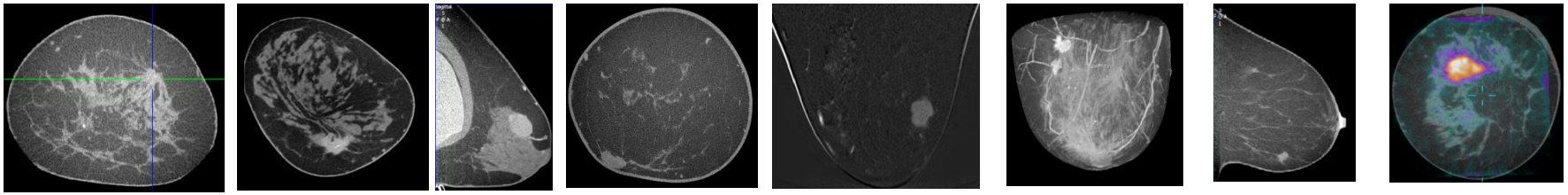
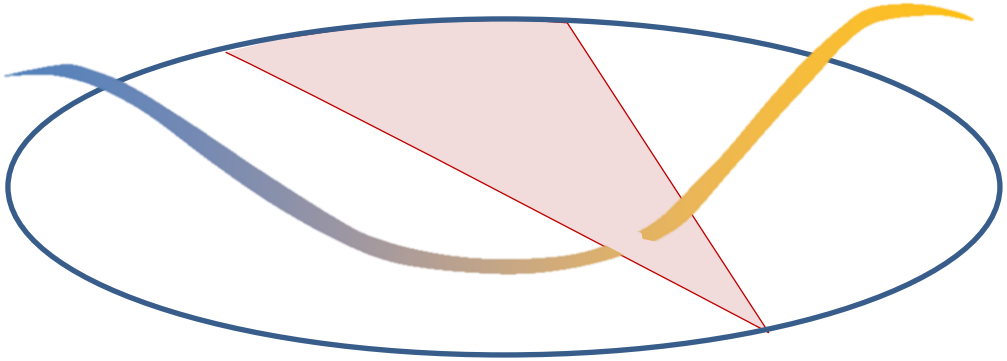


2013 ICTP/IAEA Training Course on Radiation Protection of Patients • Trieste

Breast CT and Dosimetry

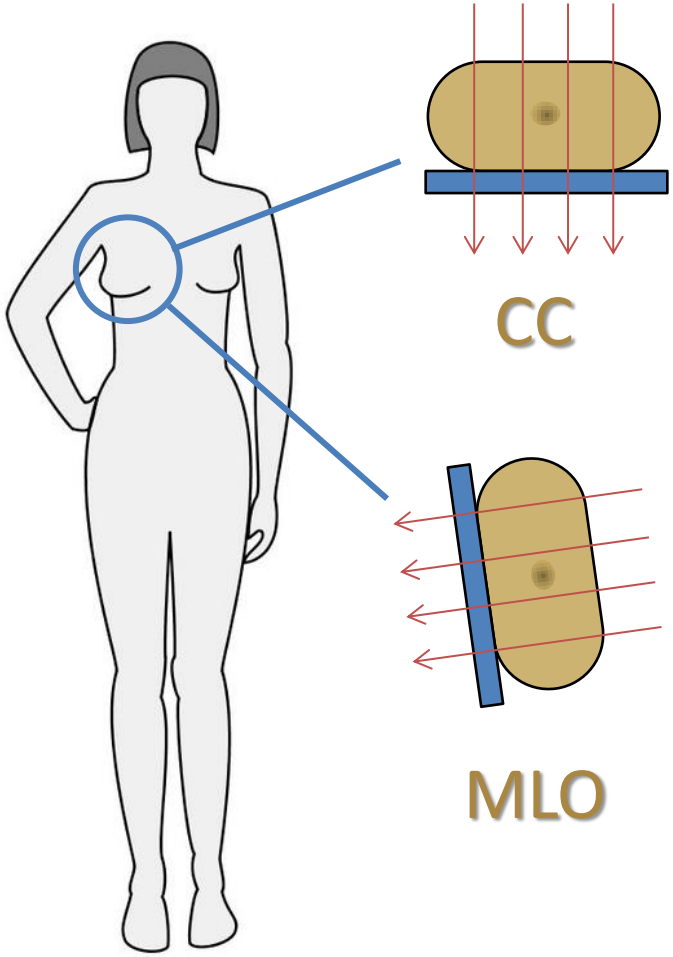


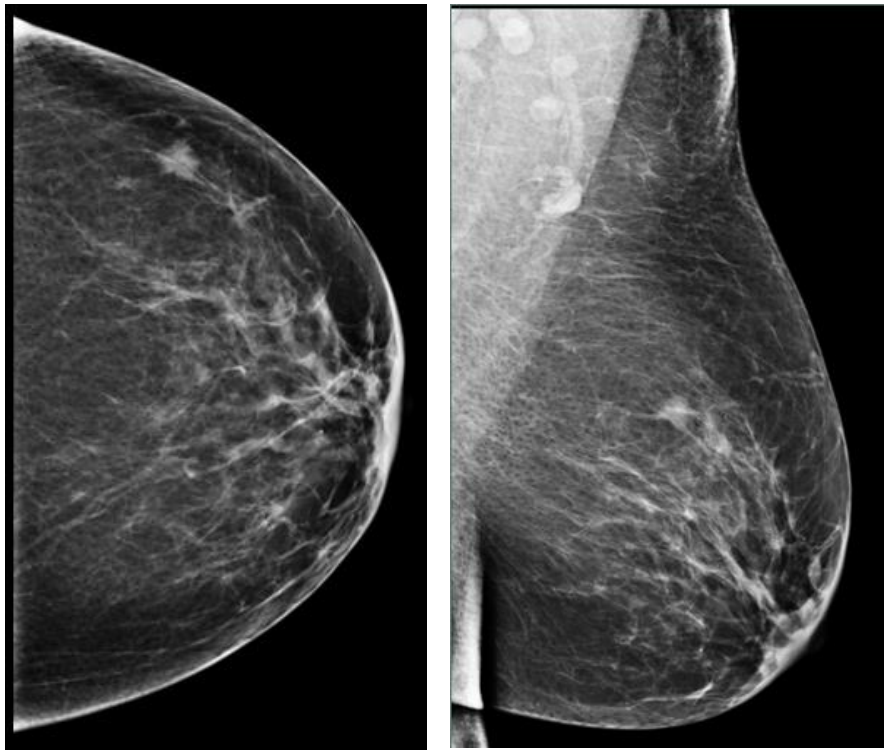
John M. Boone, Ph.D., FAAPM, FSBI, FACR
Professor and Vice Chair (Research) of Radiology
Professor of Biomedical Engineering
University of California Davis Medical Center
Sacramento, California

Breast CT and Dosimetry

- Breast CT Background
- Technical Development
- Initial Clinical Results
- Dose Issues in Breast CT
- Summary

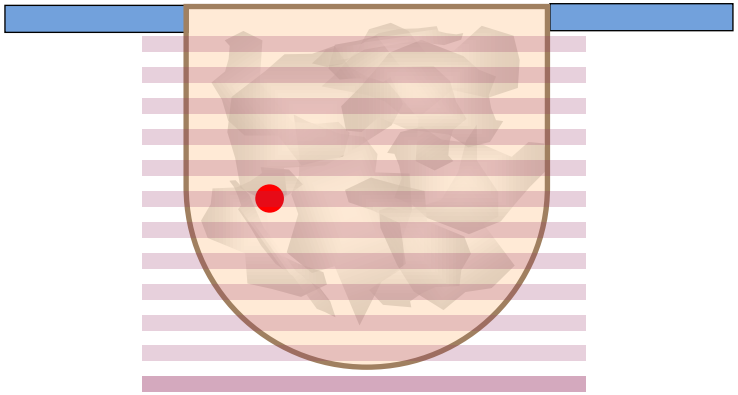
Mammography: Standard of Care





CC MLO

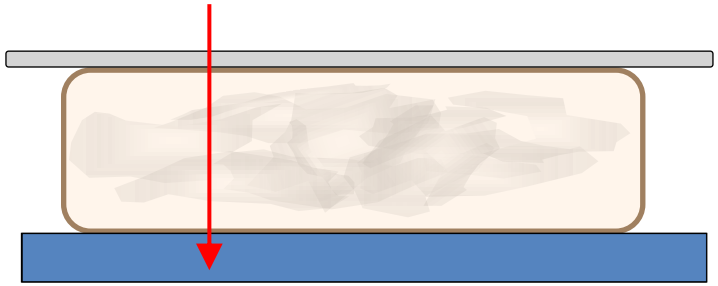
Breast CT

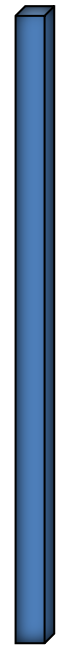


230 μm × 230 μm × 250 μm

~0.0156 mm^3

Mammography

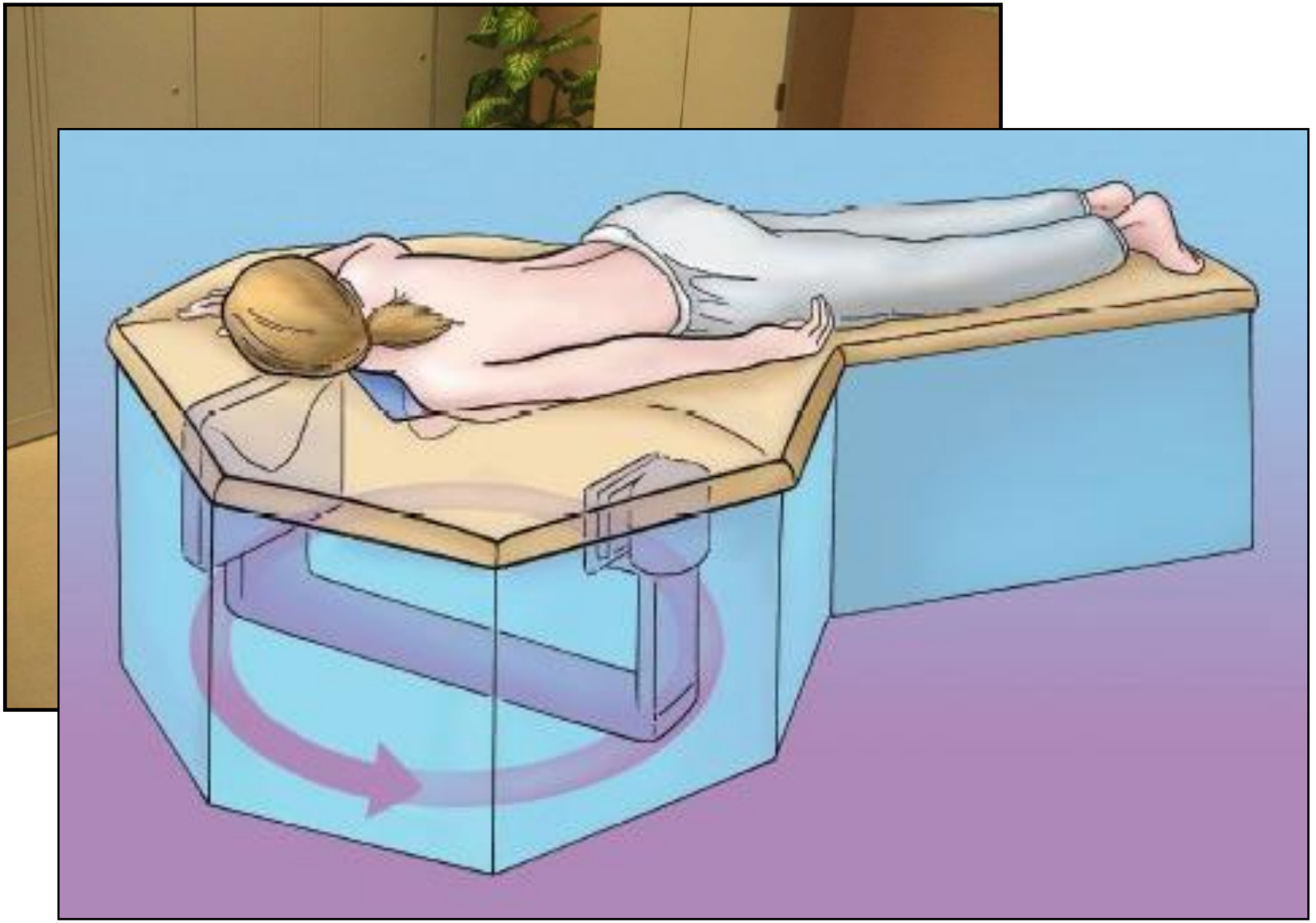


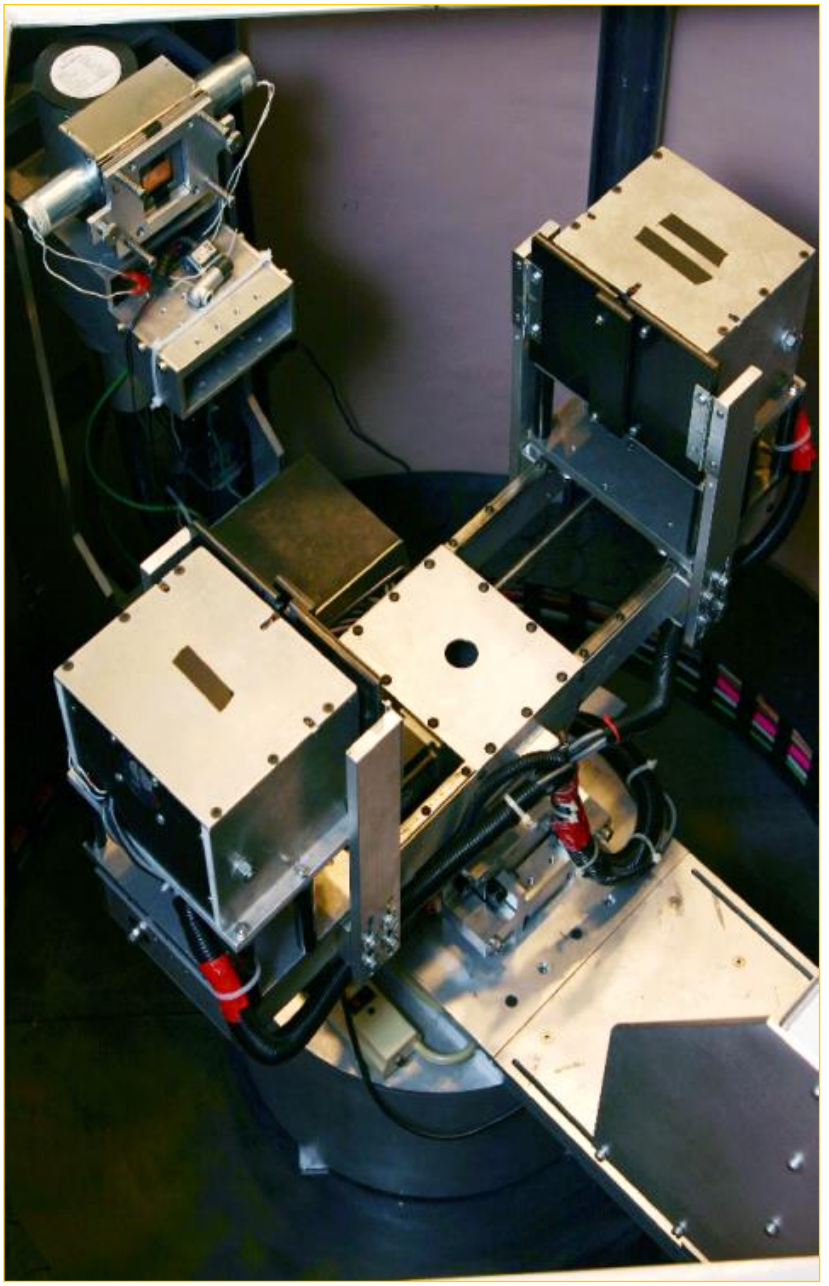


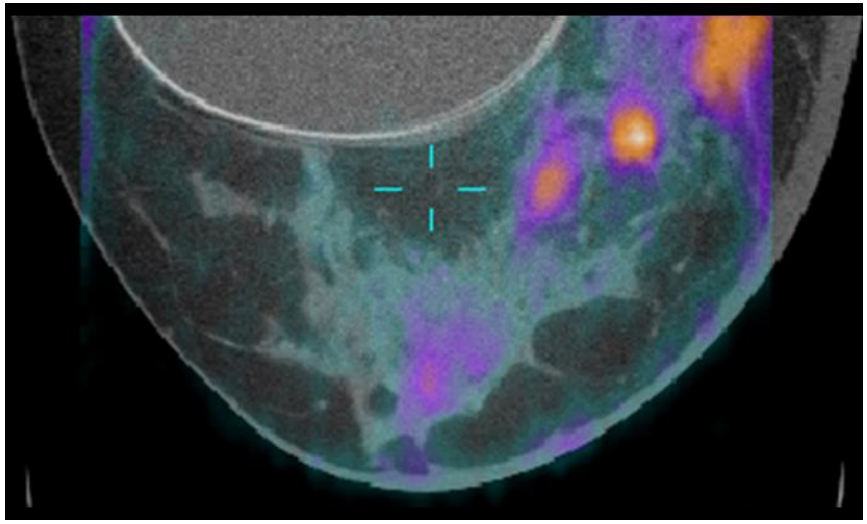
~0.50 mm^3

70 μm × 70 μm × 50,000 μm

Dedicated Breast CT



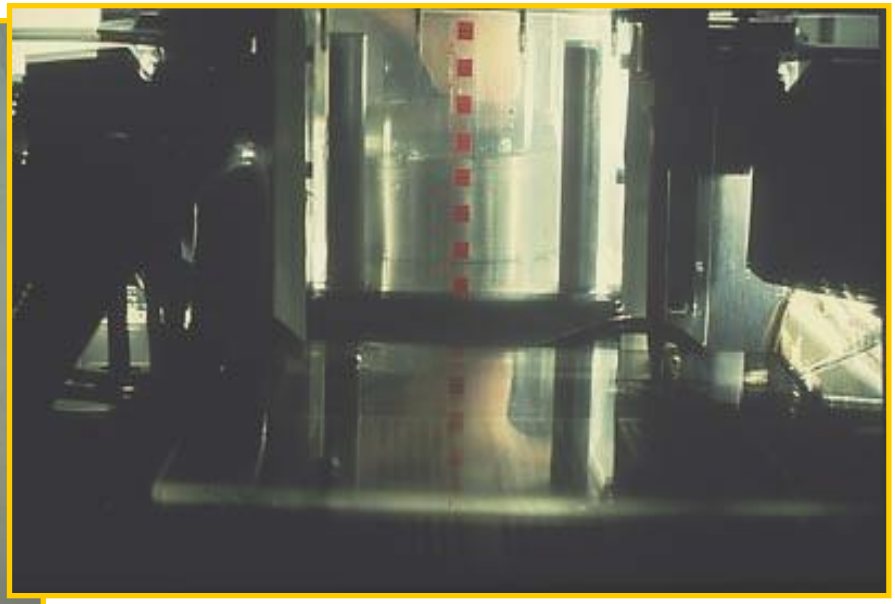




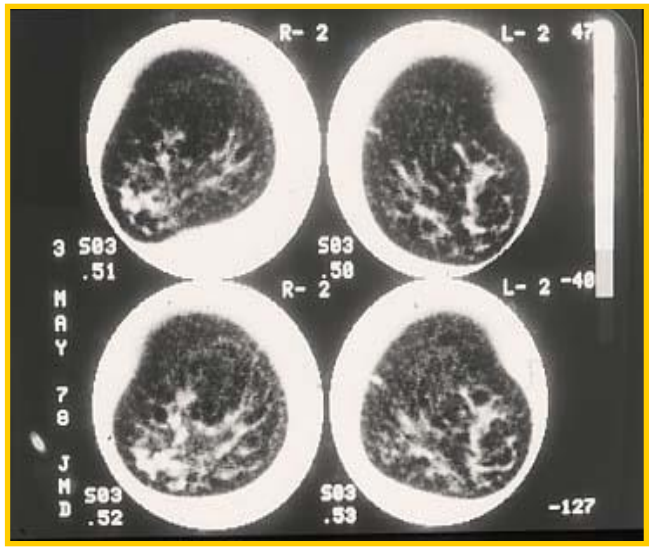
Computed Tomographic Mammography--CTM

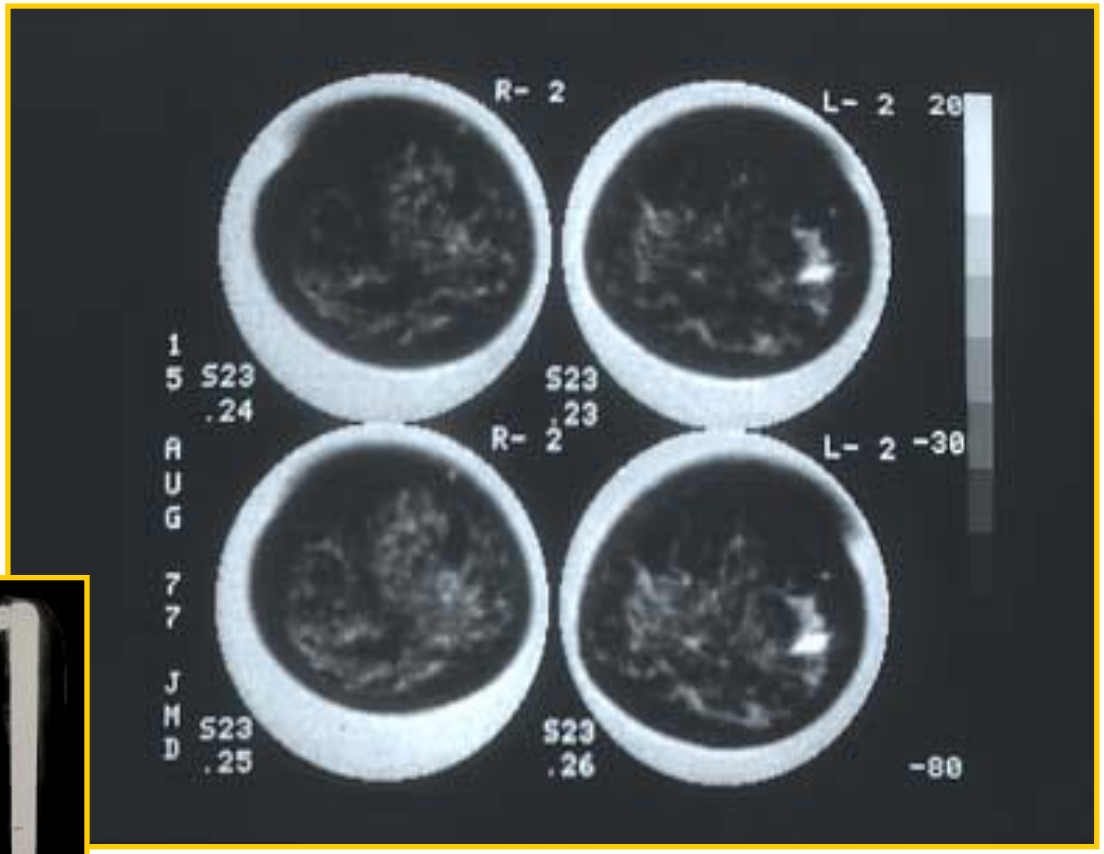
Mayo Clinic 1975

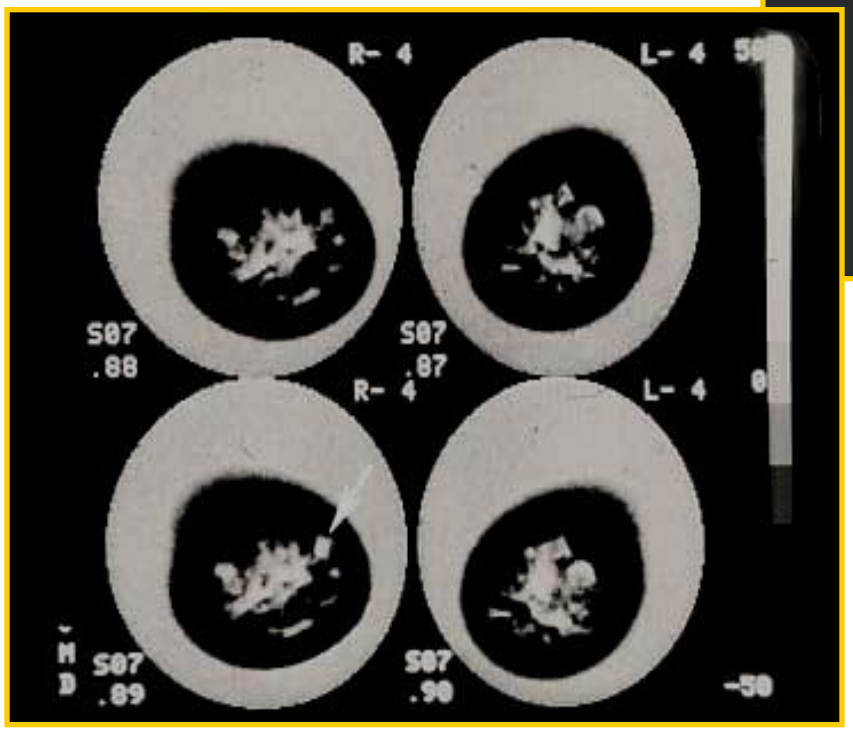
John J. Gisvold, Philip R. Karsell, David F. Reese



