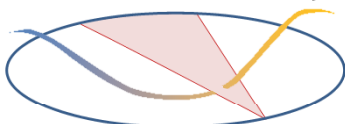


Evolution of the UC Davis Breast CT Scanner

Breast Tomography Project



University of California Davis



John M. Boone, Ph.D., FAAPM, FSBI, FACR
Professor and Vice Chair (for Research) of Radiology
Professor of Biomedical Engineering
University of California Davis
Sacramento, California 95817

IEEE Signal Processing Society, September 10, 2014

Corporate Disclosures (required by UC Davis):

CT Imaging, **Consultant**

Varian Imaging Systems, **Consultant**

Fuji Medical Systems, **Research Funding**

Hologic Corporation, **Research Funding**

Siemens Medical Systems, **Research Funding**

Varian Imaging Systems, **Research Funding**

Stanford Research Institute, **NIH Research Funding (R21 subcontract)**

Creativ Microtech, **NIH Research Funding (R21 subcontract)**

Acknowledgements:

California BCRP 7EB-0075

California BCRP 11I-0114

R01 CA•89260

R01 EB•002138-10 (BRP)

R01 CA•129561 (RDB)

P30 CA•093373 (CCSG)

Susan G. Komen Foundation

University of Pittsburgh



Evolution of the UC Davis Breast CT Scanner

- Introduction to Breast Cancer Screening
- Breast CT Hardware (evolution)
- **Breast CT Software**
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Cancer Screening

Cancer screening aims to detect cancer before symptoms appear.

Lung Cancer — smokers — Low Dose CT

Breast Cancer — women — Mammogram

Prostate Cancer — men — PSA (blood test)

Colon Cancer — people > 50 — Colonoscopy

Breast Cancer Statistics (2006)

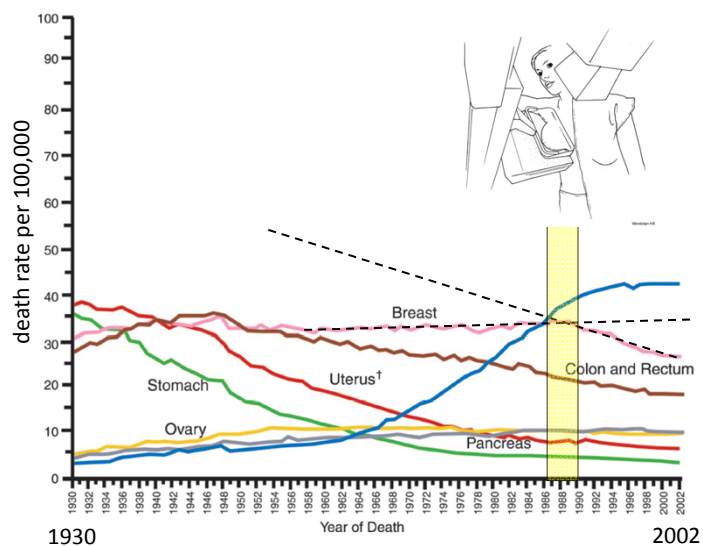
212,290 new cases

40,970 deaths

1 / 8 women will get breast cancer (12.5%)

Ravdin, *et al.*, NEJM

Cancer Incidence and Screening



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

Mammography: Standard of Care

The diagram illustrates the standard of care for mammography. On the left, a human figure has a blue circle highlighting the breast area. Two diagrams show the imaging techniques: **CC** (Cranio-Caudal) and **MLO** (Mediolateral Oblique). The CC diagram shows a breast with a blue horizontal line below it and four red vertical arrows pointing downwards. The MLO diagram shows a breast with a blue vertical line to its left and four red horizontal arrows pointing to the left. On the right, two mammography images are shown: a CC image and an MLO image, both labeled with their respective abbreviations below them.

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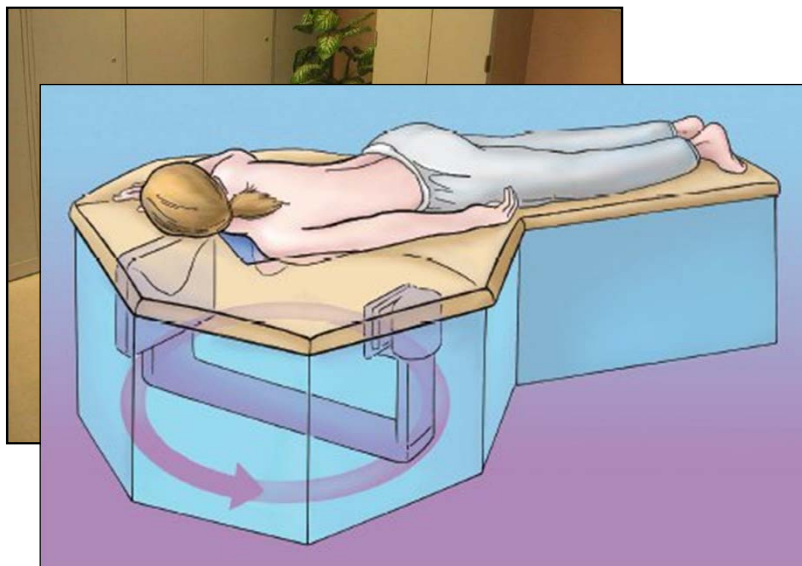
Breast CT

Mammography

This slide compares Breast CT and Mammography. On the left, under **Breast CT**, a 3D perspective view of a breast is shown above a stack of multiple thin, blue, semi-transparent slices representing CT scans. A red dashed line connects a small blue cube on one slice to a red dot on a mammography image. On the right, under **Mammography**, a diagram shows a breast being compressed between a **compression paddle** (top) and a **detector** (bottom), with a red arrow indicating the direction of compression. Below this is a mammography image with a red dot. A vertical blue bar is positioned between the two images, with a red dashed line connecting the red dot in the Breast CT image to the red dot in the Mammography image.

