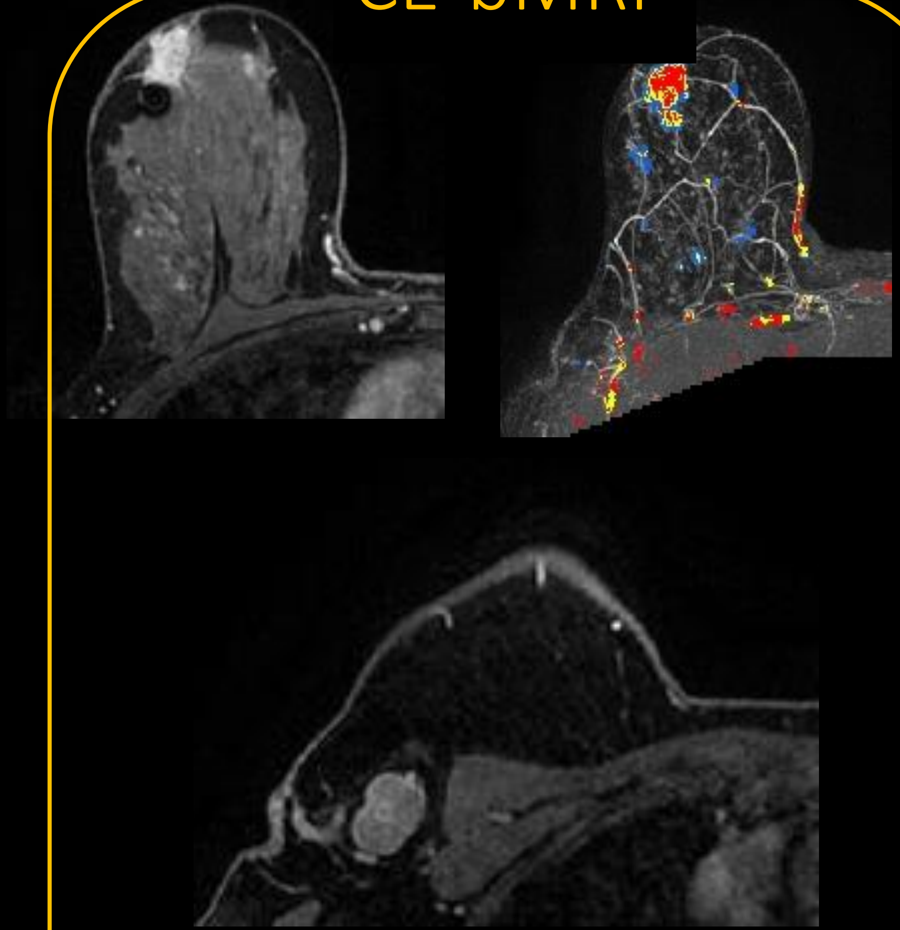
Clinical Example 2: Masses

CE-bCT



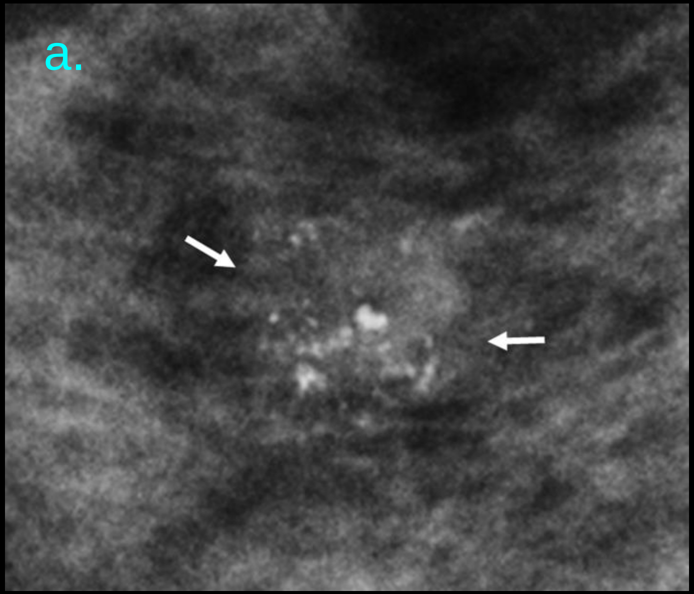
CT 240 sec post contrast

CE-bMRI

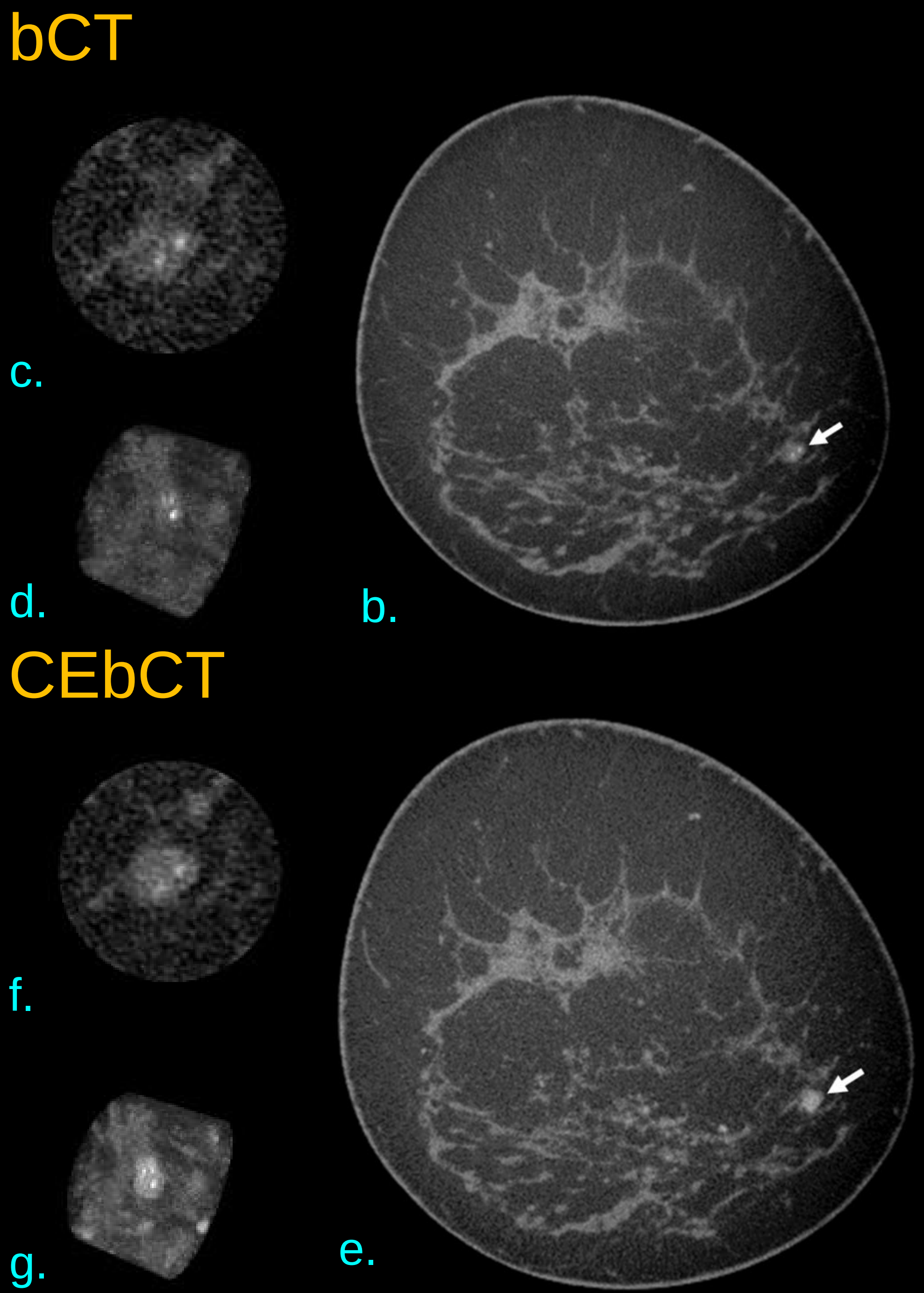


T1 Fat sup 90 sec post contrast

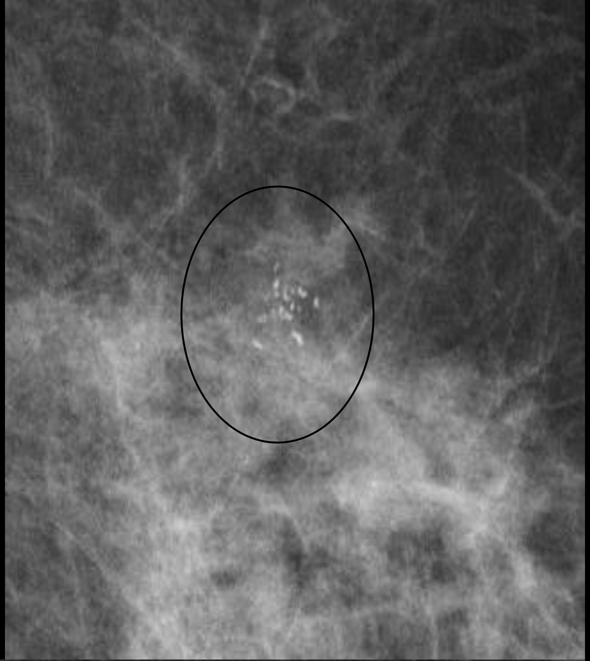
Clinical Example 3: calcs

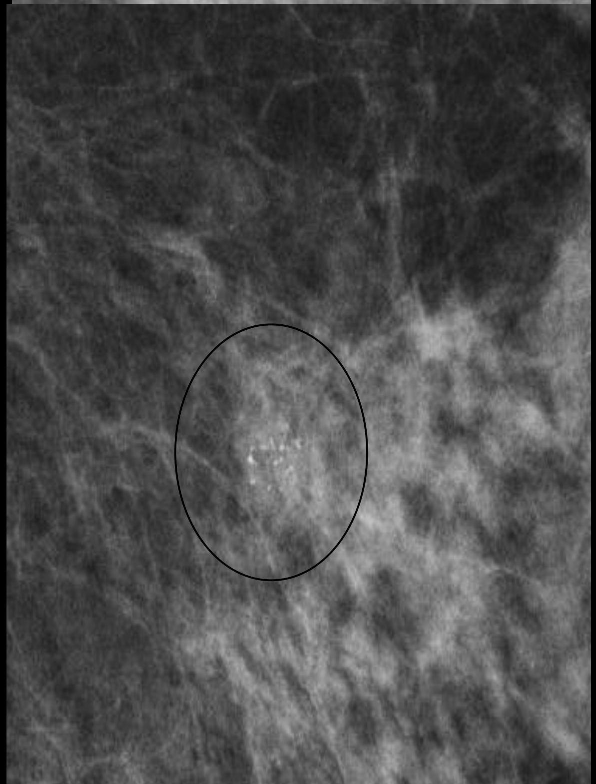


mammogram

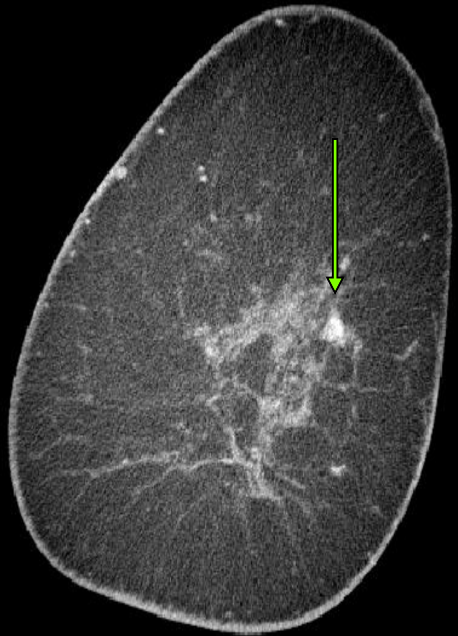


Clinical Example 4: more calcs



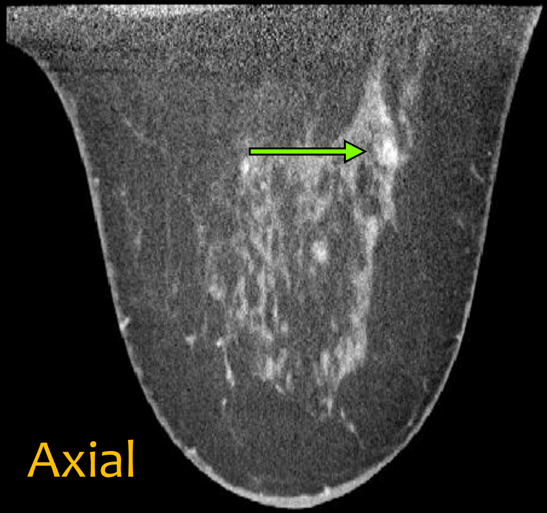


MLO
DBT



Coronal

Sagittal



Axial

CE-bCT

DCIS and IDC

Temporal subtraction contrast-enhanced dedicated breast CT

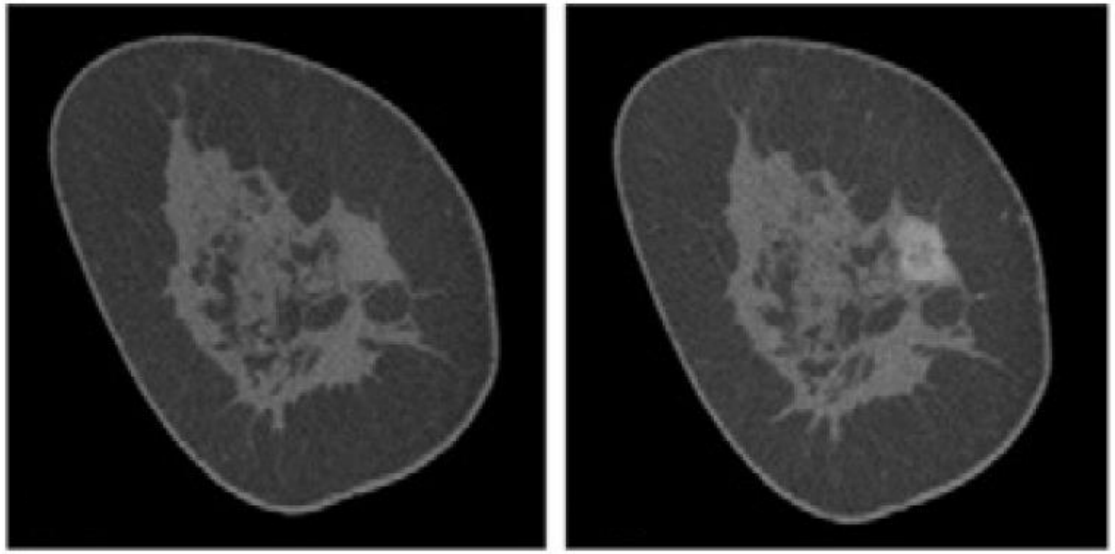
Peymon M Gazi[1,2], Shadi Aminololama-Shakeri[2], Kai Yang[3] and John M Boone[1,2]

[1] Department of Biomedical Engineering, University of California, Davis, One Shields Avenue, Davis, CA 95616, USA
[2] Department of Radiology, University of California, Davis Medical Center, 4860 Y street, Suite 3100 Ellison Building, Sacramento, CA 95817, USA
[3] Department of Radiology, Massachusetts General Hospital, 55 Fruit Street Boston, MA 2114, USA

E-mail: john.boone@ucdmc.ucdavis.edu

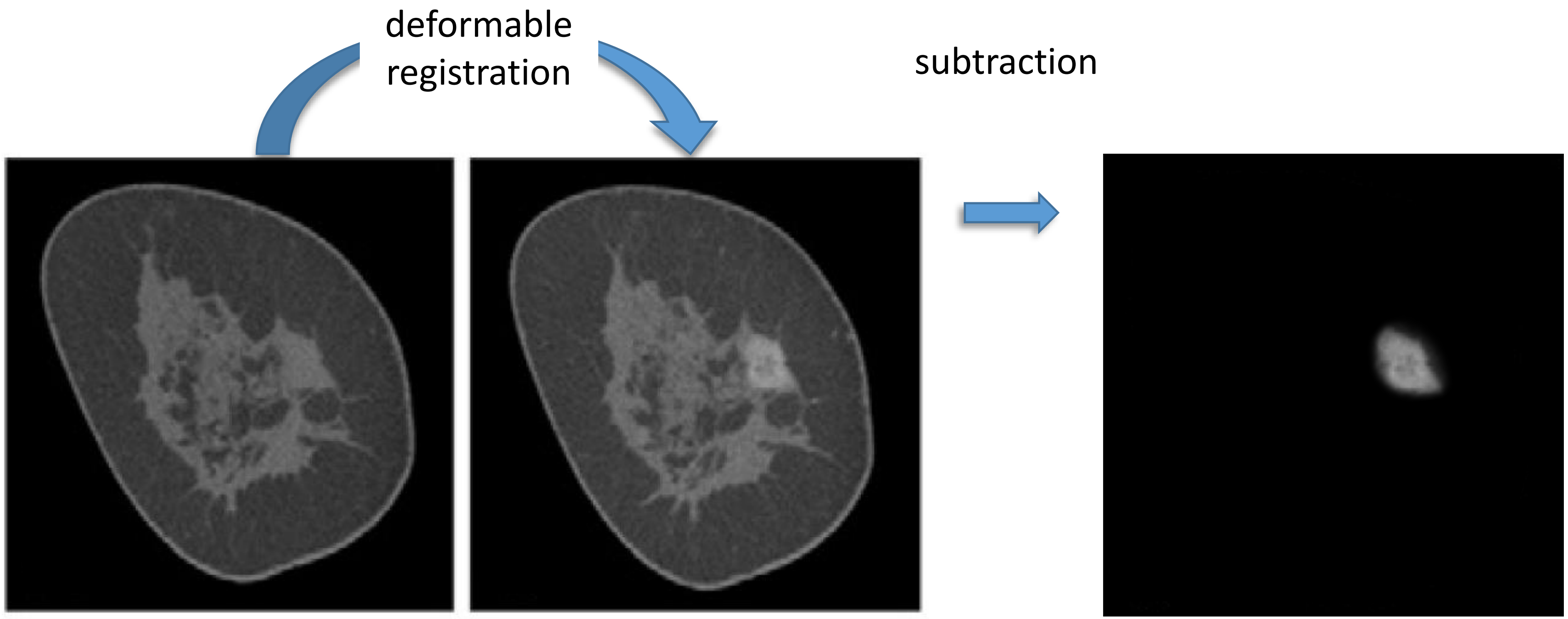
Received 1 February 2016, revised 12 June 2016
Accepted for publication 27 June 2016
Published 5 August 2016

CrossMark



Pre-contrast bCT (time 0)

Post-contrast bCT (time 90 secs)



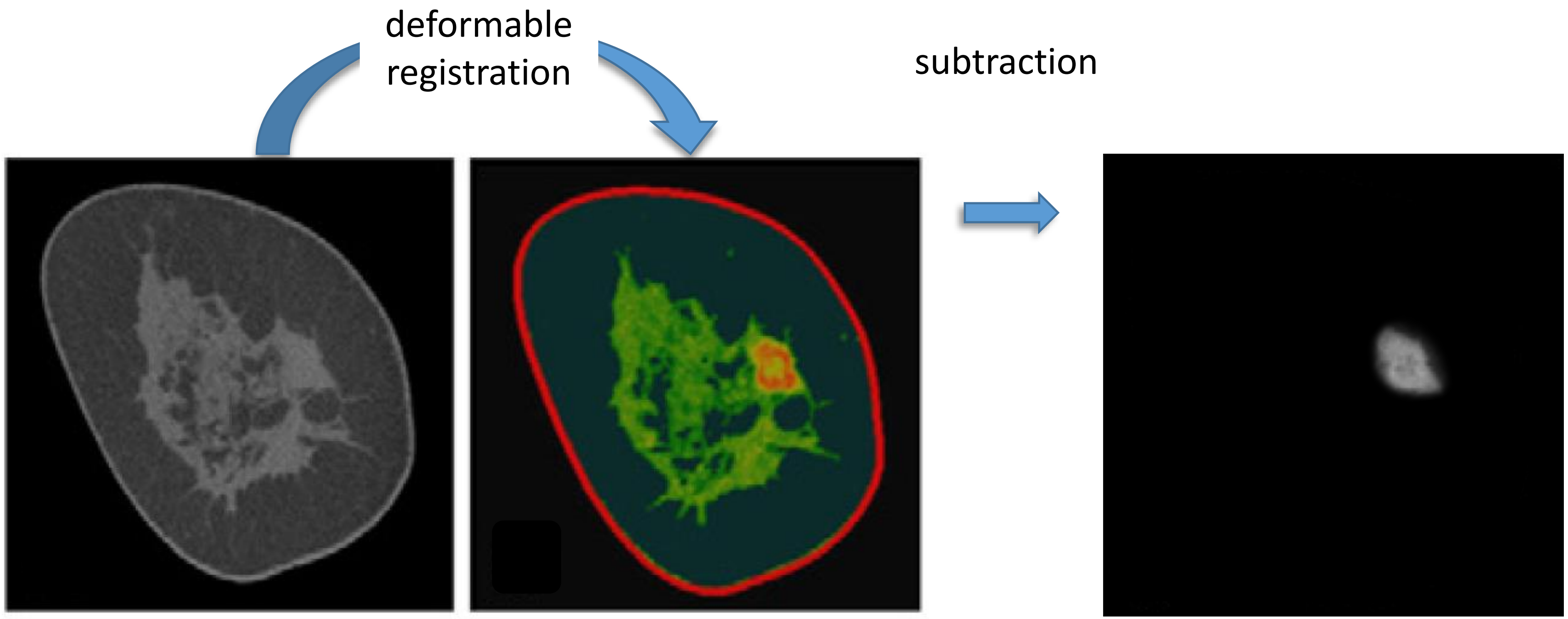
Pre-contrast bCT

Post-contrast bCT

Intensity difference adaptive DEMONS (IDAD)

$$\overrightarrow{D(p)} = (M(p)-F(p))\left(\frac{\overrightarrow{(\nabla F(p)\,c(p) + \nabla M(p))}}{\left\|\overrightarrow{\nabla F(p)\,c(p)+\nabla M(p)}\right\|^2 + \frac{[M(p)-F(p)]^2}{k^2}}\right).$$

c(p) = intensity difference correction factor



Pre-contrast bCT

Post-contrast bCT

Intensity difference adaptive DEMONS (IDAD)