10 sec scan in water bath
116 kVp, 300 mAs
10 mm slice thickness
1.56 x 1.56 mm pixels
4 to 6 10 mm slices per breast
256 shades of gray (8 bit)







CTM: 1.56 x 1.56 x 10 mm voxels
Voxel volume: over 900 times smaller

Special thanks to Cynthia McCollough and John Gisvold for providing this information

Breast CT and Dosimetry

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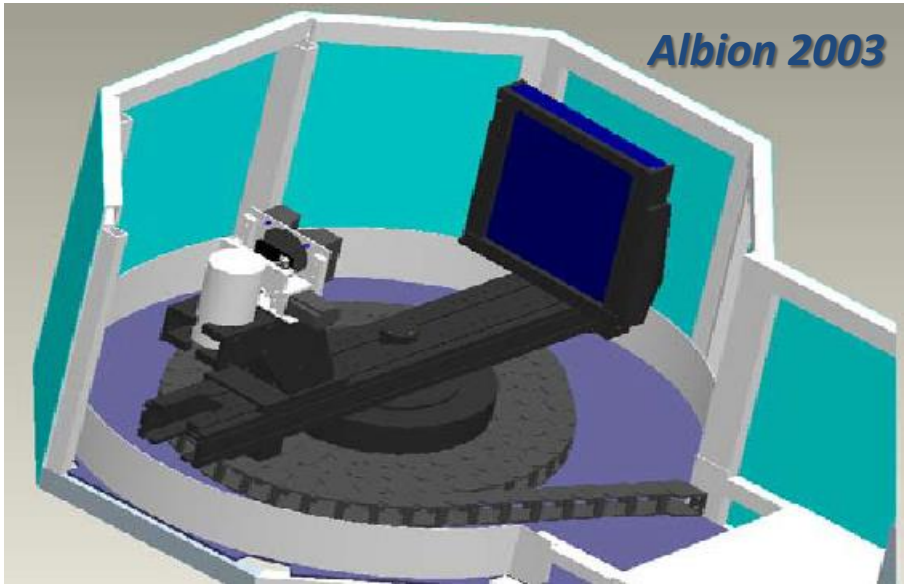
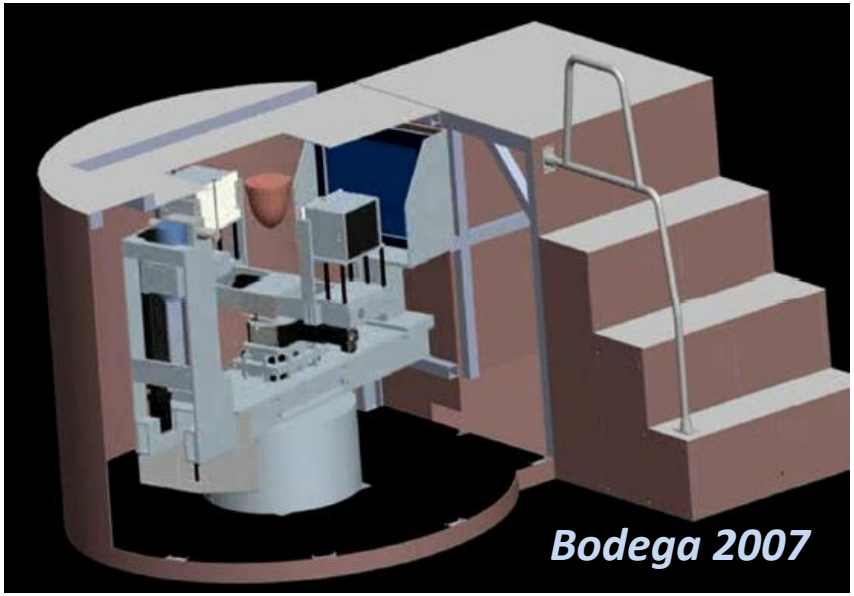
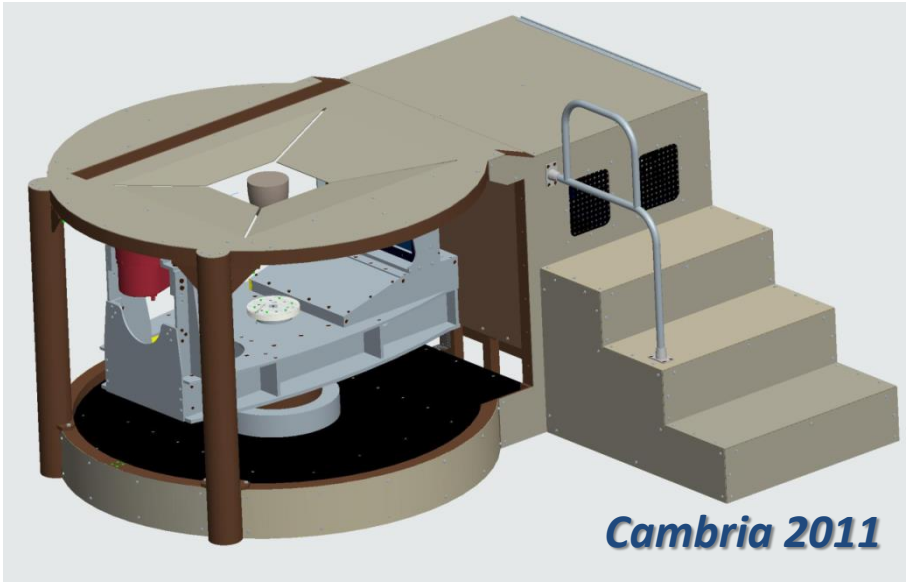
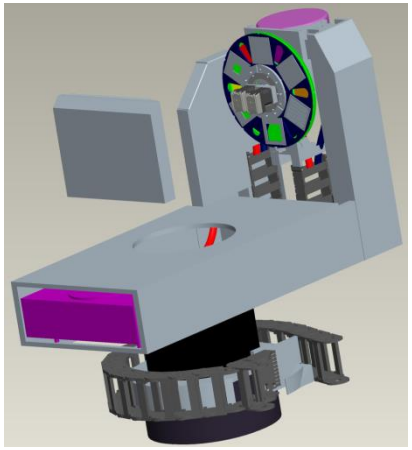
Computer aided design / computer aided manufacture (CAD/CAM)

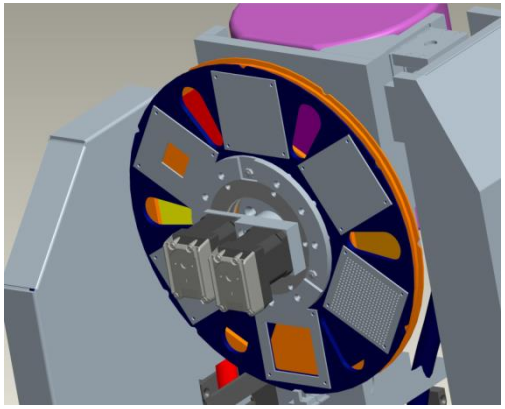






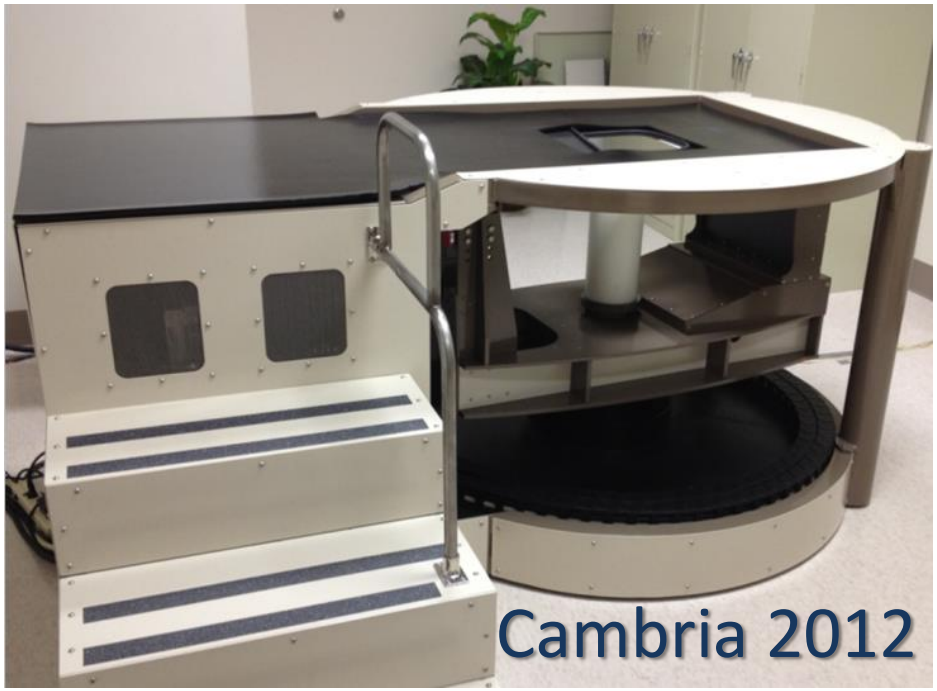


Doheny 2012

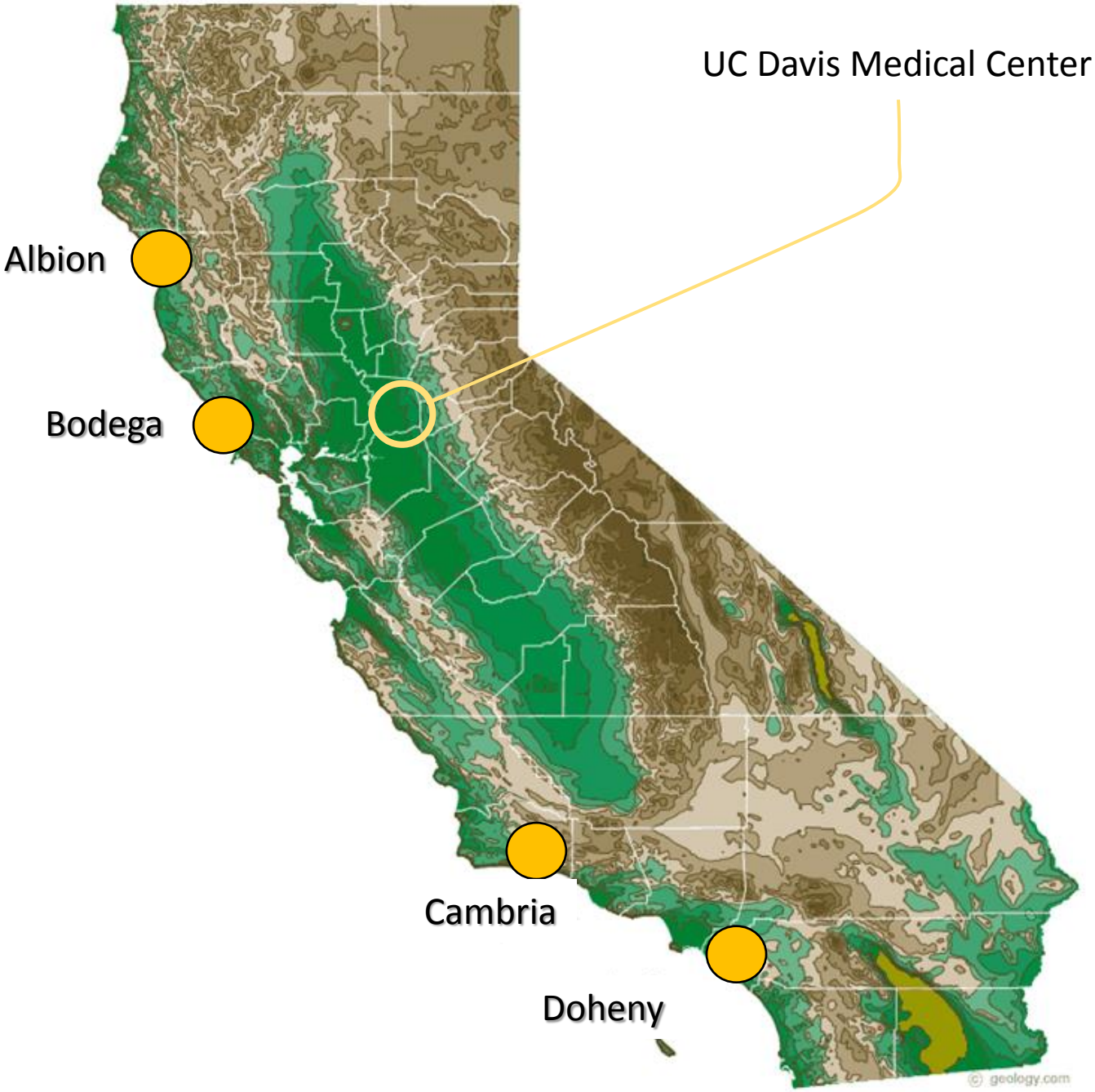



Albion 2004


Bodega 2007


Cambria 2012

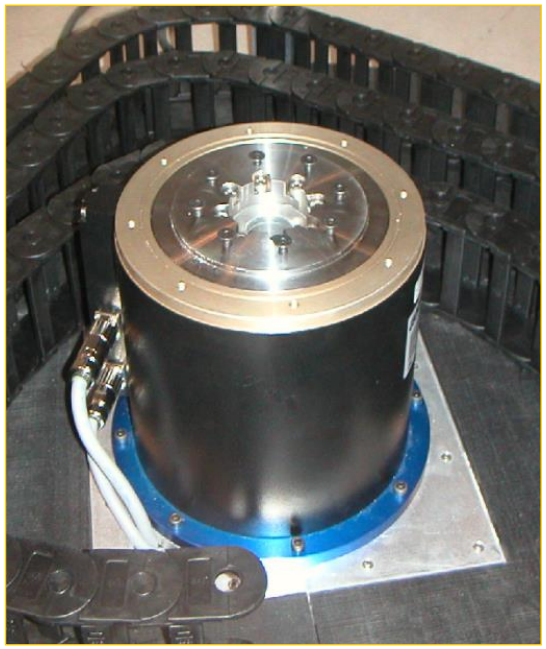

Doheny 2013


UC Davis Medical Center
Albion
Bodega
Cambria
Doheny
© geology.com

Cambria 2011

Components (Albion and Bodega)

Varian 4030CB
194 μm pixels
2x2 388 μm
1024 x 768 x 30 FPS



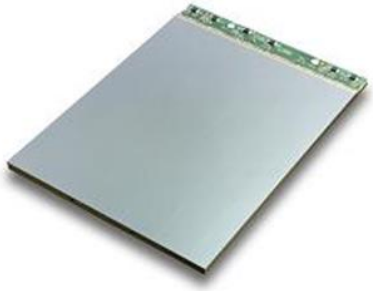
Kollmorgen
Servo Motor
- Propulsion
- Bearing
- Angle Encoder

Comet 1 kW Tube

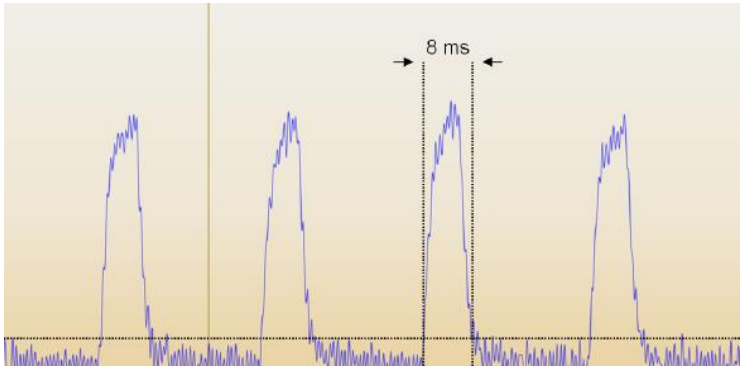
Components (Cambria and Doheny)

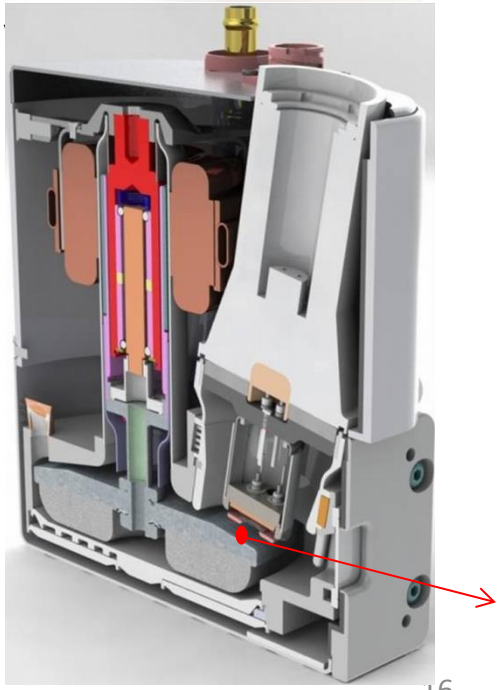
Varian 4030CB

Yaskawa
Servo Motor
- Propulsion
- Bearing
- Angle Encoder

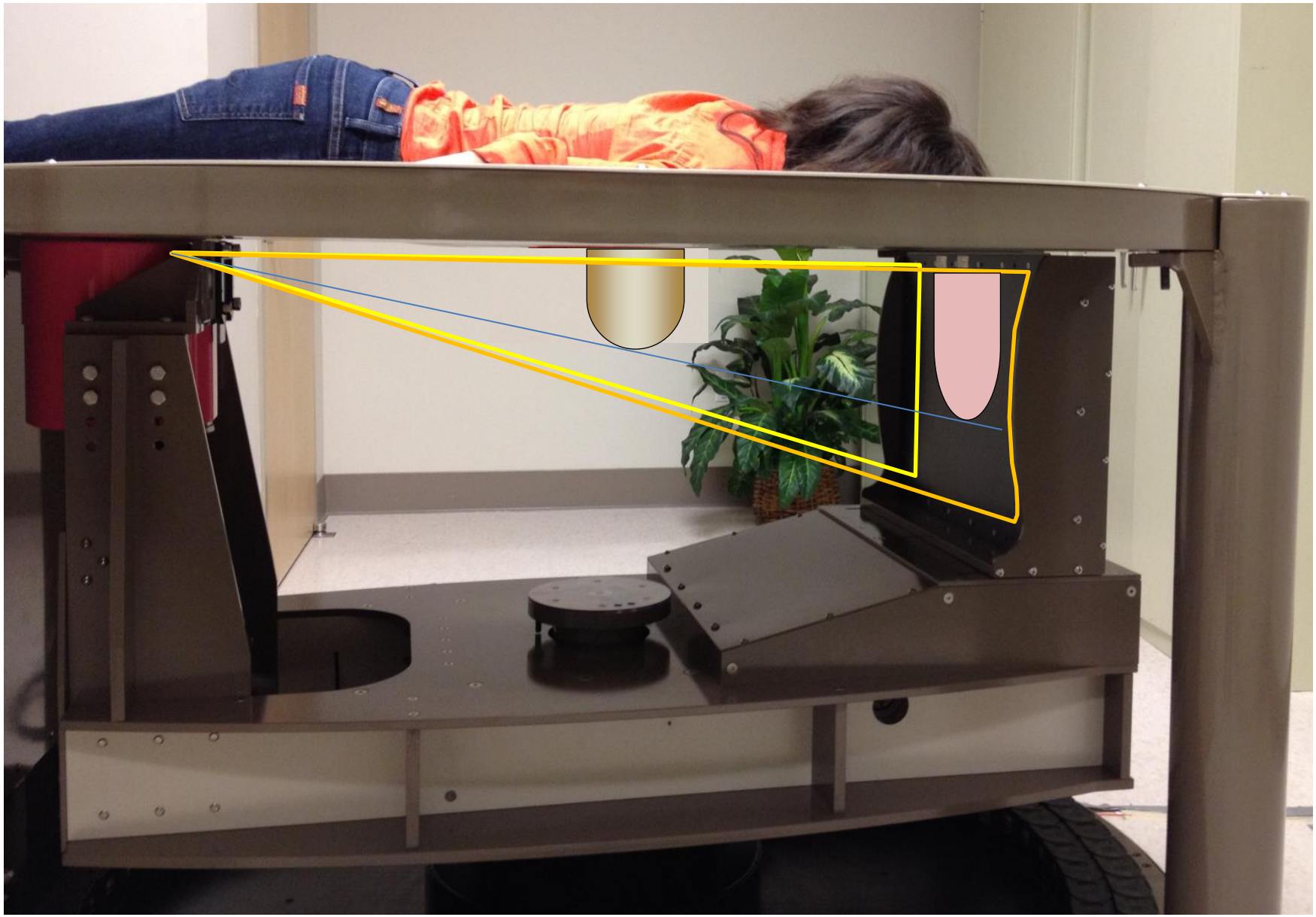


Dexela 2329
.075 mm pixels
26 FPS / CMOS
70 FPS @ 2x2





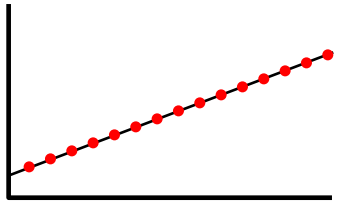
Half Cone Beam CT Geometry

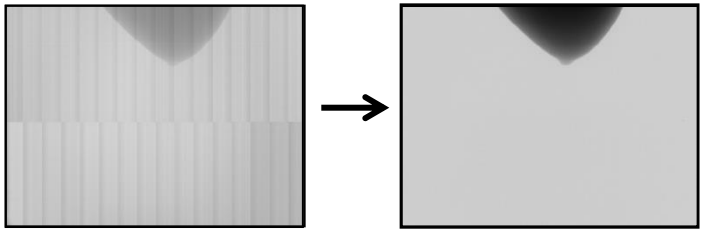


calibration, corrections, reconstruction

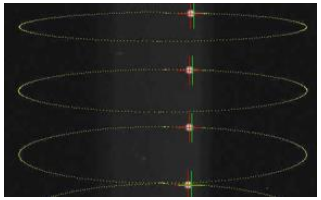
Flat Field Correction

$$I_{corr} = \bar{g} \frac{\left[I_{raw} - I_{r-offset}\right]}{\left[I_{grain} - I_{g-offset}\right]}$$

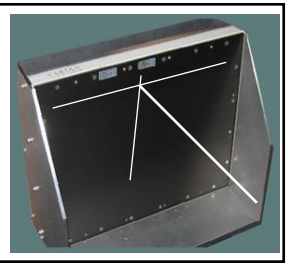




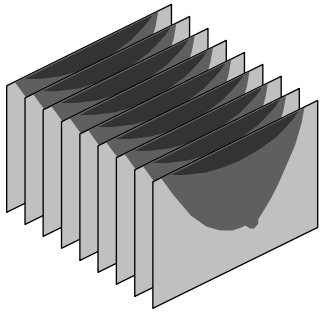
Geometric Calibration

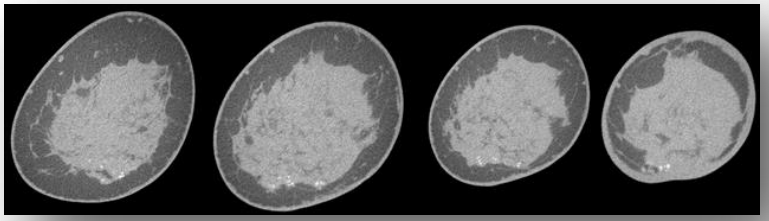


$$u_{wr} = y_{obj} \cdot \frac{D + u_{wr} \cdot \sin\phi}{C + x_{obj}} \cdot \frac{1}{\cos\phi}, \quad v_{wr} = z_{obj} \cdot \frac{D + u_{wr} \cdot \sin\phi}{C + x_{obj}}.$$



FDK Reconstruction Code





2003 ~42 minutes

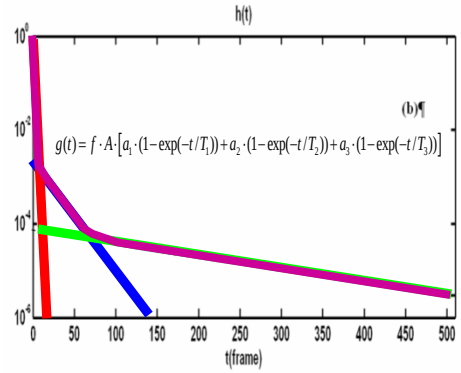
2008 ~35 minutes

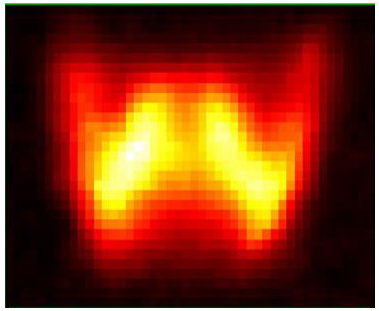
>100x

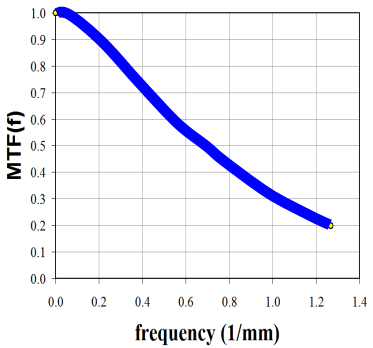
2010 ~20 seconds

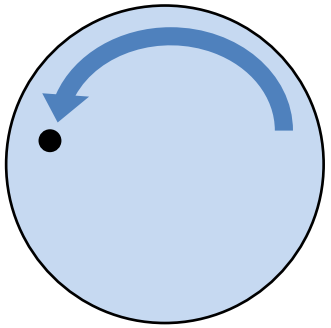
```
float tempi,tempr;
double theta,wi,wpi,wpr,wr,wtemp;

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;
}
```