10

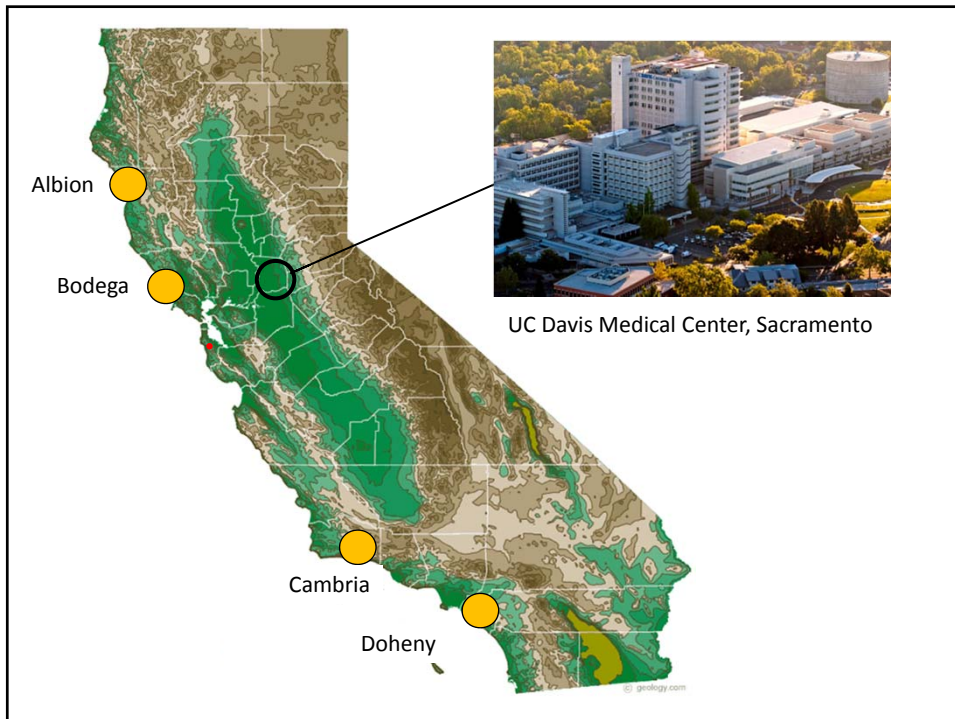
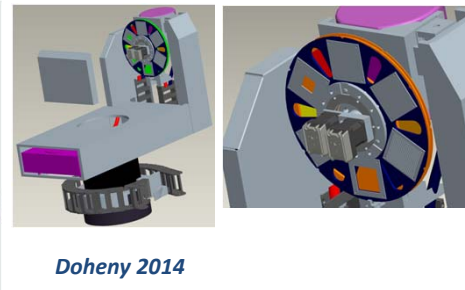
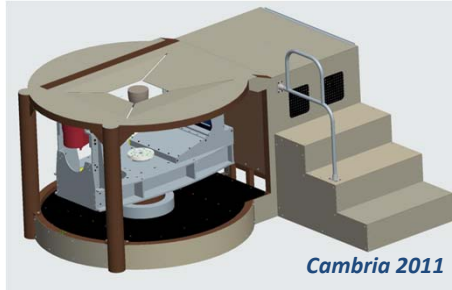
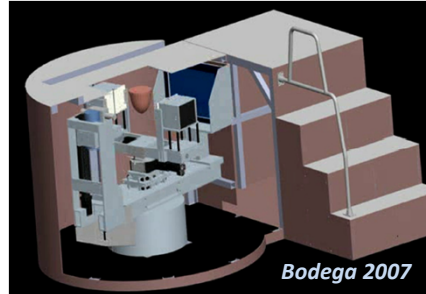
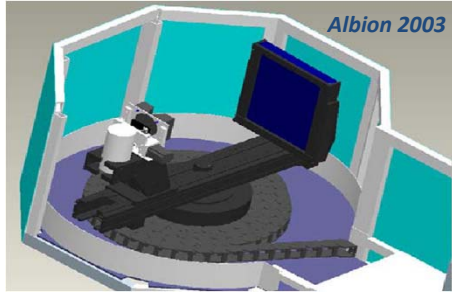
Dedicated Breast CT