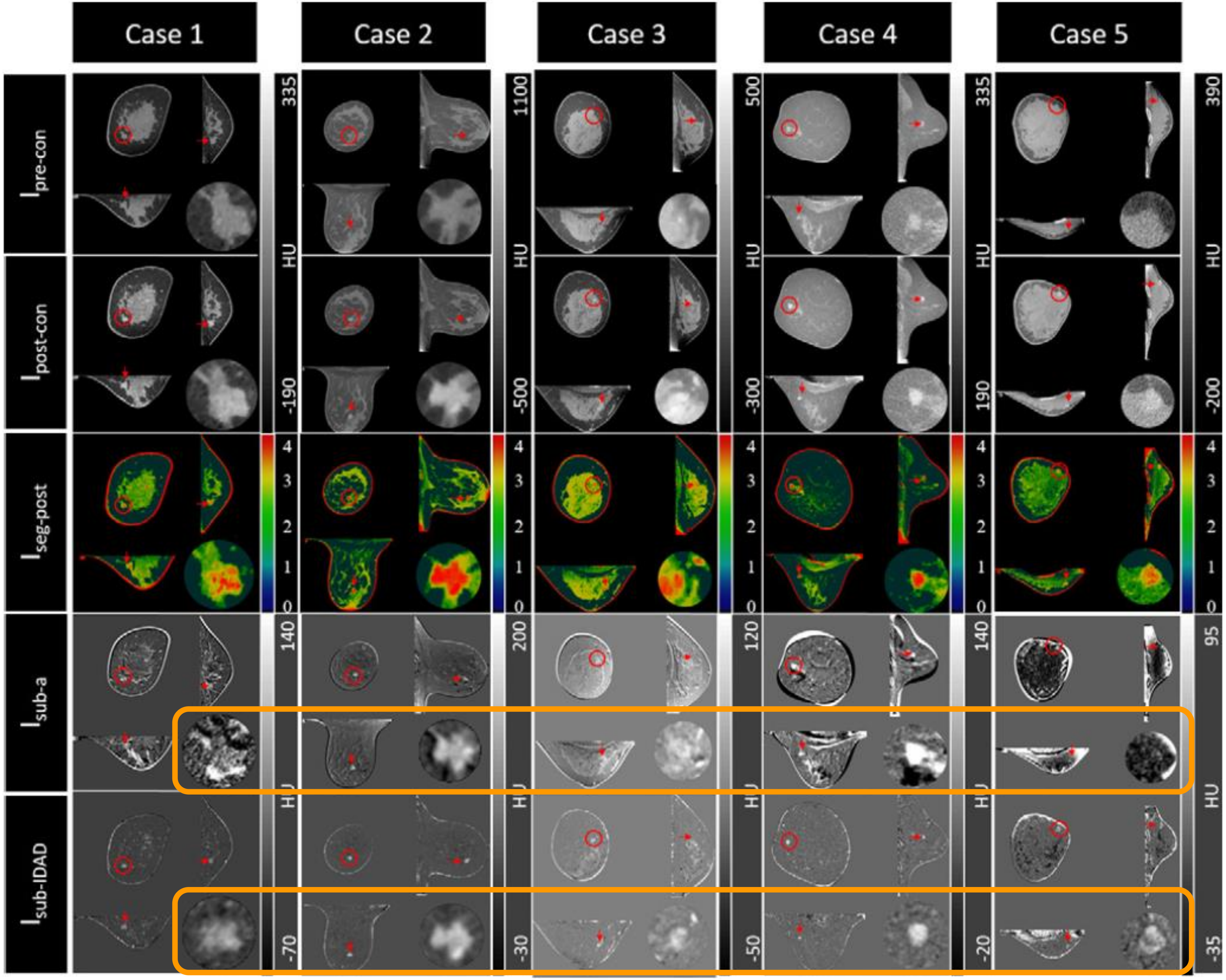
$$\overrightarrow{D(p)} = (M(p) - F(p)) \left(\frac{\overrightarrow{(\nabla F(p) c(p) + \nabla M(p))}}{\left\| \overrightarrow{\nabla F(p) c(p) + \nabla M(p)} \right\|^2 + \frac{[M(p) - F(p)]^2}{k^2}} \right).$$

c(p) = intensity difference correction factor

Subtraction Examples

⬇

better quantitation



Breast CT: *Technology development and clinical potential*

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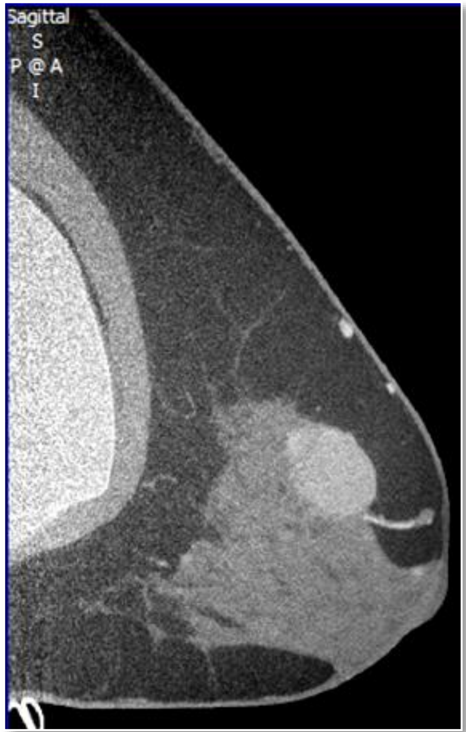
- **Observer Performance**
- Other Cool Spinoffs
- Summary



The Breast Tomography Project
University of California, Davis

Breast CT: *Technology development and clinical potential*

Introduction

Technology Development

Radiation Dose Assessment

Image Quality Metrics

Clinical Observations

Observer Performance

Other Cool Spinoffs

Summary

Anatomical Noise

Anatomical Noise

Burgess, et al (2001)

$$NPS_a(f) = \alpha\, f^{-\beta}$$

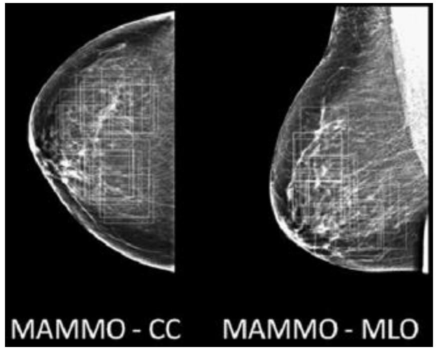
anatomical noise

total noise

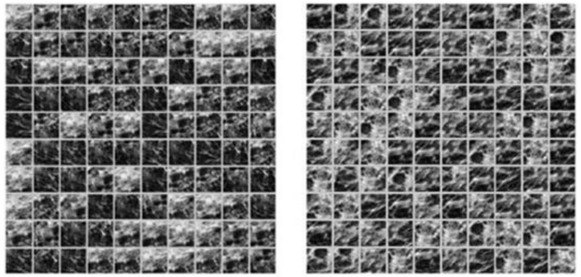
quantum noise

$$NPS(f) = NPS_a(f) + NPS_q(f)$$

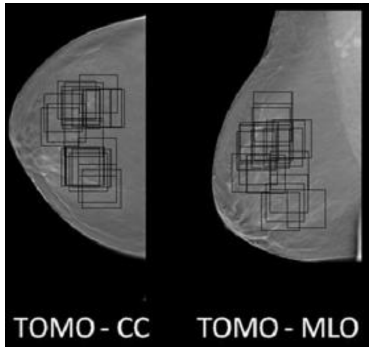
A. E. Burgess, F. L. Jacobson, and P. F. Judy, "Human observer detection experiments with mammograms and power-law noise," Med. Phys. **28**, 419–437 (2001).



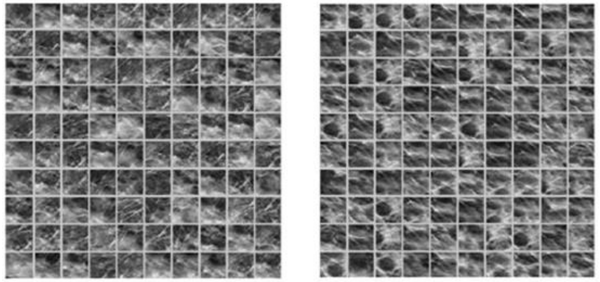
mammo



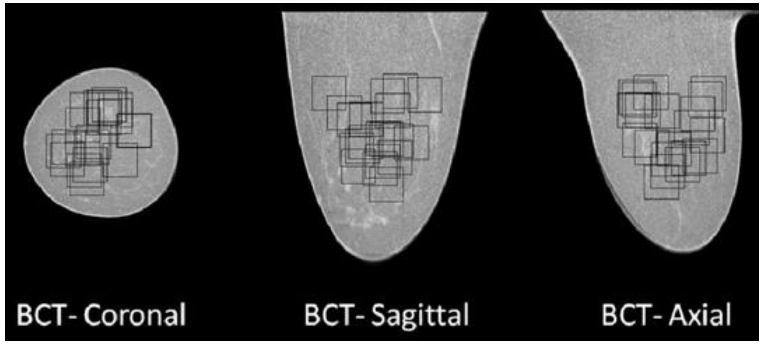
MAMMO - CC MAMMO - MLO



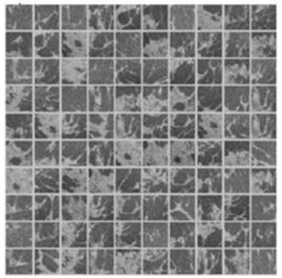
tomo



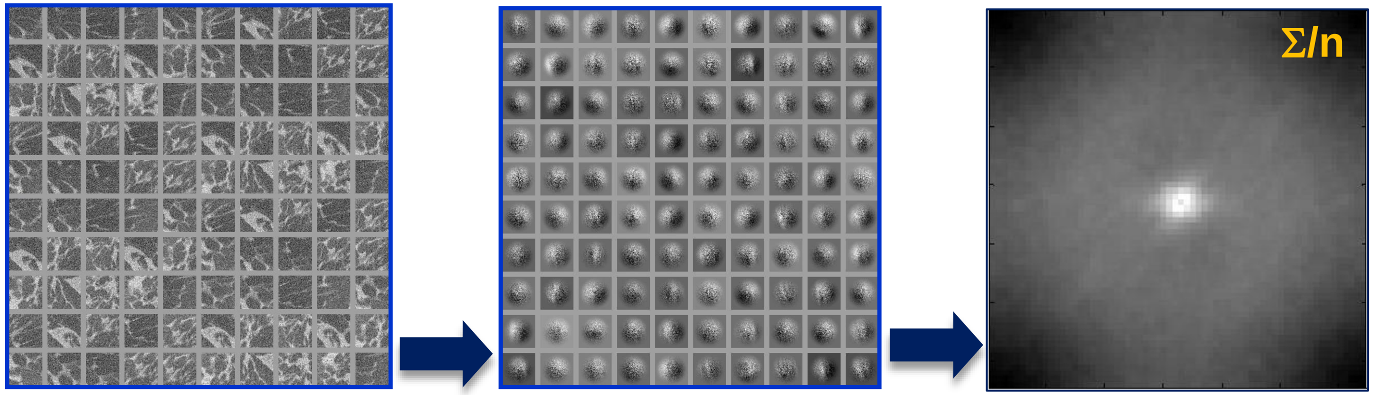
TOMO - CC TOMO - MLO



Breast CT



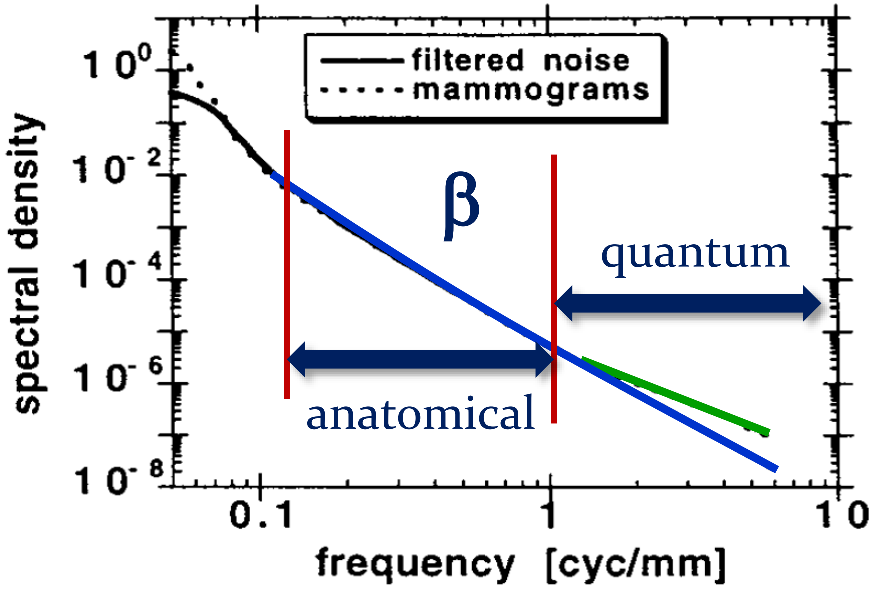
BCT- Coronal



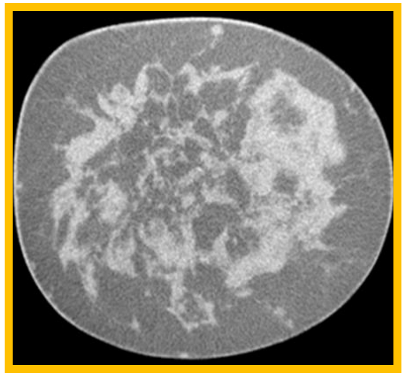
Hanning filter **2D-NPS**

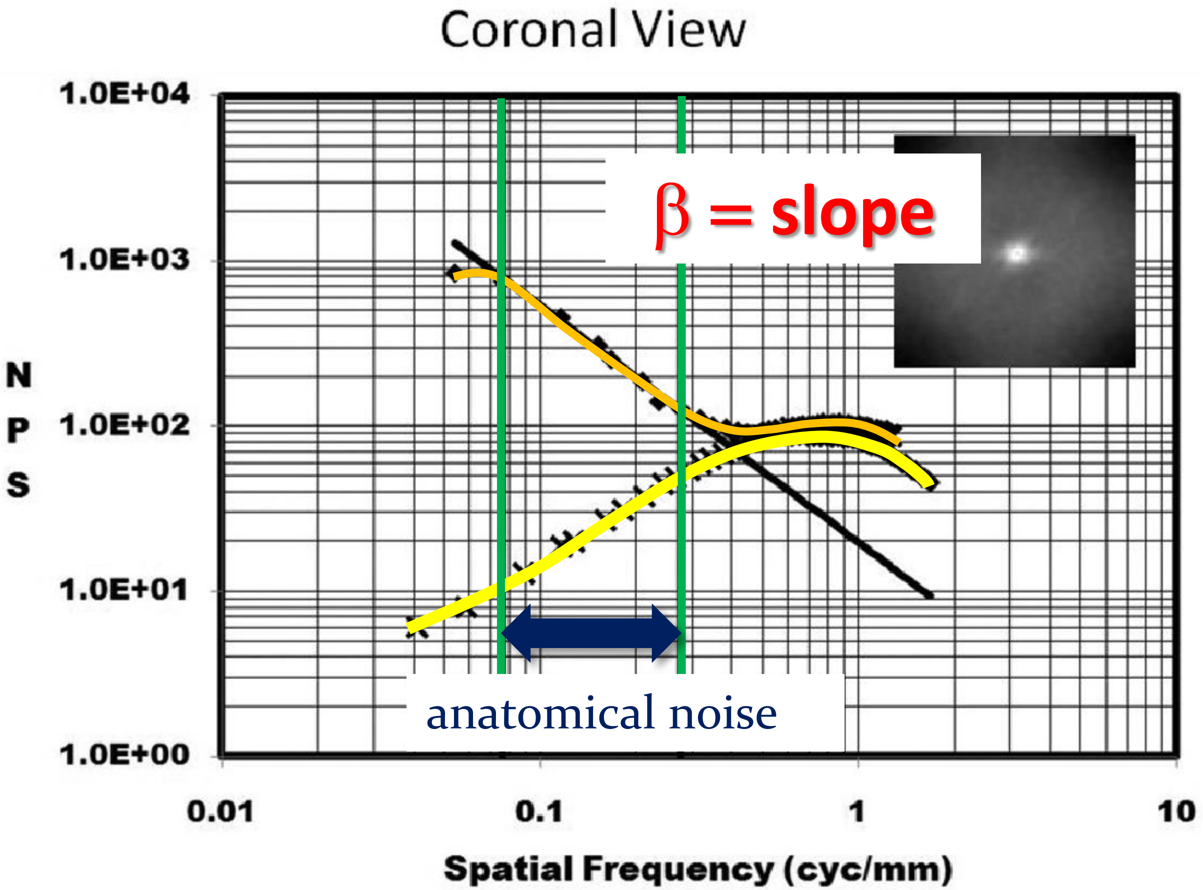
$$NPS_a(f) = \alpha f^{-\beta}$$

$$f = \sqrt{u^2 + v^2}$$



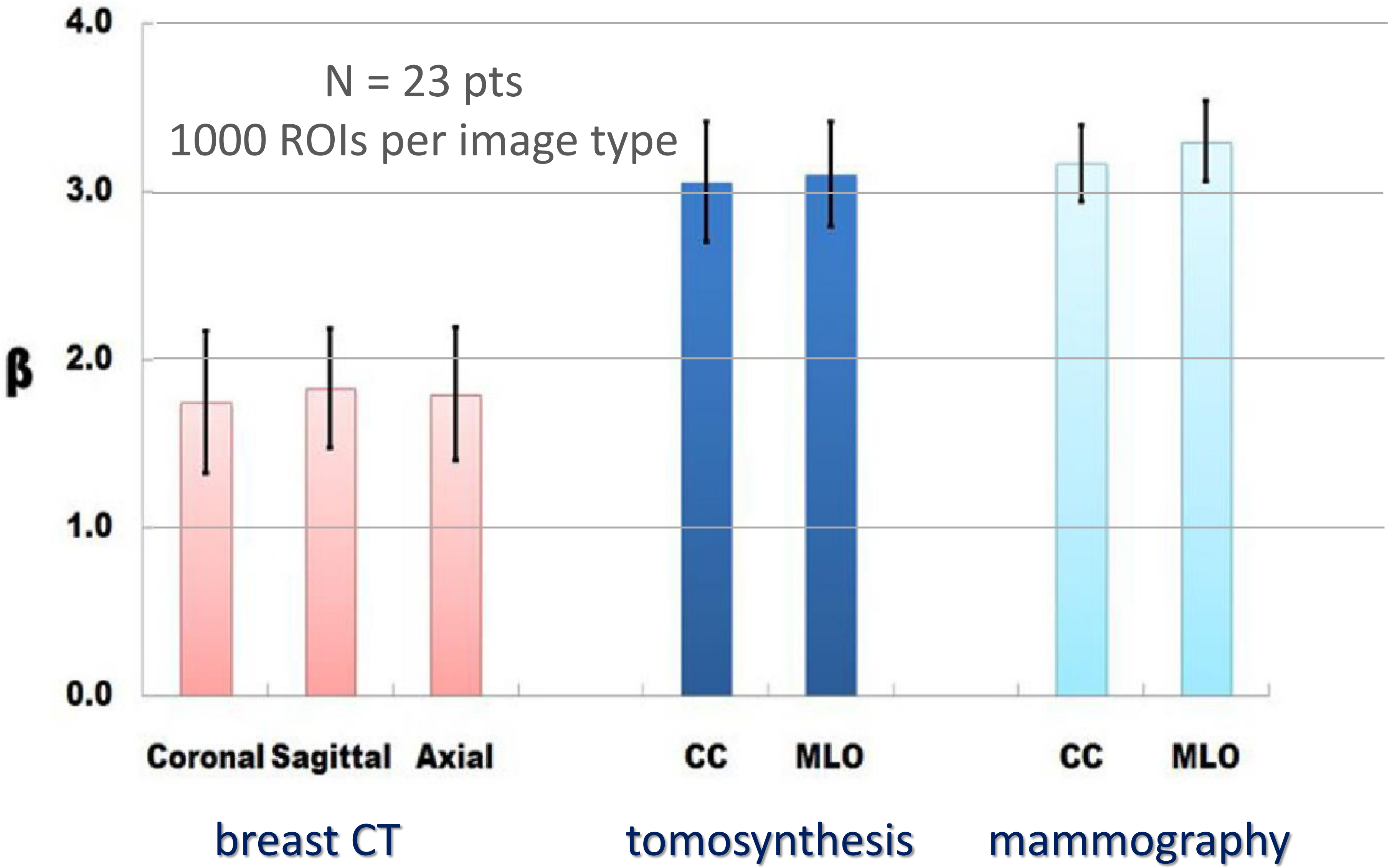
$$NPS(f) = NPS_a(f) + NPS_q(f)$$



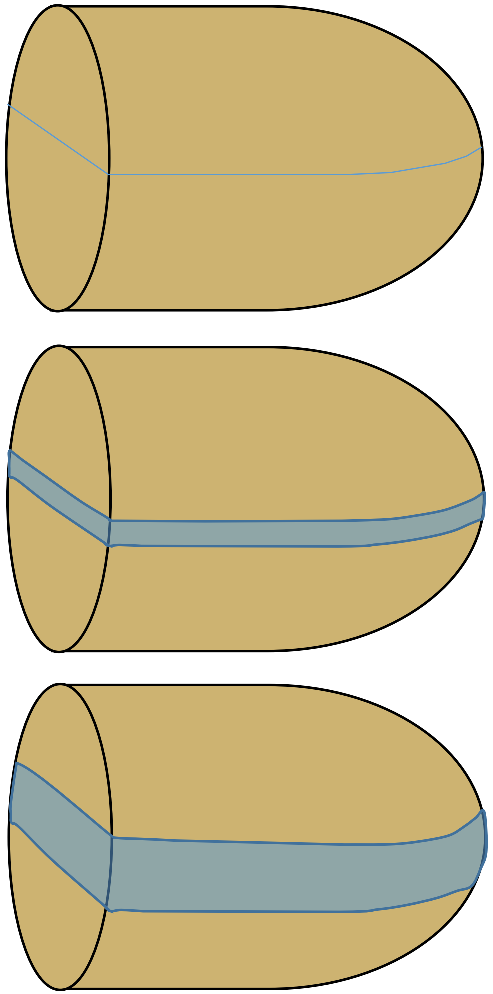


$$NPS_a(f) = \alpha f^{-\beta}$$

Breast CT, Tomosynthesis, and Mammography Texture Comparisons



Use breast CT images to generate images of different thickness



Anatomical complexity in breast parenchyma and its implications for optimal breast imaging strategies

Lin Chen
Biomedical Engineering Graduate Group, University of California Davis, Sacramento, California 95817

Craig K. Abbey
Department of Psychology, University of California Santa Barbara, Santa Barbara, California 93106

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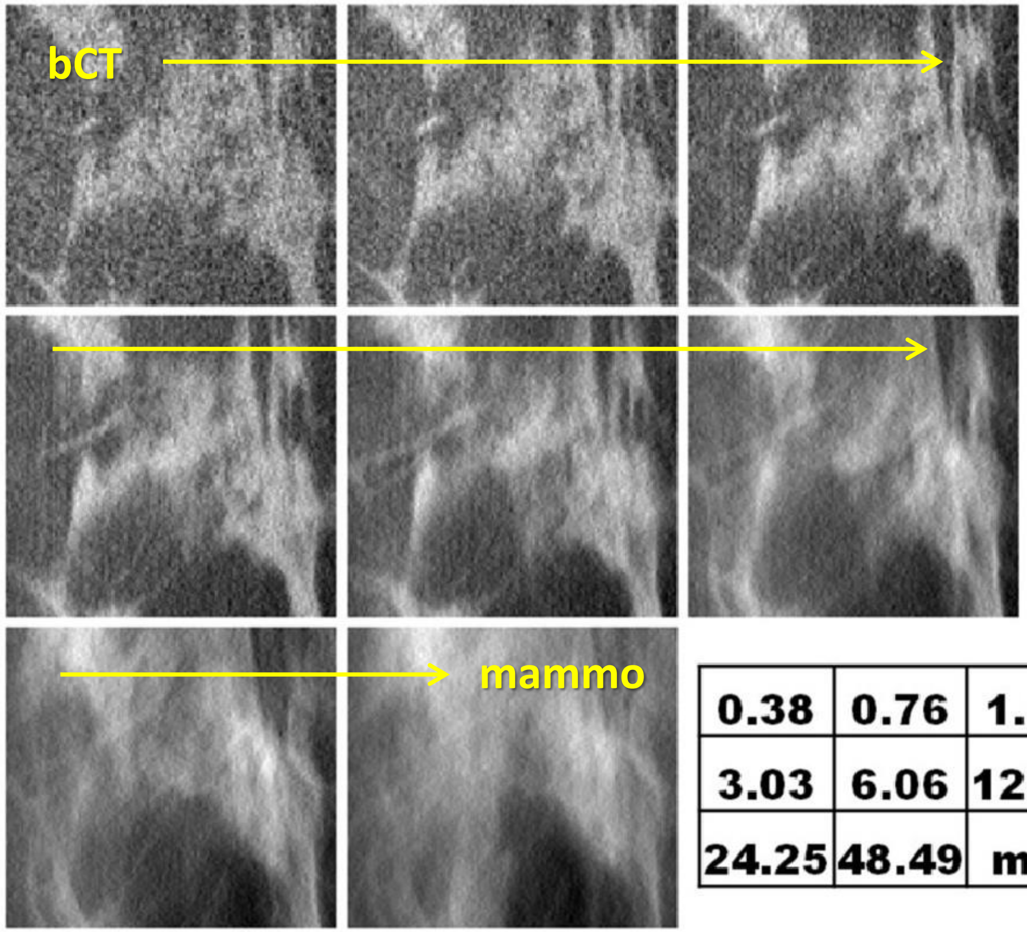
John M. Boone[a)]
Department of Radiology, University of California Davis and Department of Biomedical Engineering, University of California Davis, Sacramento, California 95817