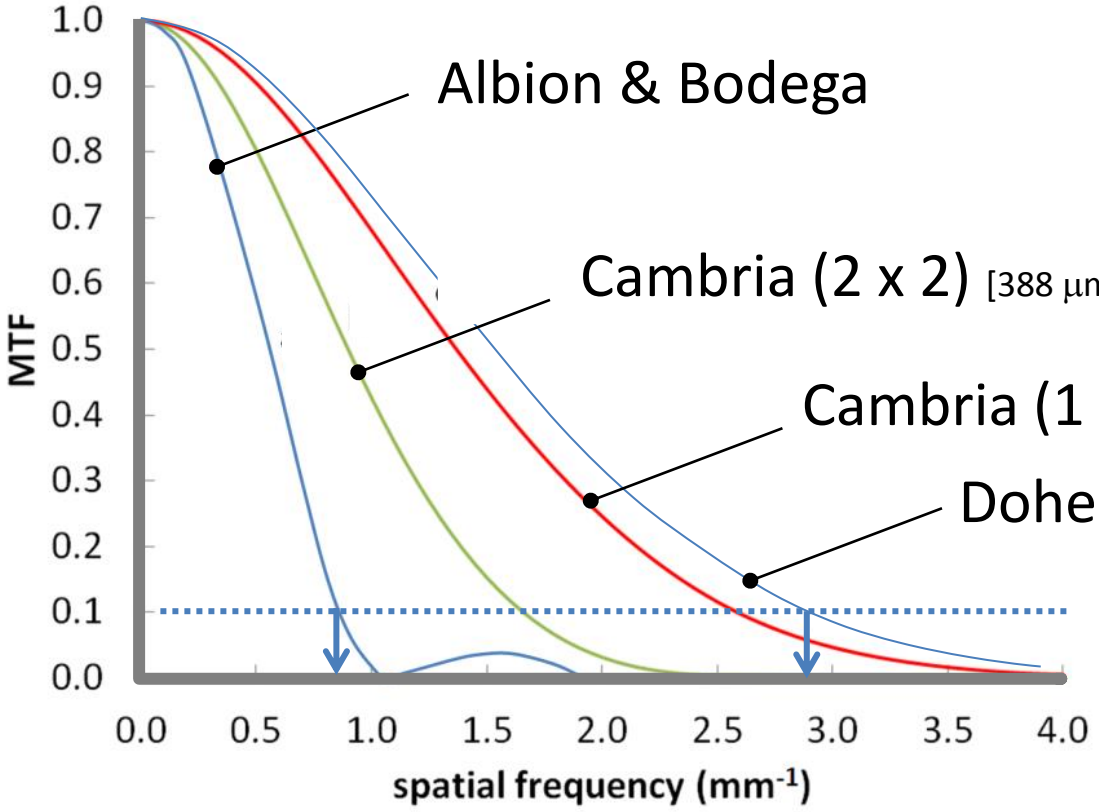
Spatial Resolution: Modeled & Measured MTF's





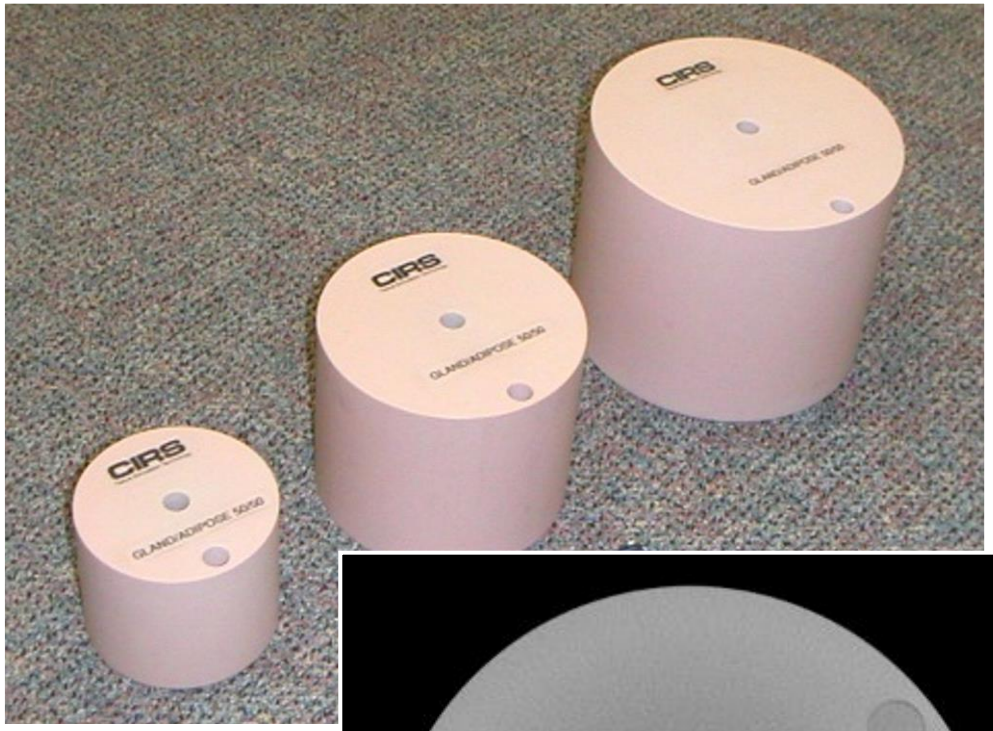


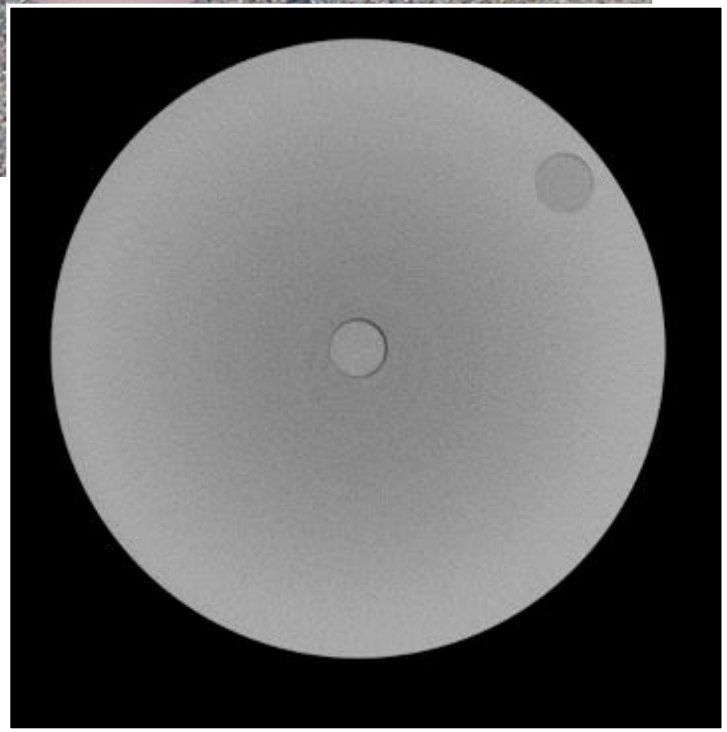


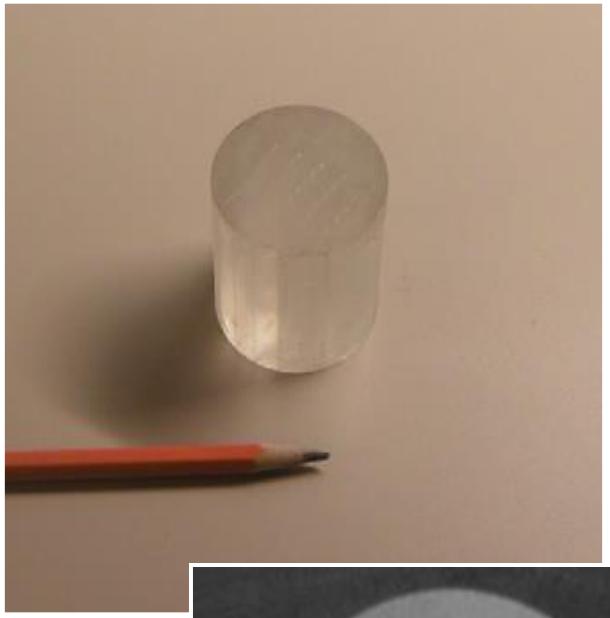


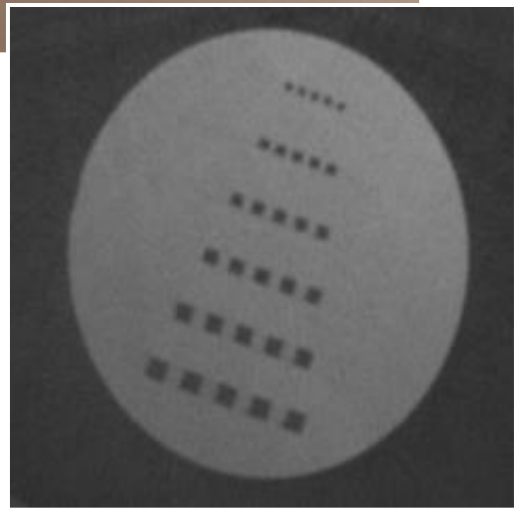
3X Spatial Resolution

Phantom Imaging

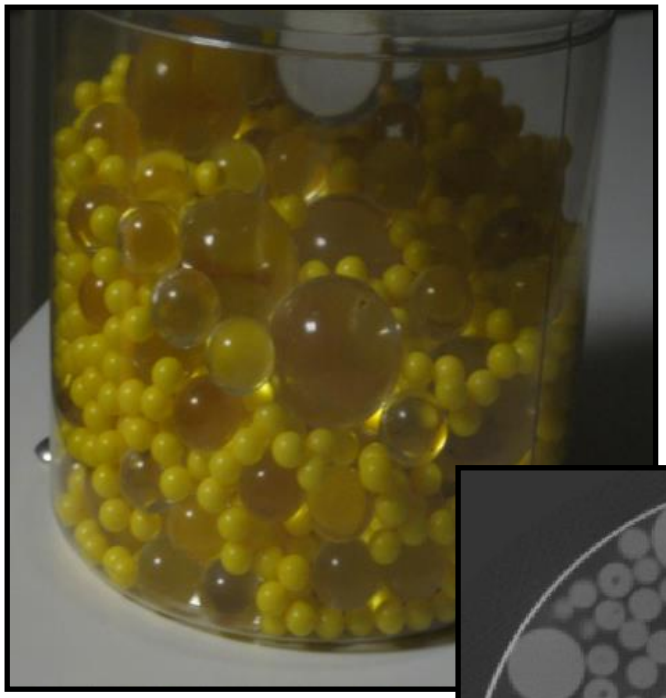


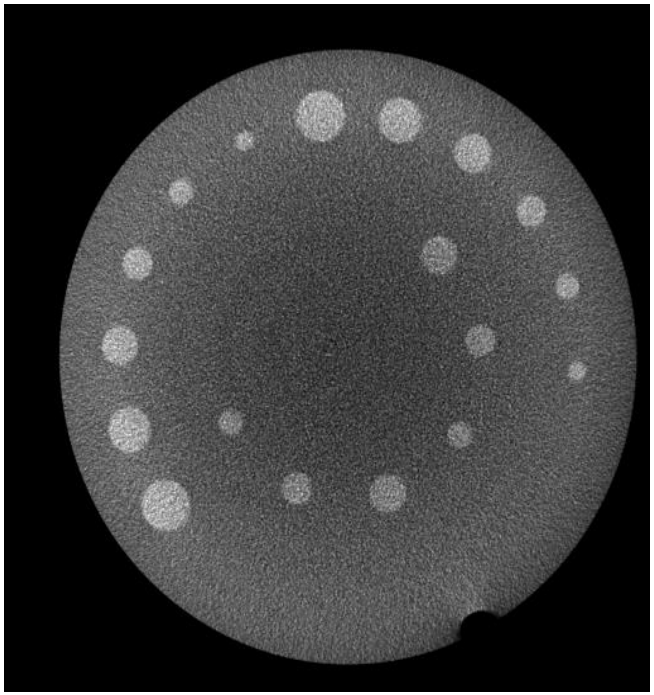


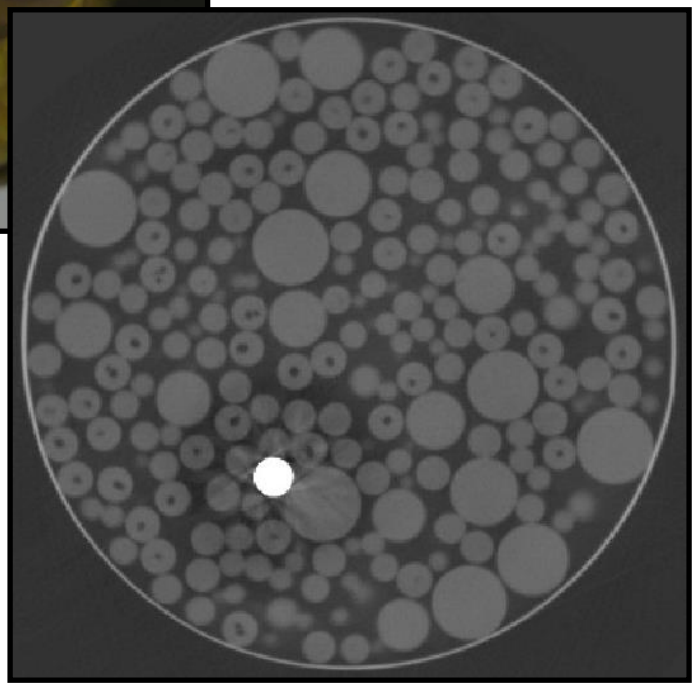




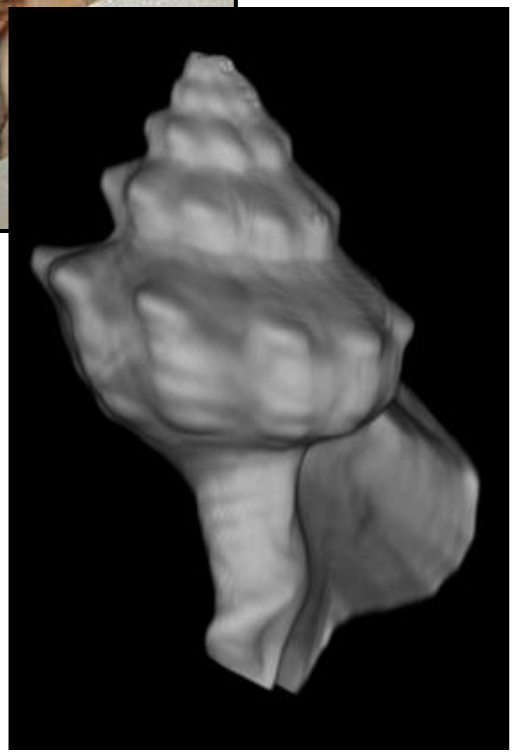
Phantom Imaging

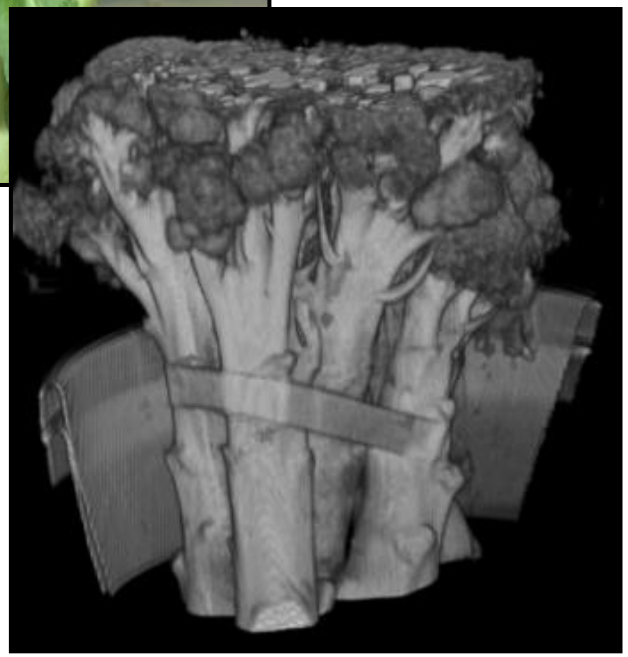






Phantom Imaging





Breast CT and Dosimetry

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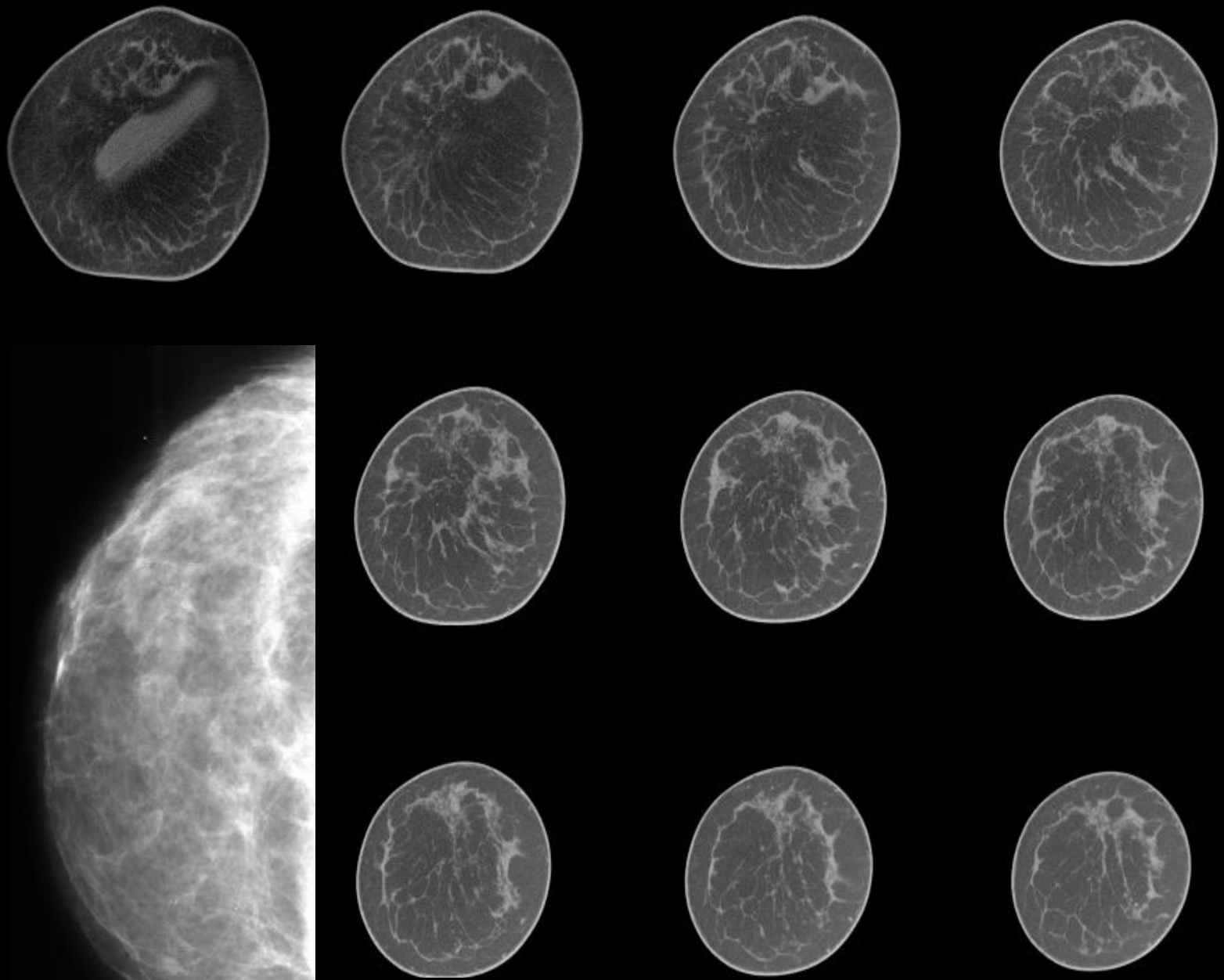
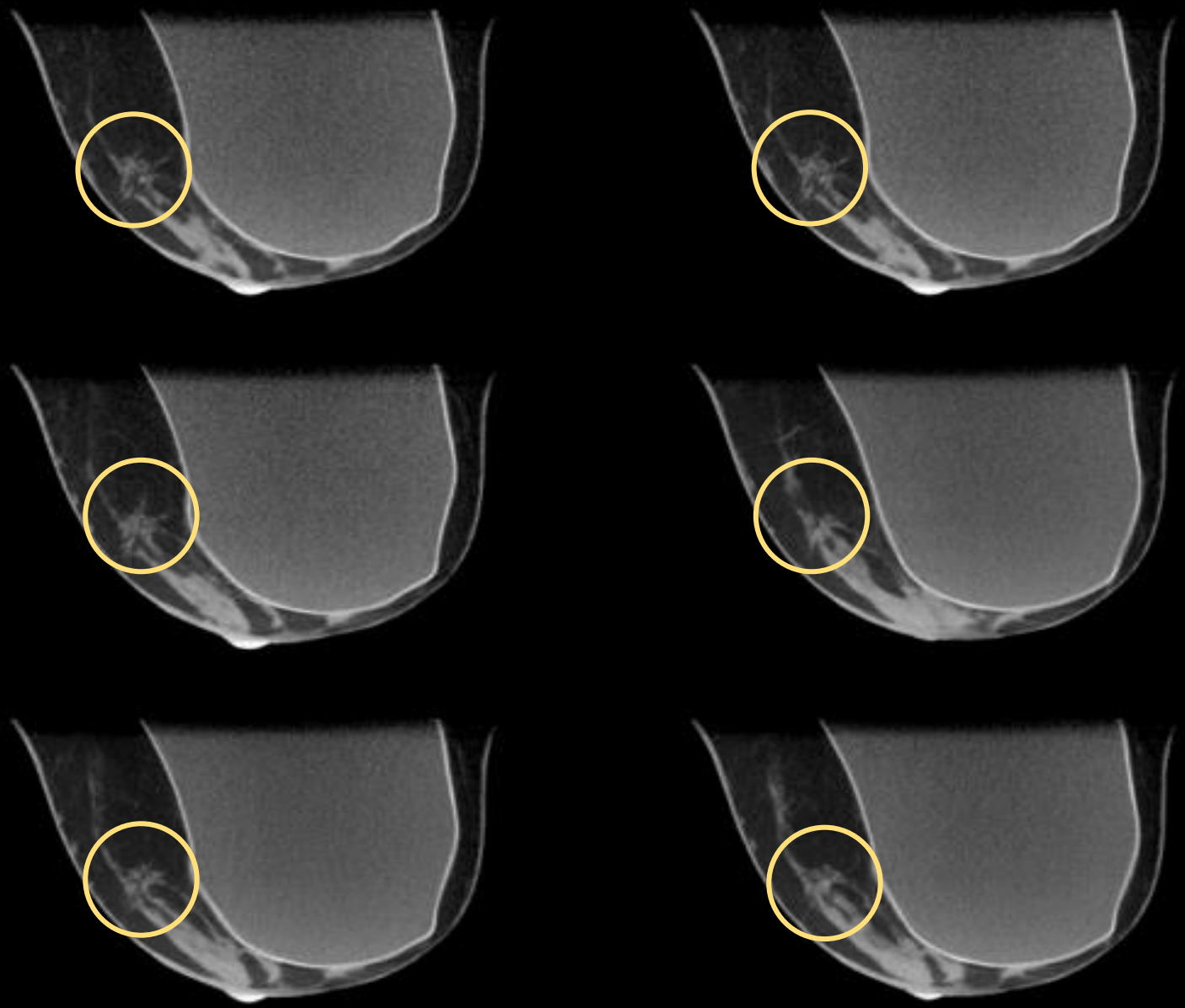
Patient Imaging
Radiologist Observers

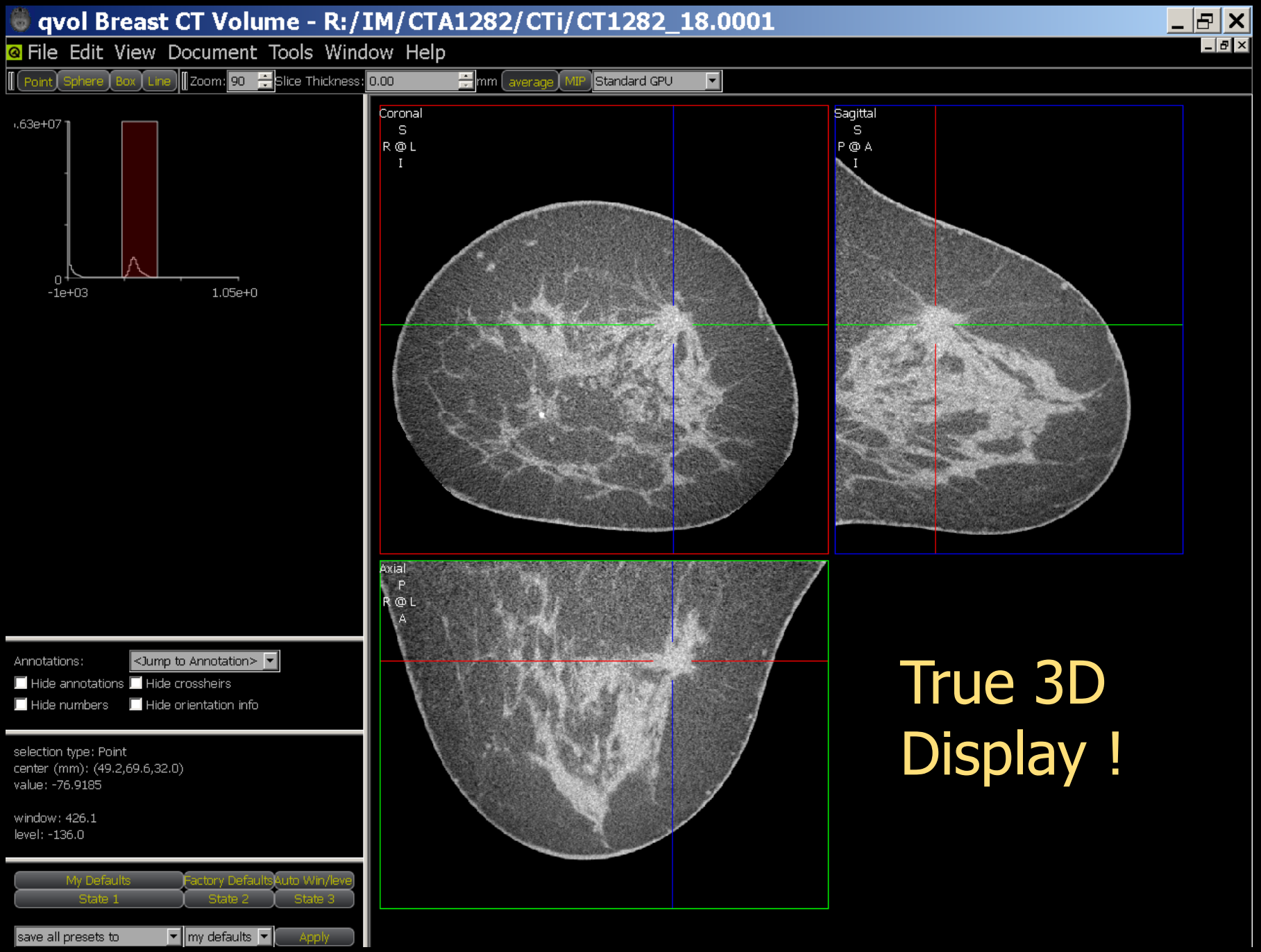
Over 600 patients imaged at two sites



second volunteer imaged: January 2005



first breast cancer imaged: January 2005


qvol Breast CT Volume - R:/IM/CTA1282/CTi/CT1282_18.0001
File Edit View Document Tools Window Help
Point Sphere Box Line
Zoom: 90
Slice Thickness: 0.00
mm
average
MIP
Standard GPU
.63e+07
0
-1e+03
1.05e+0
Coronal
S
R @ L
I
Sagittal
S
P @ A
I
Axial
P
R @ L
A
Annotations:
<Jump to Annotation>
Hide annotations
Hide crossheirs
Hide numbers
Hide orientation info
selection type: Point
center (mm): (49.2,69.6,32.0)
value: -76.9185
window: 426.1
level: -136.0
My Defaults
Factory Defaults
Auto Win/leve
State 1
State 2
State 3
save all presets to
my defaults
Apply
True 3D
Display !