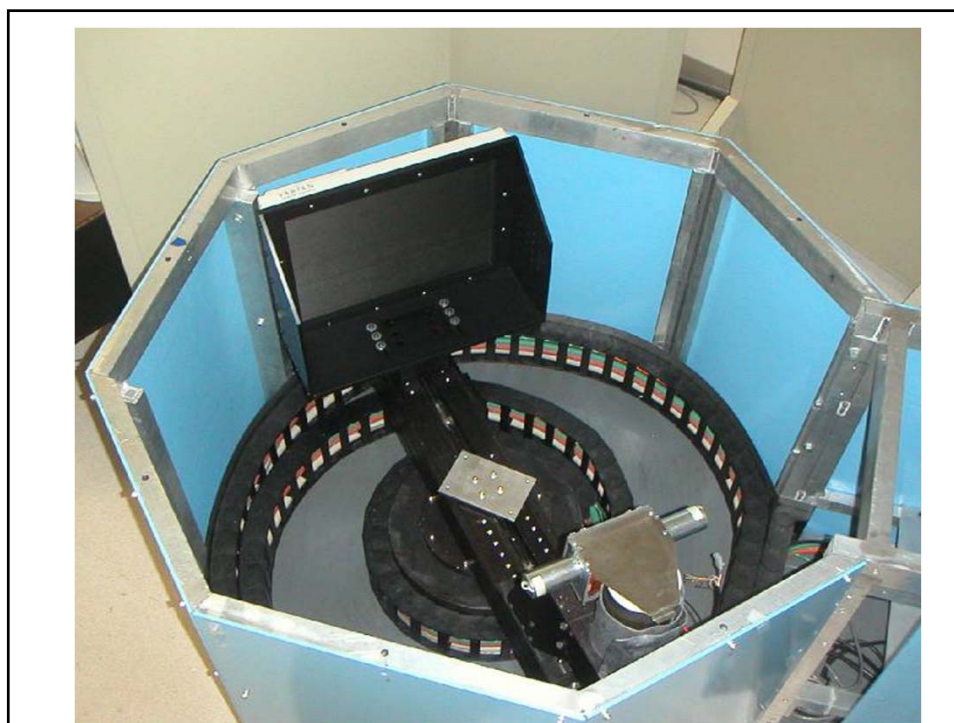


Evolution of the UC Davis Breast CT Scanner

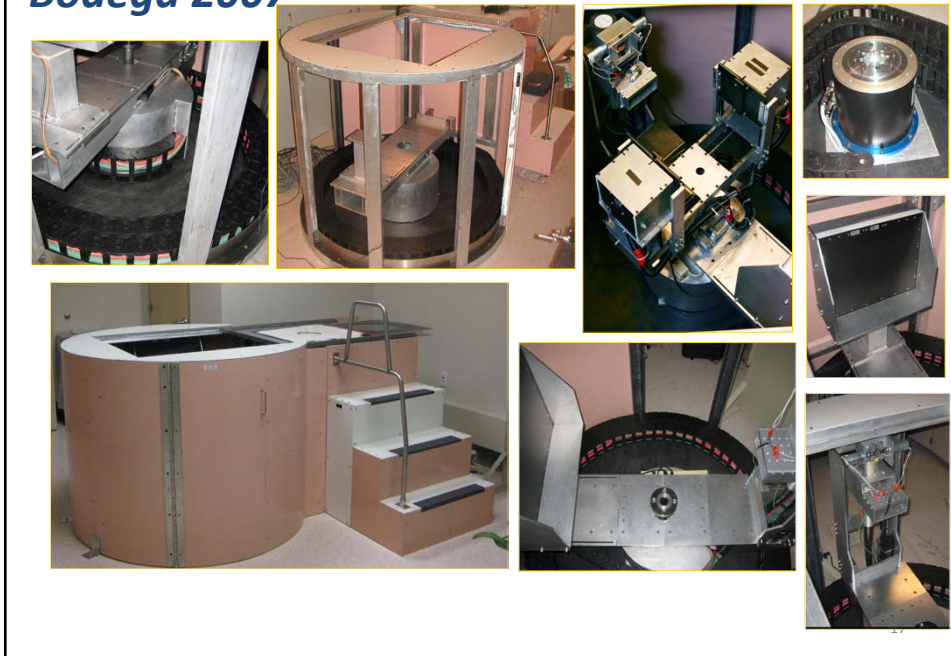
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Computer aided design / computer aided manufacture (CAD/CAM)





Bodega 2007



Components (Albion and Bodega)



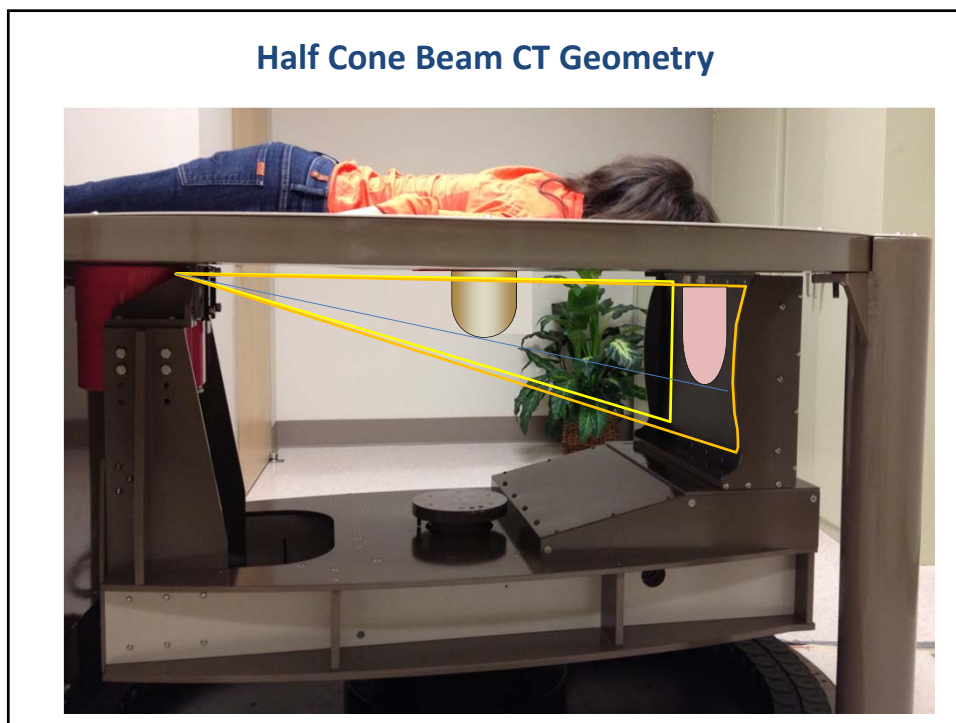
Varian 4030CB
 194 μm pixels
 2x2 388 μm
 1024 x 768 x 30 FPS



Kollmorgen
 Servo Motor
 Propulsion
 Bearing
 Angle Encoder



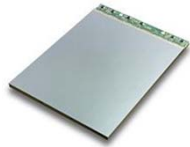
Comet 1 kW Tube



Components (Cambria and Doheny)



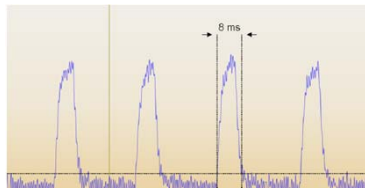
Varian 4030CB



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



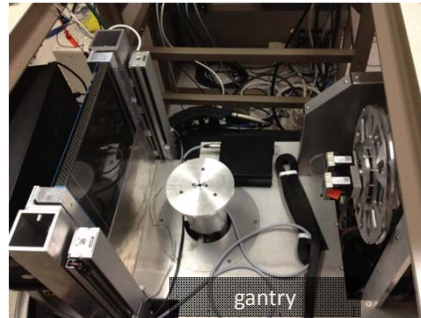
Yaskawa
Servo Motor
Propulsion
Bearing
Angle Encoder