0.38	0.76	1.52
3.03	6.06	12.12
24.25	48.49	mm

Use breast CT images to generate images of different thickness

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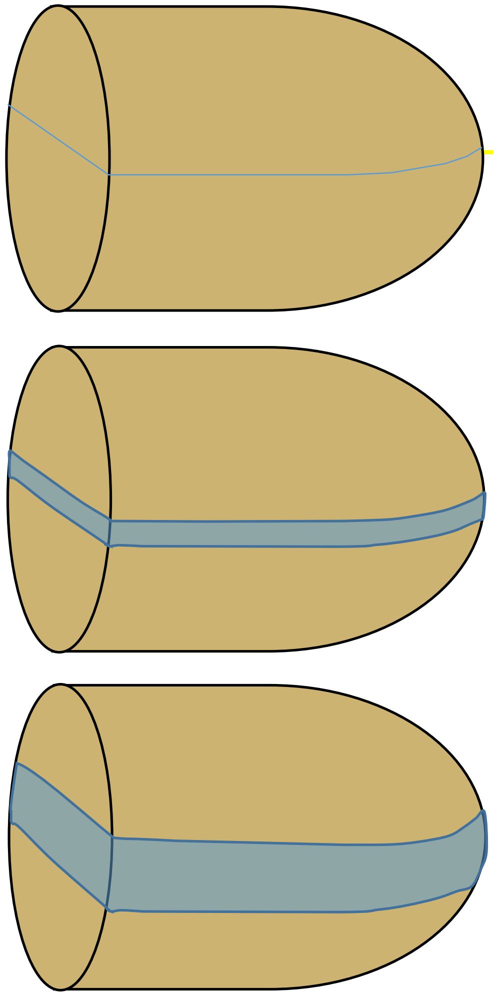
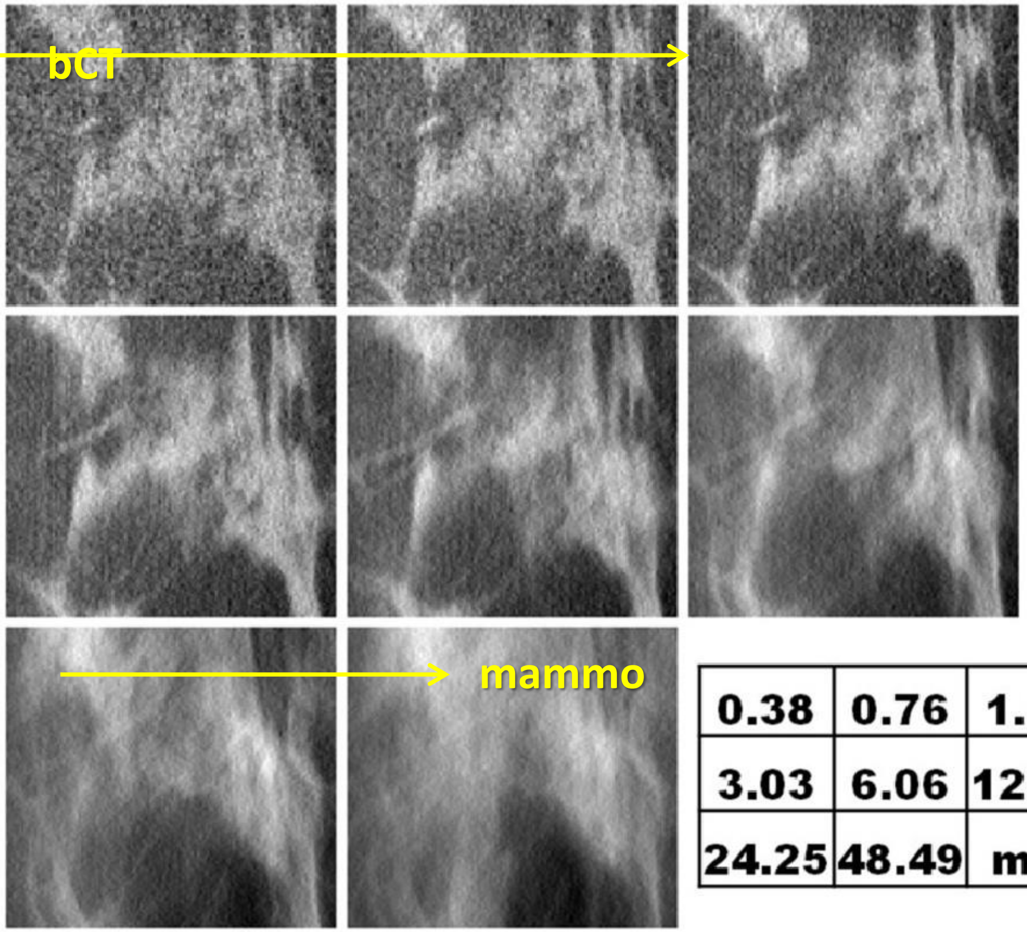
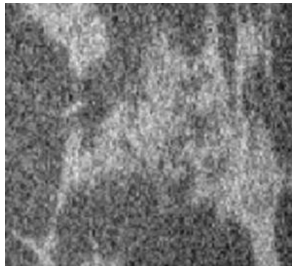
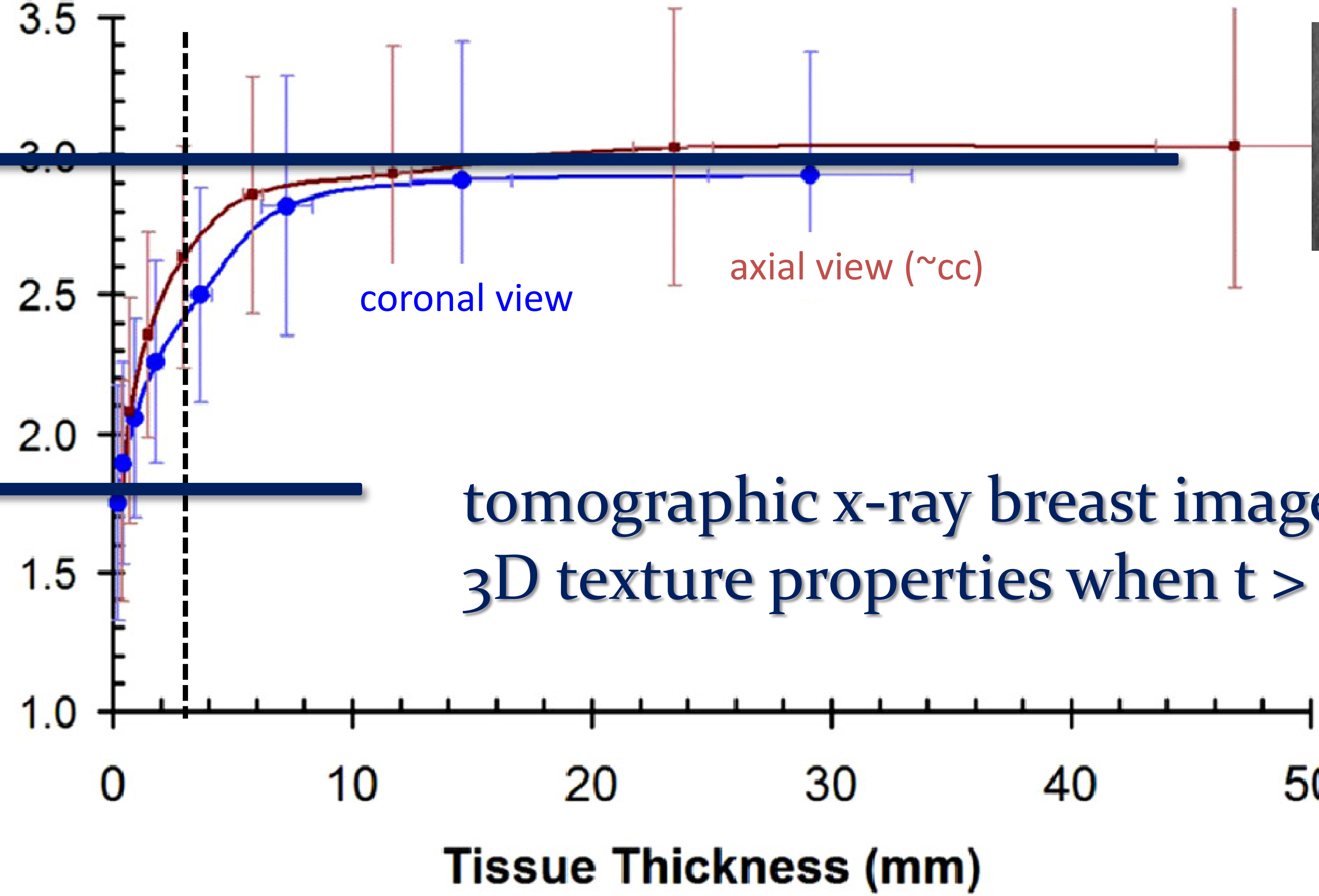


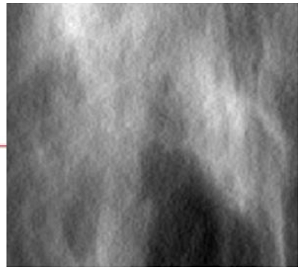


0.38	0.76	1.52
3.03	6.06	12.12
24.25	48.49	mm



breast CT





mammo

tomographic x-ray breast images lose their 3D texture properties when t > 3 mm

Comprehensive assessment of the slice sensitivity profiles in breast tomosynthesis and breast CT

Anita Nosratieh
Biomedical Engineering Graduate Group, Department of Radiology, University of California, Davis, California 95817

Kai Yang and Shadi Aminololama-Shakeri
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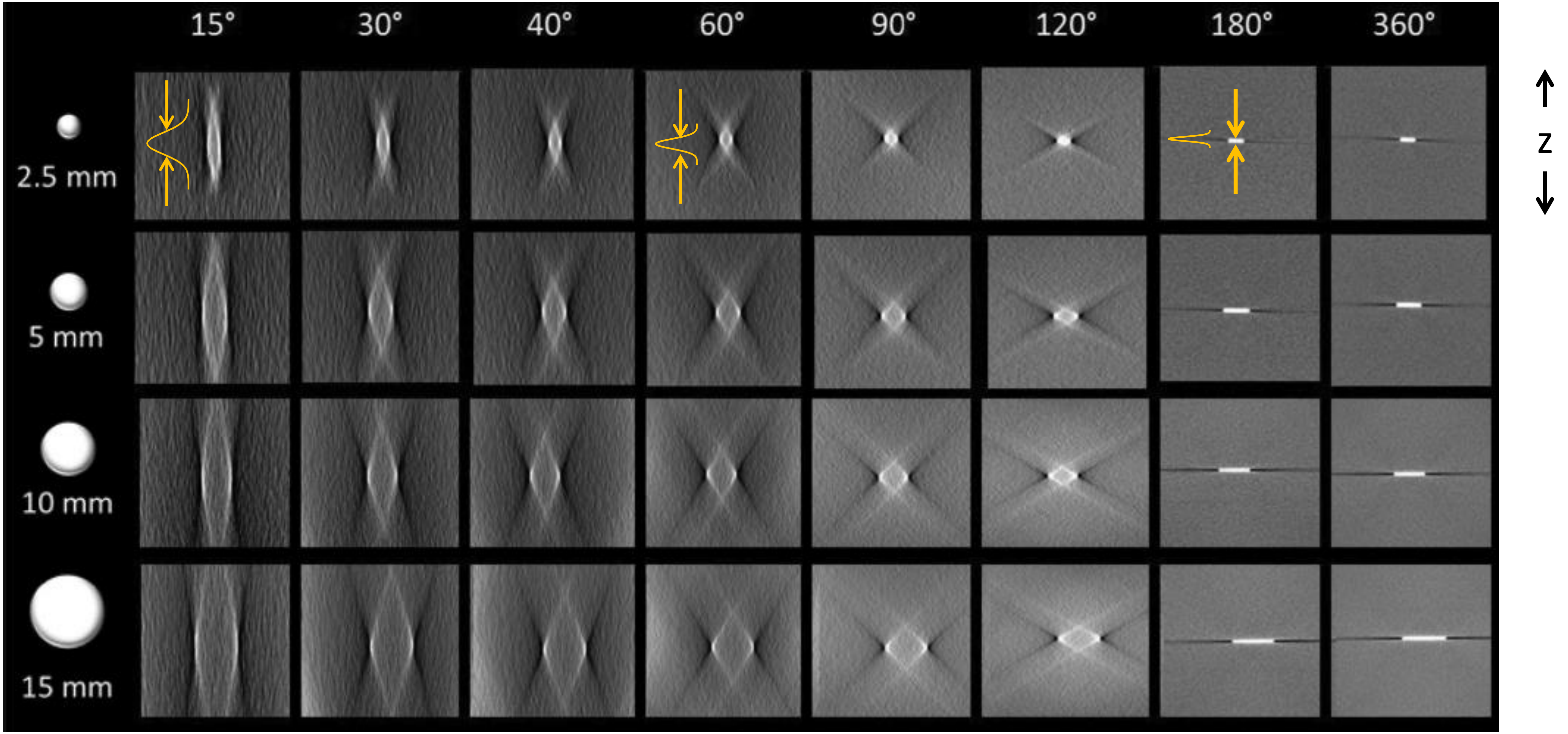
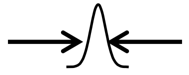
(Received 2 February 2012; revised 12 October 2012; accepted for publication 15 October 2012; published 26 November 2012)

Anita Nosratieh

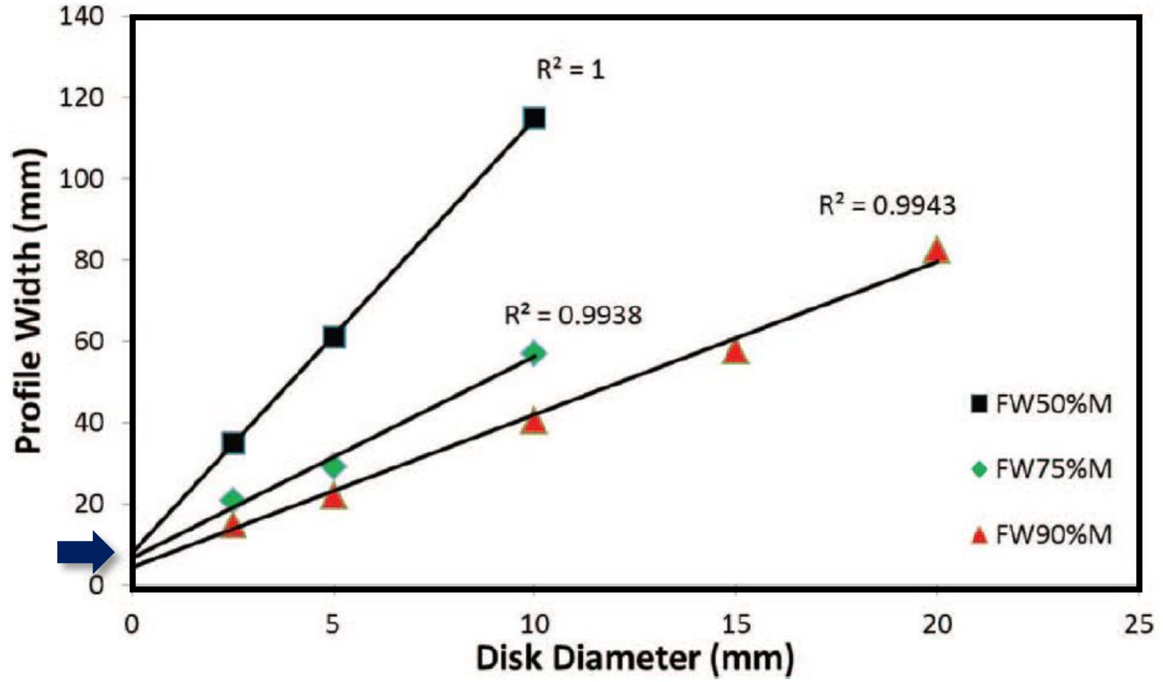
Tomographic slice thickness as a function of angle and object size



Tomographic slice thickness as a function of angle and object size

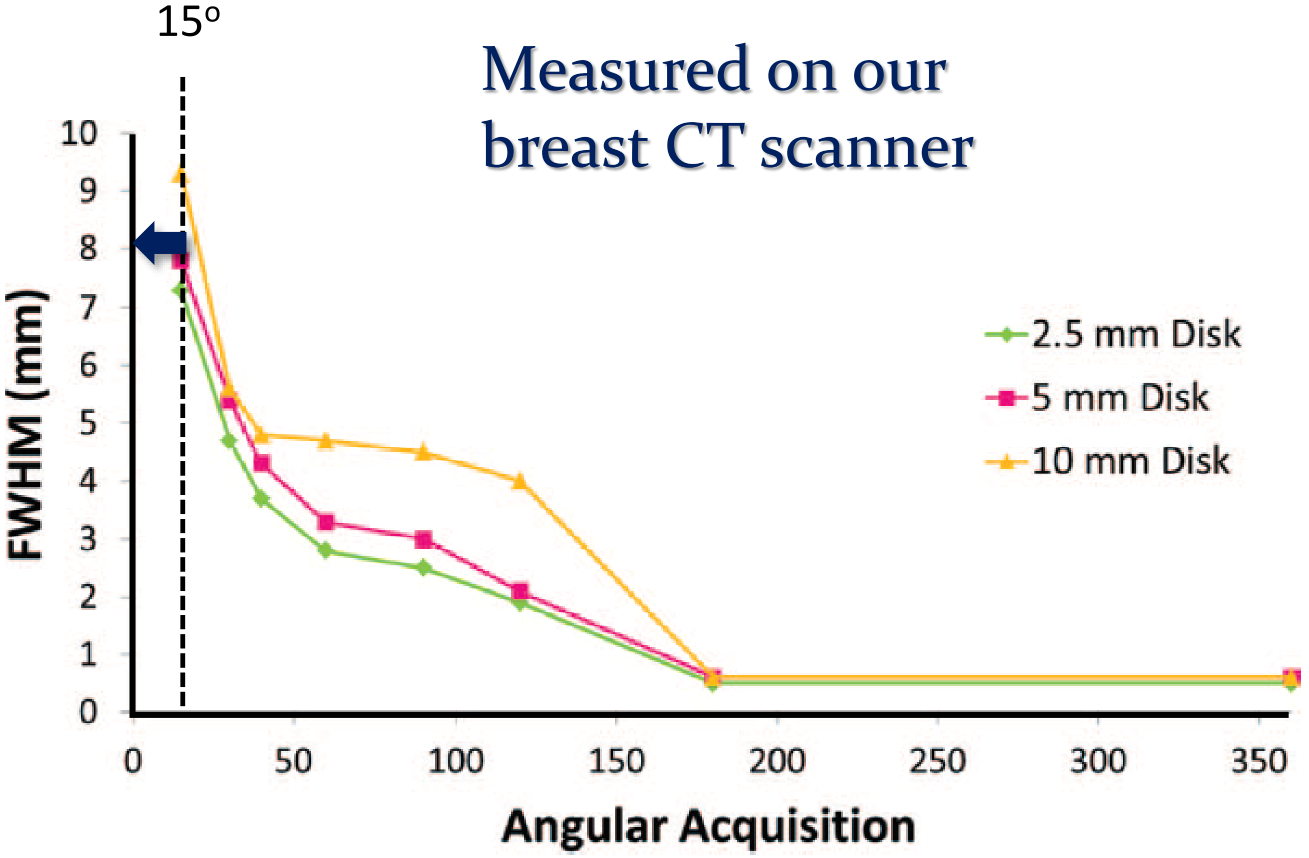


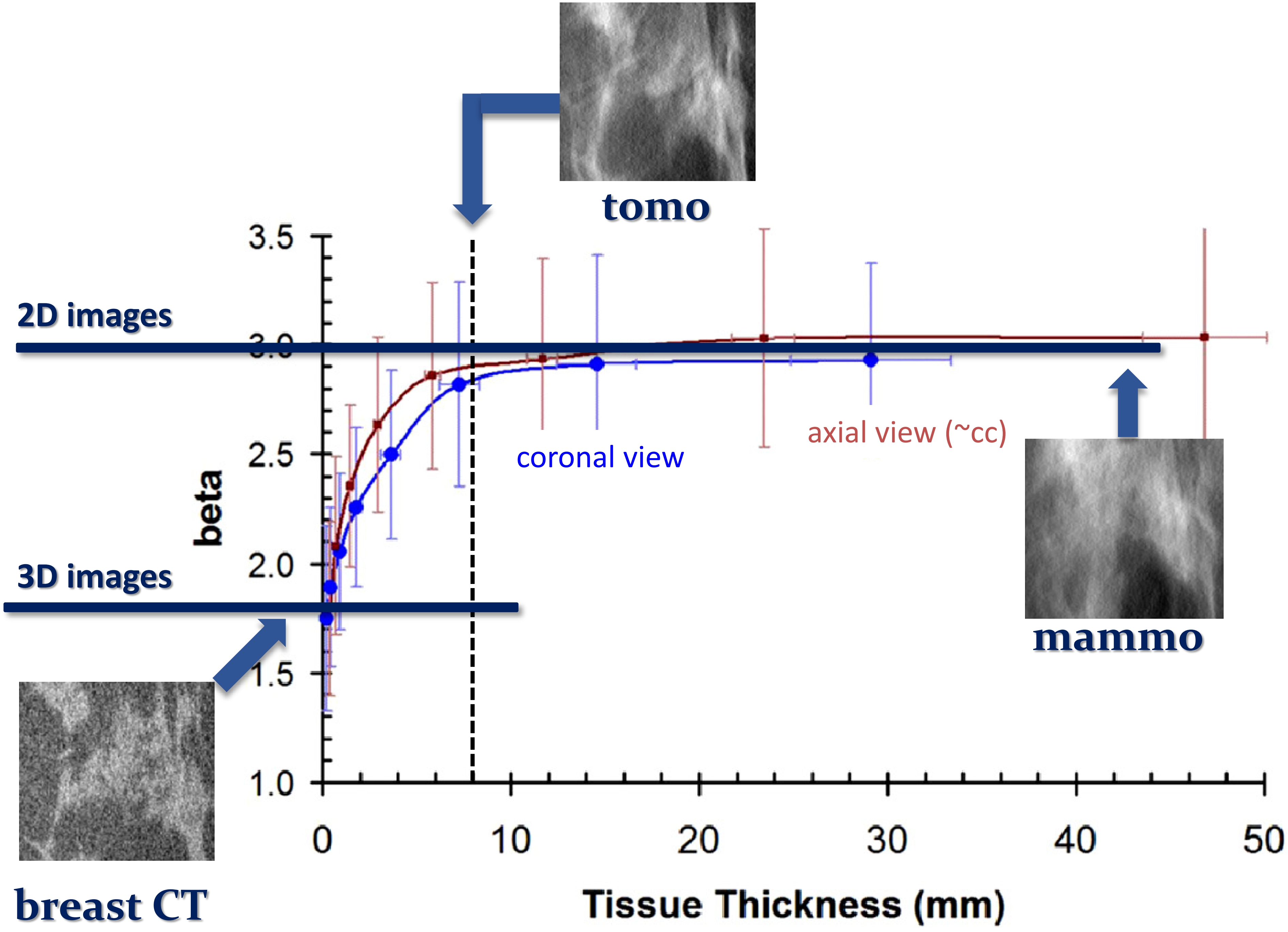
Measured on a commercial breast tomosynthesis system



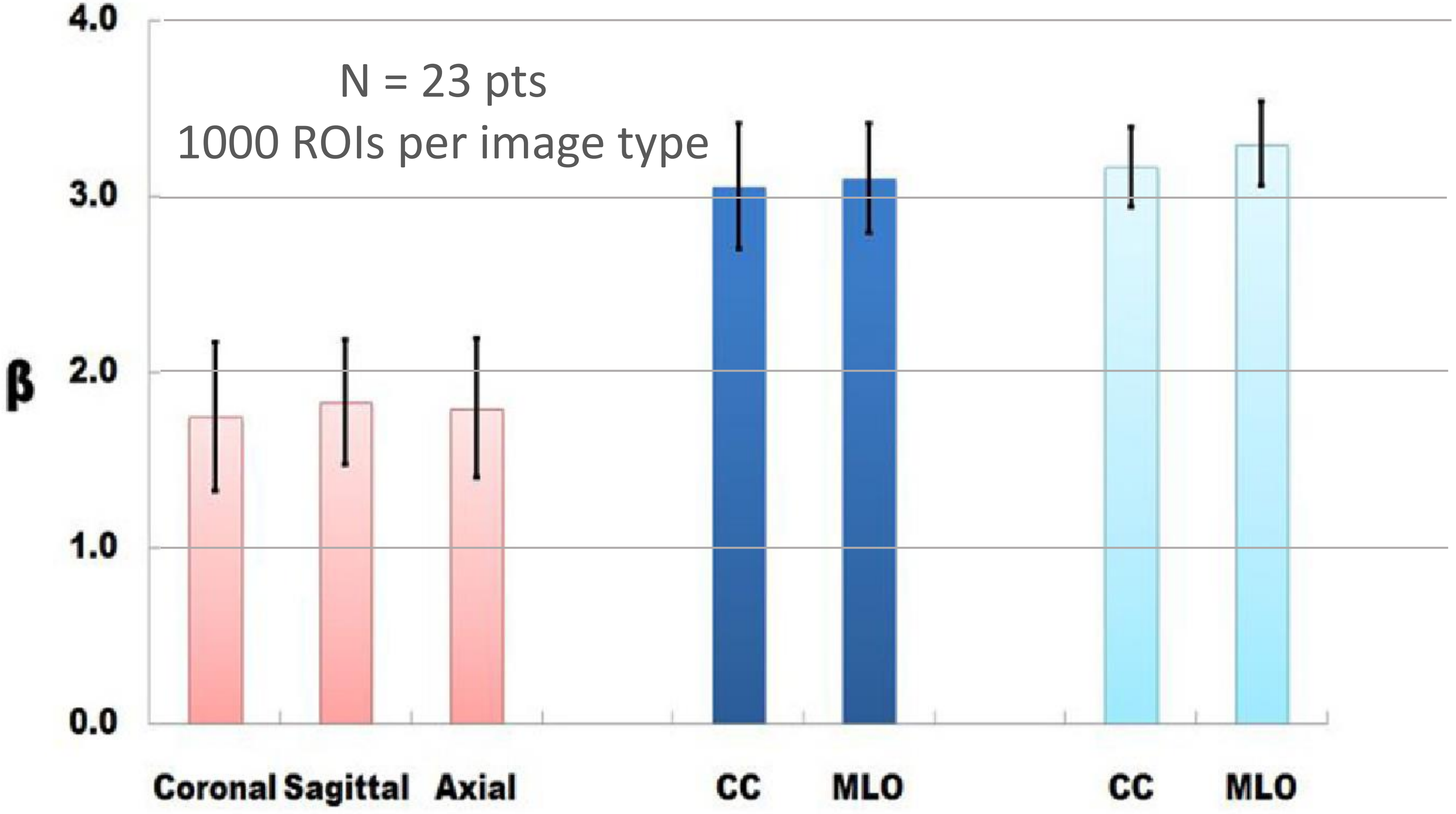
FWHM (0 mm disk) ~ 8 mm

Measured on our breast CT scanner



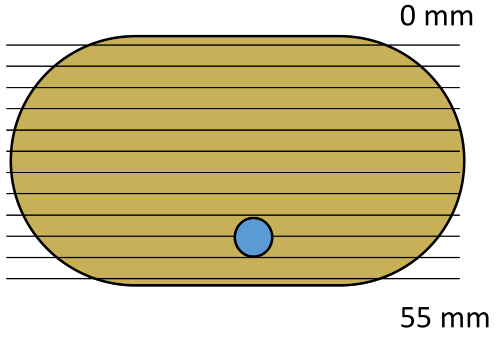

tomo
2D images
3D images
beta
3.5
3.0
2.5
2.0
1.5
1.0
coronal view
axial view (~cc)
mammo
breast CT
0
10
20
30
40
50
Tissue Thickness (mm)