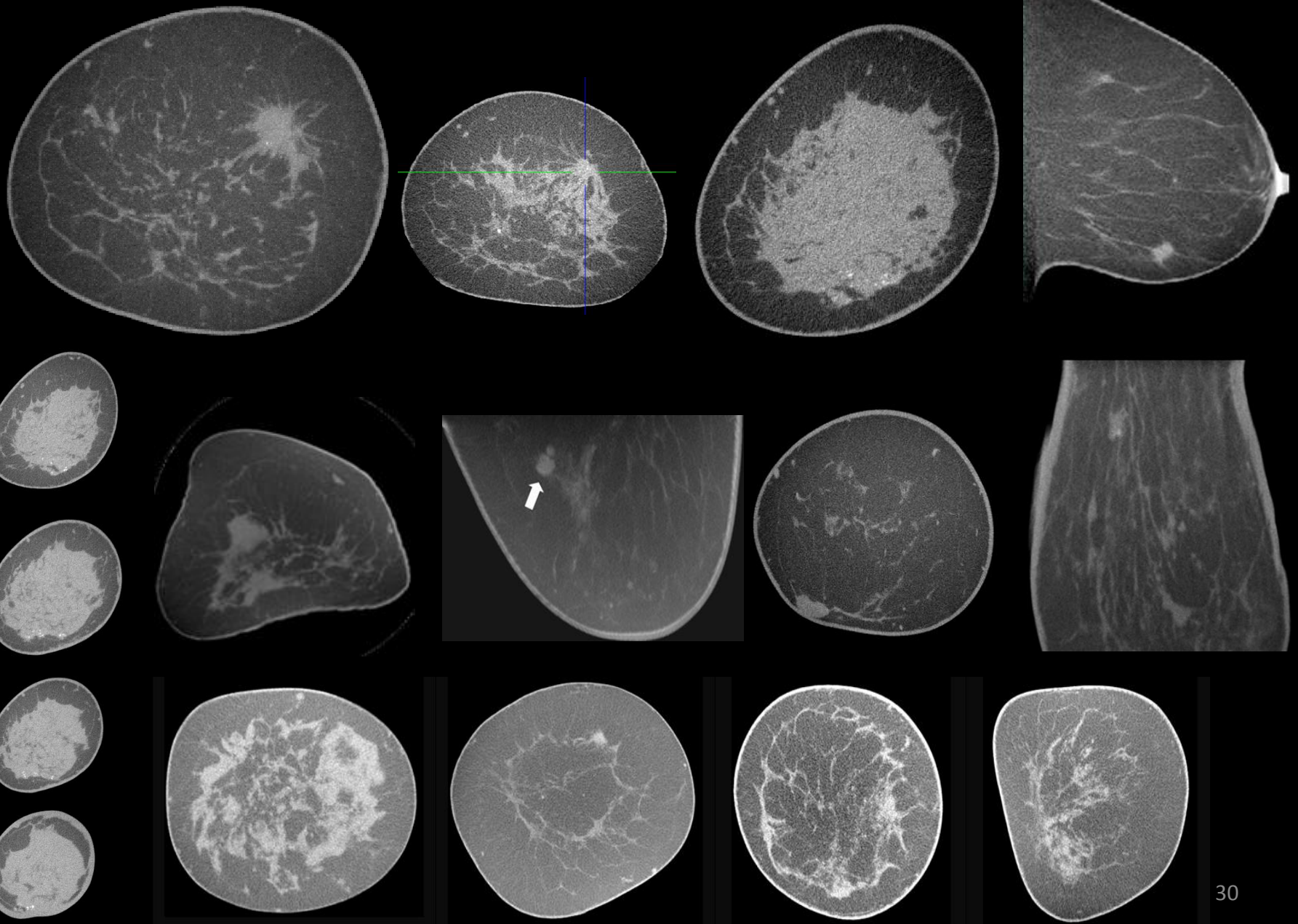
Radiology

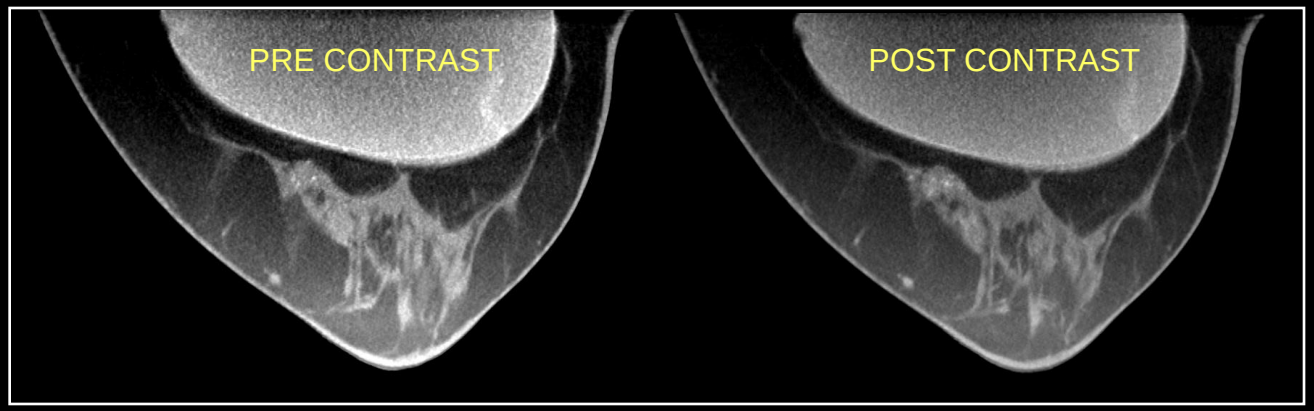
2008

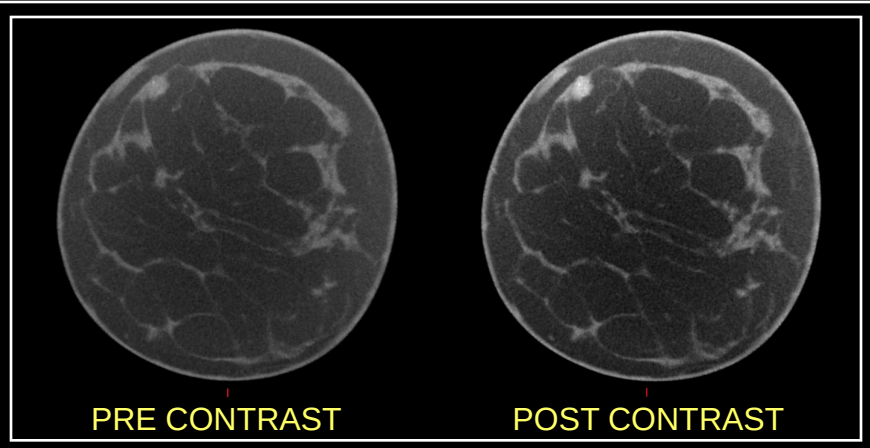
Dedicated Breast CT: Initial Clinical Experience[1]

Karen K. Lindfors, MD
John M. Boone, PhD
Thomas R. Nelson, PhD
Kai Yang, MS
Alexander L. C. Kwan, PhD[2]
DeWitt F. Miller, BE

bCT (no injected contrast)





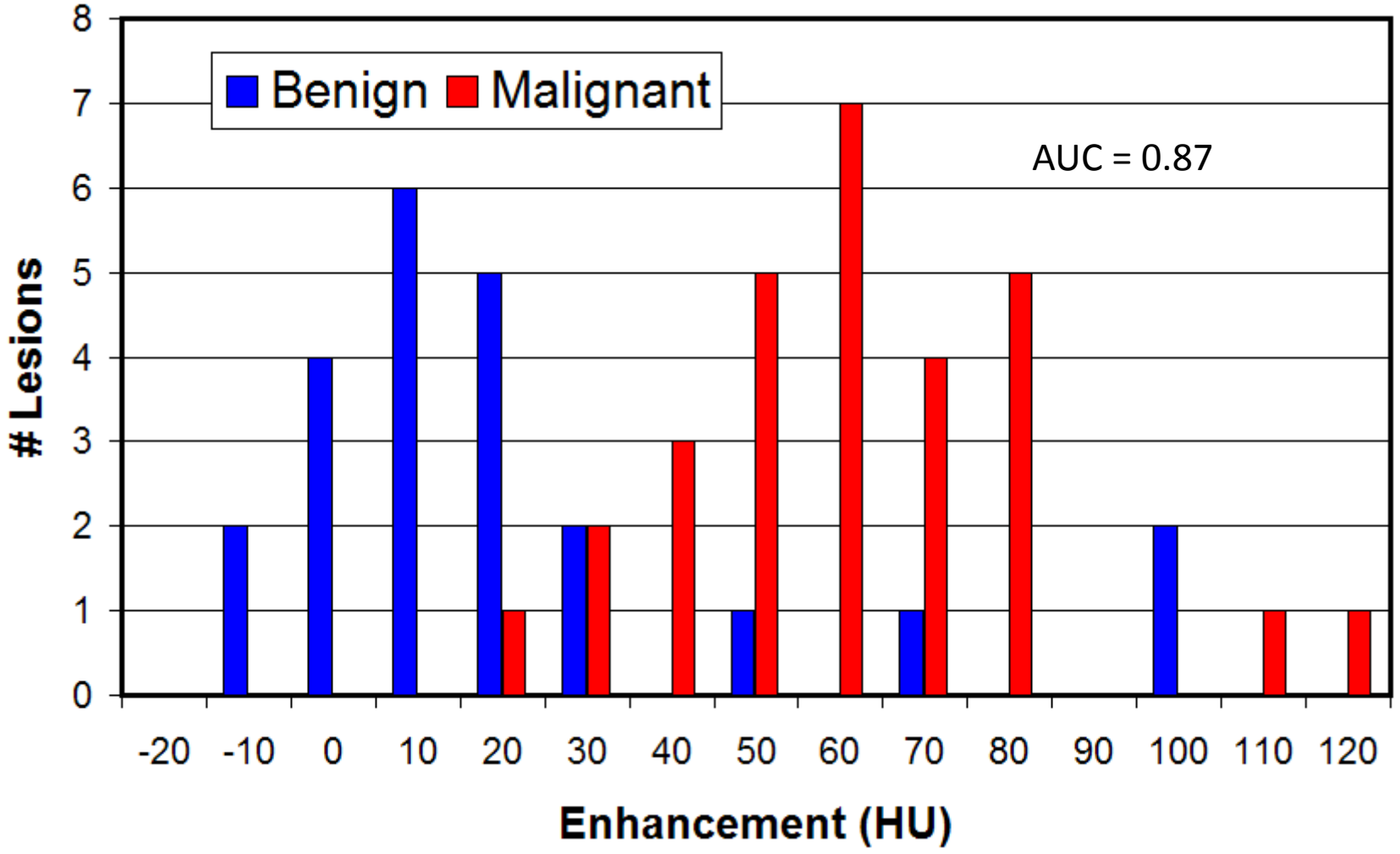


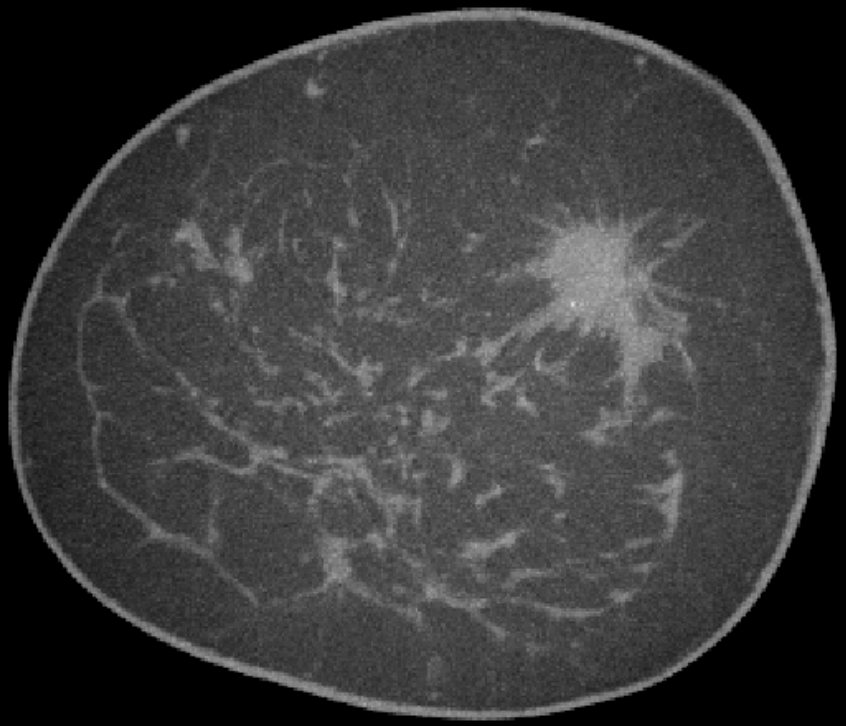
bCT (with contrast)

Radiology

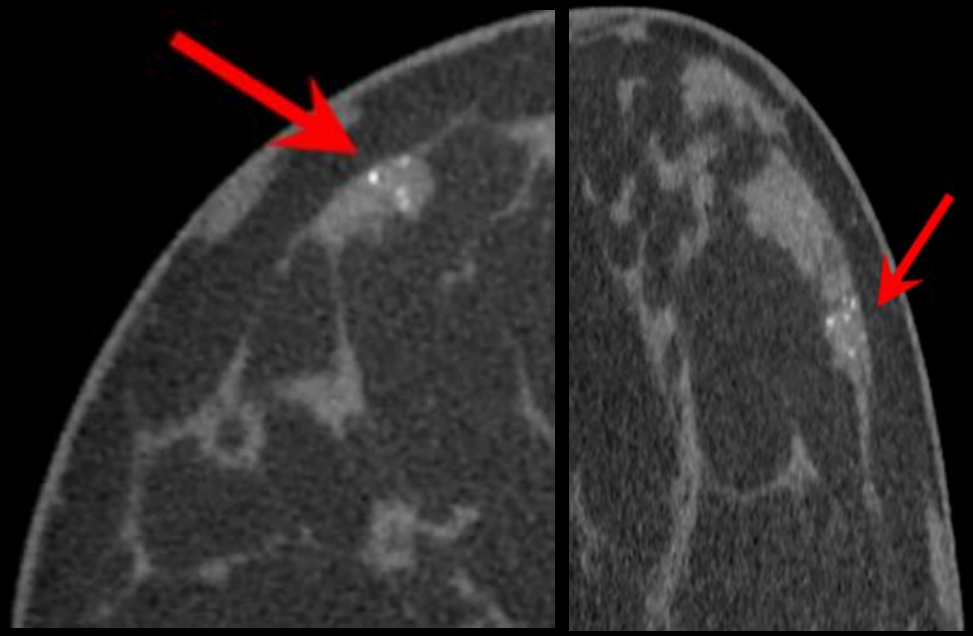
2010

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





mass lesion



microcalcifications

Prospective Clinical Trial

Shadi Shakeri, M.D.

105 patients /103 lesions (BIRADS 4 or 5)

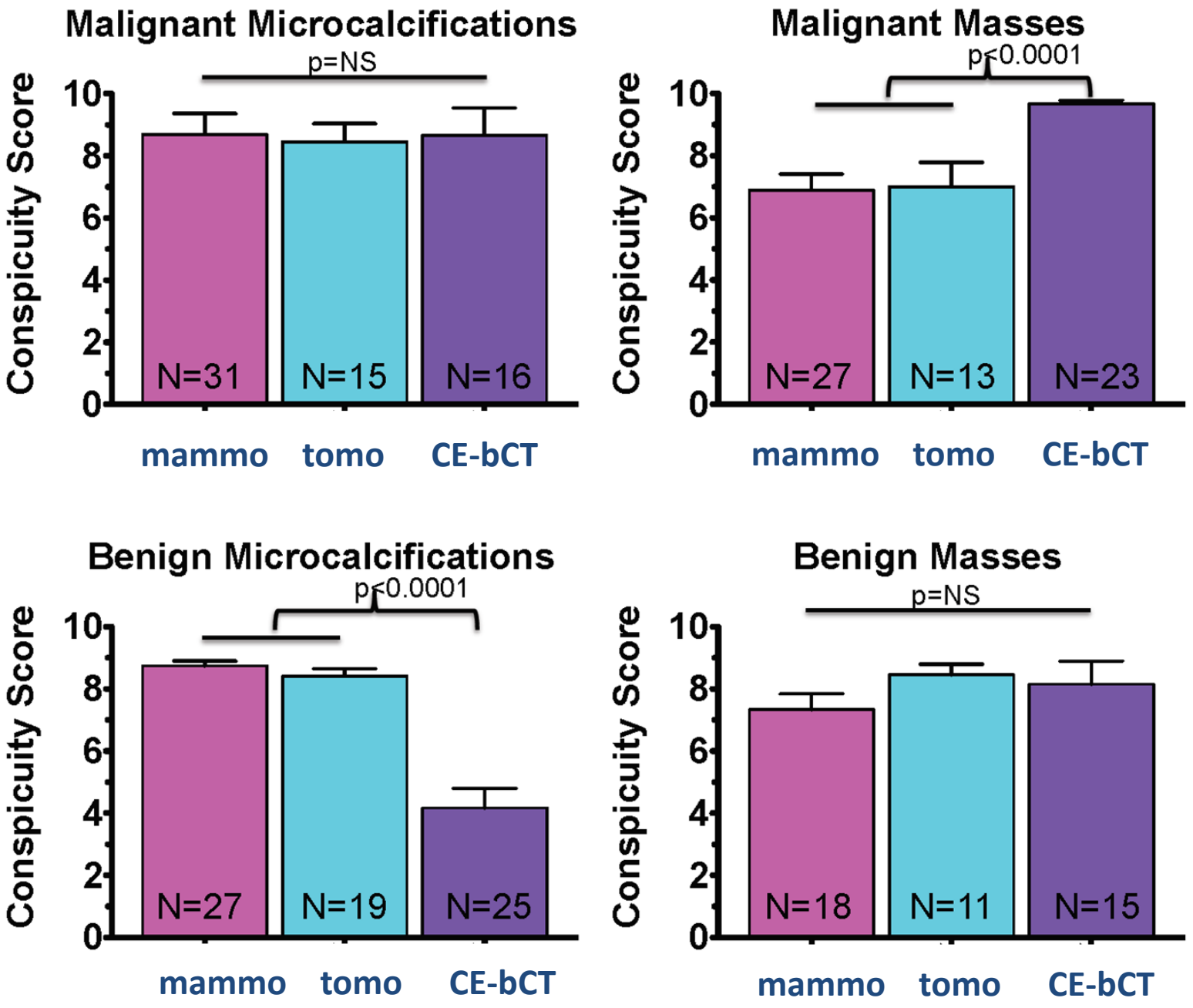
- imaged on VCO mammo / tomo / CE-bCT
- all biopsied

	microcalcifications	masses
malignant	31	27
benign	27	18
total	58	45

2 Radiologists Rated Lesions using a 0 to 10 Conspicuity Score

0 = not seen 10 = excellent

one-way ANOVA with correction for multiple comparisons


Malignant Microcalcifications
p=NS
Conspicuity Score
10
8
6
4
2
0
N=31
N=15
N=16
mammo
tomo
CE-bCT
Malignant Masses
p<0.0001
Conspicuity Score
10
8
6
4
2
0
N=27
N=13
N=23
mammo
tomo
CE-bCT
Benign Microcalcifications
p<0.0001
Conspicuity Score
10
8
6
4
2
0
N=27
N=19
N=25
mammo
tomo
CE-bCT
Benign Masses
p=NS
Conspicuity Score
10
8
6
4
2
0
N=18
N=11
N=15
mammo
tomo
CE-bCT

Computer (Mathematical) Observer

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

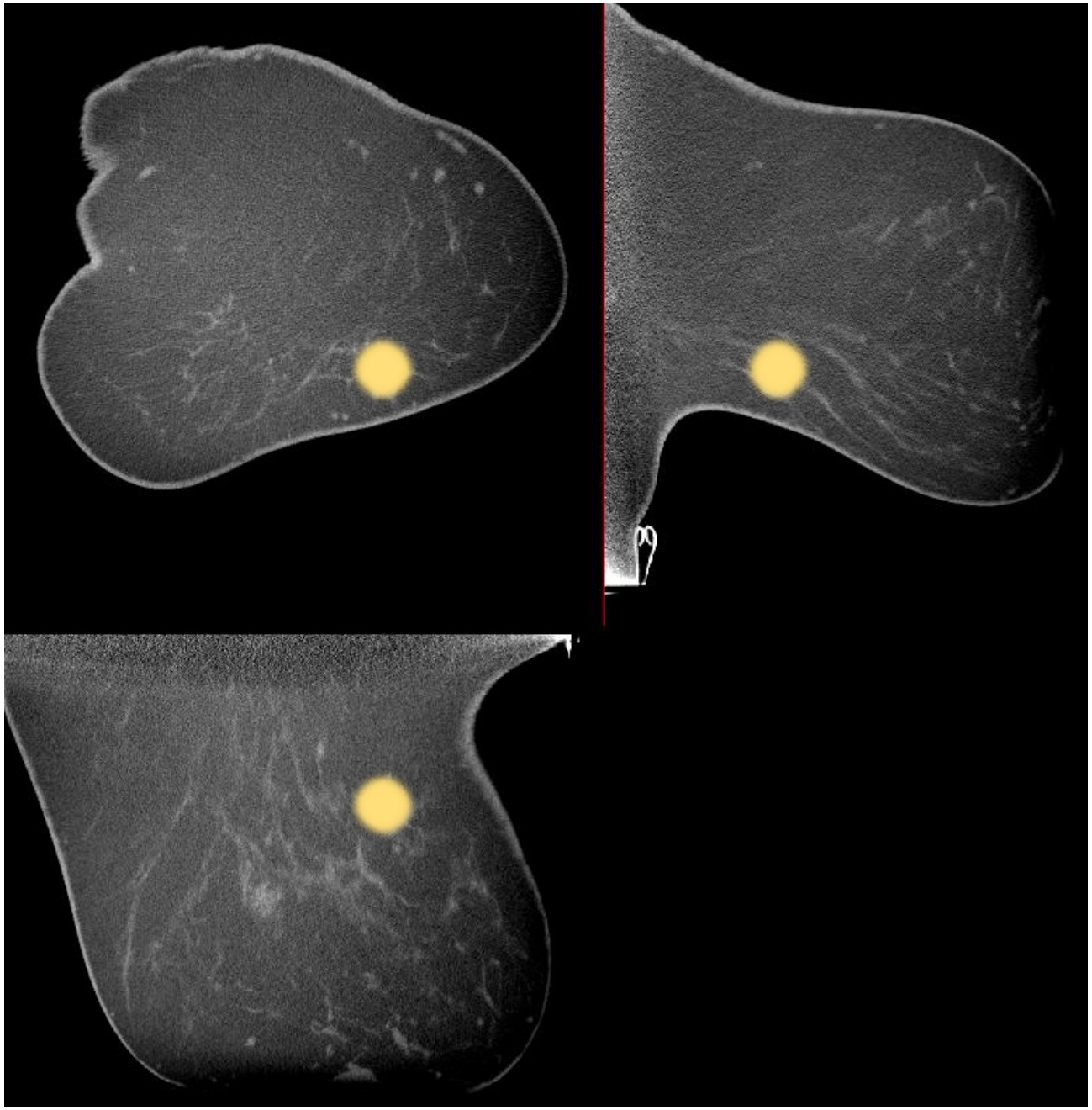
Nathan J. Packard
Carestream Health Inc., Rochester, New York 14615