Doheny Fabrication



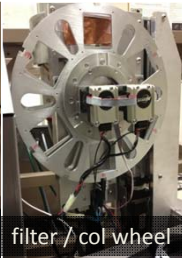
frame



gantry



switch box

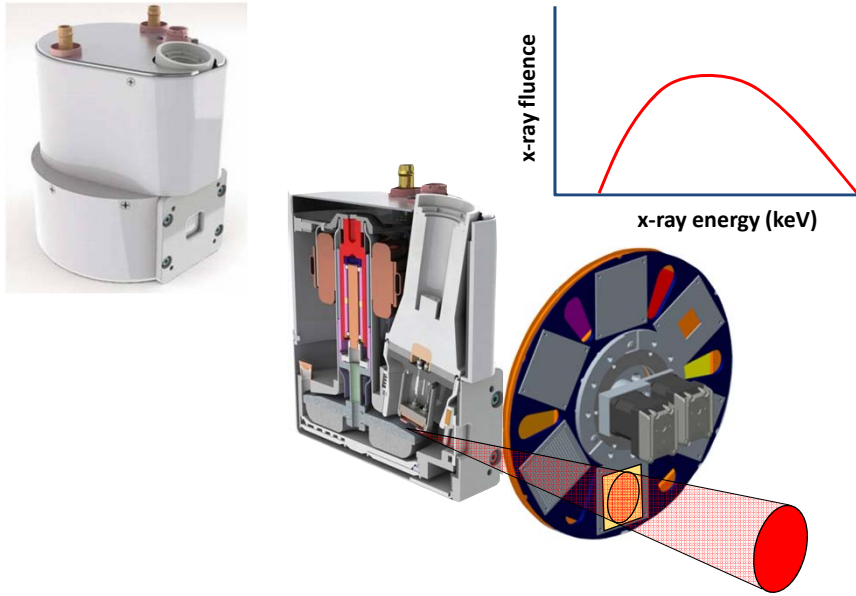


filter / col wheel



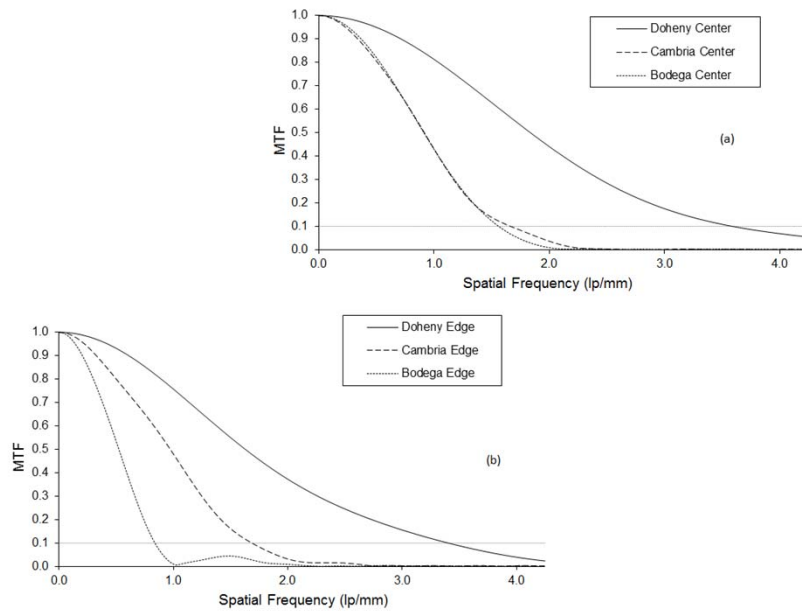
finished scanner

Engineering impacts physics



23

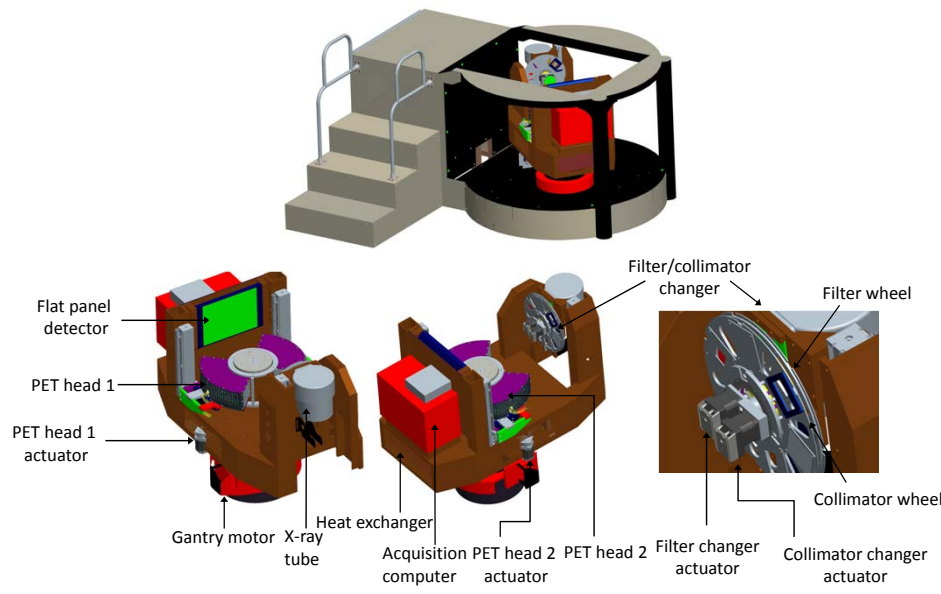
Engineering impacts image quality

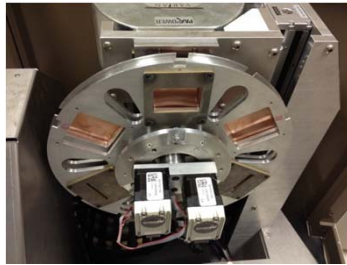


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Doheny: Software Control of Hardware Components