Breast CT, Tomosynthesis, and Mammography Texture Comparisons

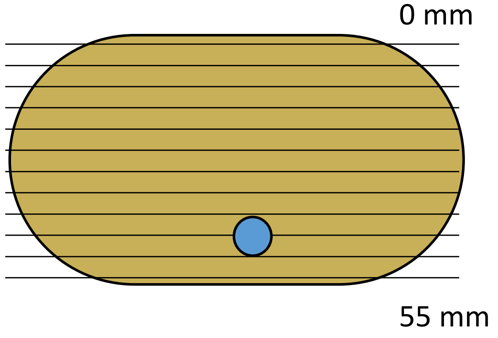


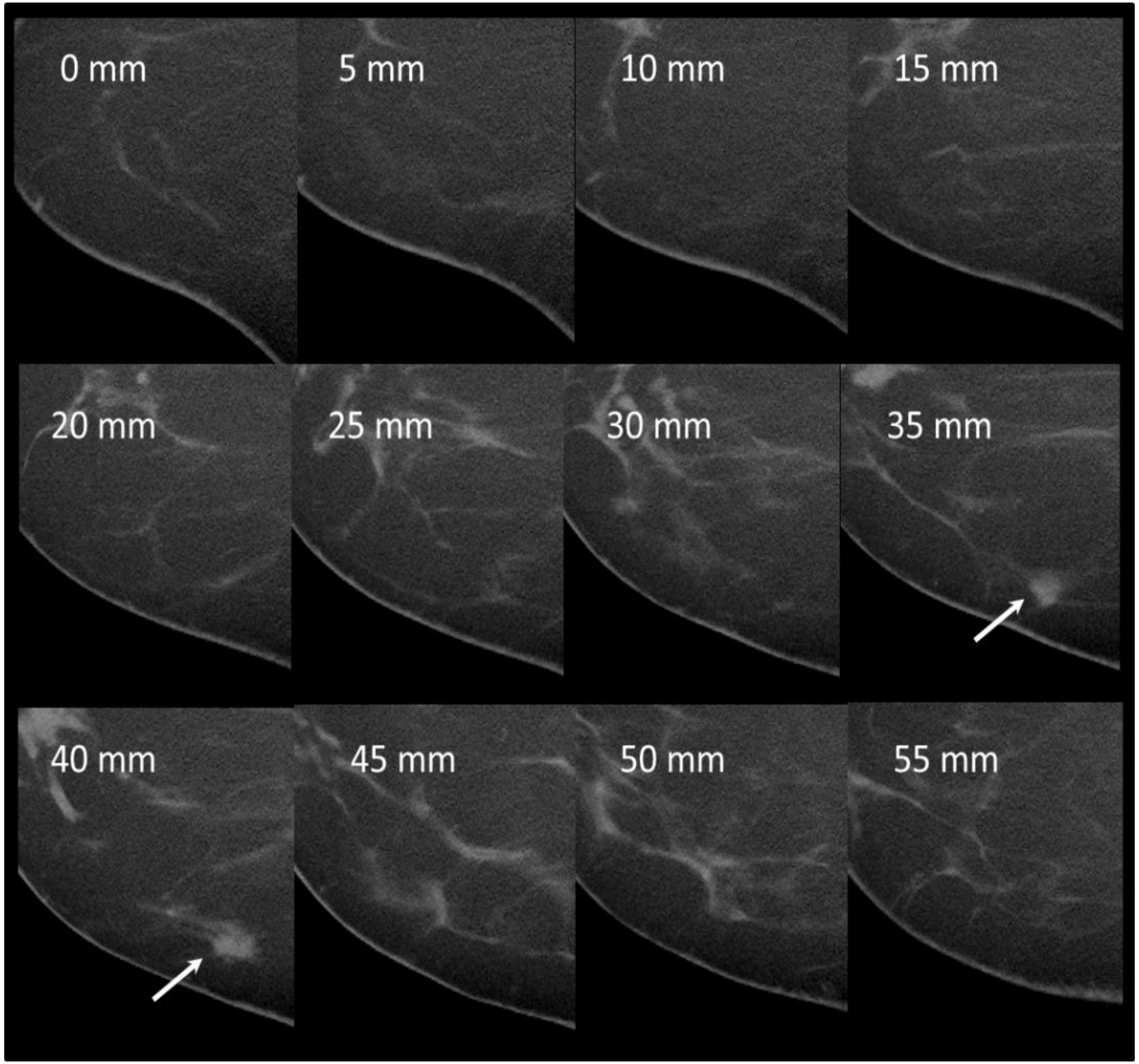
breast CT tomosynthesis mammography

Mammography

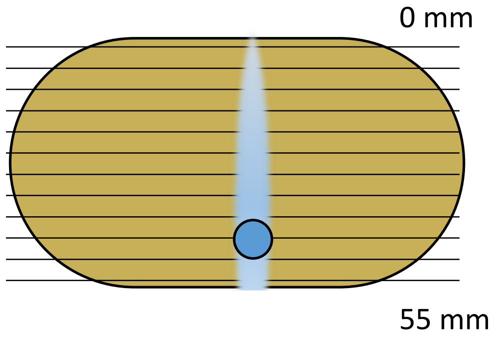


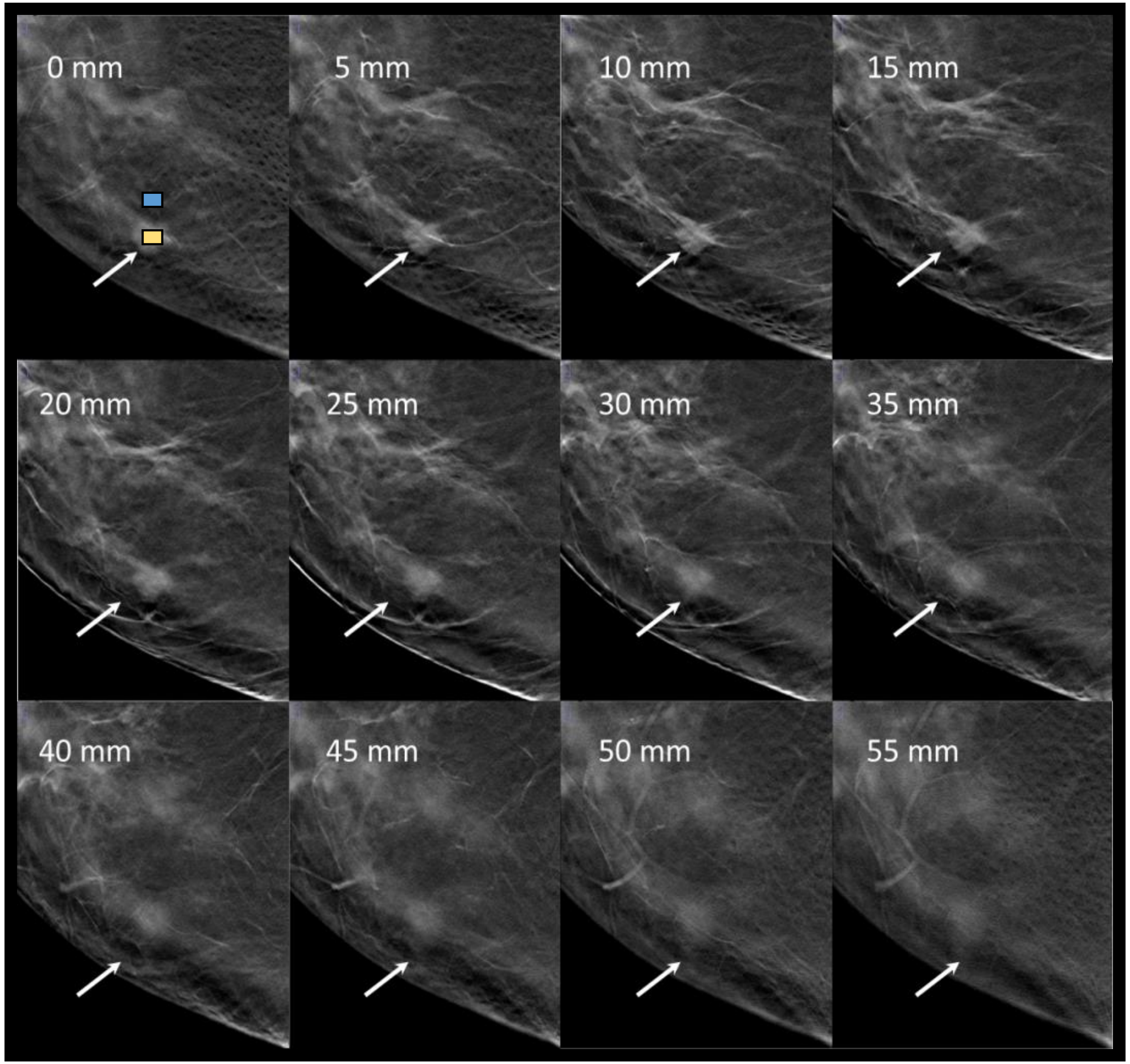
Breast CT Images





Tomosynthesis





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Computer Observer

Computer (PWMF) Observer Performance

Effect of slice thickness on detectability in breast CT using a prewhitened matched filter and simulated mass lesions

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Craig K. Abbey
Department of Psychology, University of California, Santa Barbara, California 93106

Kai Yang
Department of Radiology, University of California Davis Medical Center, Sacramento, California 95817

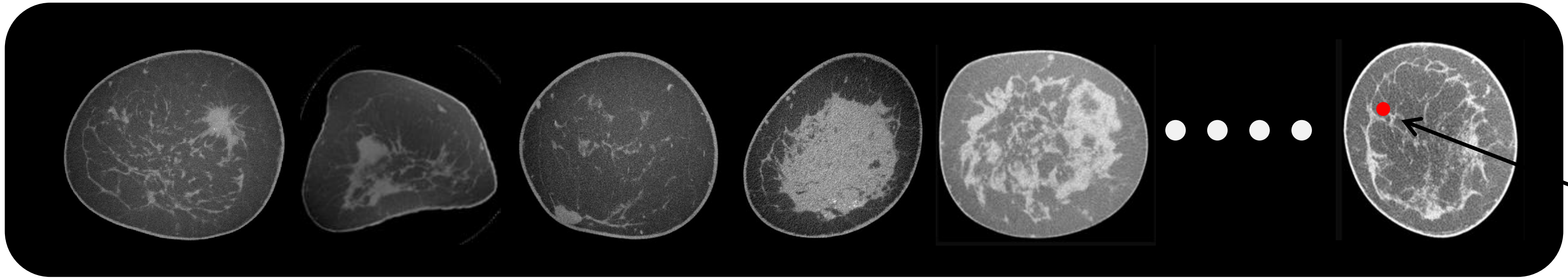
John M. Boone[a)]
Department of Radiology, University of California Davis Medical Center, Sacramento, California 95817 and Department of Biomedical Engineering, University of California, Davis, California 95616

(Received 11 April 2011; revised 22 December 2011; accepted for publication 25 January 2012; published 14 March 2012)

Signal Known Exactly (SKE)

Evaluated versus slice thickness (from 0.4 mm to 44 mm)

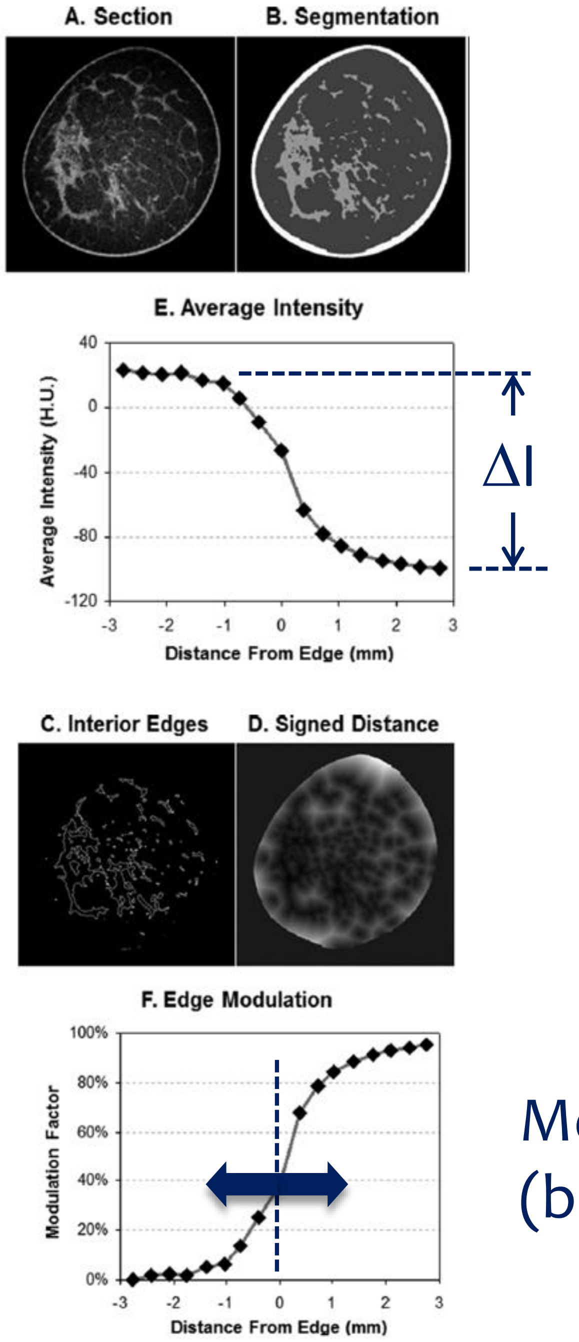
bCT   "mammo"



Real breast CT data sets (N=151)

Simulated Spherical Lesions
from 1 mm to 15 in diameter

Simulated lesion insertion into real breast CT data sets with different slice thickness

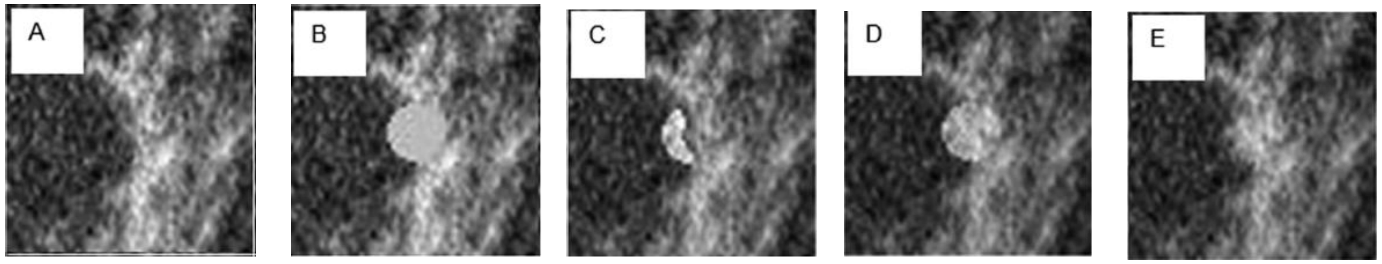


$$f_{sim}[i,j,k] = f[i,j,k] + \Delta I \, M_{TB}(d[i,j,k]) \, M([D/2] - d_{LC}[i,j,k])$$

Lesion Intensity

Modulation (blurring)

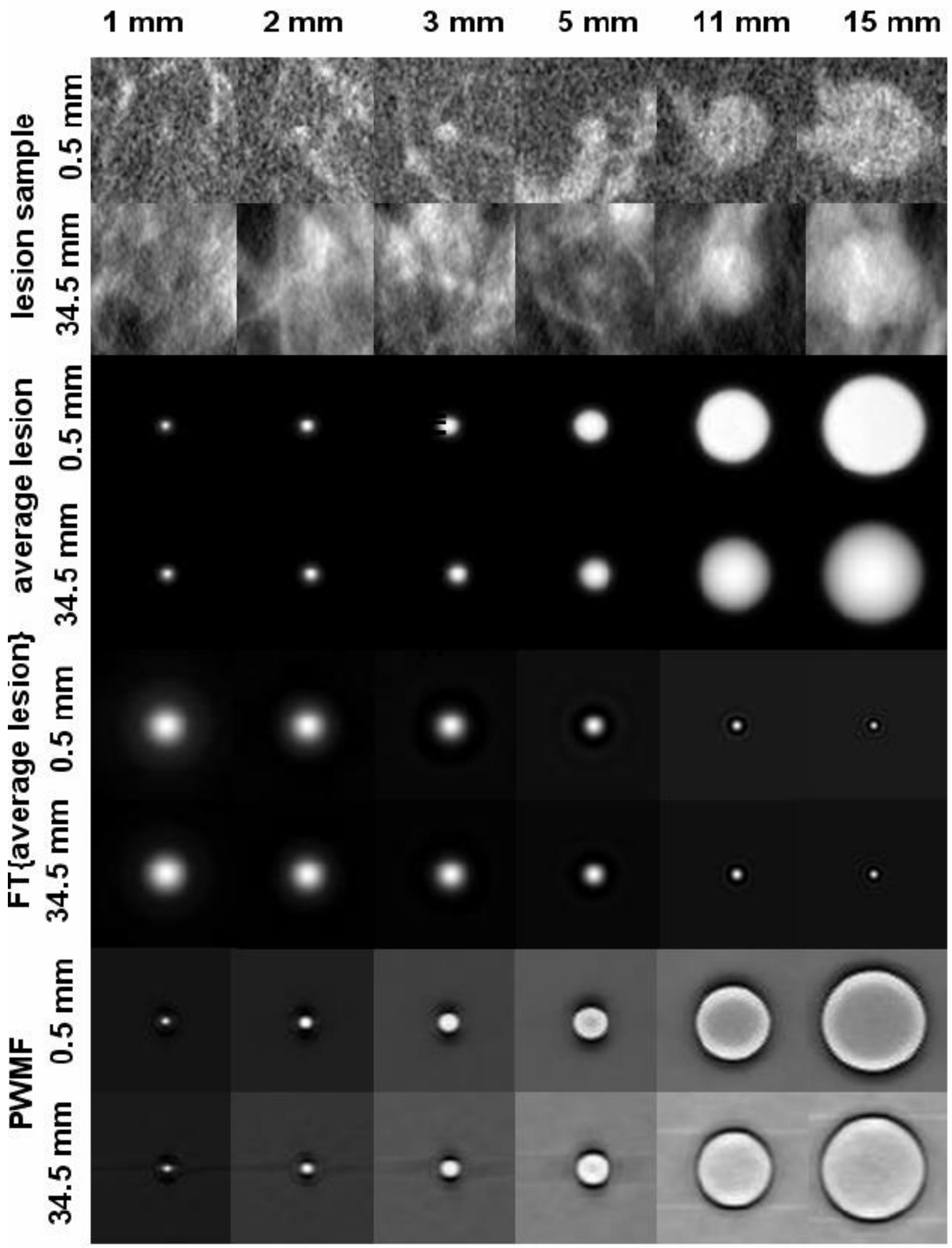
adaptive lesion insertion model



no lesion

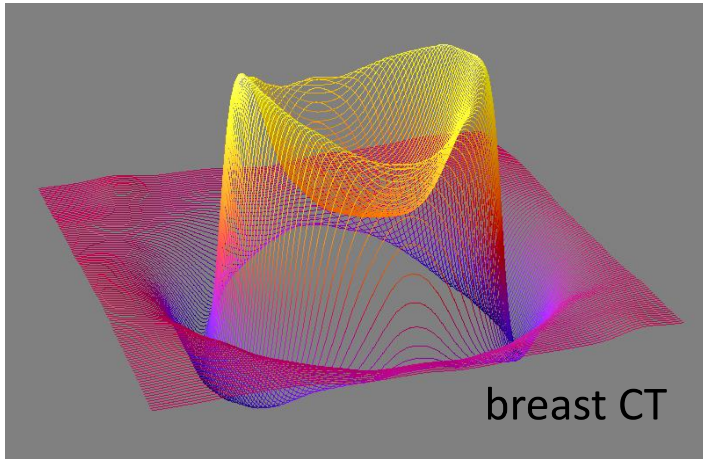
other lesion insertion models

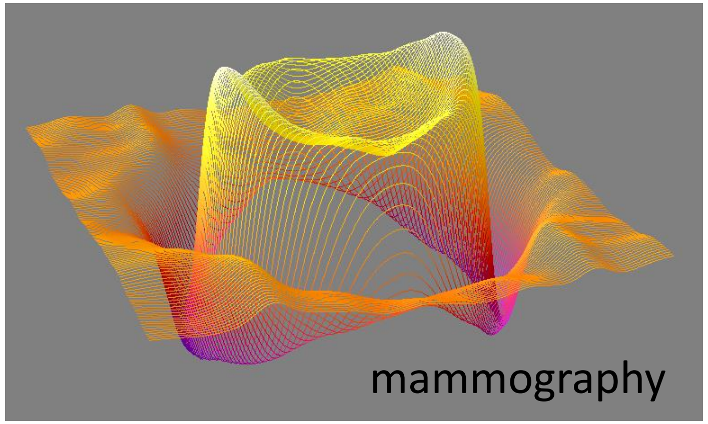
our model



Pre-whitened Matched Filter

$$PWMF = FT^{-1}\left\{\frac{FT\{\overline{S}(x,y)\}}{\overline{PS}(f_x,f_y)}\right\}$$





S(x,y): 1000 samples

PS(x,y): 1000 samples

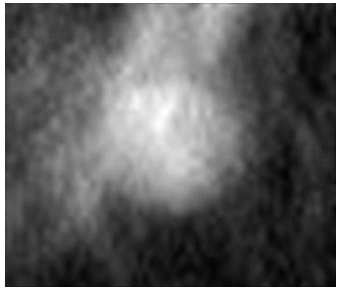
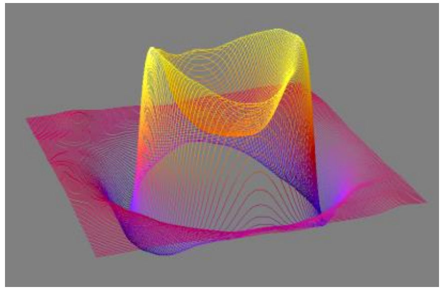
For 9 slice thicknesses