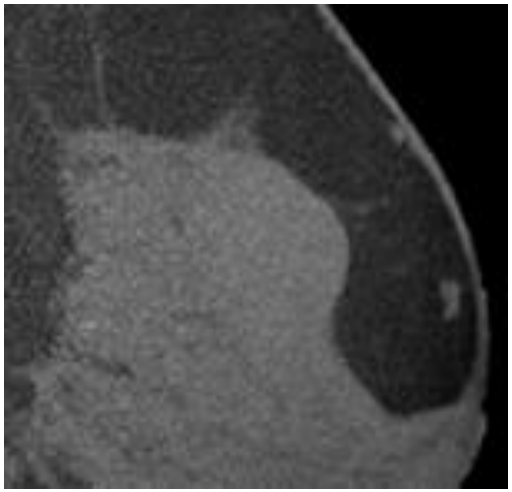
Craig K. Abbey
Department of Psychology, University of California, Santa Barbara, California 93106

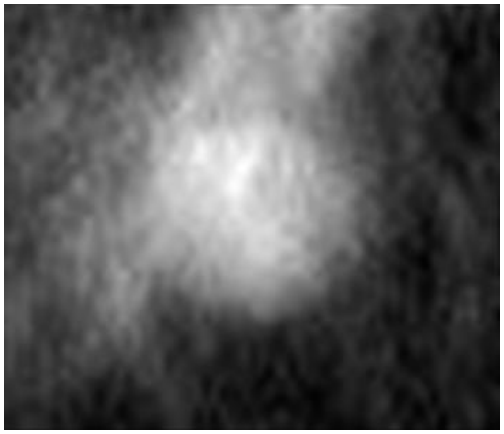
Kai Yang
Department of Radiology, University of California Davis Medical Center, Sacramento, California 95817

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)



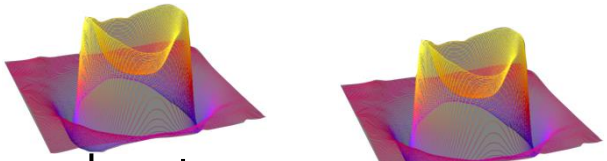


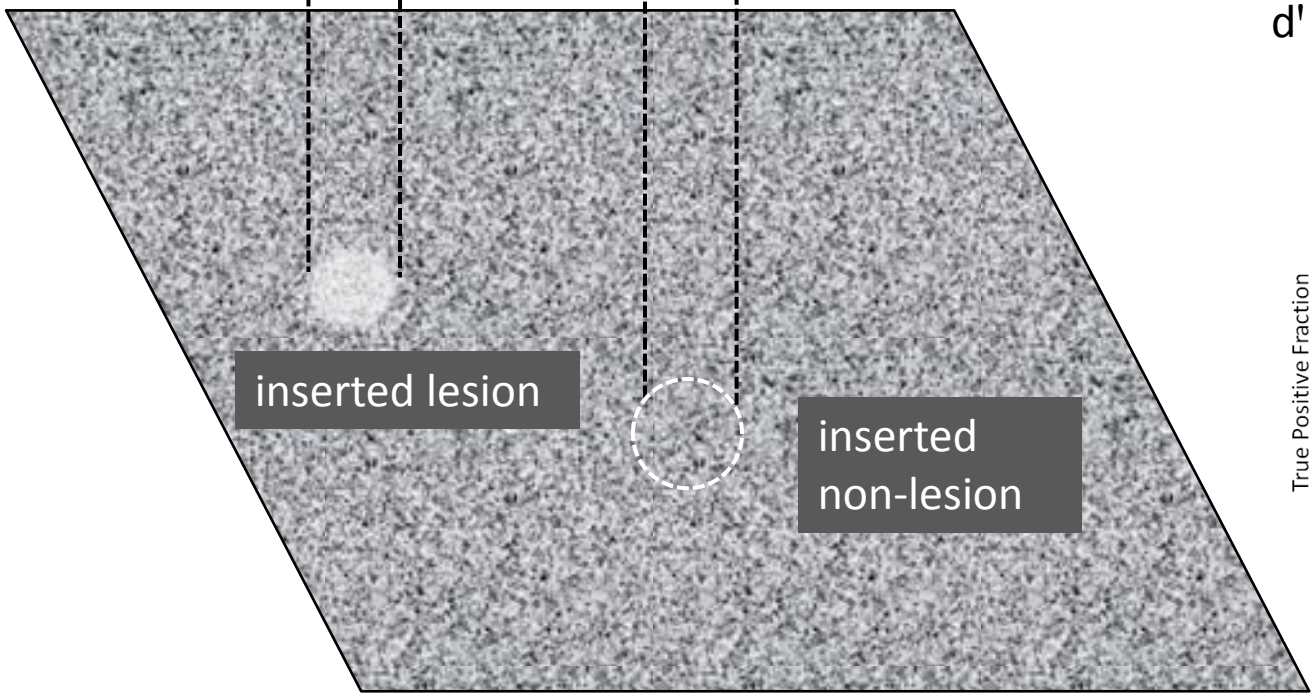


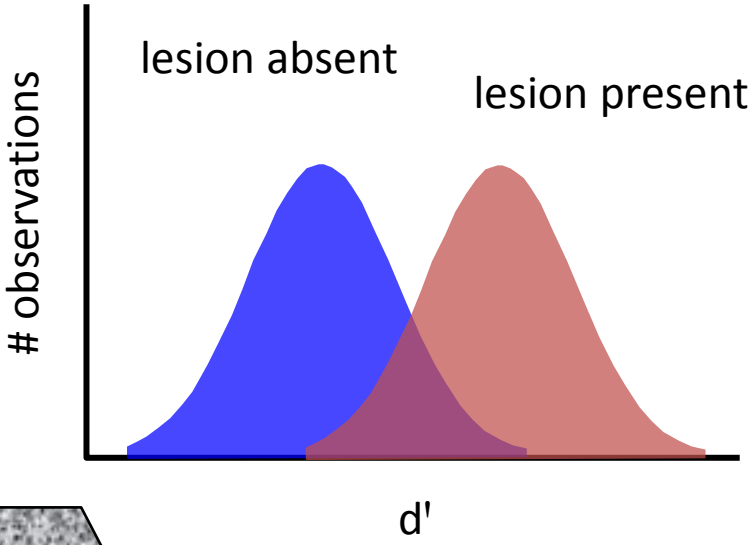
pre-whitened matched filter
"computer observer"

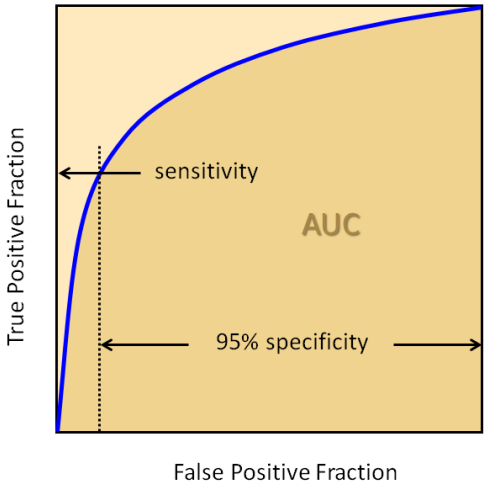
$$\sum(f_i \times I_i) = d'$$

filter

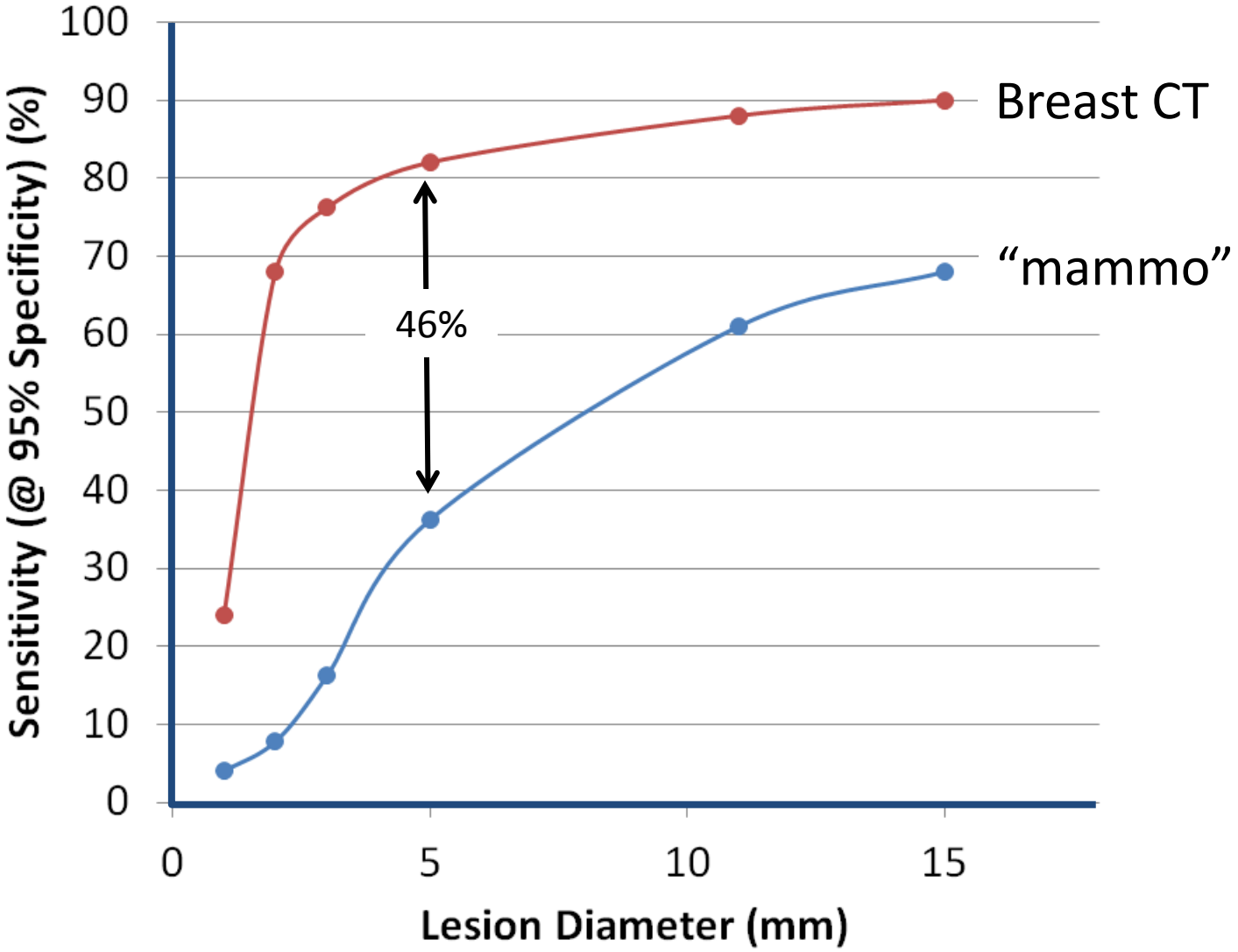








breast CT image (actual images are used)



mass lesions only / results do not reflect microcalcifications

Breast CT and Dosimetry

- Breast CT Background
- Technical Development
- Initial Clinical Results
- **Dose Issues in Breast CT**
- Summary

Radiology

Medical Physics

2001

John M. Boone, PhD
Thomas R. Nelson, PhD
Karen K. Lindfors, MD
J. Anthony Seibert, PhD

Dedicated Breast CT: Radiation Dose and Image Quality Evaluation[1]

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

J. M. Boone[a)]
Department of Radiology, U.C. Davis Medical Center, 4701 X Street, X-ray Imaging Laboratory and Department of Biomedical Engineering, Sacramento, California 95817

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

T. R. Nelson
Department of Radiology, University of California, San Diego, California 92037

(Received 21 July 2003; revised 26 September 2003; accepted for publication 4 November 2003; published 14 January 2004)

2004

Technique factors and their relationship to radiation dose in pendant geometry breast CT

John M. Boone,[a)] Alexander L. C. Kwan, J. Anthony Seibert, Nikula Shah, and Karen K. Lindfors
Department of Radiology, University of California Davis Medical Center, Sacramento, California

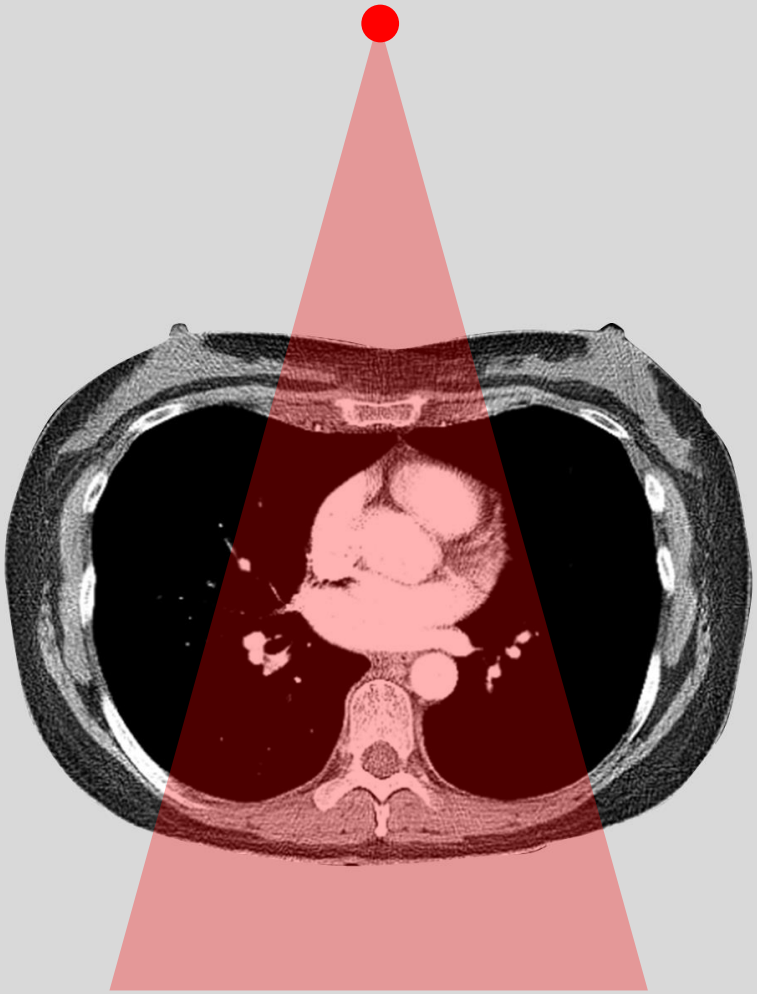
Thomas R. Nelson
Department of Radiology , University of California San Diego, La Jolla, California

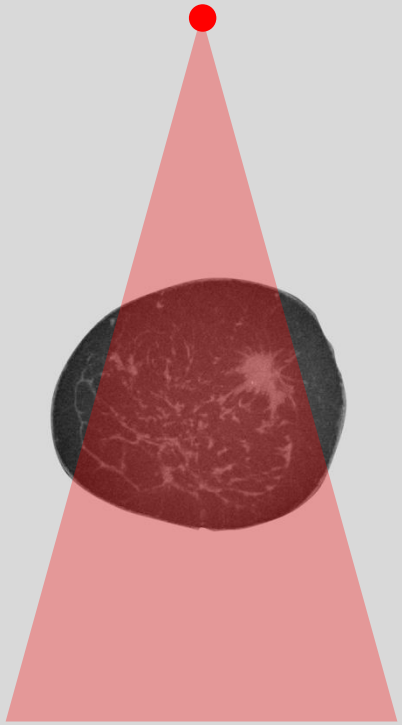
(Received 11 July 2005; revised 13 September 2005; accepted for publication 3 October 2005; published 22 November 2005)

2005

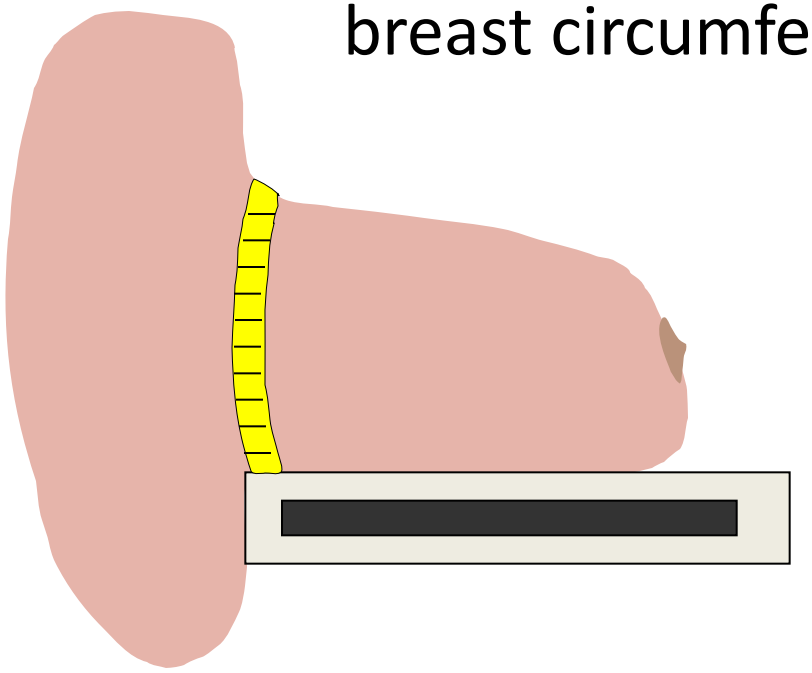
Radiation Dose from Breast CT ?