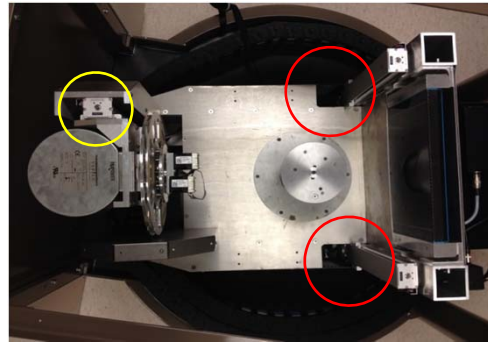


2 NEMA #17 stepping motors

3 NEMA #23 stepping motors for vertical translation of PET heads (2) and x-ray tube (1)



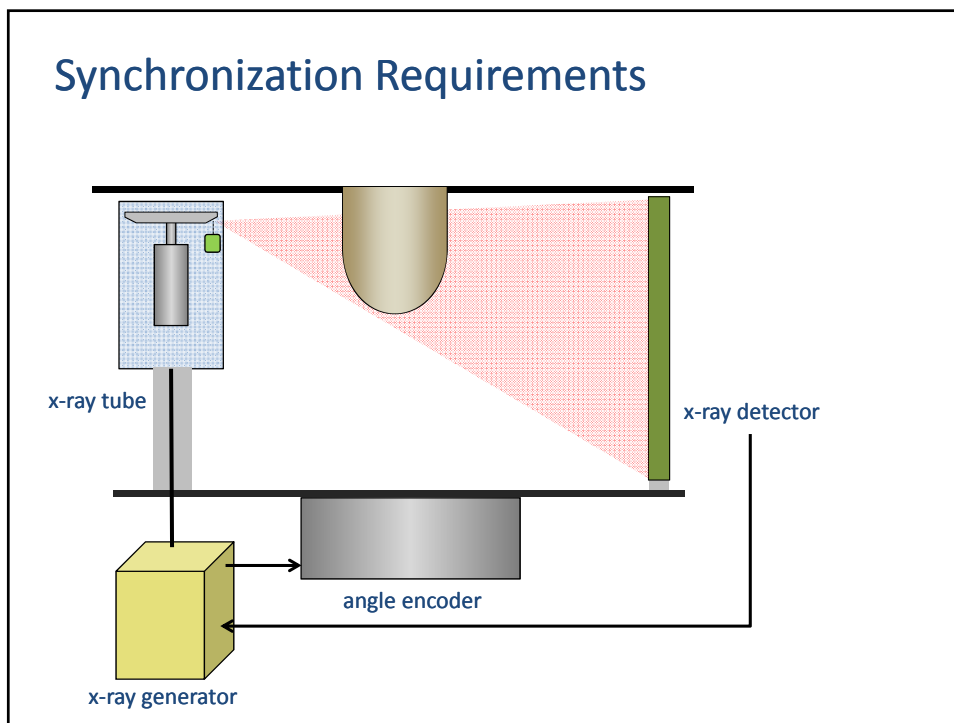
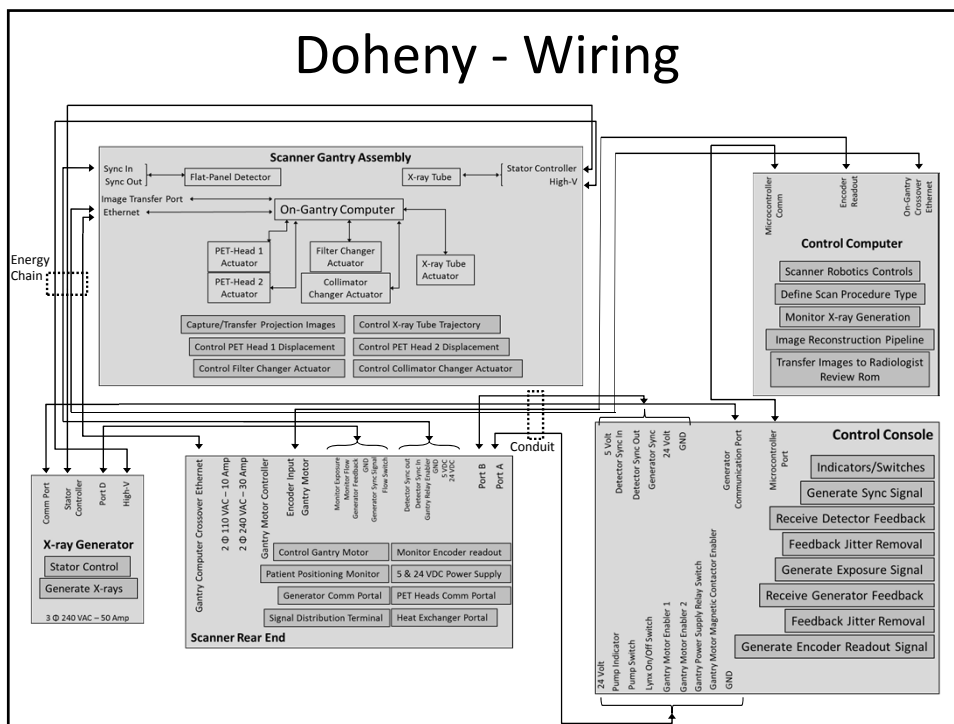
Yaskawa gantry servo motor / bearing system / angle encoder / TTL & RS232 console language