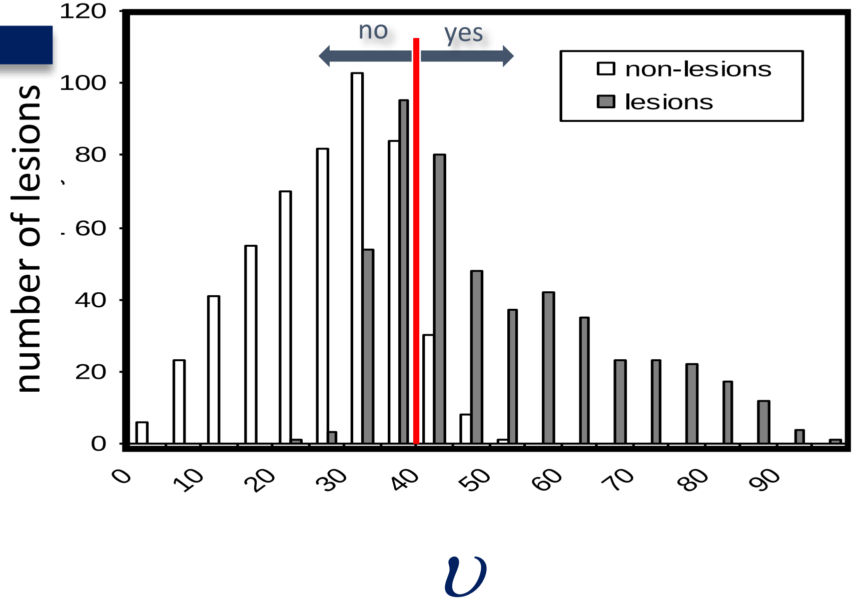
From 0.3 to 44 mm

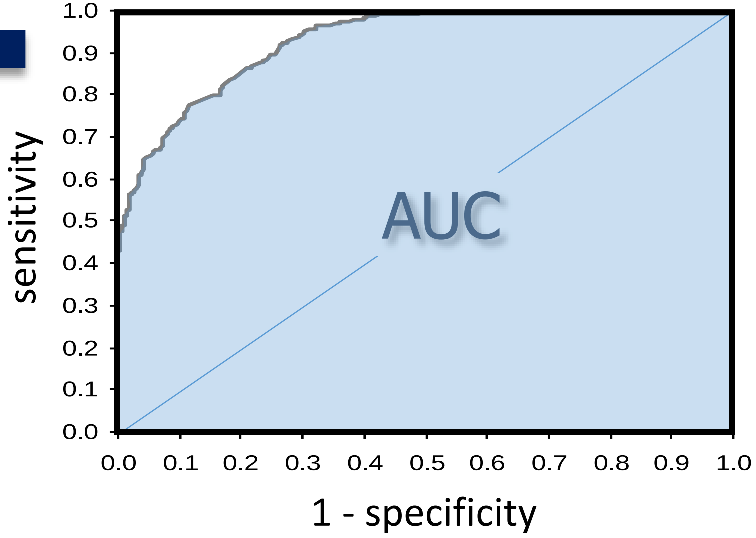
For each bCT data set:

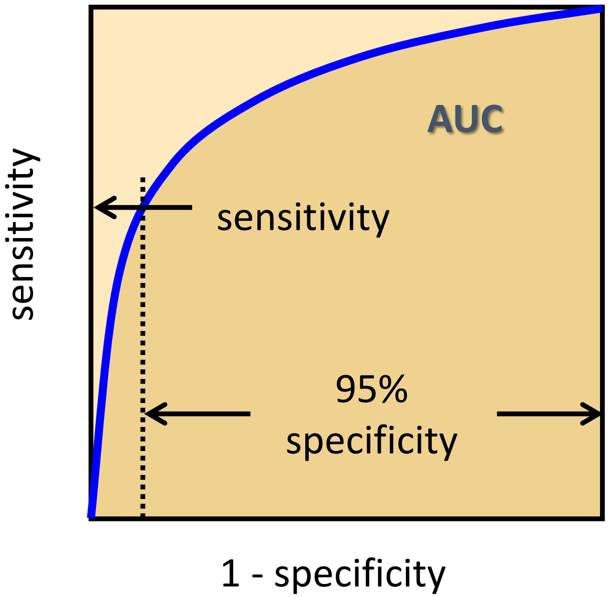
1000 true lesions &

1000 non-lesions

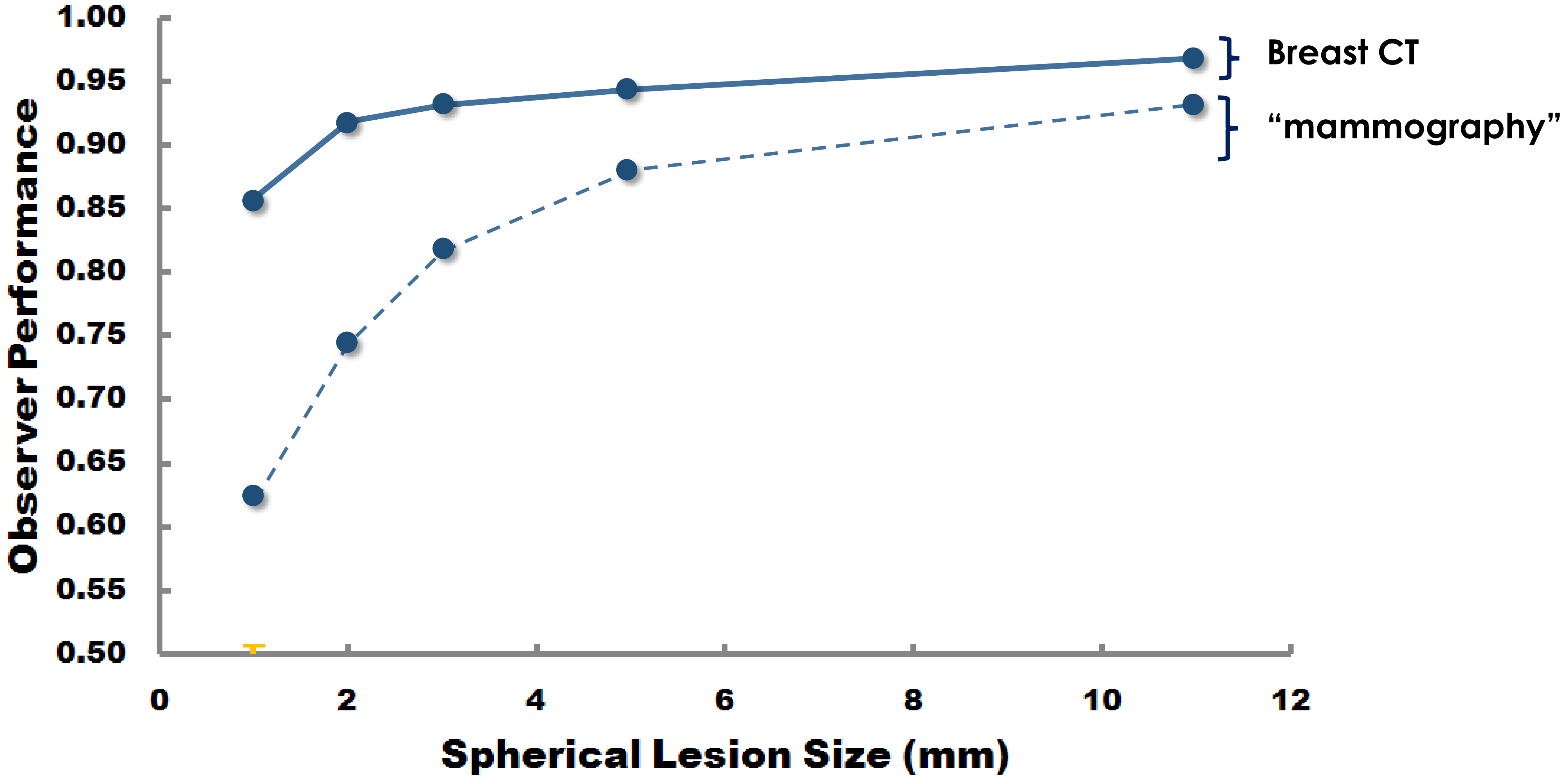
$\sum$ over all pixels {  SKE lesion ×  PWMF template applied } $= \upsilon$







Pre-whitened Matched Filter (PWMF) Performance



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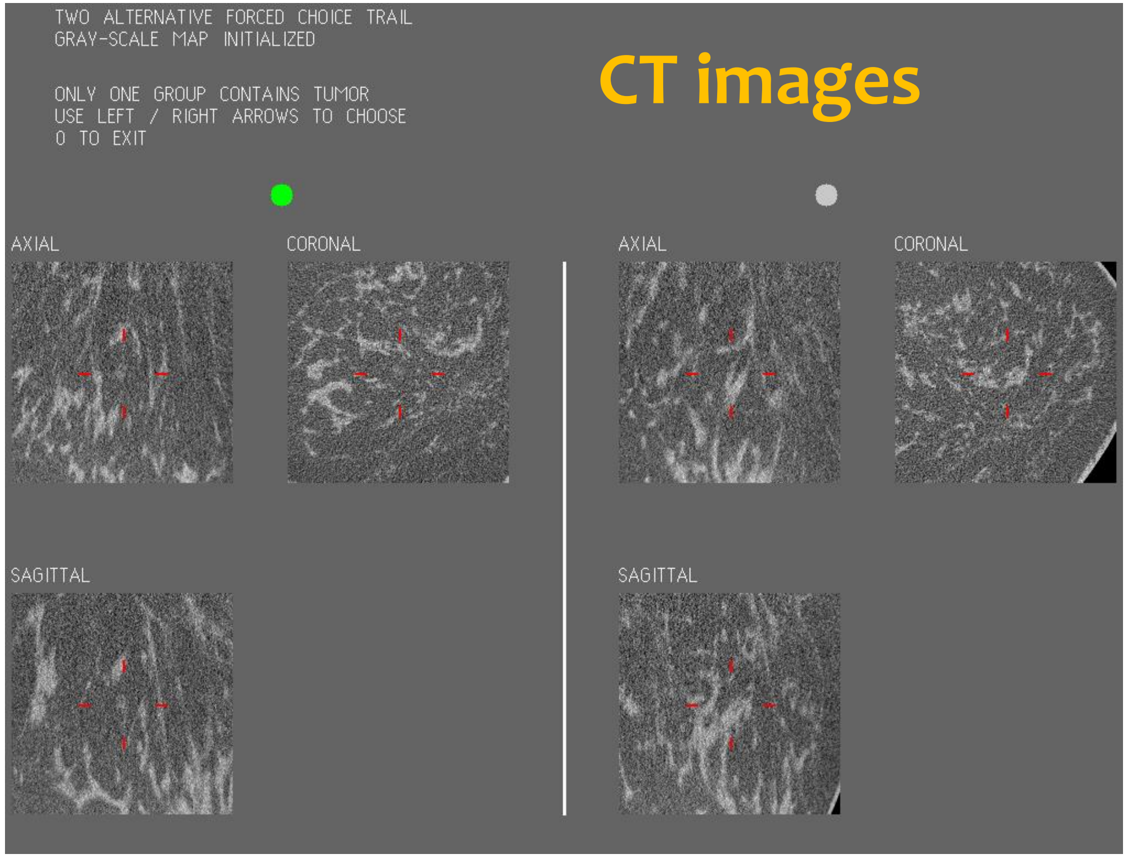
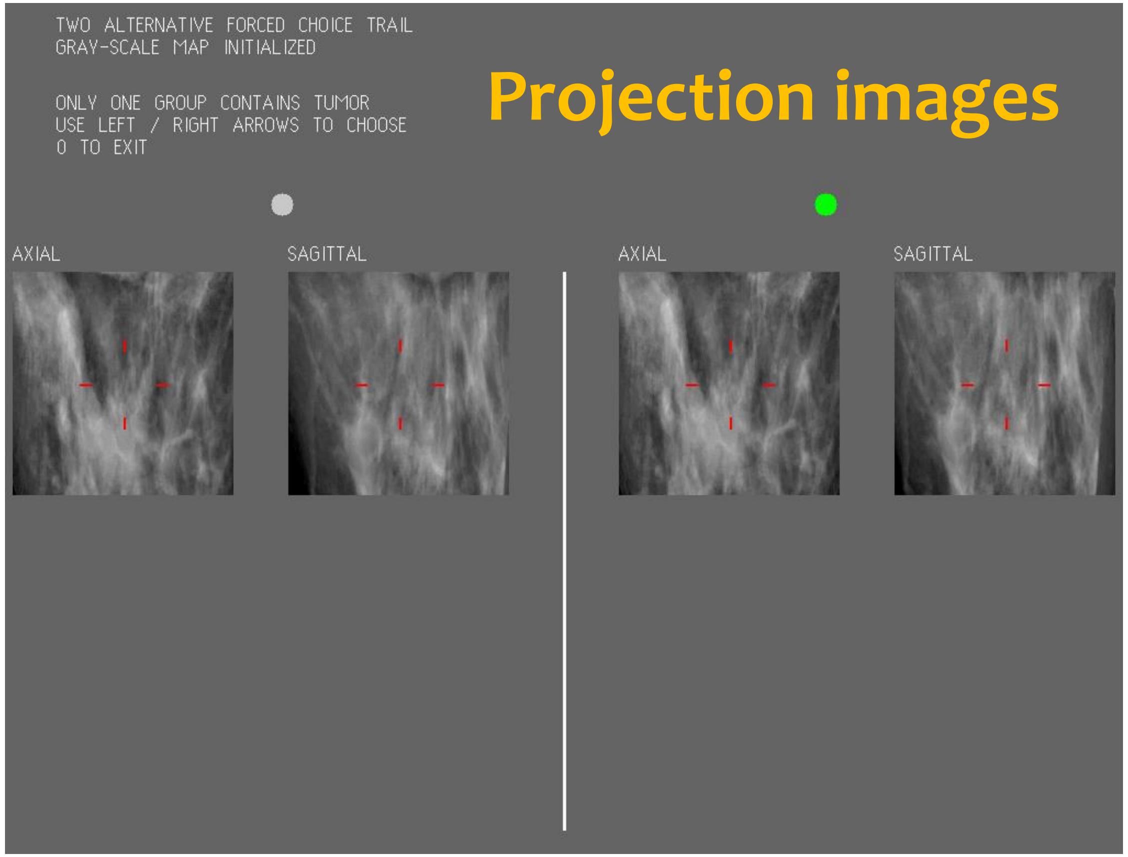
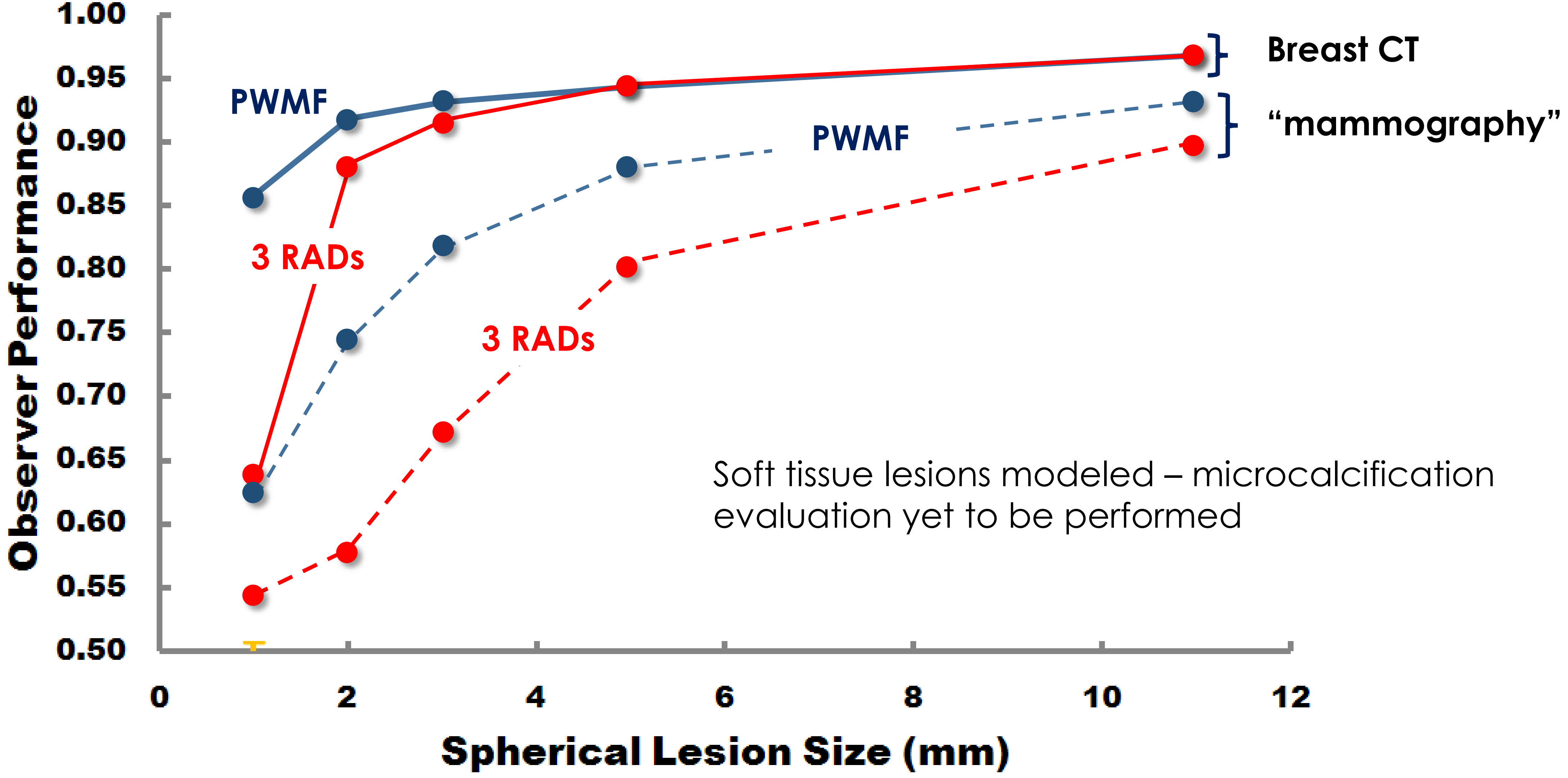
Human Observers

2-Alternative Forced Choice Design





~6000 lesions:
average of 3 breast imaging radiologists

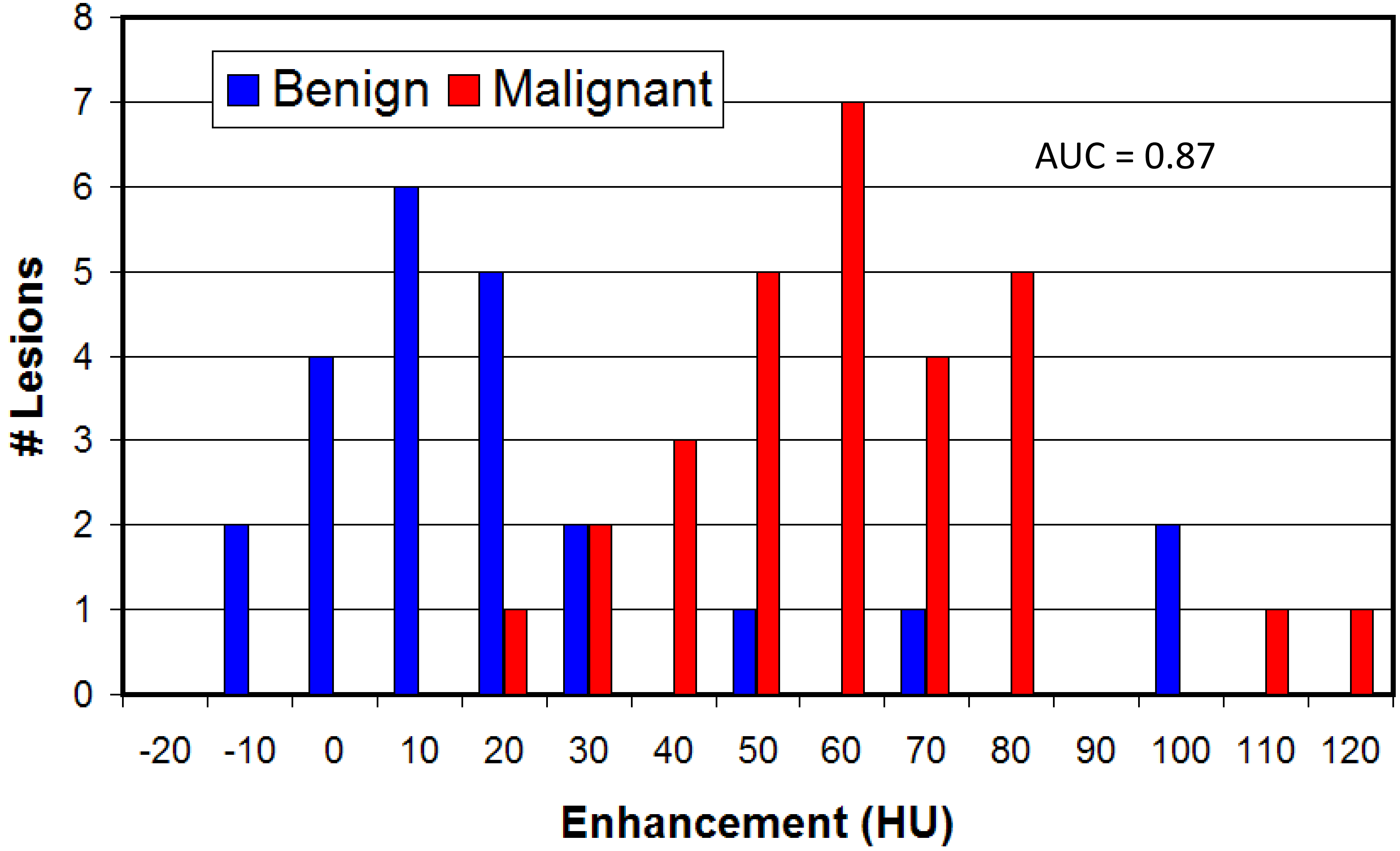

Breast CT
"mammography"
PWMF
PWMF
3 RADs
3 RADs
Soft tissue lesions modeled – microcalcification evaluation yet to be performed
Observer Performance
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0
2
4
6
8
10
12
Spherical Lesion Size (mm)

Radiology

2010

Contrast-enhanced Dedicated Breast CT: Initial Clinical Experience[1]

Nicolas
Karen
Shonk
Shih-Y
Laurel
Wayne
John M



Shadi Shakeri

Karen Lindfors

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Differentiation of ductal carcinoma in-situ from benign micro-calcifications by dedicated breast computed tomography

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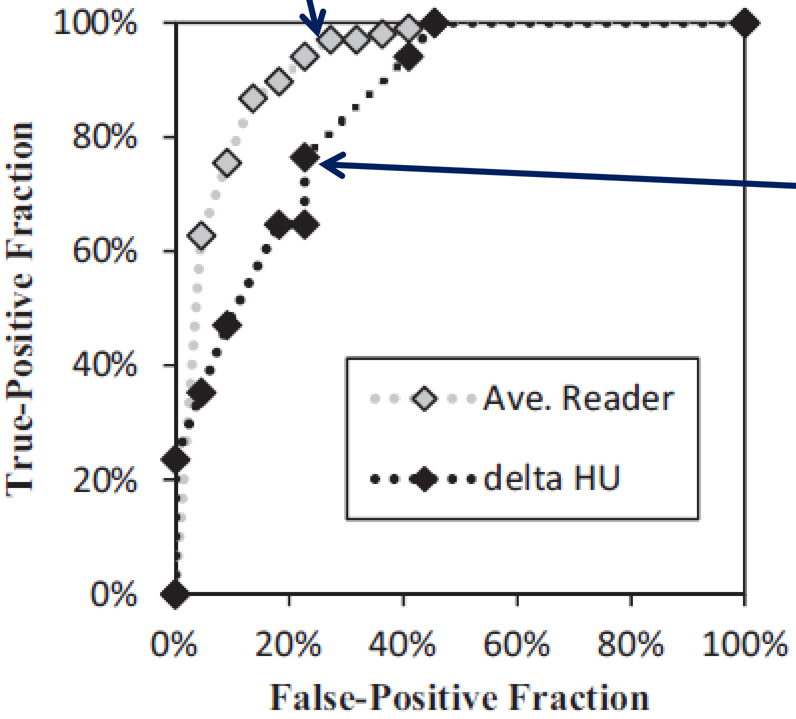
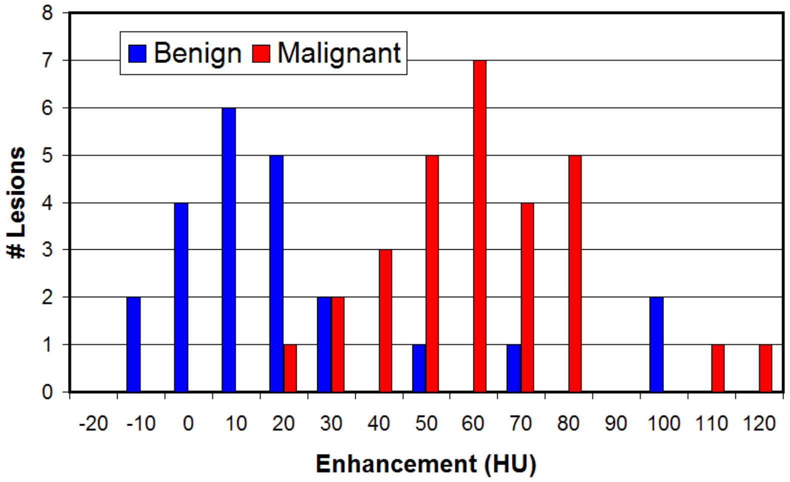
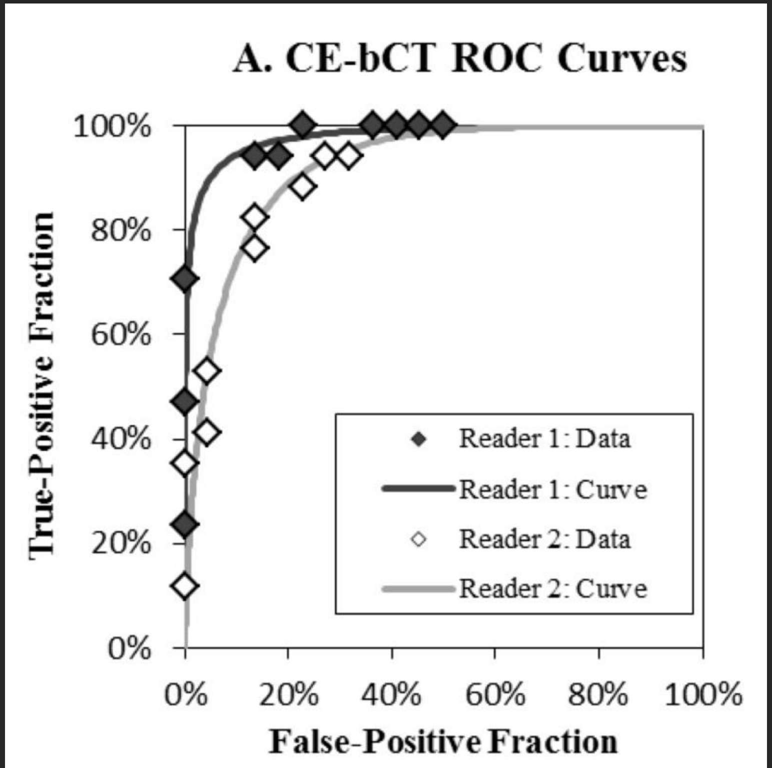
AUC = 0.95