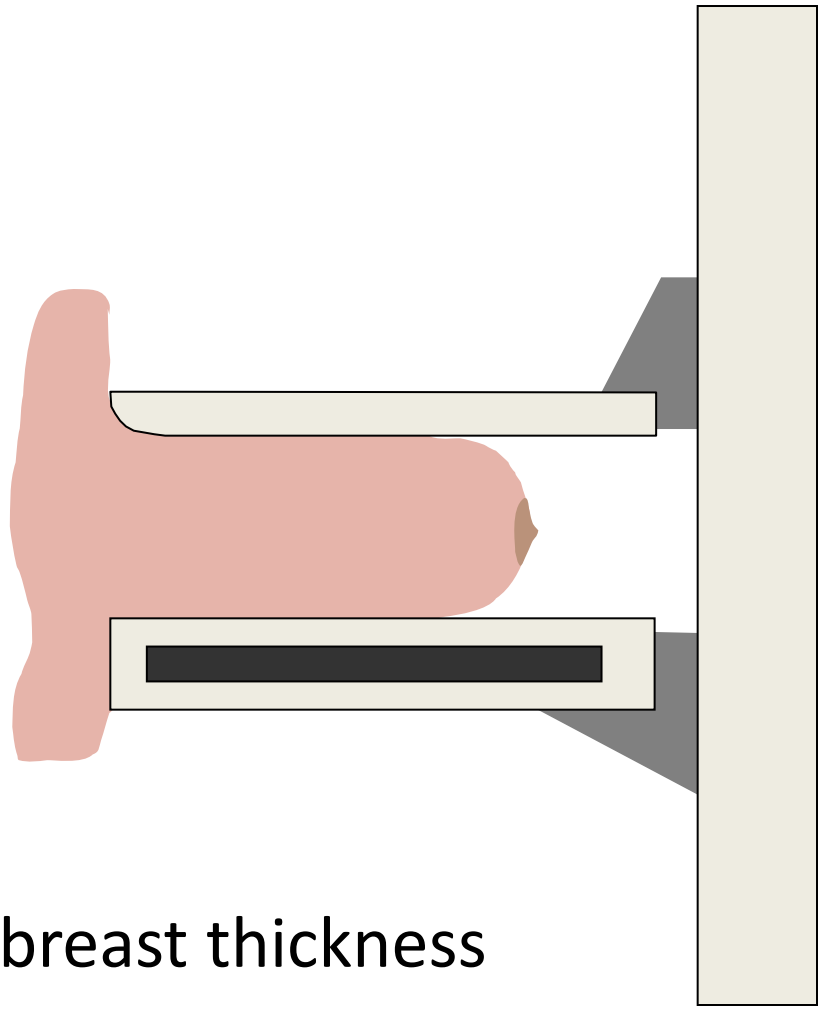
……size matters



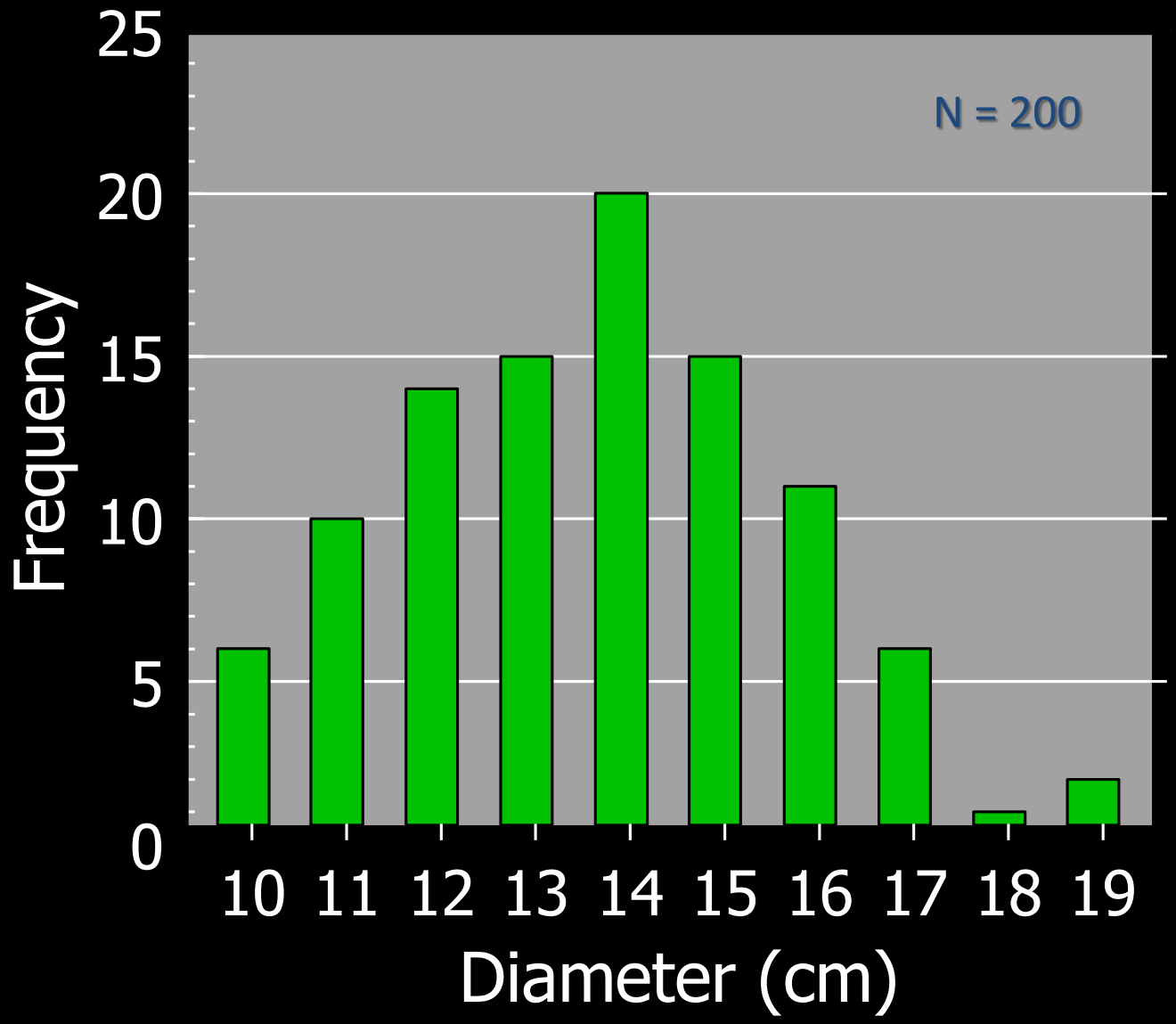


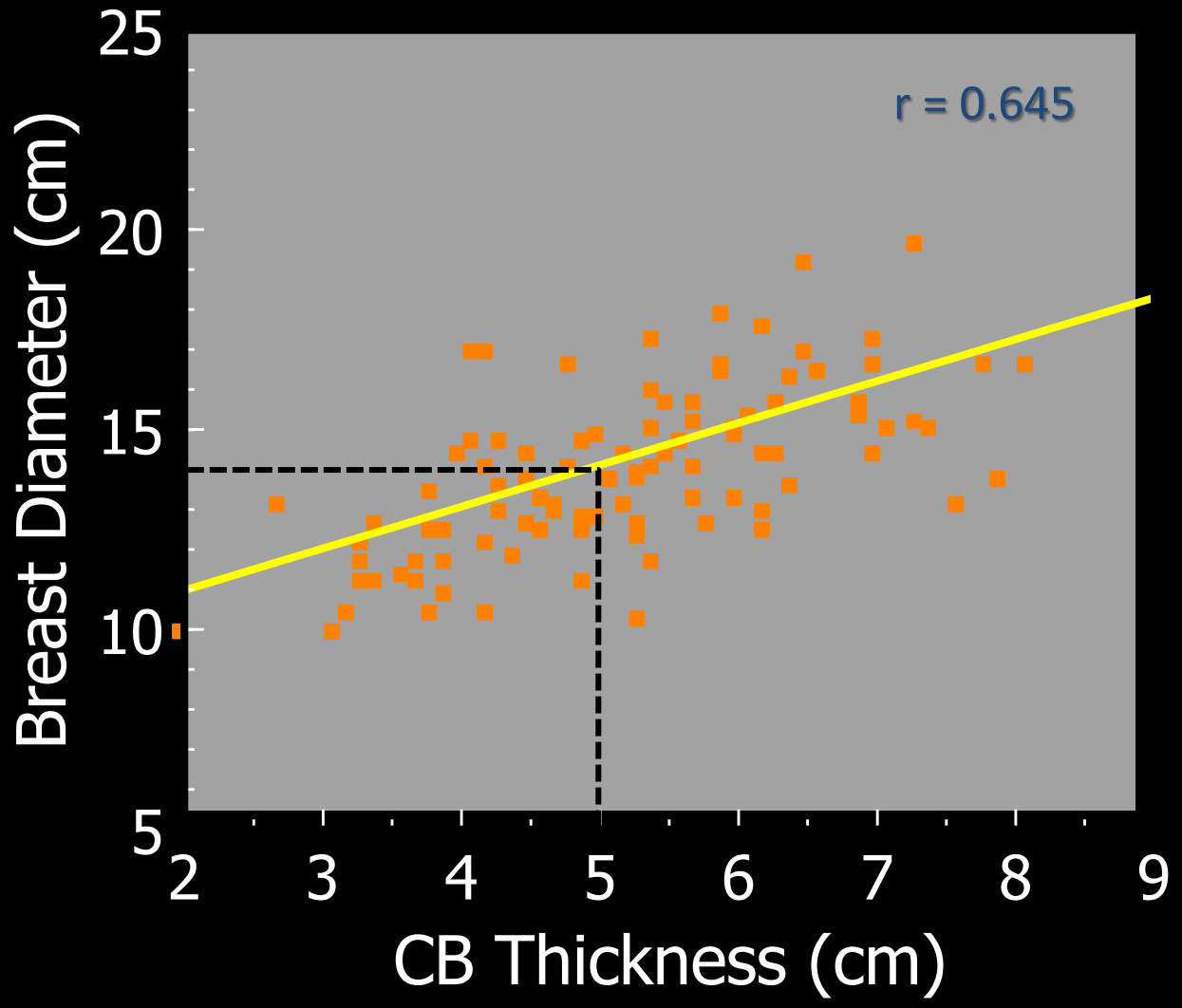
breast circumference → diameter





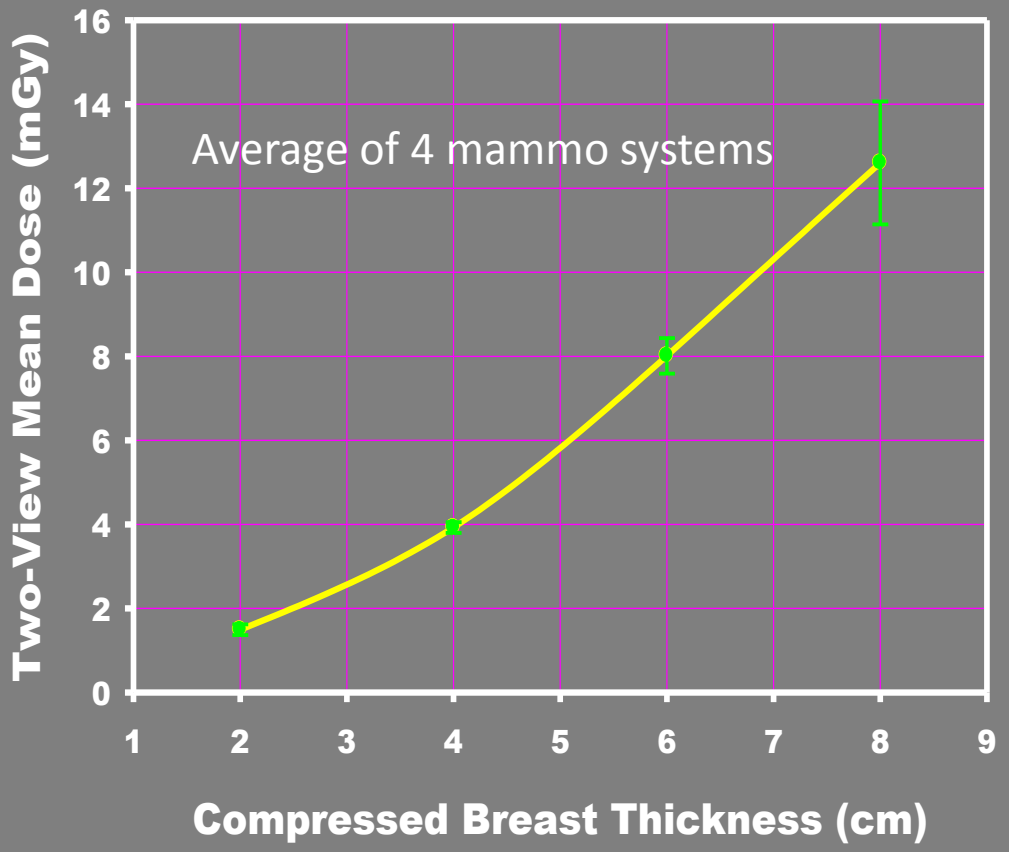
compressed breast thickness


N = 200
Frequency
25
20
15
10
5
0
10 11 12 13 14 15 16 17 18 19
Diameter (cm)

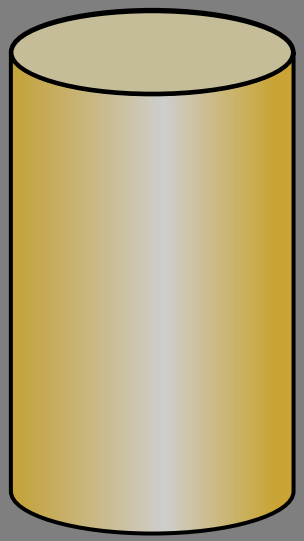

r = 0.645
Breast Diameter (cm)
25
20
15
10
5
2
3
4
5
6
7
8
9
CB Thickness (cm)

Mean Glandular Dose in Mammography

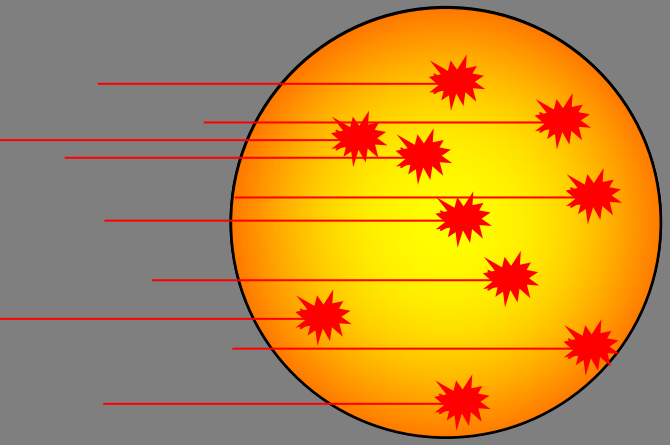
two-view mammography dose versus CB thickness

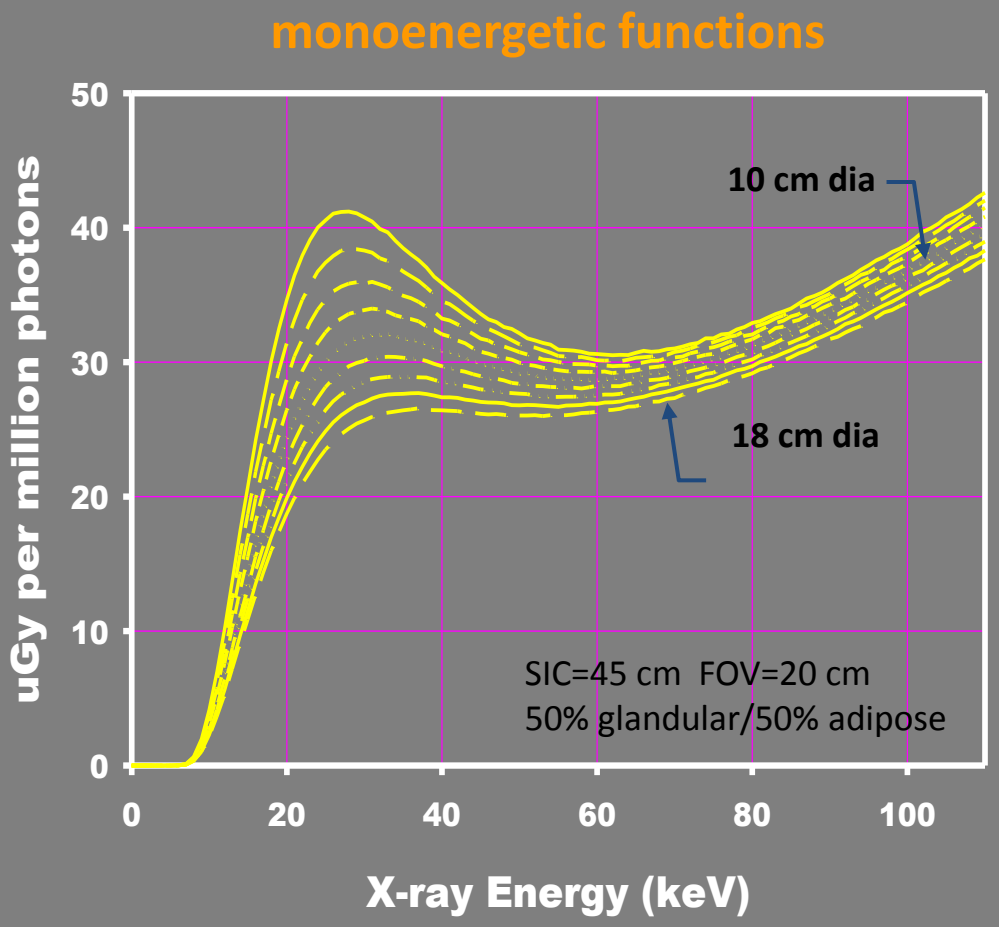


Monte Carlo Assessment of Dose Deposition



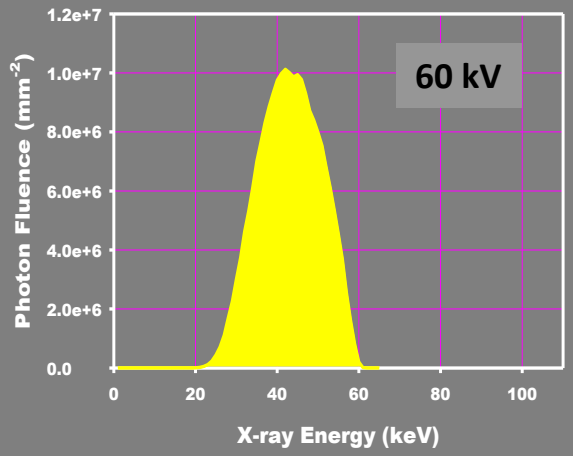
breast modeled as a cylinder

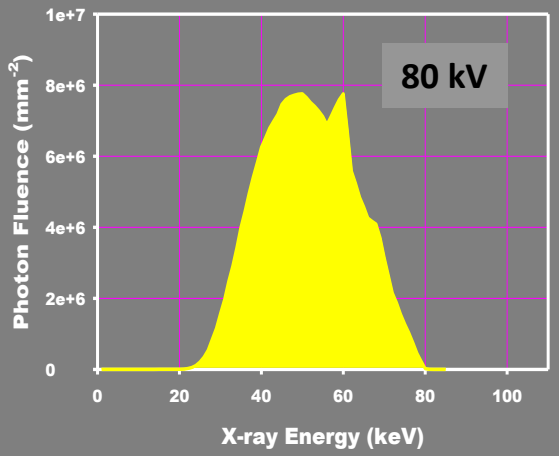


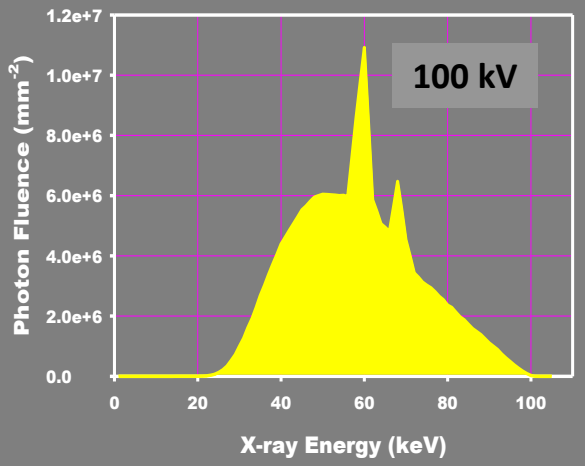


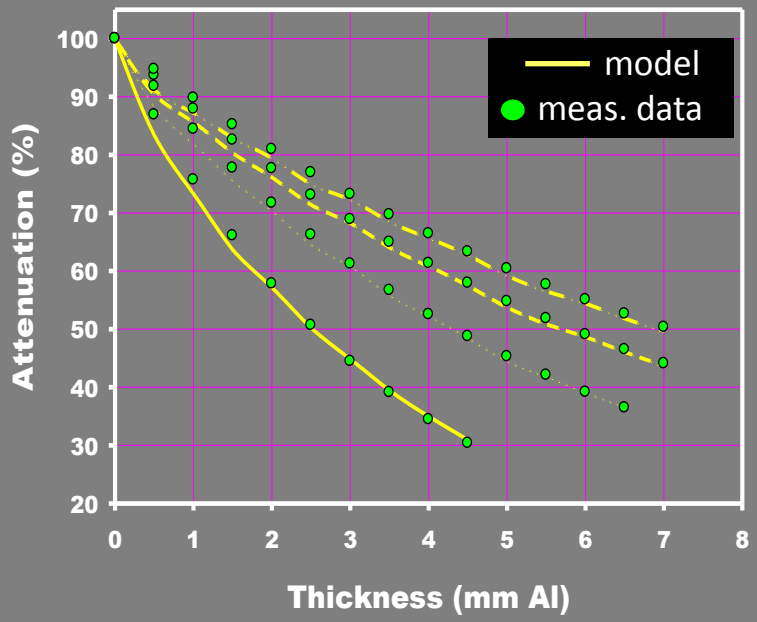
JM Boone, N. Shah, and T.R. Nelson, "A Comprehensive Analysis of DgN_{CT} Coefficients for Pendant-Geometry Cone-Beam Breast Computed Tomography", Medical Physics 31: 226-235 (2004)

X-ray spectral model for bCT beams



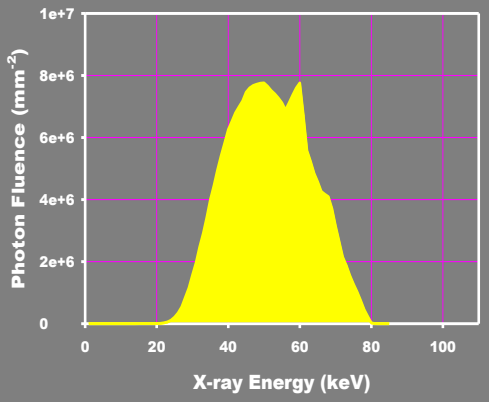


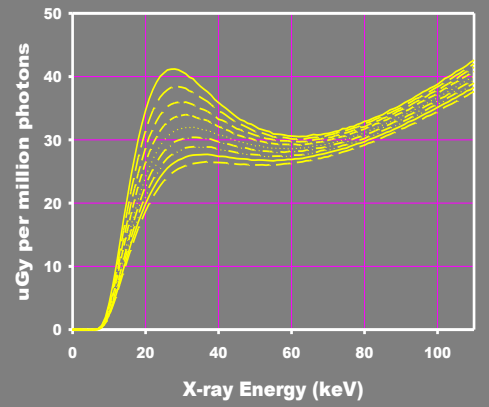


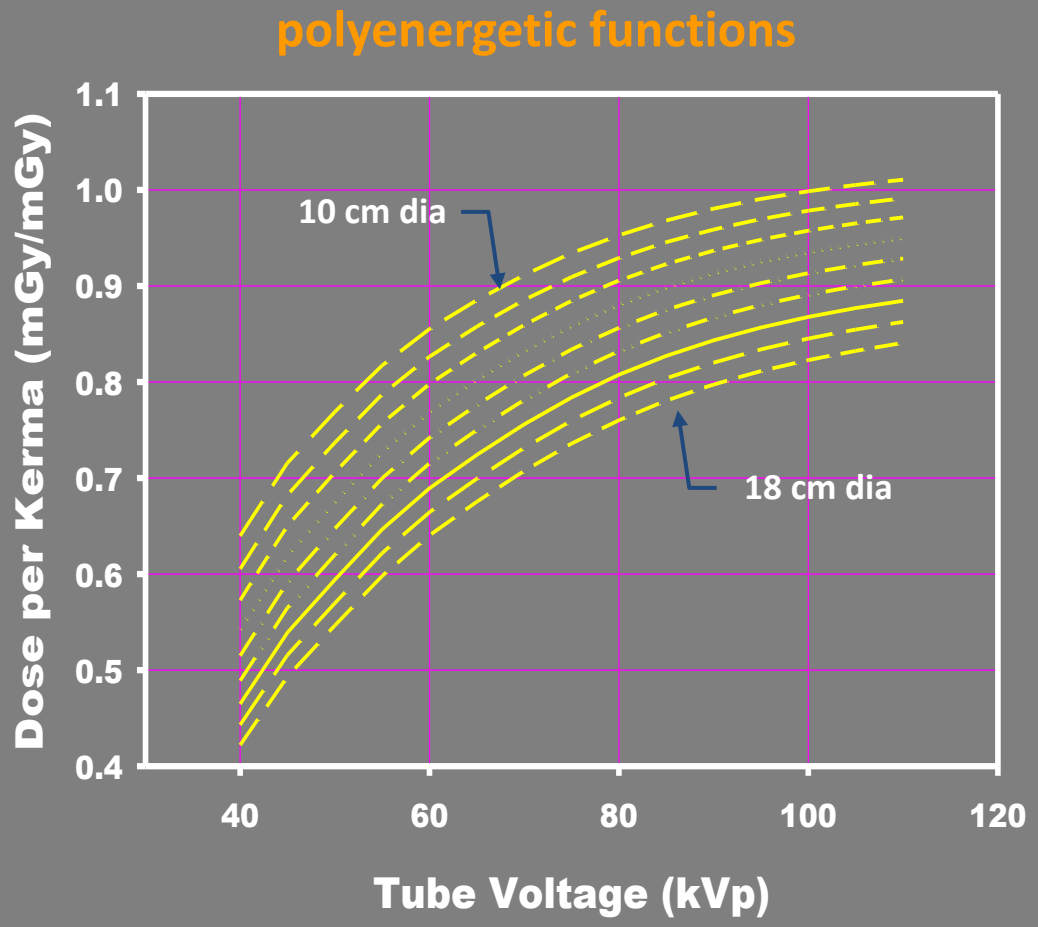


JM Boone and JA Seibert, *An accurate method for computer-generating tungsten anode x-ray spectra from 30 kV to 140 kV*, Medical Physics **24**;1661-670, 1997.

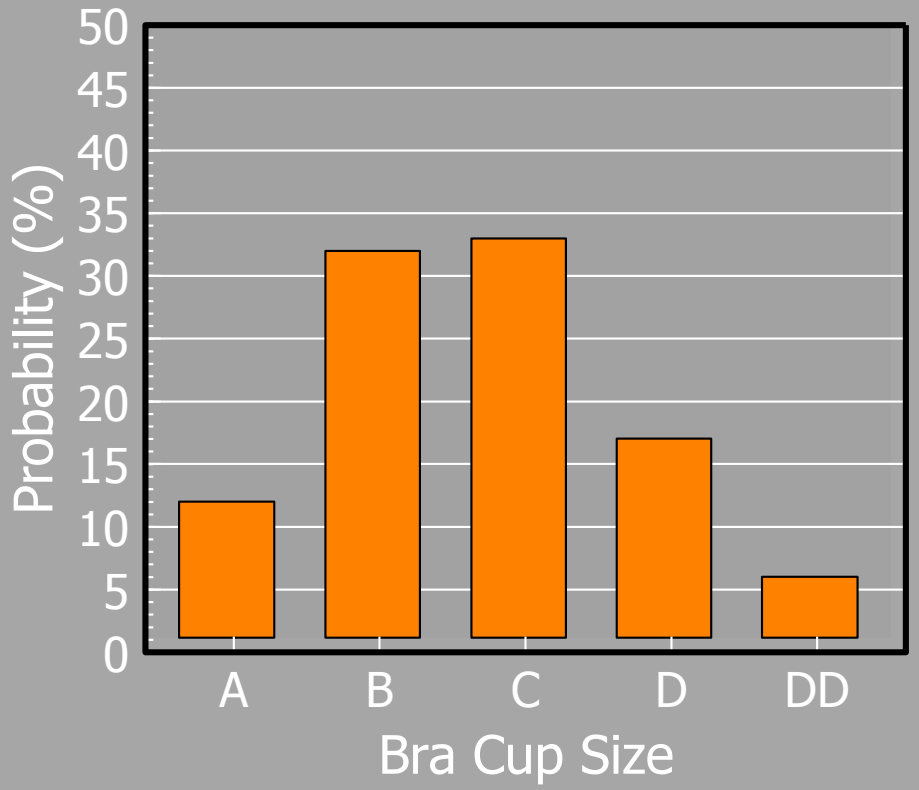
Converting m-DgN to p-DgN using spectral weighting

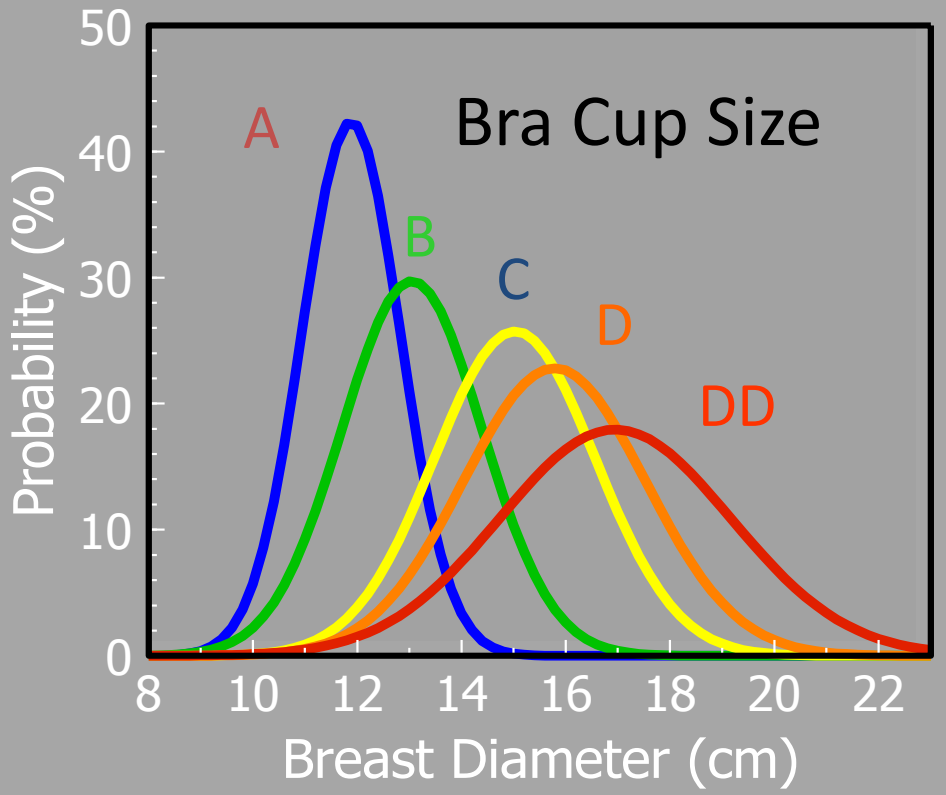


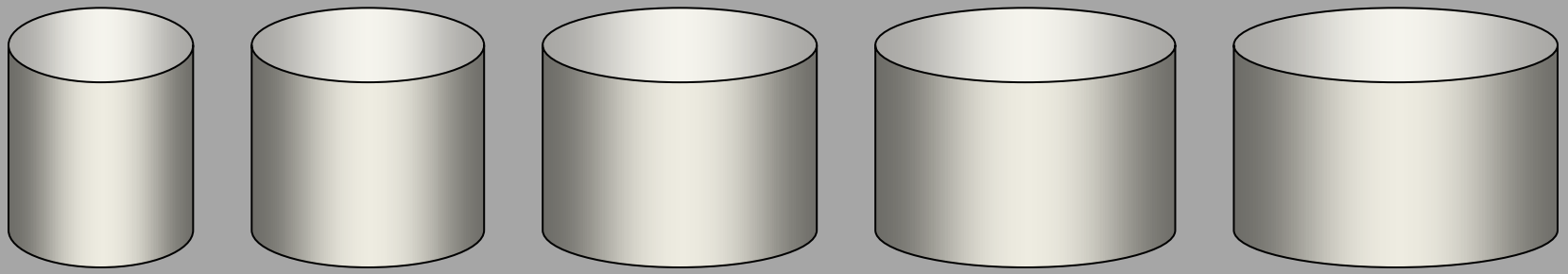




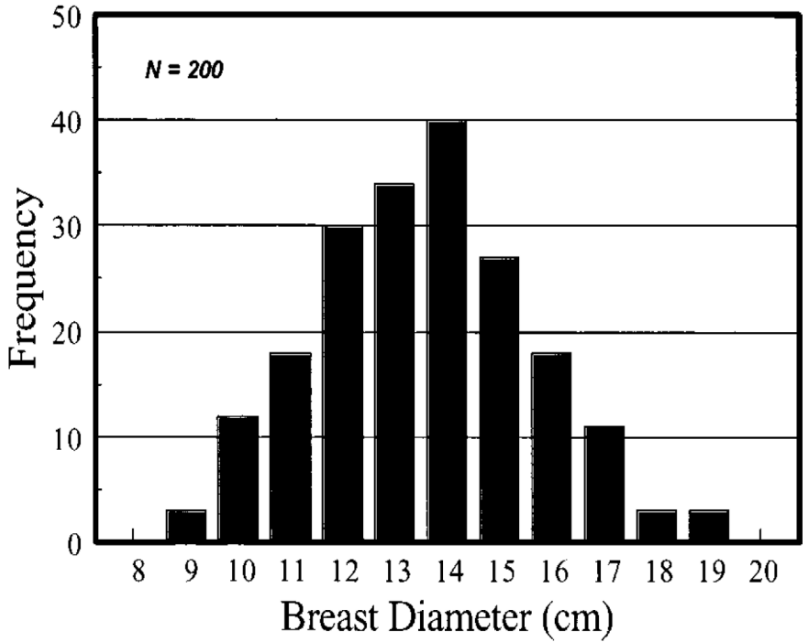
JM Boone, N. Shah, and T.R. Nelson, "A Comprehensive Analysis of DgN_{CT} Coefficients for Pendant-Geometry Cone-Beam Breast Computed Tomography", Medical Physics 31: 226-235 (2004)