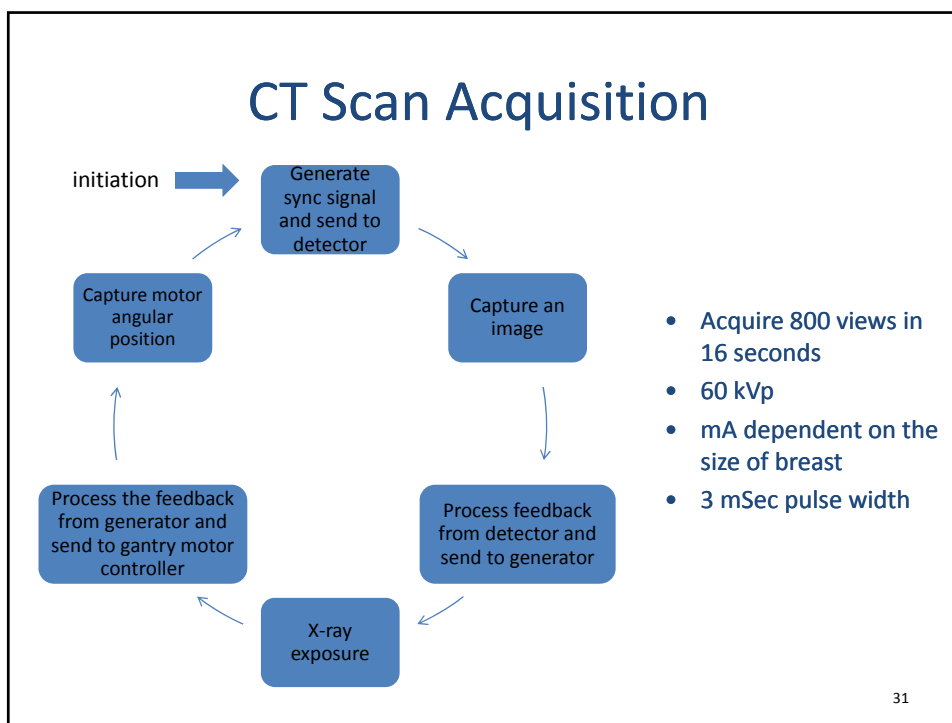


Arduino micro-controller



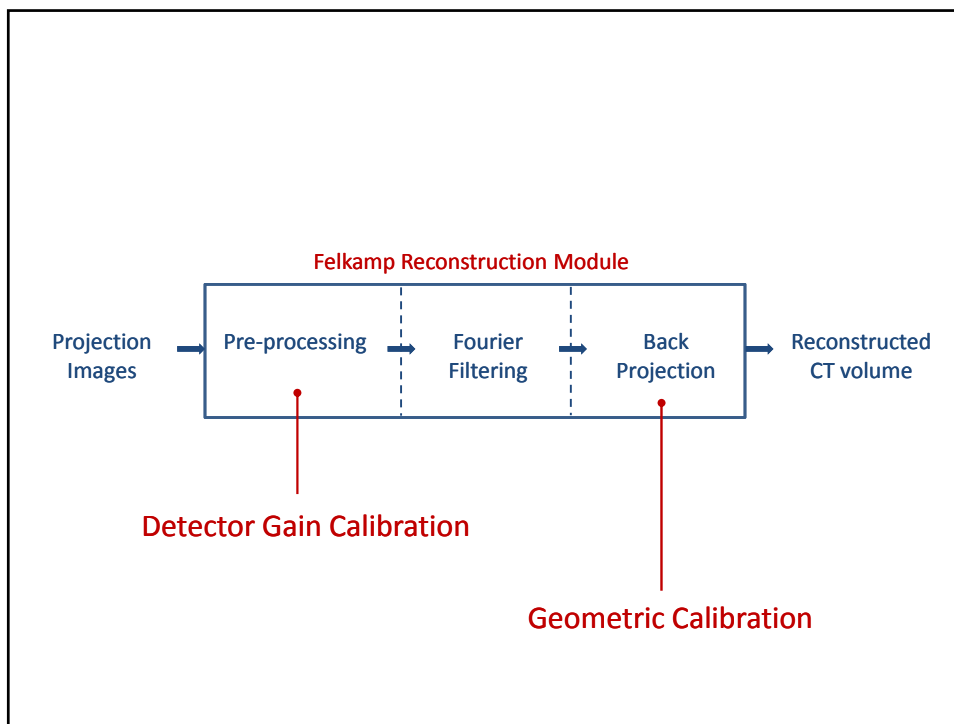
Stepping motor with integrated controller (uses programmable firmware)





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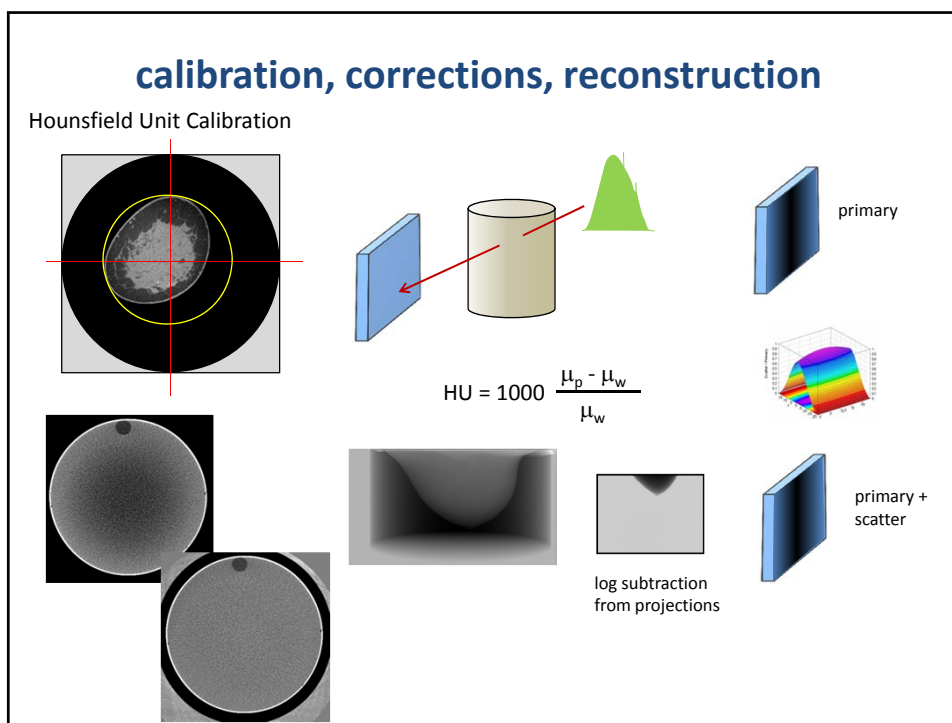
calibration, corrections, reconstruction