AUC = 0.87

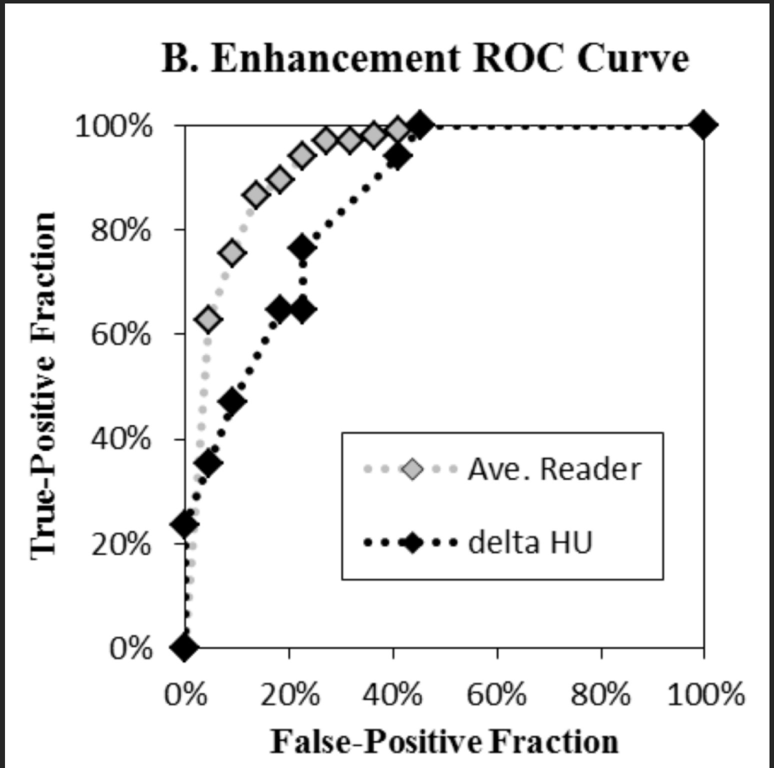




ROC performance plots for CE-bCT



Comparison of the AUC from measured lesion enhancement to the average AUC of the two readers



Reader 1: AUC = 0.98 ± 0.022;
Reader 2: AUC = 0.92 ± 0.042

Performance was significantly higher for the radiologists compared to the enhancement values alone (AUC of 0.94 compared to 0.85, $p < 0.026$).

Breast CT: *Technology development and clinical potential*

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- Image Quality Metrics
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- Observer Performance
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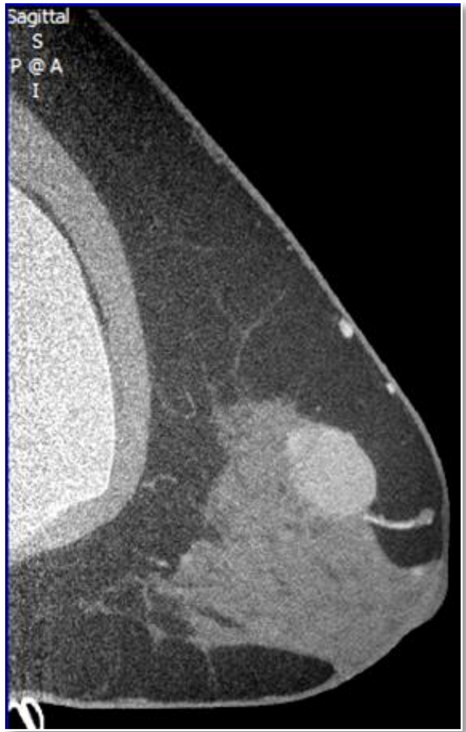


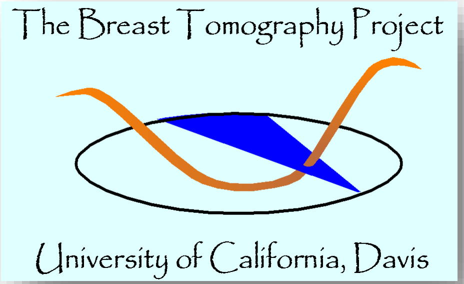
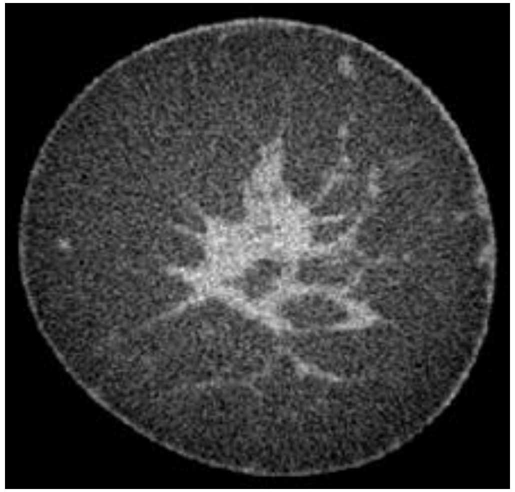
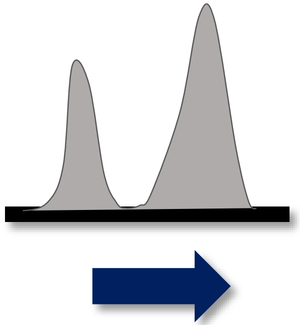
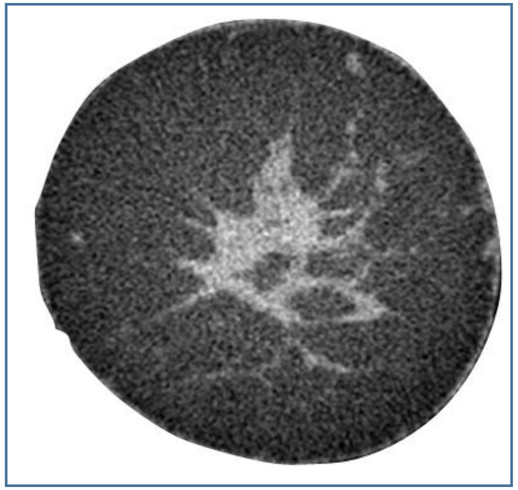


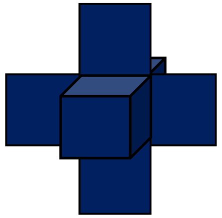
Image Segmentation





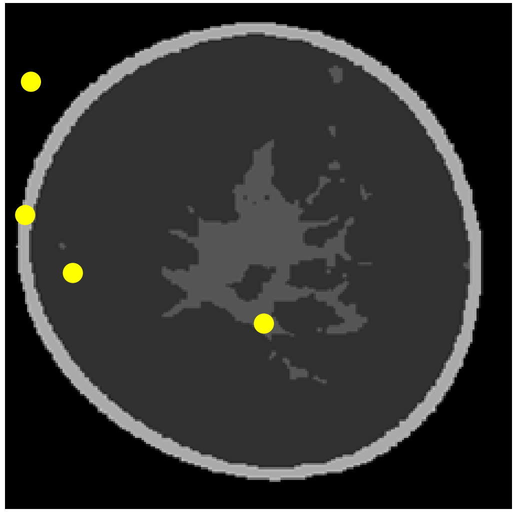
air segmentation





Iterative 7-point 3D median filter / two-means clustering analysis

air
skin
adipose
glandular



3D segmented data set

Classification of breast computed tomography data

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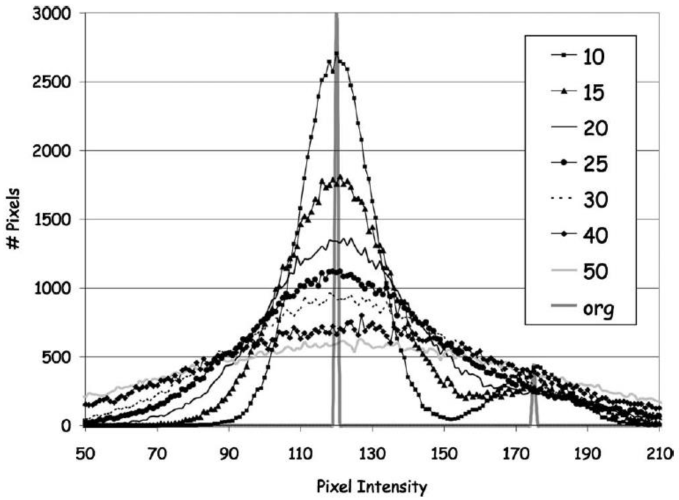
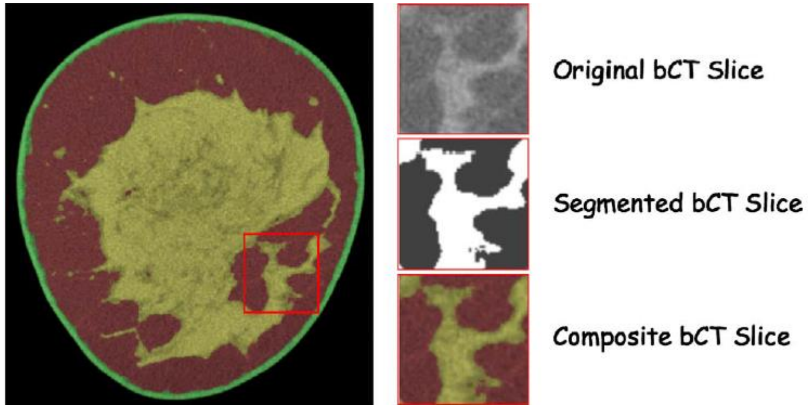
(Received 25 September 2006; revised 10 January 2008; accepted for publication 11 January 2008; published 26 February 2008)





An unsupervised automatic segmentation algorithm for breast tissue classification of dedicated breast computed tomography images

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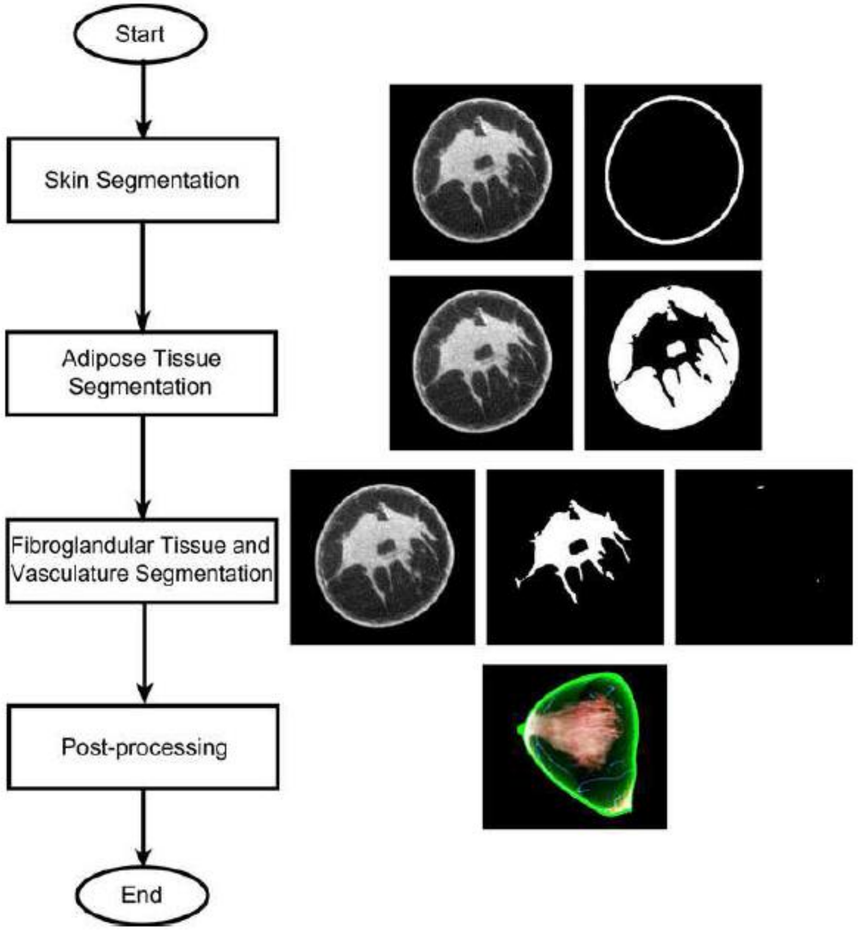
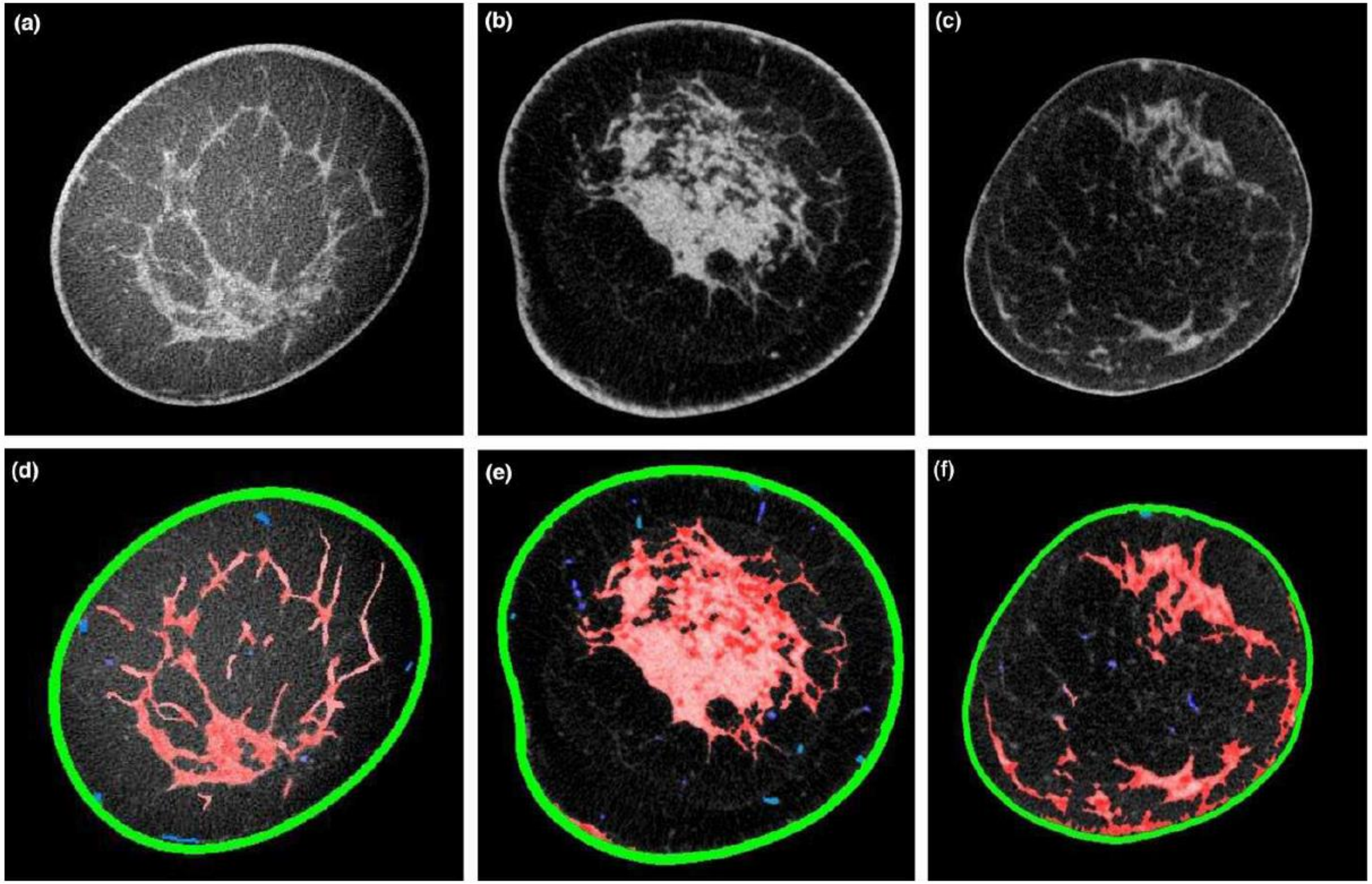
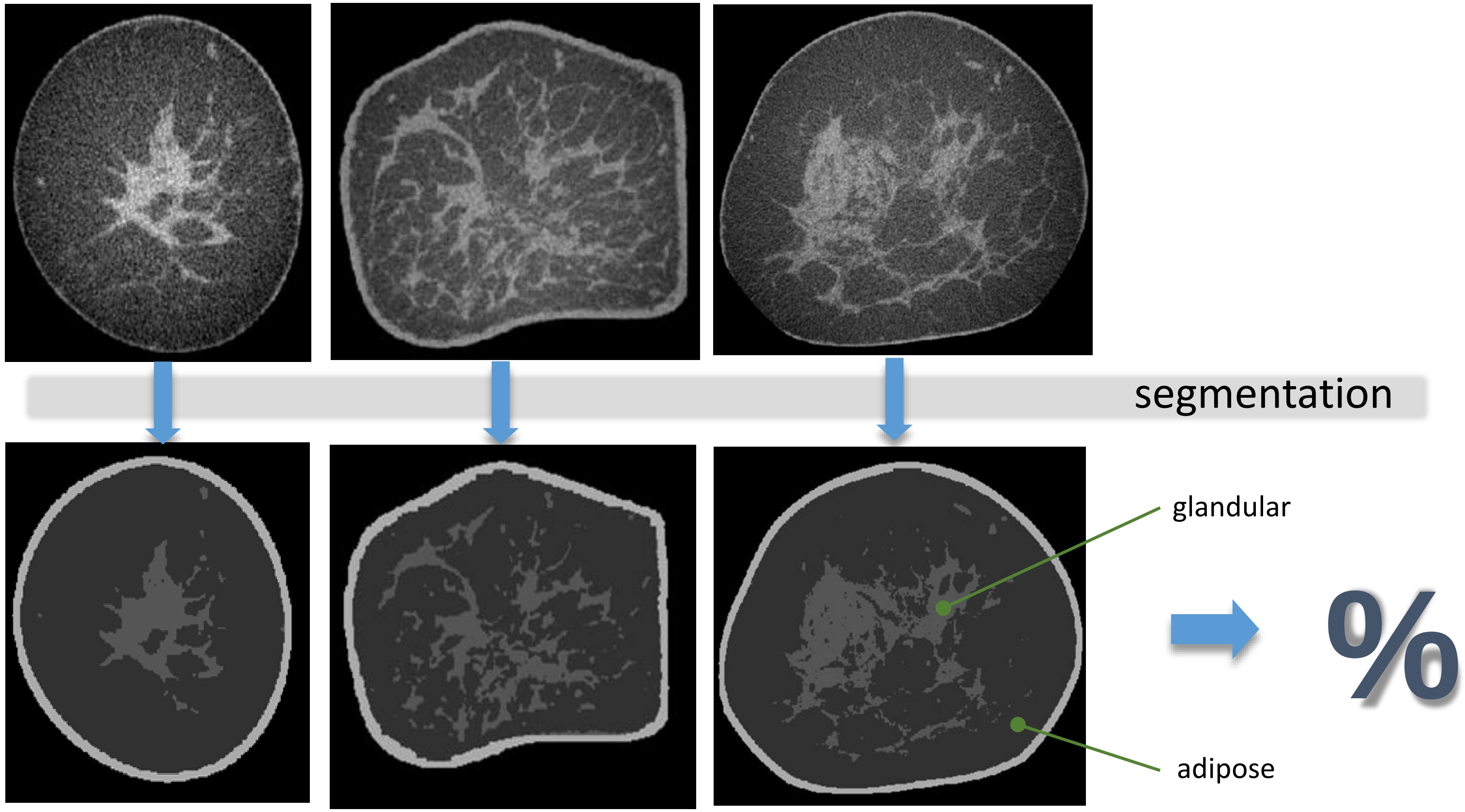
(Received 18 December 2017; revised 27 February 2018; accepted for publication 4 April 2018; published xx xxxx xxxx)


Start
Skin Segmentation
Adipose Tissue Segmentation
Fibroglandular Tissue and Vasculature Segmentation
Post-processing
End


(a)
(b)
(c)
(d)
(e)
(f)

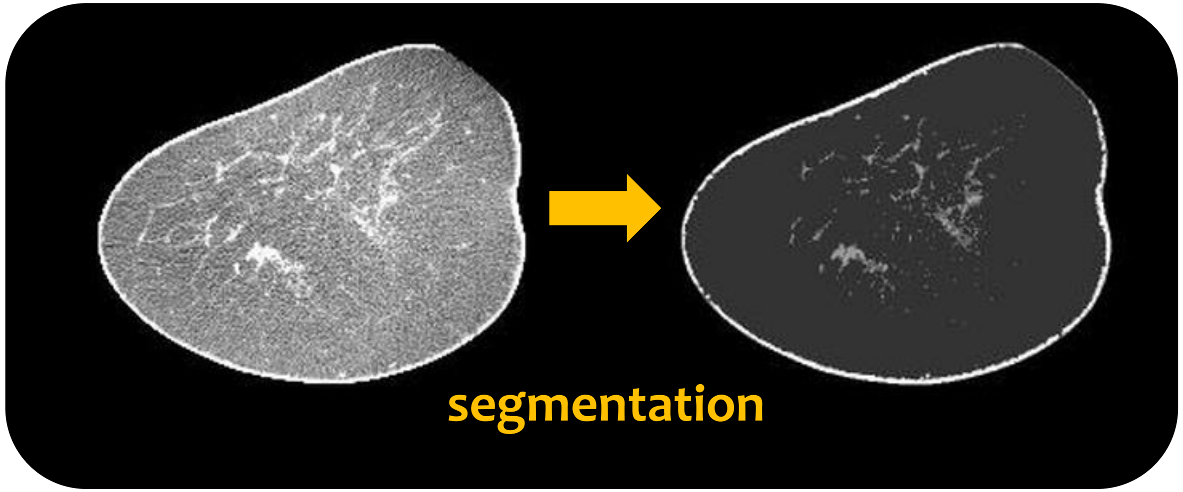
Breast Density Analysis



risk assessment & dosimetry

validation of 2D approaches (M. Yaffe)

Breast Density (amplitude)