Probability (%)
50
45
40
35
30
25
20
15
10
5
0
A
B
C
D
DD
Bra Cup Size

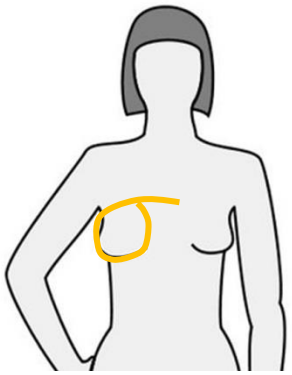

Probability (%)
50
40
30
20
10
0
Bra Cup Size
A
B
C
D
DD
8
10
12
14
16
18
20
22
Breast Diameter (cm)

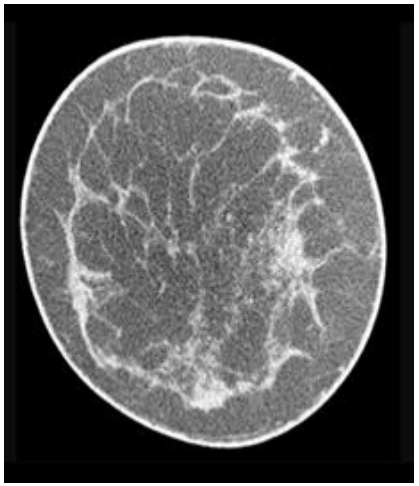


Comparison of breast dimensions



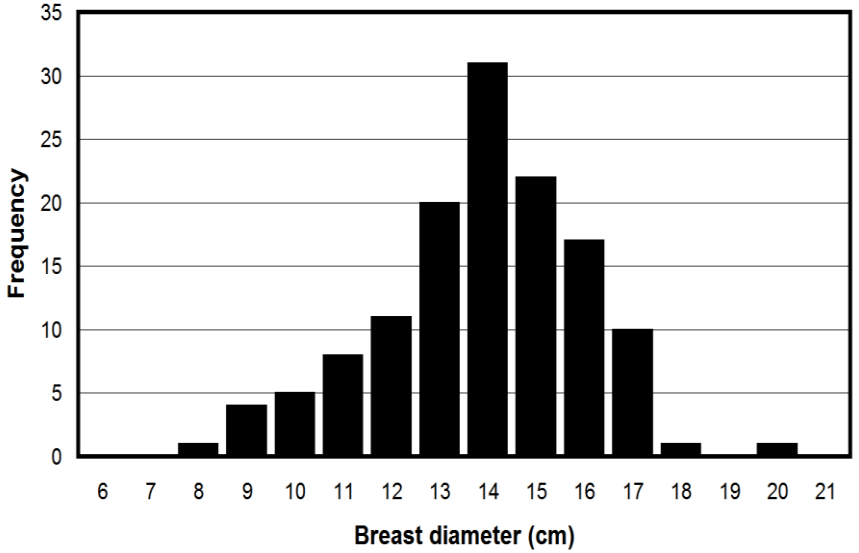
2001 tape measure results (N = 200)





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

2008 assessment on bCT images (N = 137)



Technique factors and their relationship to radiation dose in pendant geometry breast CT

John M. Boone,[a] Alexander L. C. Kwan, J. Anthony Seibert,
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Department of Radiology, University of California Davis Medical Center, Sacramento, California

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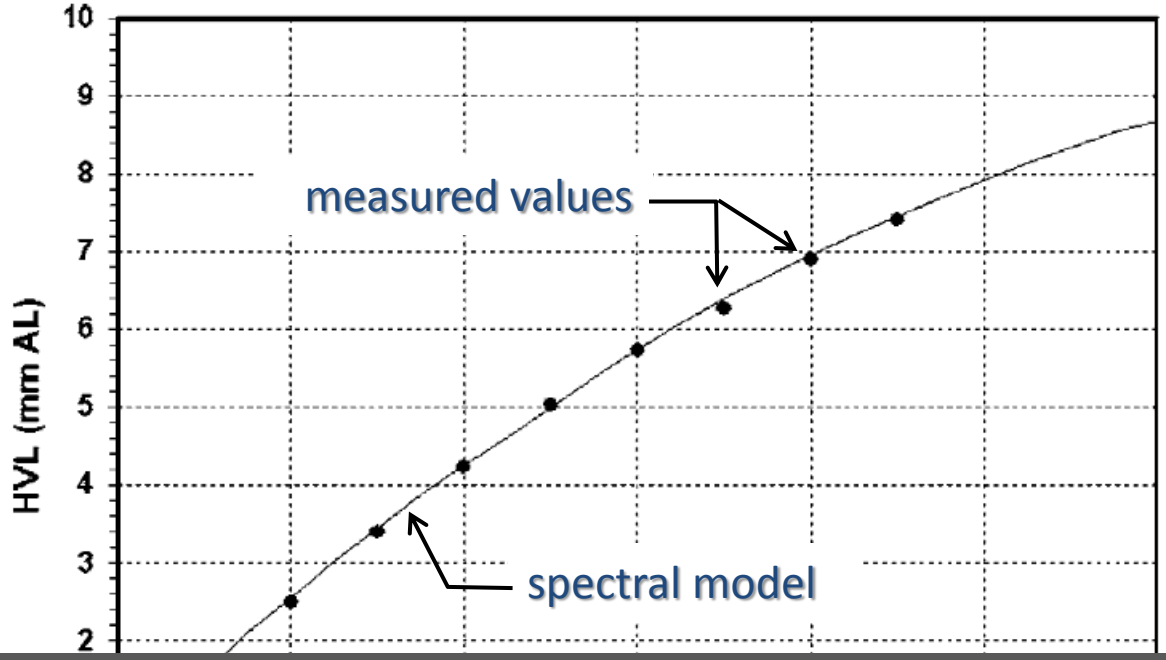
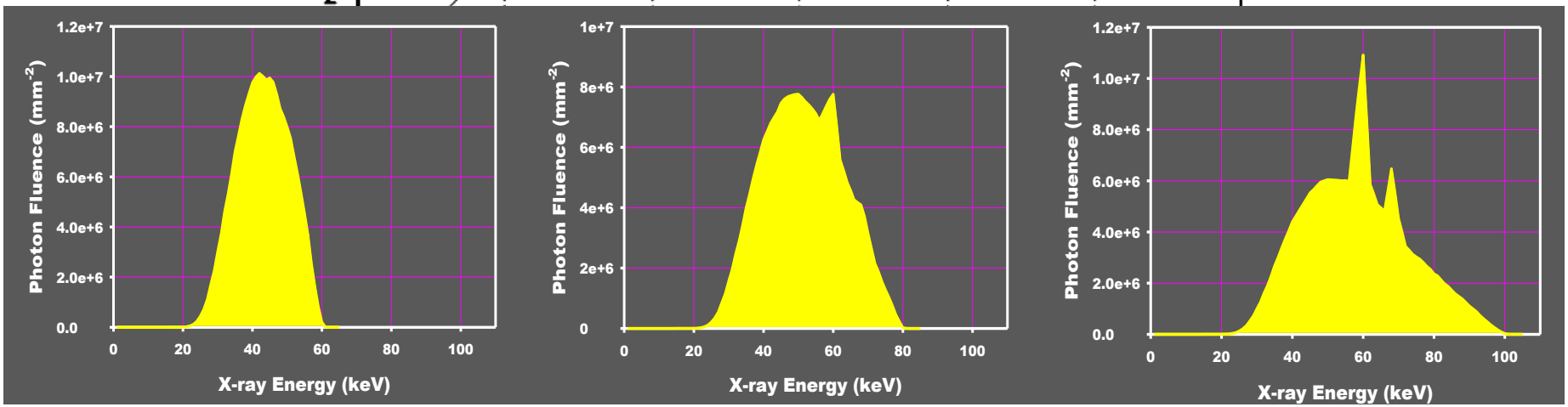
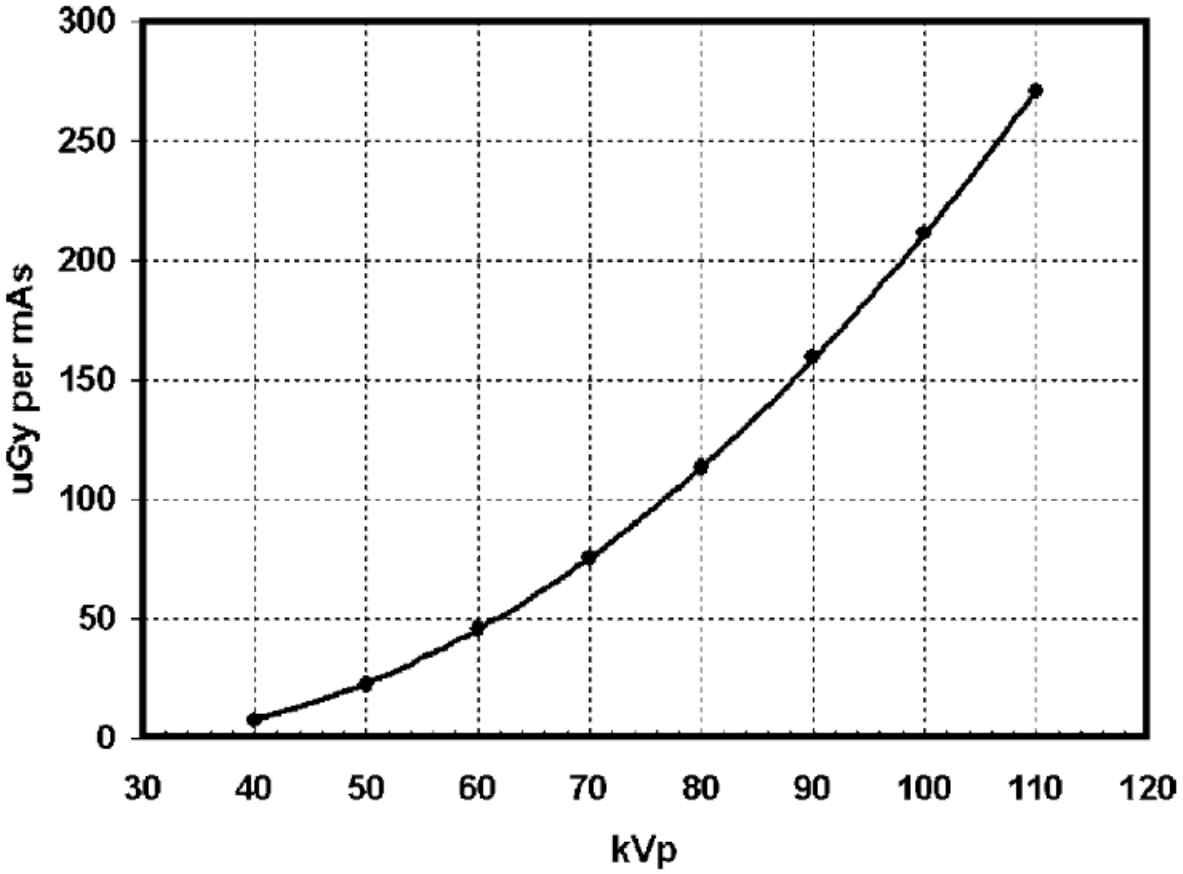
(Received 11 July 2005; revised 13 September 2005; accepted for publication 3 October 2005; published 22 November 2005)

actual and modeled x-ray spectra were “tuned”



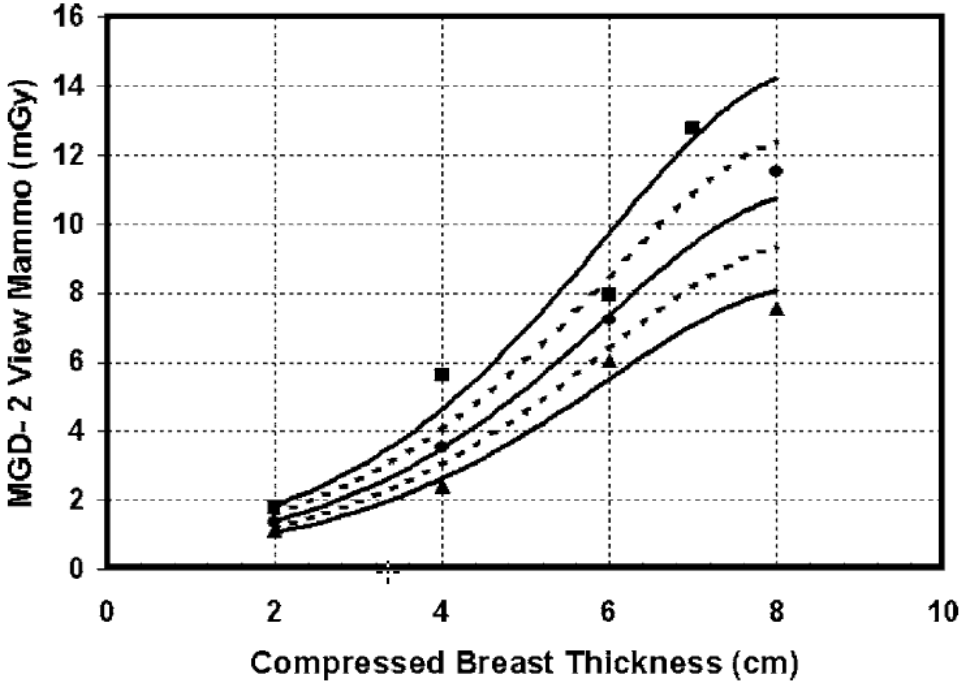


X-ray system output carefully measured

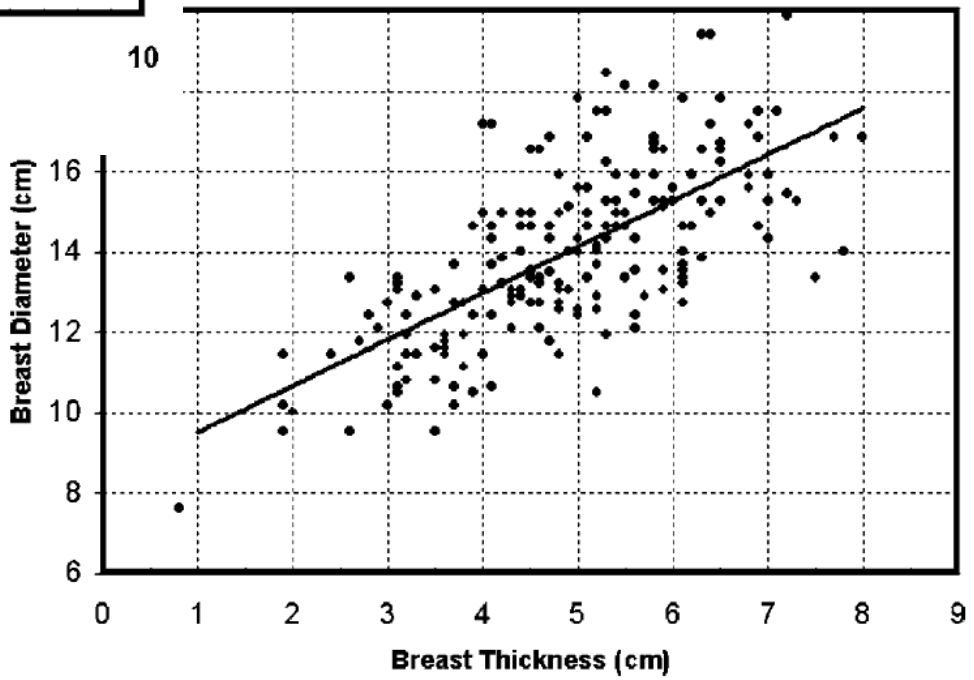


	K @ iso	mR/mAs	HVL	E_{ave} (ent)	E_{ave} (exit)	BH factor	Trans (%) [14]	Φ/mGy
kVp	A	B	C	D	E	F	G	H
30	0.08	0.09	1.57	26.9	28.1	5.6	0.91	1.1074e+007
35	0.35	0.40	2.10	30.2	31.4	4.2	1.61	1.3927e+007
40	0.81	0.93	2.55	32.9	34.4	3.8	2.21	1.6310e+007
45	1.46	1.67	3.03	35.8	37.6	3.5	2.81	1.8772e+007
50	2.30	2.63	3.44	38.2	40.2	3.3	3.28	2.0741e+007
55	3.32	3.81	3.88	40.8	43.1	3.0	3.73	2.2675e+007
60	4.54	5.20	4.26	43.0	45.6	3.0	4.10	2.4225e+007
65	5.95	6.81	4.63	45.2	48.0	2.7	4.42	2.5541e+007
70	7.54	8.64	5.01	47.4	50.4	2.9	4.73	2.6711e+007
75	9.33	10.68	5.38	49.5	52.8	2.7	5.01	2.7711e+007
80	11.31	12.94	5.74	51.5	55.0	2.8	5.25	2.8512e+007
85	13.47	15.42	6.07	53.3	57.0	2.5	5.47	2.9144e+007
90	15.83	18.12	6.39	55.0	58.9	2.3	5.66	2.9622e+007
95	18.37	21.03	6.68	56.5	60.6	2.5	5.83	2.9974e+007
100	21.10	24.16	6.95	58.0	62.3	2.5	5.98	3.0222e+007
105	24.03	27.51	7.21	59.3	63.9	2.5	6.12	3.0382e+007
110	27.14	31.08	7.46	60.7	65.4	2.4	6.25	3.0473e+007
115	30.44	34.86	7.70	62.0	67.0	2.4	6.37	3.0507e+007
120	33.94	38.86	7.92	63.2	68.5	2.4	6.48	3.0496e+007

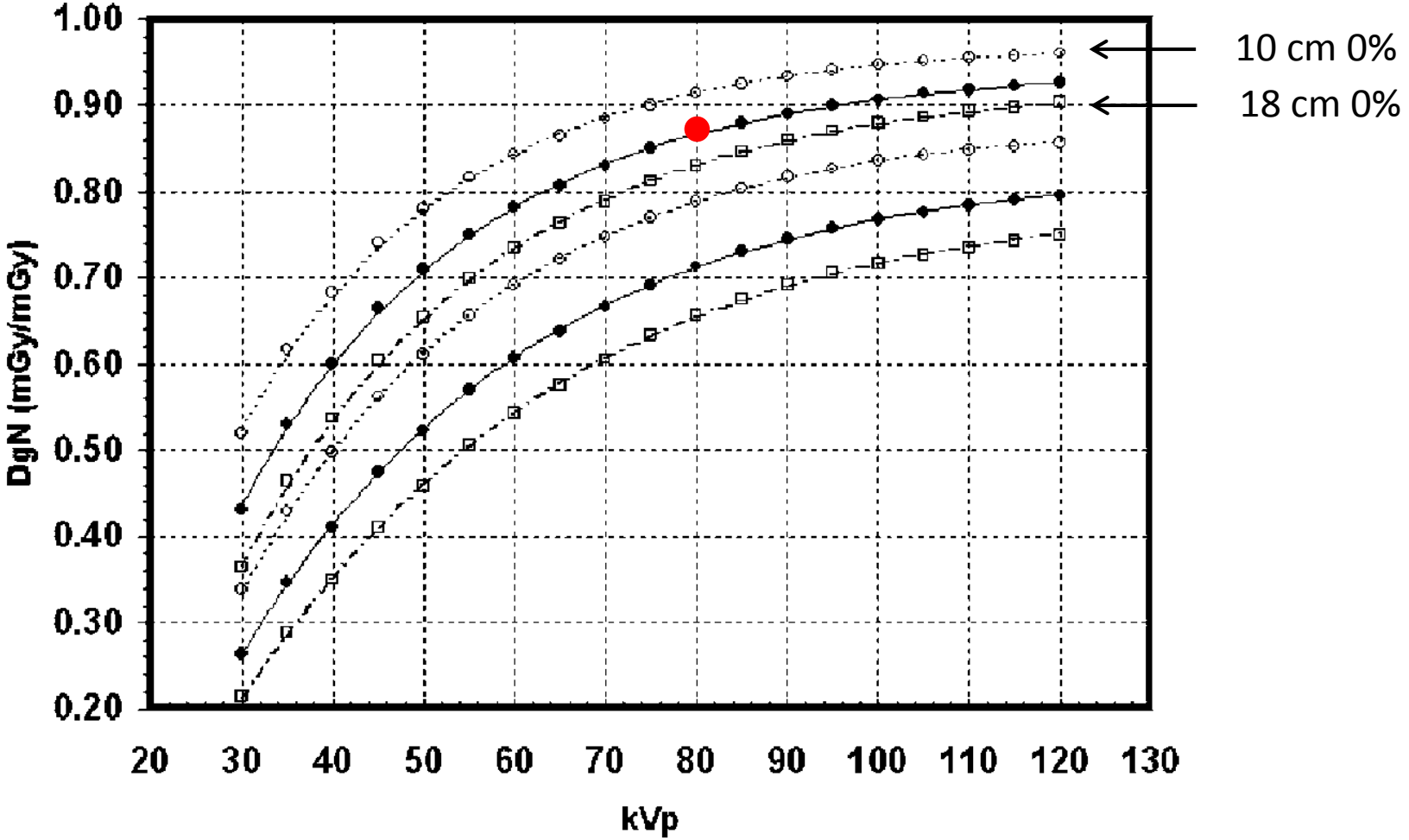
MGD(t) in two-view mammography



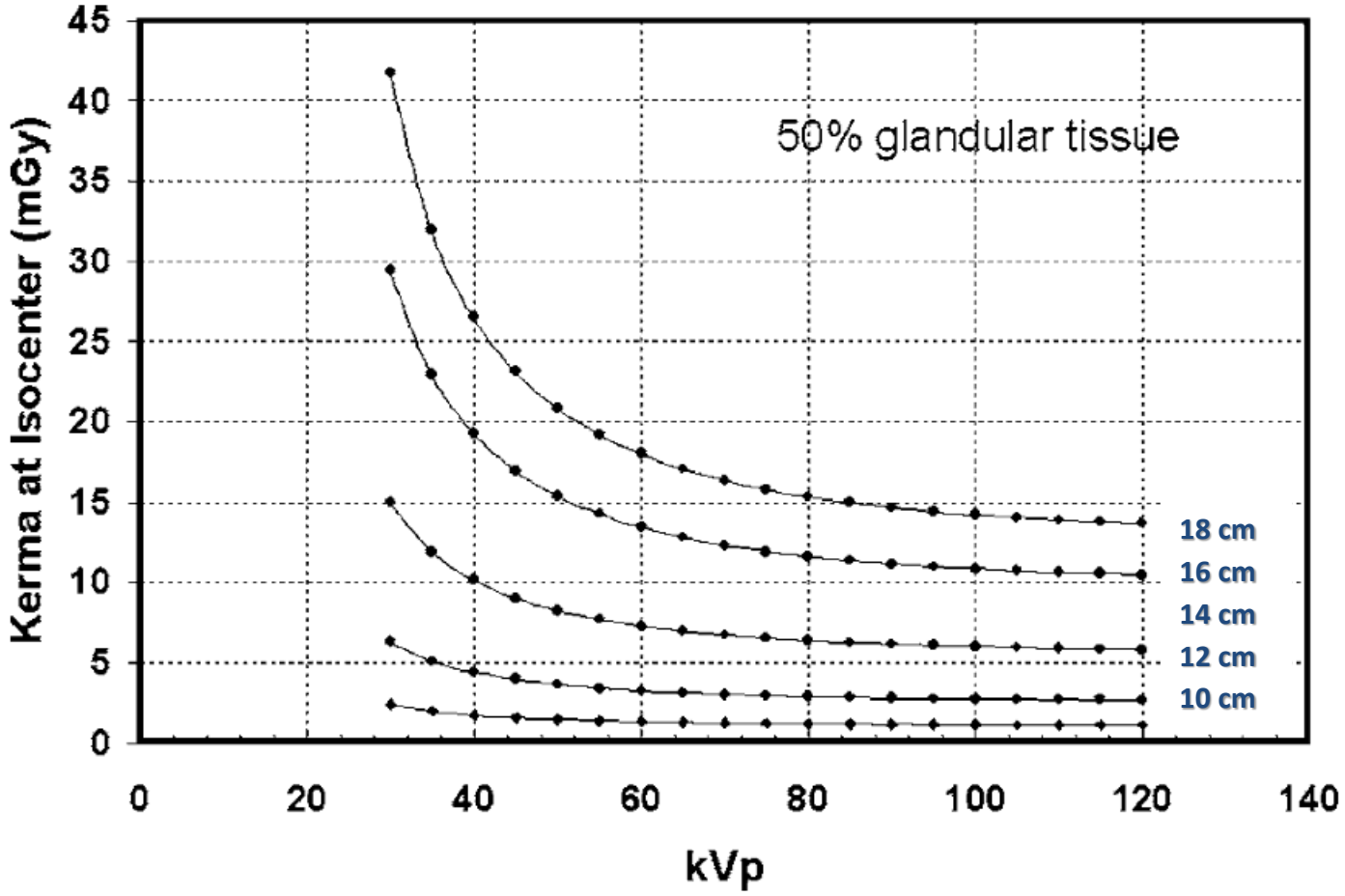
Relationship between bCT(D) and mammo(T)