Flat Field Correction

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

Geometric Calibration

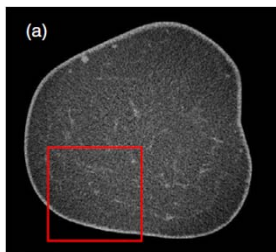
$$u_{wr} = y_{obj} \cdot \frac{D + u_{wr} \cdot \sin \phi}{C + x_{obj}} \cdot \frac{1}{\cos \phi}, \quad y_{wr} = z_{obj} \cdot \frac{D + u_{wr} \cdot \sin \phi}{C + x_{obj}}$$



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Reconstruction Algorithm (2): **constrained TV minimization**



Investigation of iterative image reconstruction in low-dose breast CT

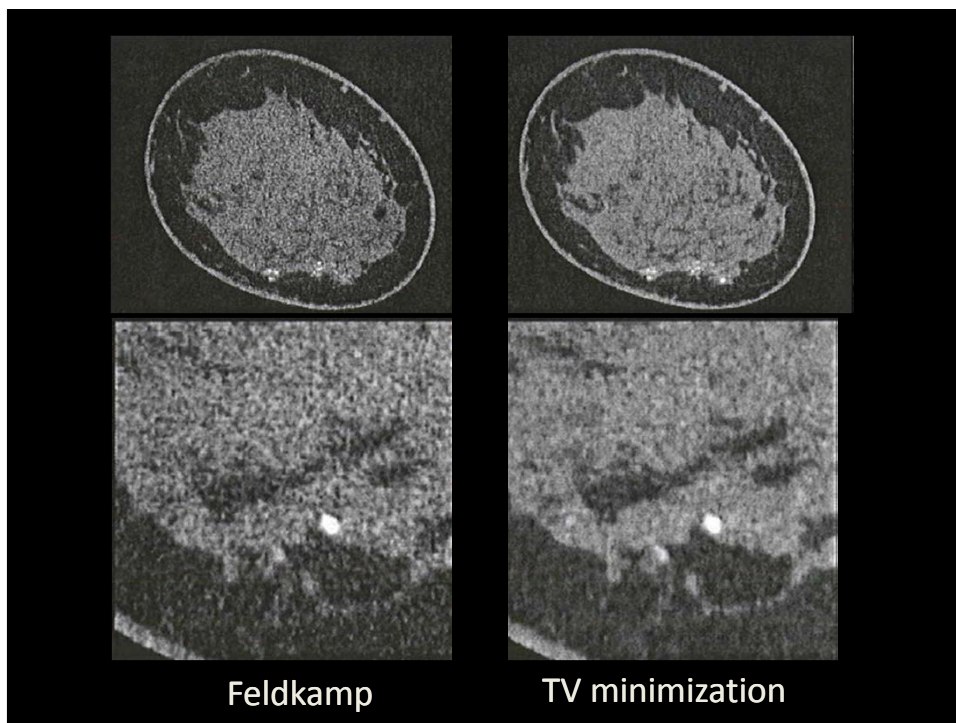
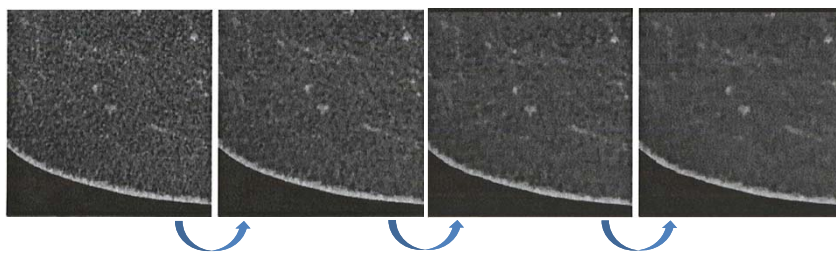
Junguo Bian¹, Kai Yang², John M Boone², Xiao Han³, Emil Y Sidky¹ and Xiaochuan Pan^{4,5}

¹ Department of Radiology, Massachusetts General Hospital and Harvard Medical School

² Department of Radiology, University of California, Davis, CA, USA

³ Department of Radiology, The University of Chicago, Chicago, IL, USA

⁴ Departments of Radiology and Radiation and Cellular Oncology, The University of Chicago, Chicago, IL, USA



Reconstruction Algorithm (3): denoising projections

Dedicated breast computed tomography: Volume image denoising via a partial-diffusion equation based technique