The myth of the 50-50 breast

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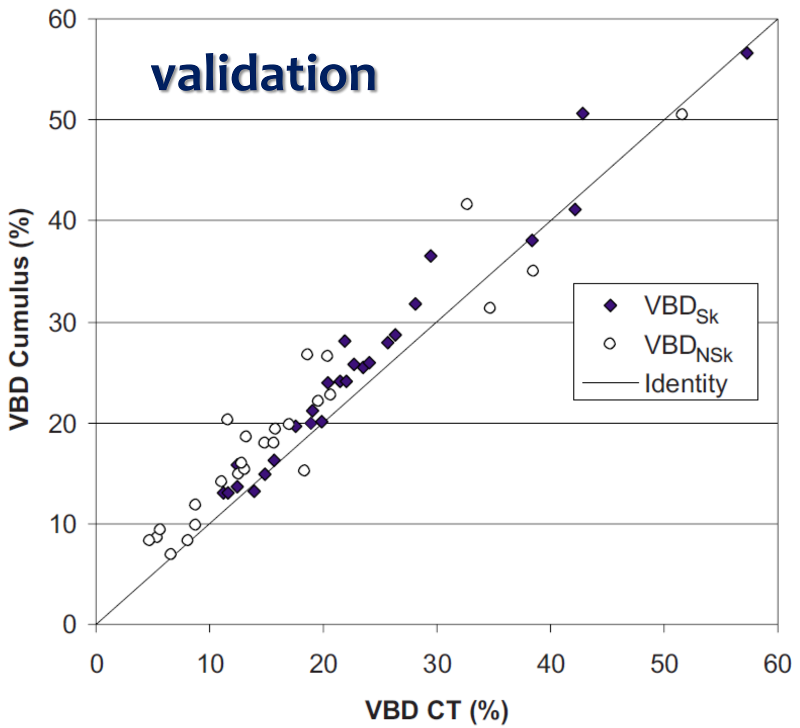
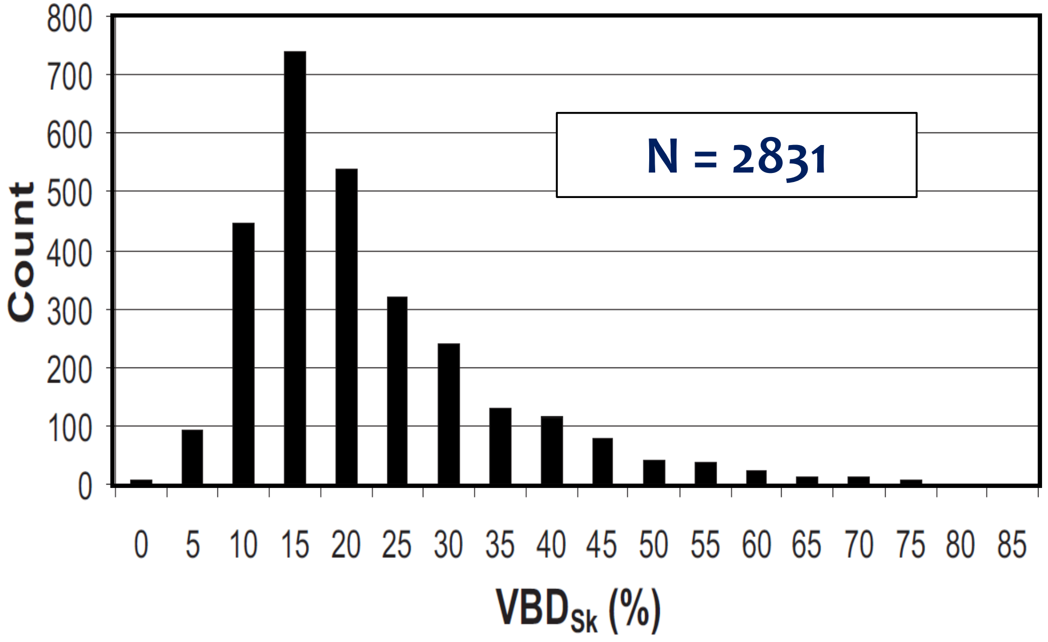
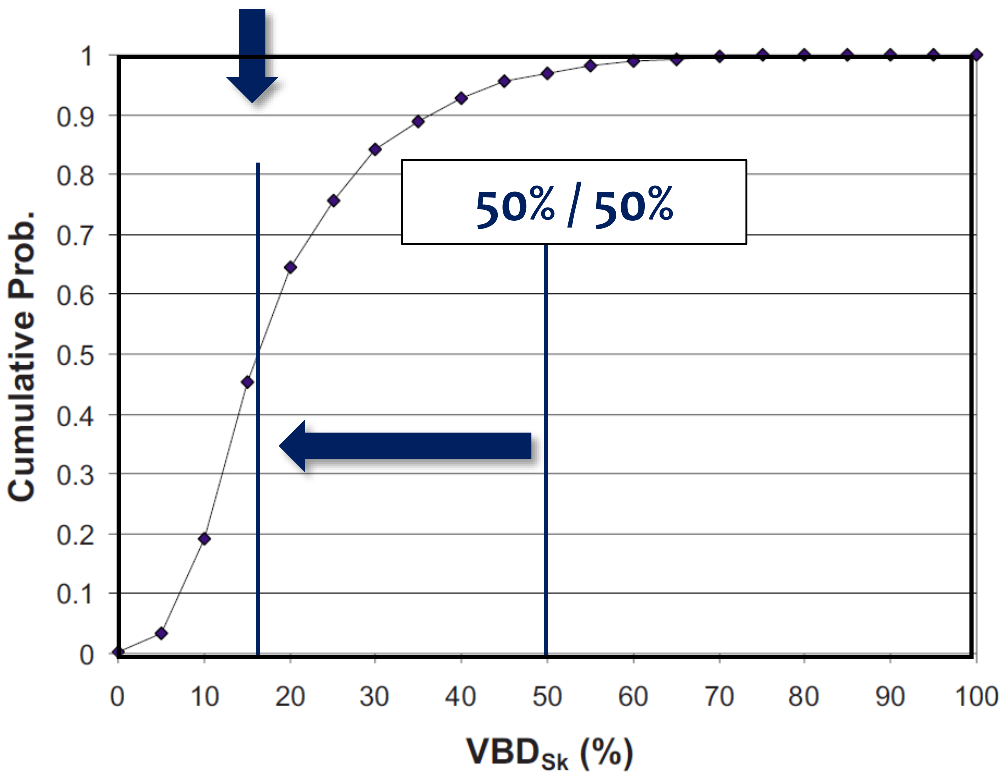
(Received 30 April 2009; revised 23 September 2009; accepted for publication 29 September 2009; published 5 November 2009)



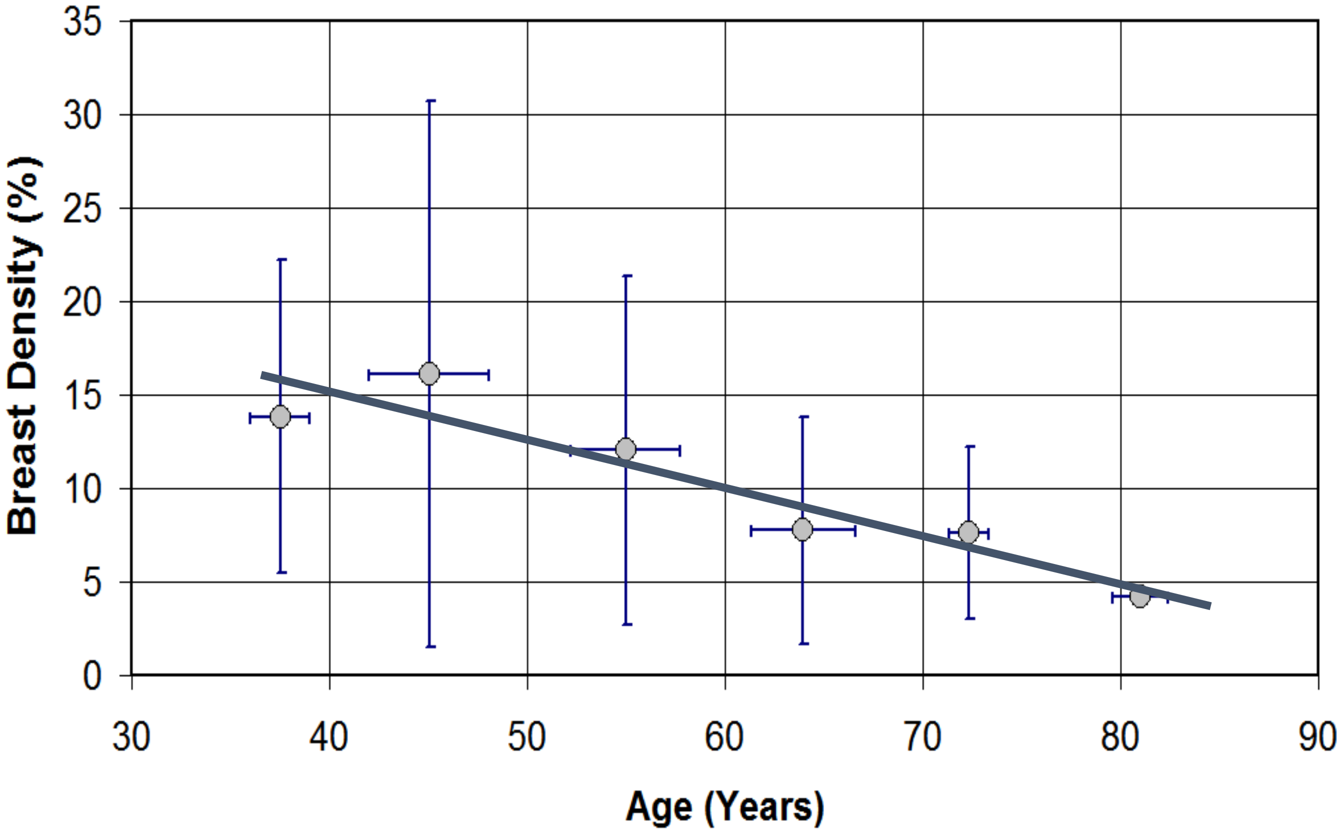
Breast Density (amplitude)



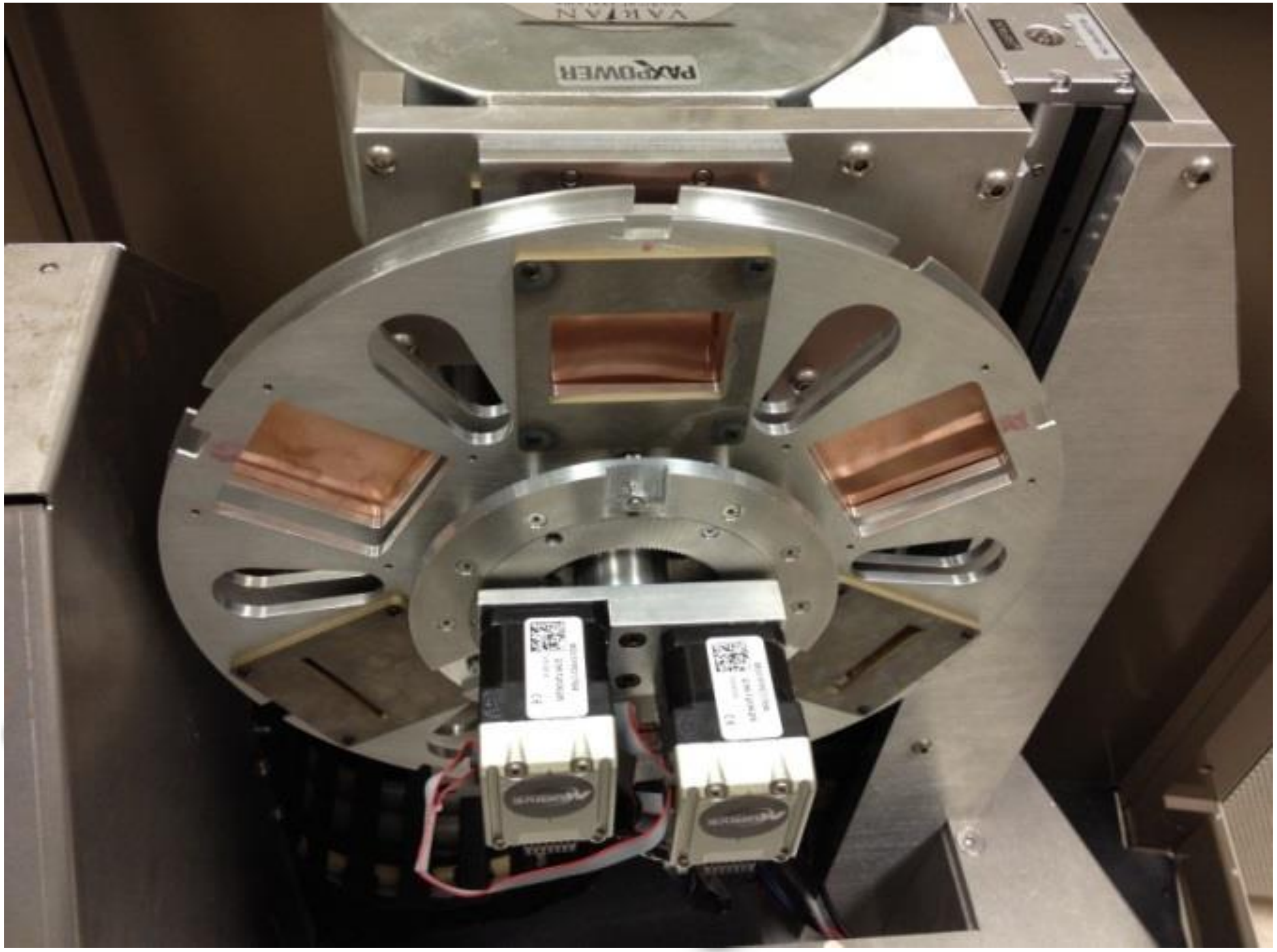
Median VBD = 16%



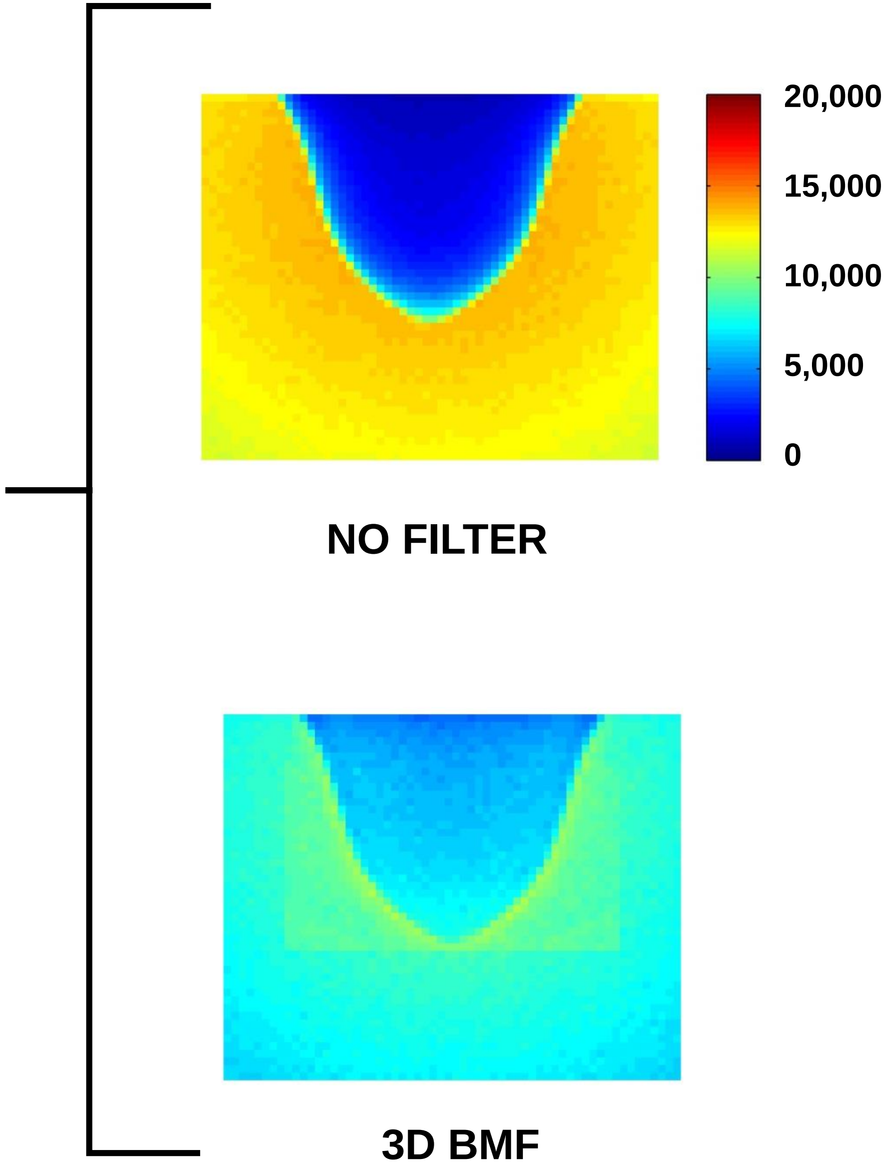
2.5% loss in breast density every decade



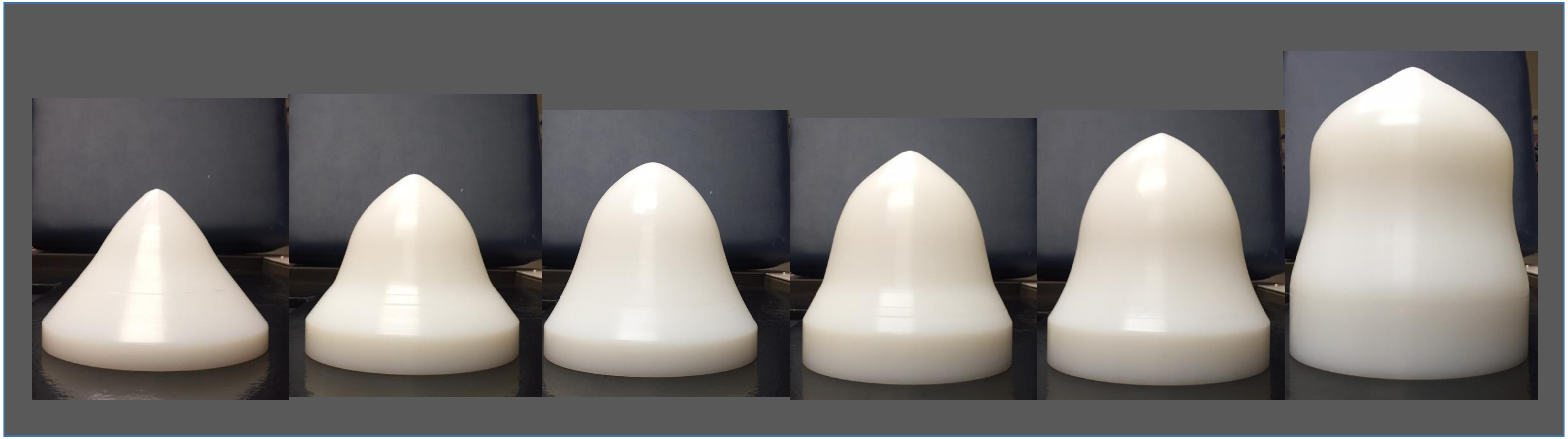
Beam Shaping Filter



V3 Phantom



Six phantoms (V1-V6)

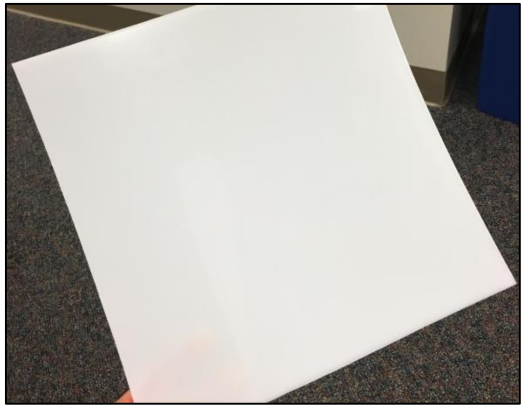


1st | 2nd | 3rd | 4th | 5th | Largest 5 breasts

N = 219 : ~ 5 sets of 43

Mean volume and shape in each quintile

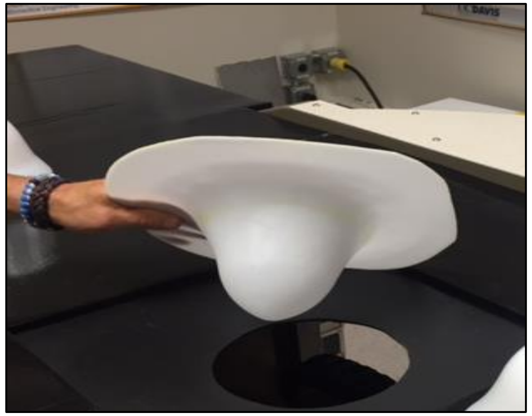
- **Physical Dosimetry**
- **Image Quality Assessment**
- **Mold for breast immobilization**



Aquaplast®
thermoplastic

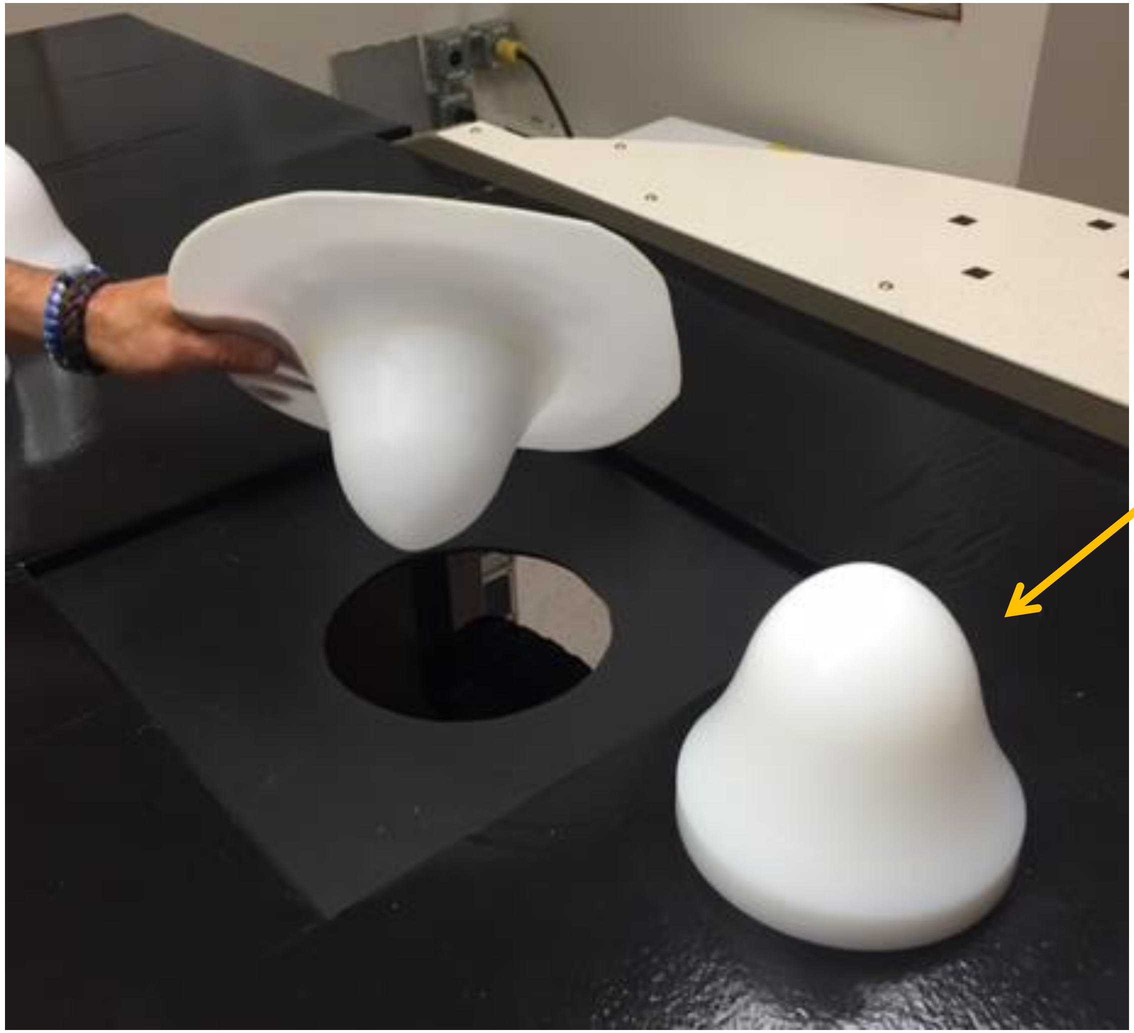
hot water bath

molding



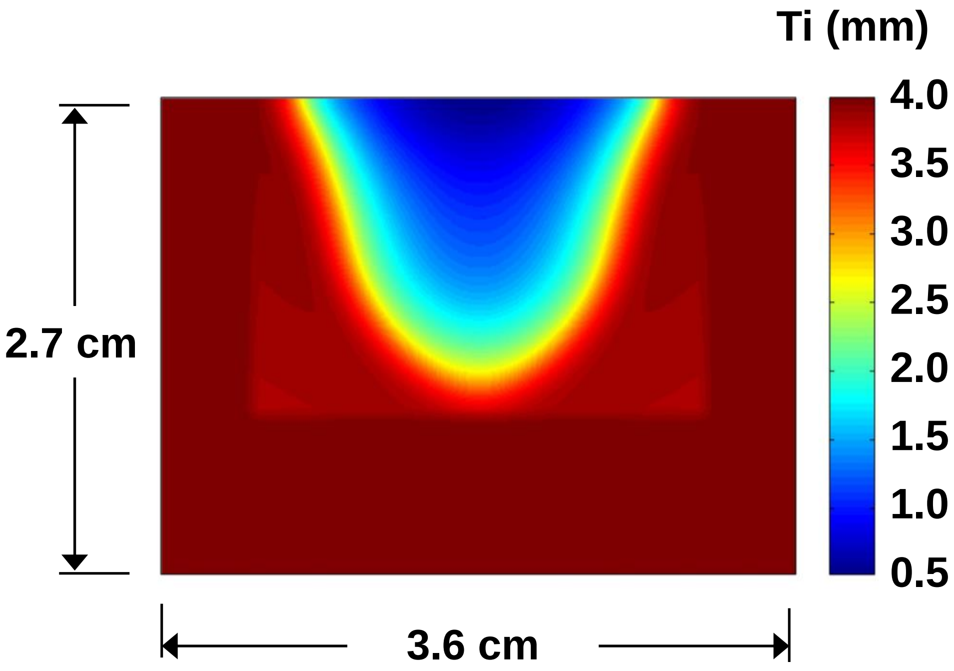
breast immobilizer

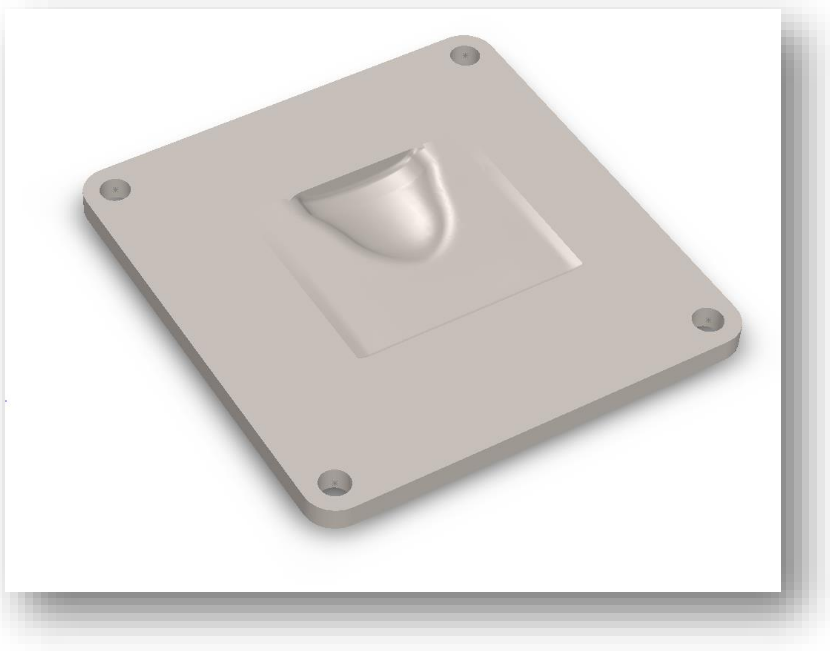
Breast Immobilization & Beam Equalization