MGD (mGy) as a function of air kerma at isocenter (mGy)



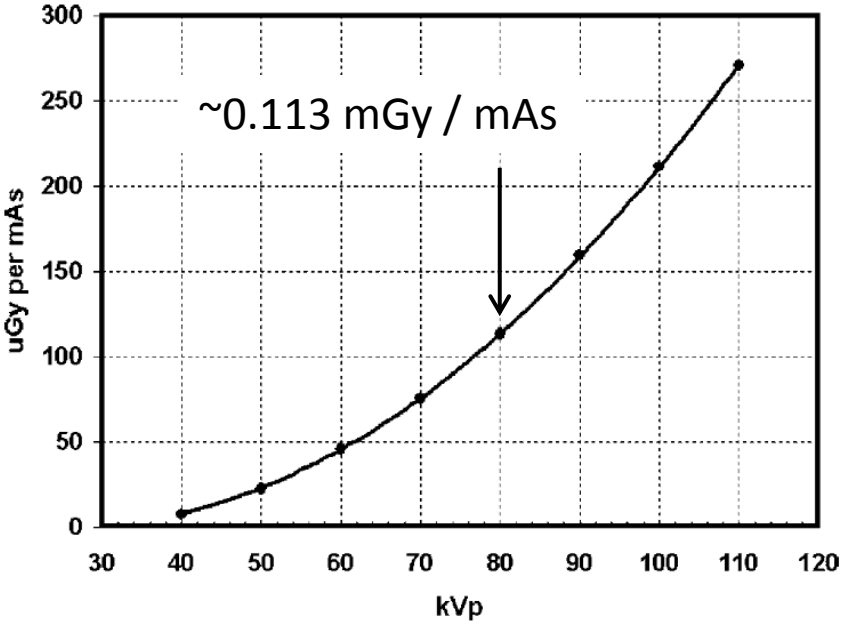
Kerma @ isocenter to yield same dose as 2V mammography



Kerma @ isocenter to yield same dose as 2V mammography

TABLE II. Air Kerma for 0% glandular/100% adipose breast composition. Air Kerma (mGy) values, calculated at the isocenter of the breast CT scanner, which deliver mean glandular doses equal to two-view mammography, for different kVp and breast diameters.

kVp	10 cm	11 cm	12 cm	13 cm	14 cm	15 cm	16 cm	17 cm	18 cm
30	1.502	2.417	3.841	5.976	9.000	12.934	17.438	21.681	24.513
35	1.292	2.057	3.234	4.978	7.418	10.546	14.069	17.307	19.363
40	1.161	1.836	2.867	4.382	6.483	9.154	12.127	14.818	16.467
45	1.073	1.689	2.625	3.992	5.876	8.256	10.884	13.235	14.638
50	1.012	1.587	2.456	3.721	5.457	7.638	10.033	12.155	13.396
55	0.967	1.512	2.334	3.526	5.155	7.194	9.421	11.381	12.508
60	0.933	1.457	2.243	3.380	4.930	6.864	8.968	10.808	11.851
				269	4.759	6.612	8.622	10.372	11.351
				183	4.626	6.417	8.354	10.033	10.963
				115	4.522	6.264	8.143	9.766	10.657
				062	4.439	6.141	7.975	9.553	10.413
				019	4.372	6.043	7.839	9.382	10.216
				984	4.318	5.963	7.730	9.243	10.057
				956	4.274	5.899	7.640	9.130	9.927
				933	4.239	5.846	7.568	9.038	9.821
				914	4.210	5.803	7.509	8.963	9.735
				899	4.186	5.769	7.461	8.902	9.665
				887	4.167	5.741	7.422	8.853	9.609
				877	4.152	5.718	7.391	8.815	9.565

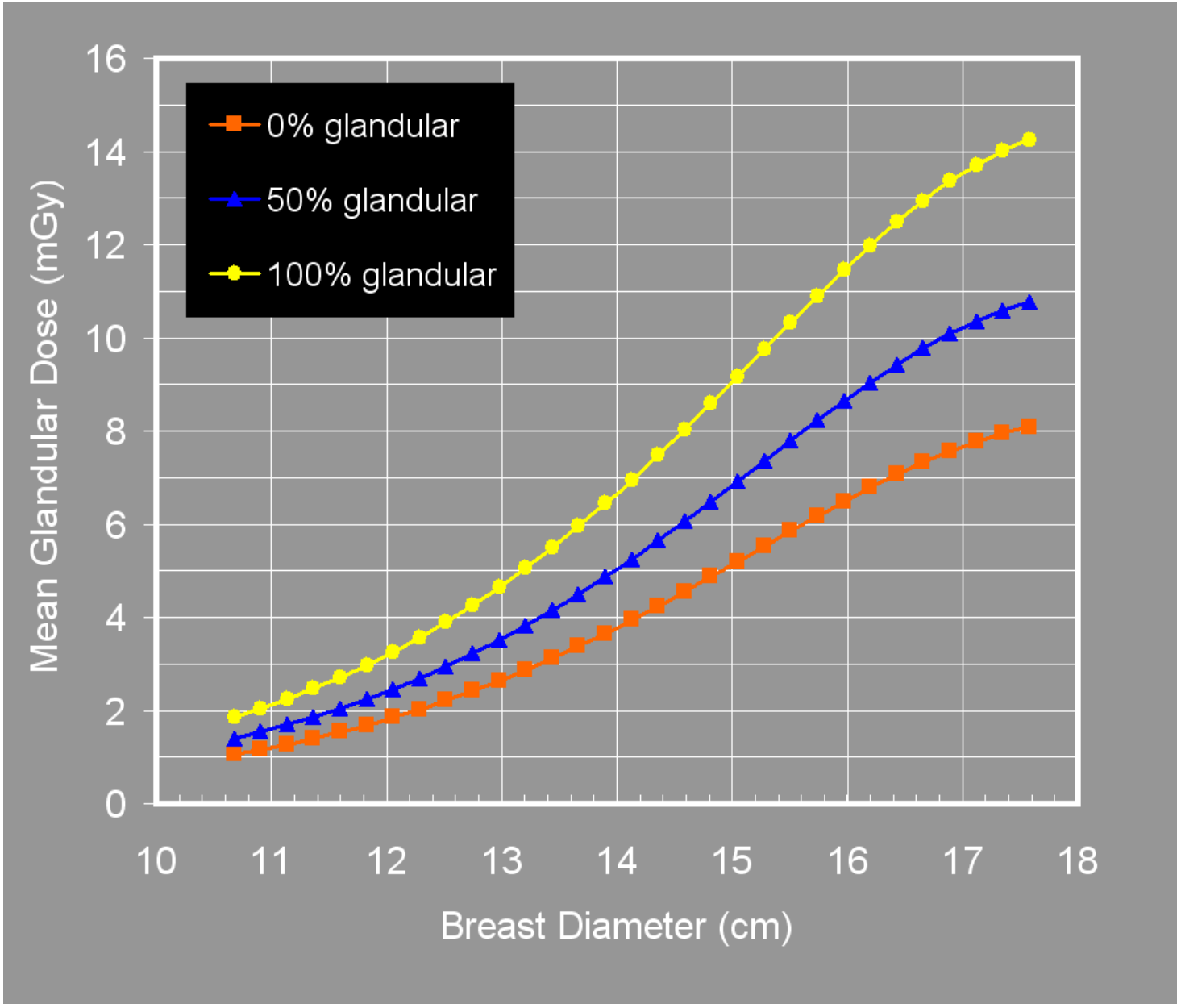


4.439 / 0.113 = 39.3 mAs

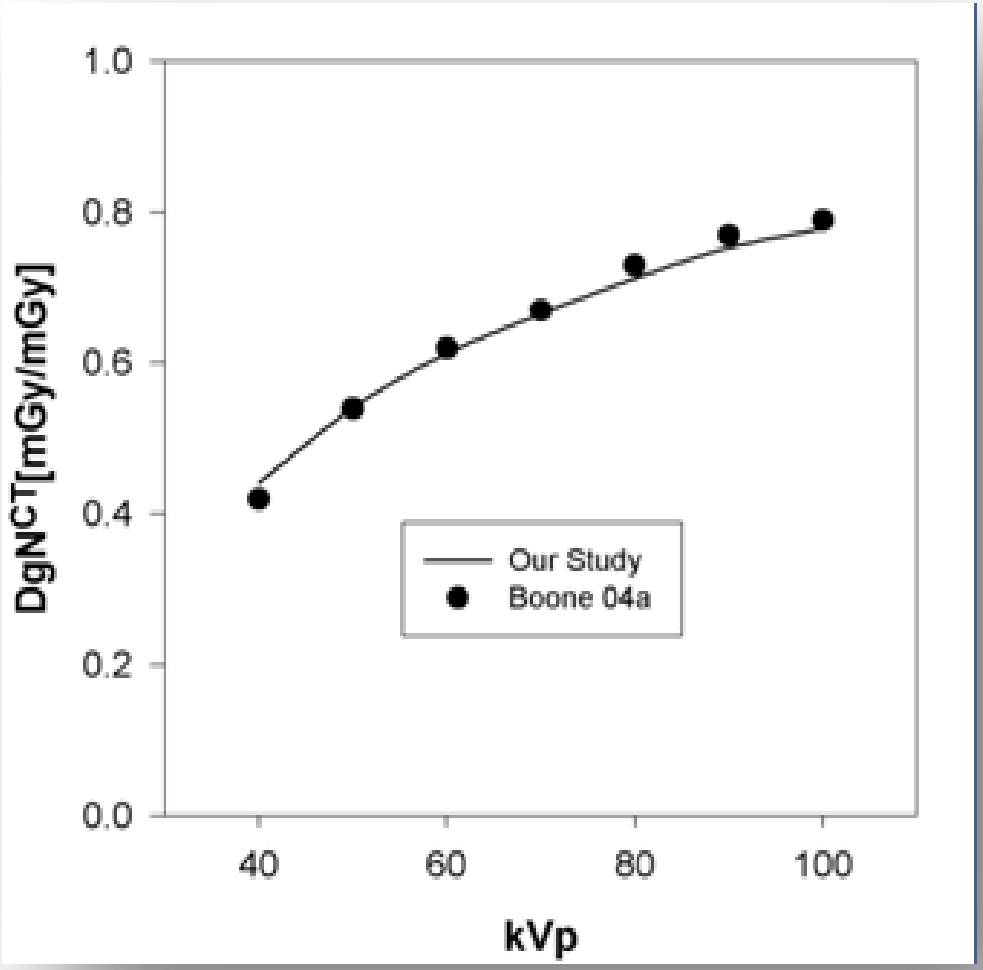
mAs (on our scanner) to yield same dose as 2V mammography

TABLE V. mAs for 0% glandular/100% adipose breast composition. The mAs values for the entire breast CT scan that delivers the same dose as two-view mammography are given in the table. To determine mA, divide the mAs values given below by the total time of the active scan (in seconds).

kVp	10 cm	11 cm	12 cm	13 cm	14 cm	15 cm	16 cm	17 cm	18 cm
30	1867.6	3005.0	4774.9	7428.5	*.*	*.*	*.*	*.*	*.*
35	369.1	587.9	924.3	1422.8	2120.0	3014.2	4021.0	4946.6	5534.0
40	143.5	227.0	354.4	541.7	801.5	1131.7	1499.3	1831.9	2035.8
45	73.6	115.9	180.1	273.9	403.2	566.5	746.8	908.1	1004.4
50	44.1	69.1	107.0	162.1	237.7	332.7	437.0	529.5	583.5
55	29.1	45.5	70.2	106.1	155.1	216.5	283.5	342.5	376.4
60	20.6	32.1	49.4	74.4	108.6	151.2	197.5	238.0	261.0
65	15.3	23.8	36.5	55.0	80.0	111.2	145.0	174.4	190.8
70	11.8	18.3	28.1	42.2	61.3	85.1	110.7	133.0	145.3
75	9.4	14.5	22.3	33.4	48.5	67.1	87.3	104.7	114.2
80	7.6	11.8	18.1	27.1	39.3	54.3	70.5	84.5	92.1
85	6.3	9.8	15.0	22.4	32.5	44.9	58.2	69.6	75.8
90	5.3	8.3	12.6	18.9	27.3	37.7	48.8	58.4	63.5
95	4.6	7.1	10.8	16.1	23.3	32.1	41.6	49.7	54.0
100	3.9	6.1	9.3	13.9	20.1	27.7	35.9	42.8	46.5
105	3.4	5.3	8.1	12.1	17.5	24.2	31.3	37.3	40.5
110	3.0	4.7	7.2	10.7	15.4	21.3	27.5	32.8	35.6
115	2.7	4.2	6.4	9.5	13.7	18.9	24.4	29.1	31.6
120	2.4	3.7	5.7	8.5	12.2	16.9	21.8	26.0	28.2

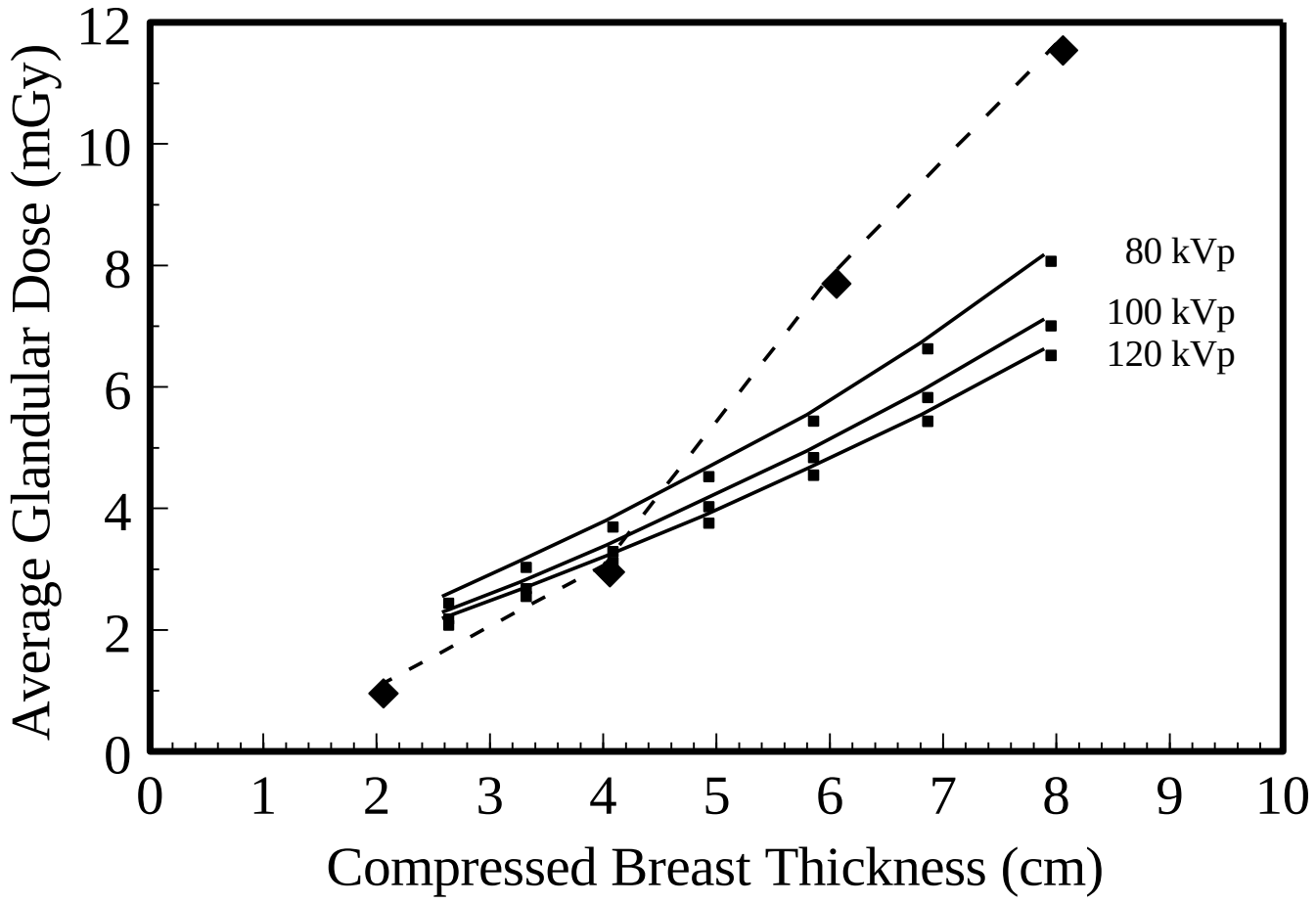

0% glandular
50% glandular
100% glandular
Mean Glandular Dose (mGy)
0
2
4
6
8
10
12
14
16
10
11
12
13
14
15
16
17
18
Breast Diameter (cm)

Dose assessment repeated by Thacker/Glick

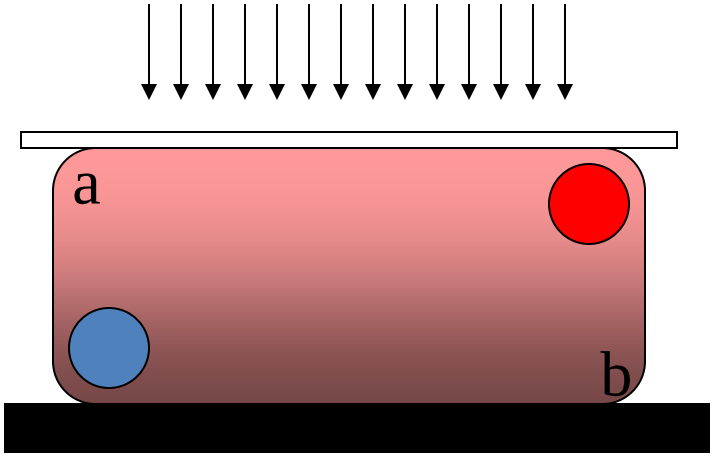


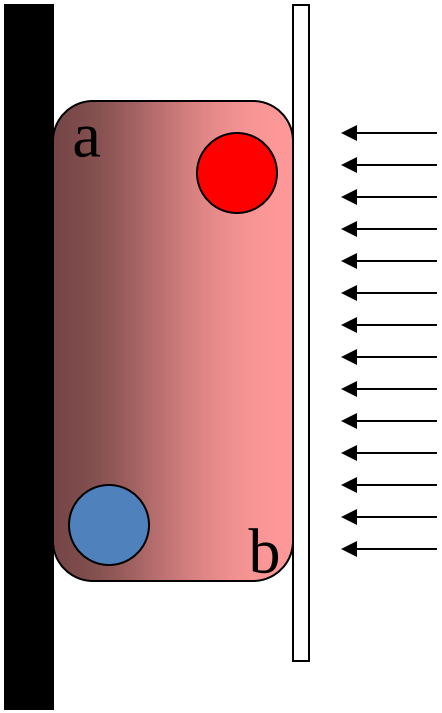
Thacker S and Glick S, PMB 2004, 5433

Other Considerations


Average Glandular Dose (mGy)
0
2
4
6
8
10
12
0
1
2
3
4
5
6
7
8
9
10
Compressed Breast Thickness (cm)
80 kVp
100 kVp
120 kVp

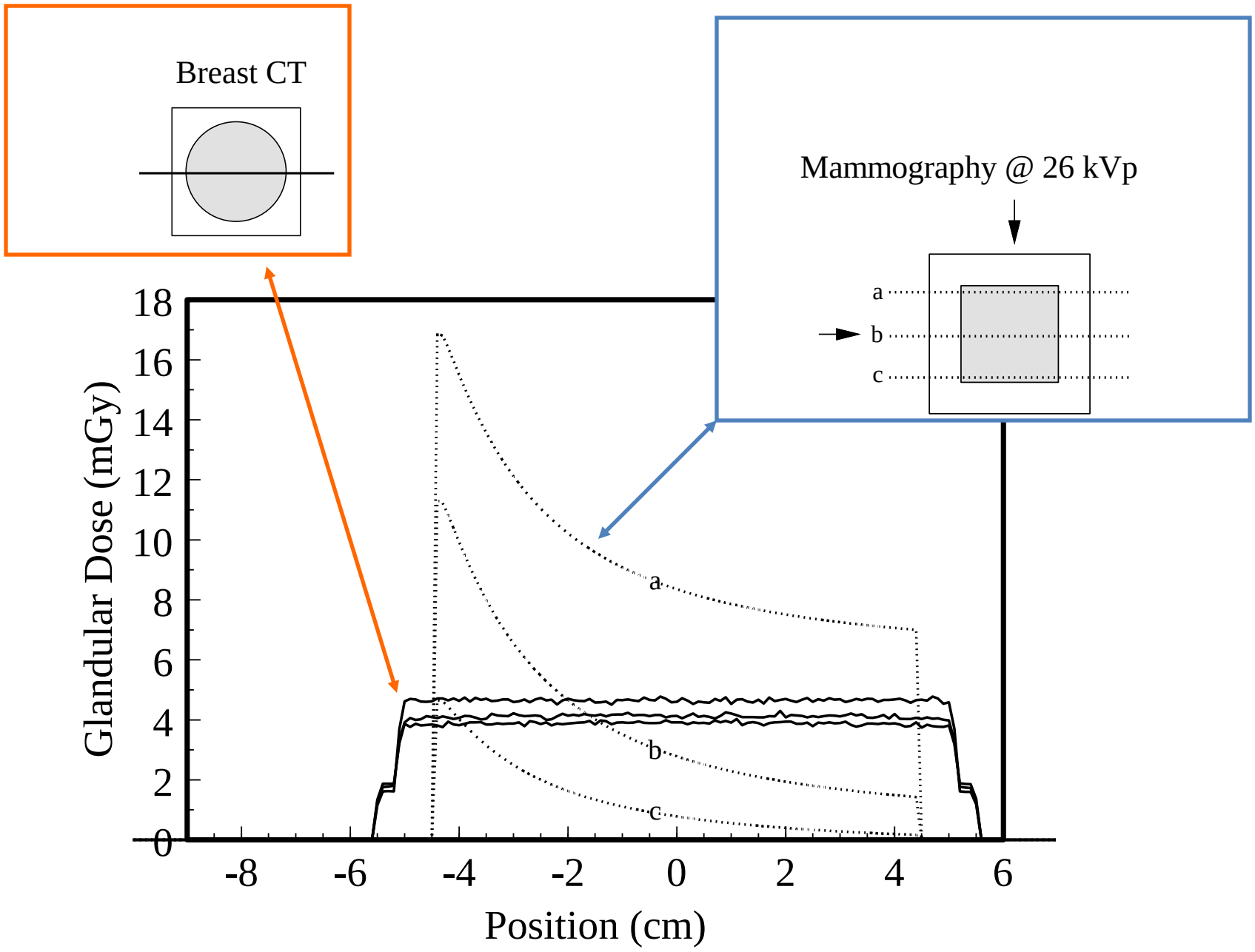
Mammography





= high dose area

= low dose area


Breast CT
Mammography @ 26 kVp
a
b
c
Glandular Dose (mGy)
Position (cm)
18
16
14
12
10
8
6
4
2
0
-8
-6
-4
-2
0
2
4
6

Other Considerations (2)

- DgN's used in mammography probably underestimate dose:
- Skin Thickness Issue
  Glandular Density Spectrum
- Quality factor for E < 25 keV ➞ 1.3

Breast CT and Dosimetry

- Breast CT Background
- Technical Development
- Initial Clinical Results
- Dose Issues in Breast CT
- Summary

Breast CT and Dosimetry: Summary

- Breast CT has strong clinical potential
- MGD levels are comparable to mammography
- MC Methods ➡ modern x-ray dosimetry
- When dosimetry methods are not available, you have to develop them yourself!

Breast Tomography Project

University of California Davis

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