Breast Alignment System

Titanium 3D Beam Modulation Filter

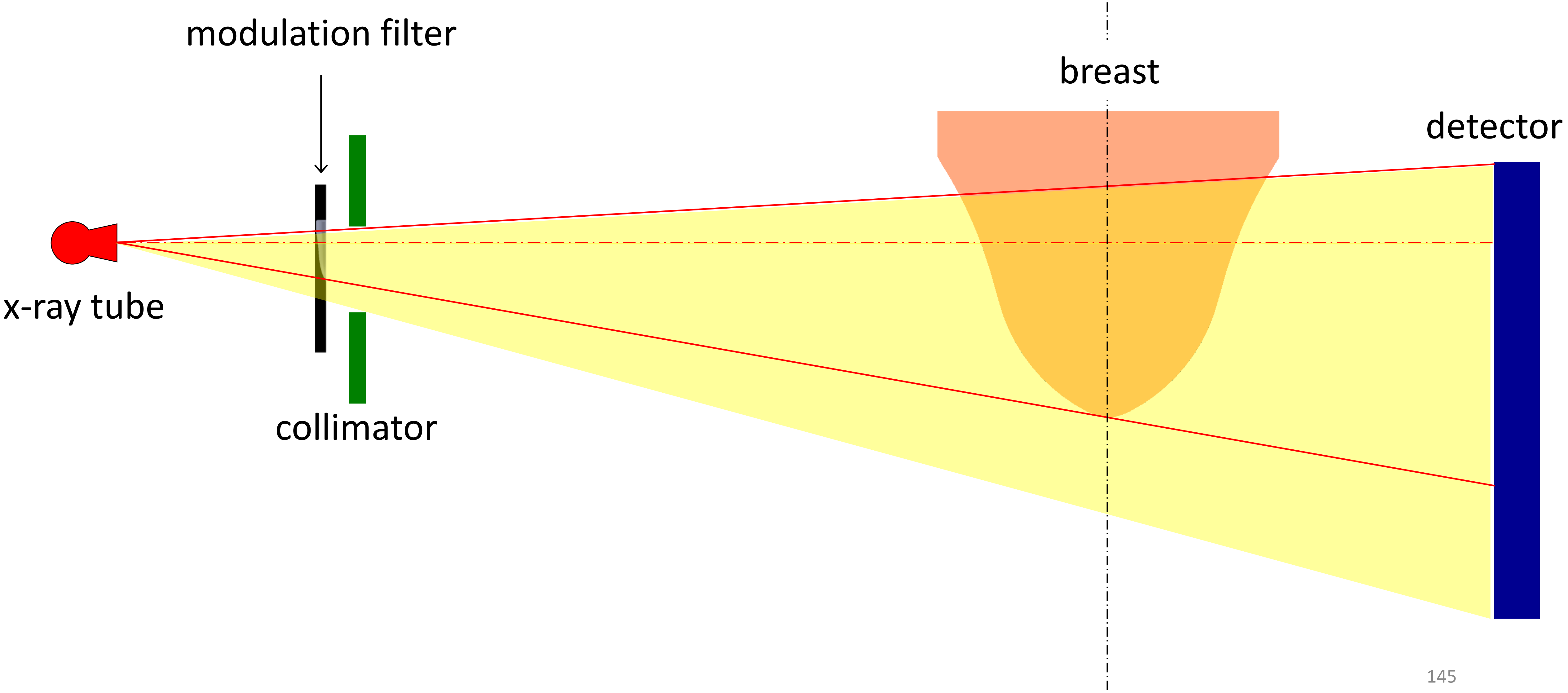




source-to-filter distance = 8 cm

V3 phantom

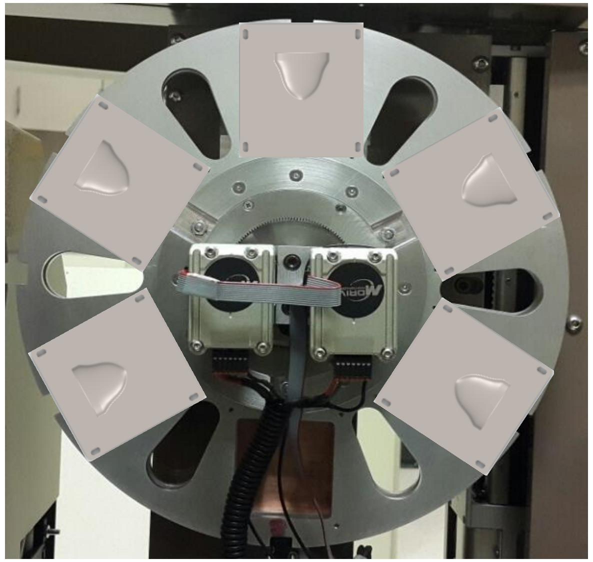
Implementation on bCT Platform



Clinical Workflow

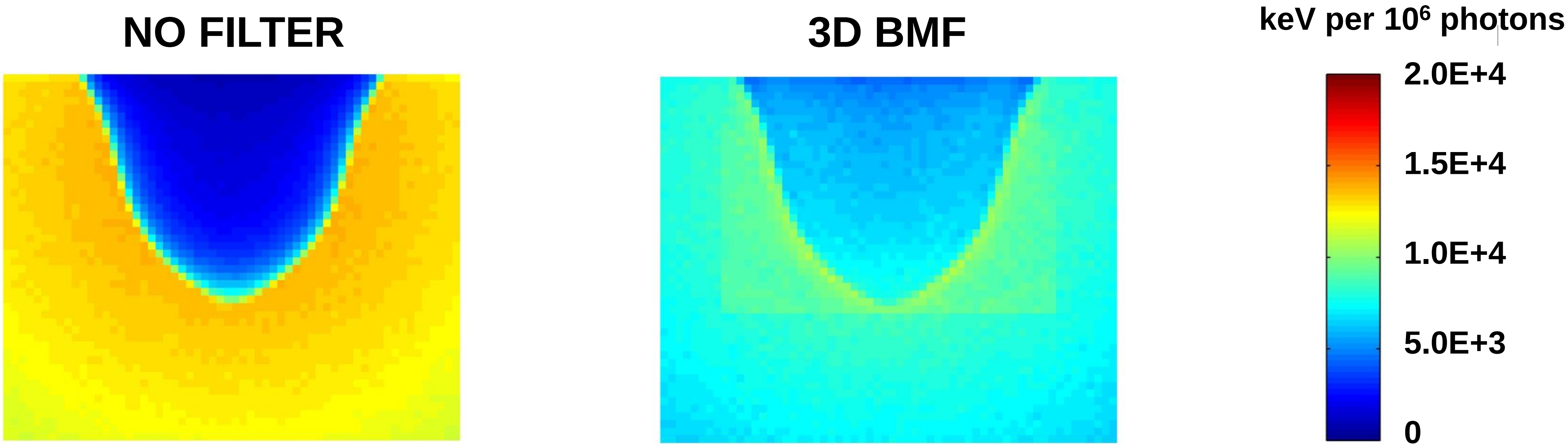
Find mold that best fits patient's breast

Select corresponding 3D-BMF



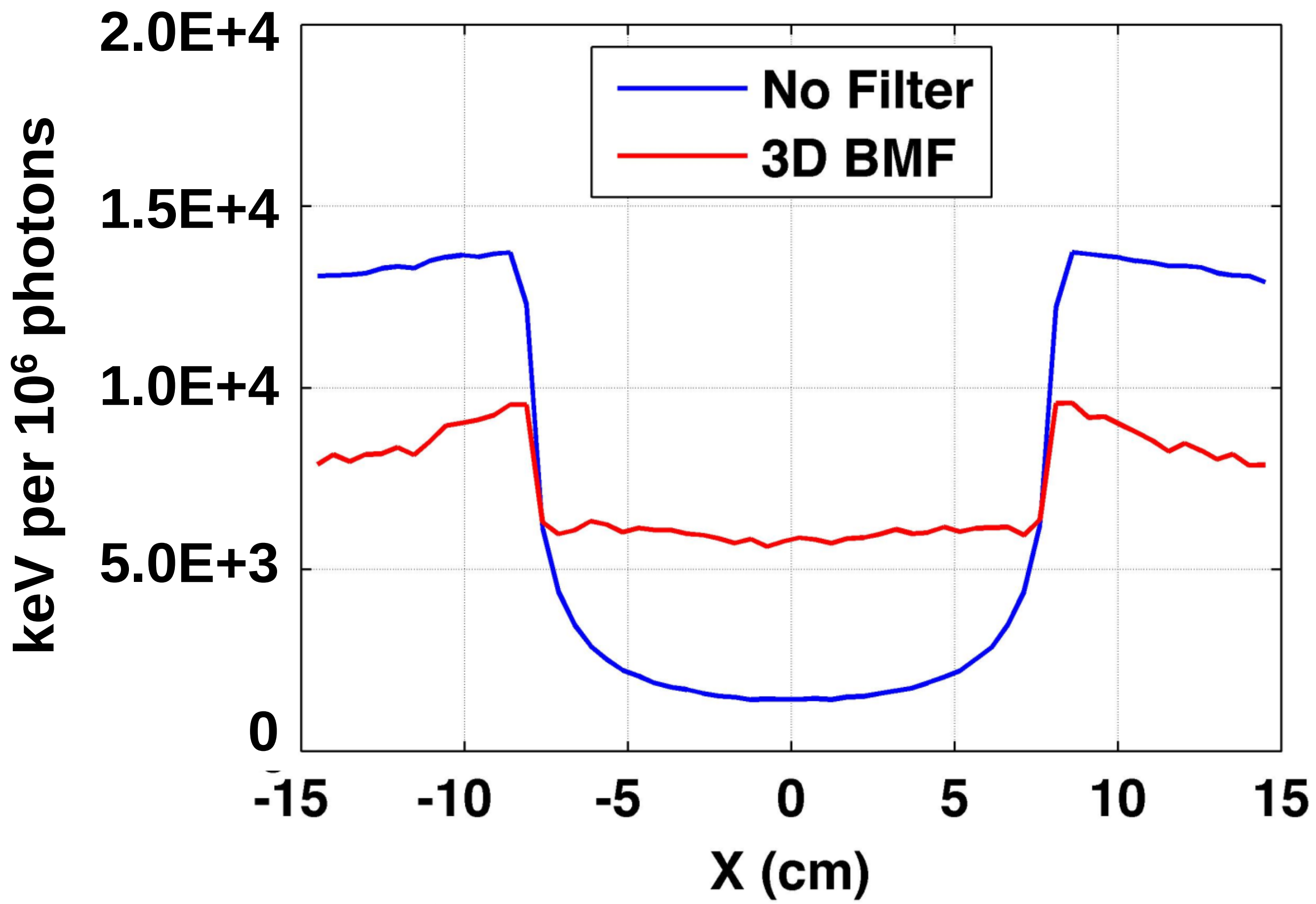
Set technique factors for pre-defined dose level

MC Simulation Results: Projection



V3 phantom

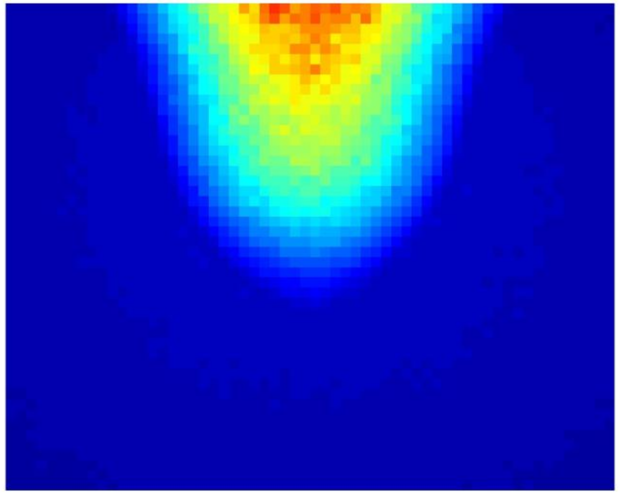
MC Simulation Results: Projection



V3 phantom

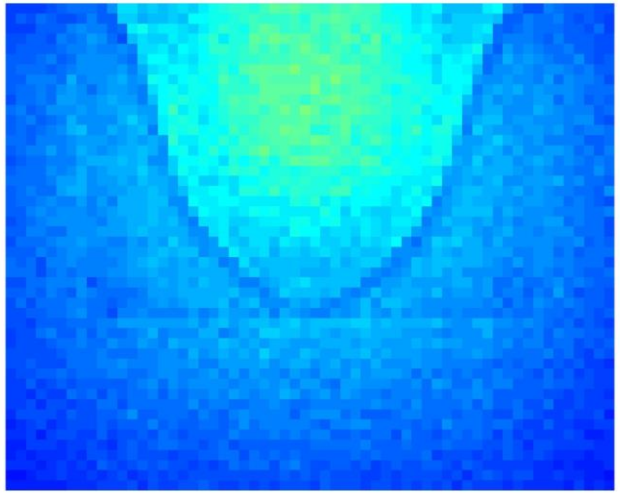
MC Simulation Results: SPR

NO FILTER

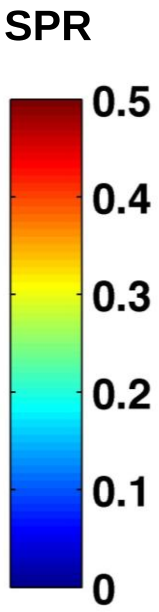


$SPR_{central}$ = 0.32

3D BMF



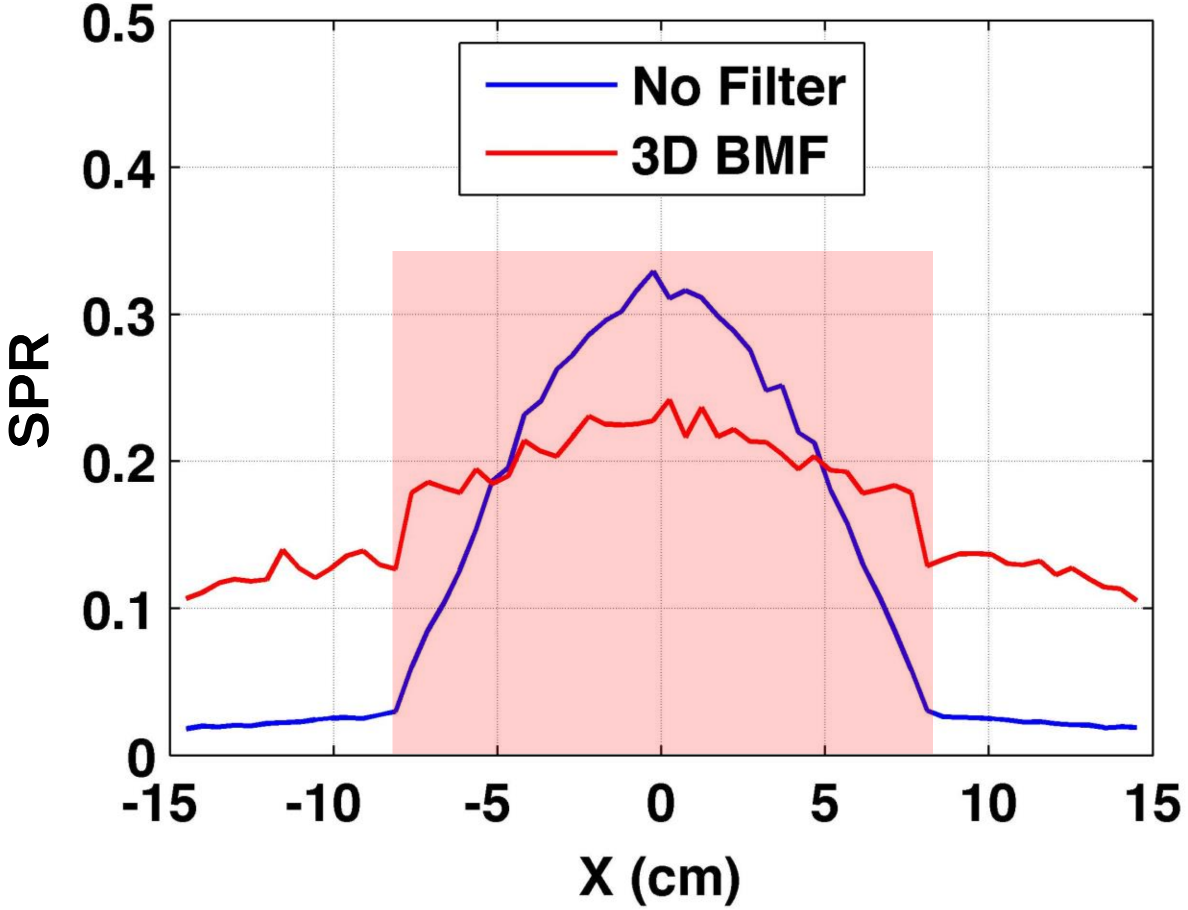
$SPR_{central}$ = 0.23



V3 phantom

	$SPR_{central}$
V1	- 11.5%
V3	-28.1%
V5	-29.4%

MC Simulation Results: SPR



V3 phantom

MC Simulation Results: Glandular Dose

- Normalized to number of quanta reaching detector under thickest region of the breast:

mGy / 10^9 photon	No Filter	3D BMF	Change
V1	26	17	-34%
V3	45	25	-45%
V5	56	34	-40%

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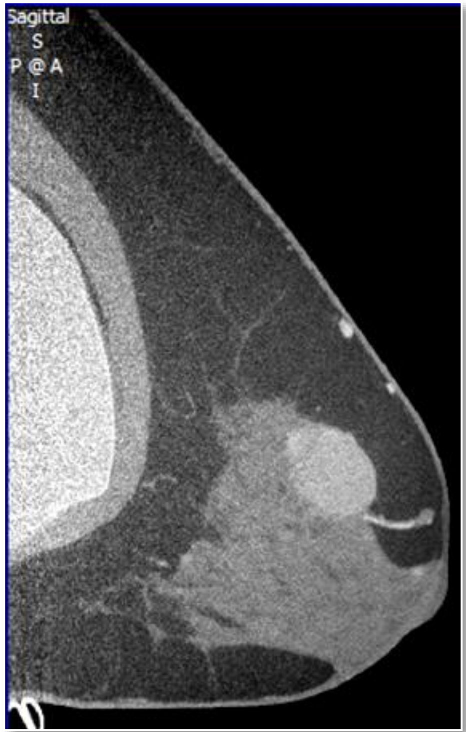
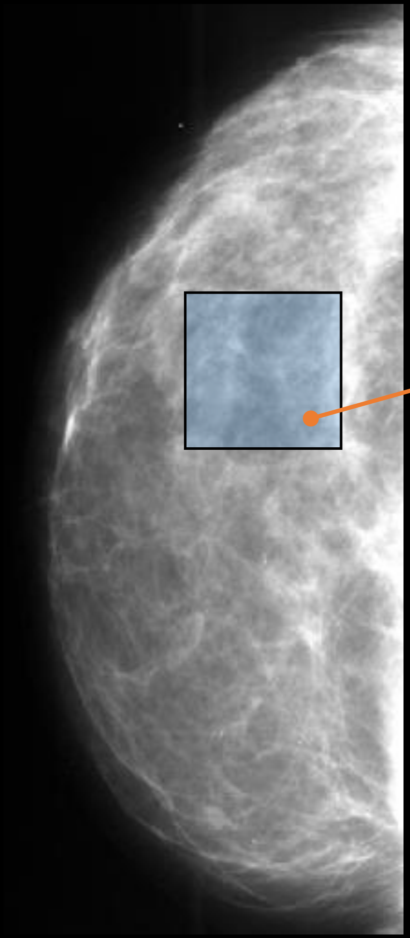
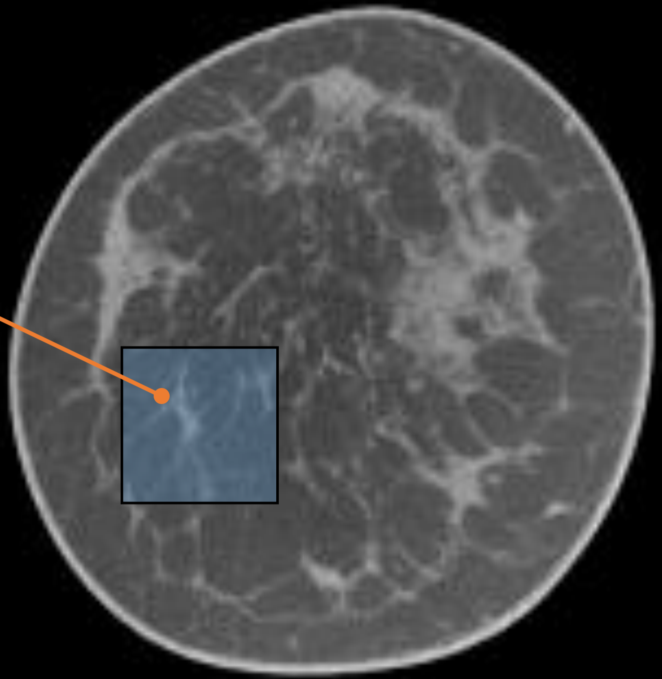


The Breast Tomography Project

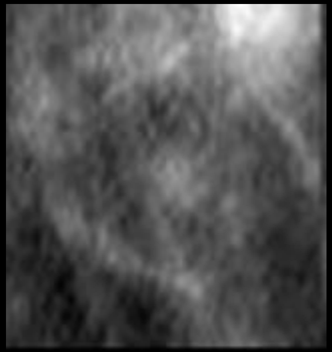
University of California, Davis



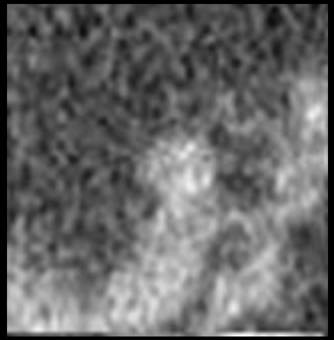
texture



$$NPS_a(f) \approx \alpha f^{-\beta}$$



$$\frac{\text{Signal}}{\text{Background}}$$



Summary:

- Breast CT has superior mass detection than mammography, based upon texture analysis, computer and human observer studies
- CE breast CT highlights malignant calcifications and is likely equivalent to CE-breast MRI
- Breast CT is FDA approved for diagnostic breast imaging, need to push the technology to achieve superior screening performance
- Breast CT is an emerging technology which will have an important role in reducing breast cancer mortality in the near future.

Future Work:

- Implement beam shaping filter with breast immobilization system
- Compare high resolution non-contrast bCT with mammography for microcalcification detection performance
- Compare CE-bCT with CE-breast MRI for cancer detection performance

Breast Tomography Project

University of California Davis