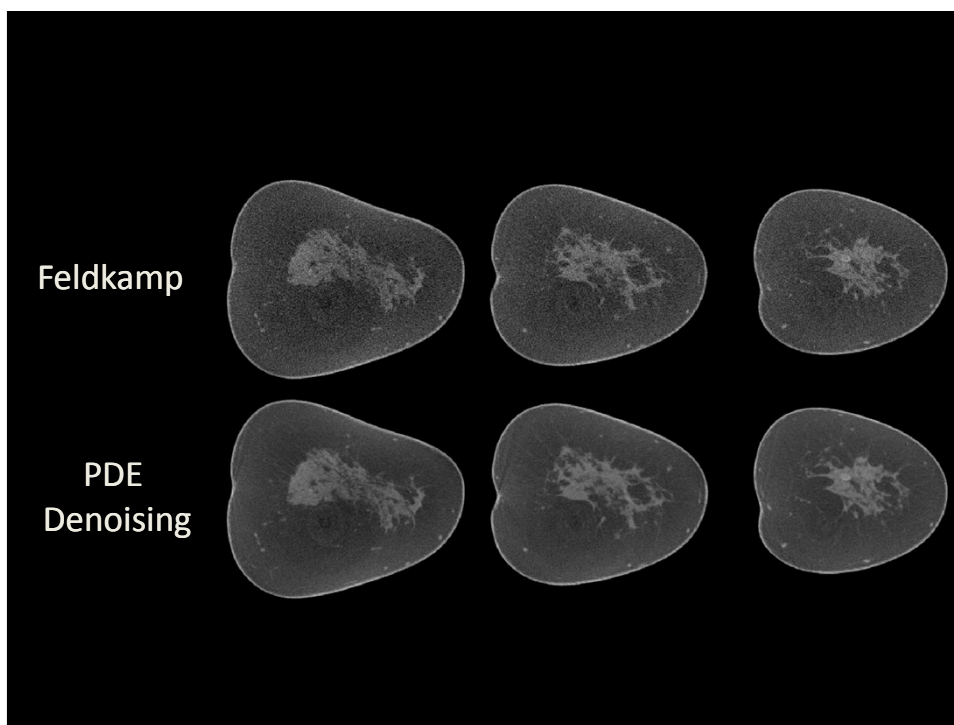
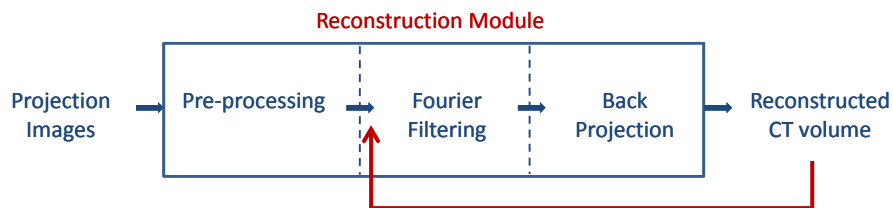
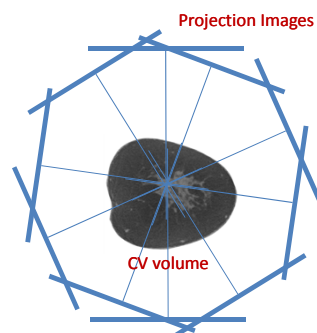
Jessie Q. Xia¹
 Department of Biomedical Engineering, Duke University, Durham, North Carolina 27708
 and Duke Advanced Imaging Laboratories, Department of Radiology, Duke University Medical Center,
 Durham, North Carolina 27705

Joseph Y. Lo
 Department of Biomedical Engineering, Duke University, Durham, North Carolina 27708, Duke Advanced
 Imaging Laboratories, Department of Radiology, Duke University Medical Center, Durham,
 North Carolina 27705, and Medical Physics Graduate Program, Duke University Medical Center,
 Durham, North Carolina 27708

Kai Yang
 Department of Biomedical Engineering, University of California Davis, Davis, California 95616
 and Department of Radiology, University of California Davis Medical Center, Sacramento,
 California 95817

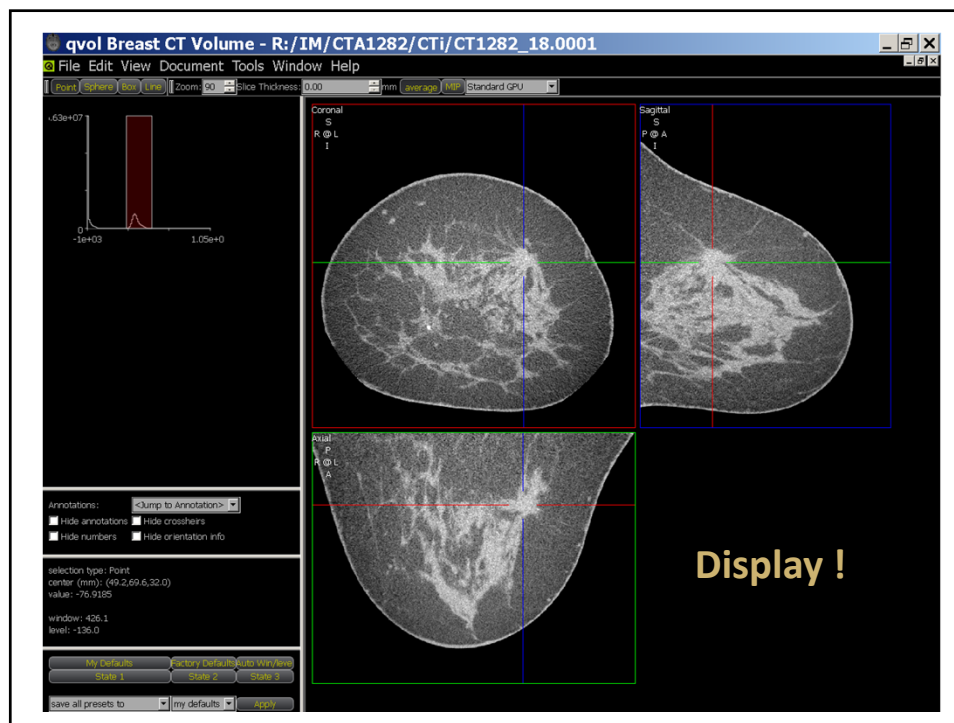
Carey E. Floyd, Jr.
 Department of Biomedical Engineering, Duke University, Durham, North Carolina 27708, Duke Advanced Imaging
 Laboratories, Department of Radiology, Duke University Medical Center, Durham, North Carolina 27705,
 and Medical Physics Graduate Program, Duke University Medical Center, Durham, North Carolina 27708

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



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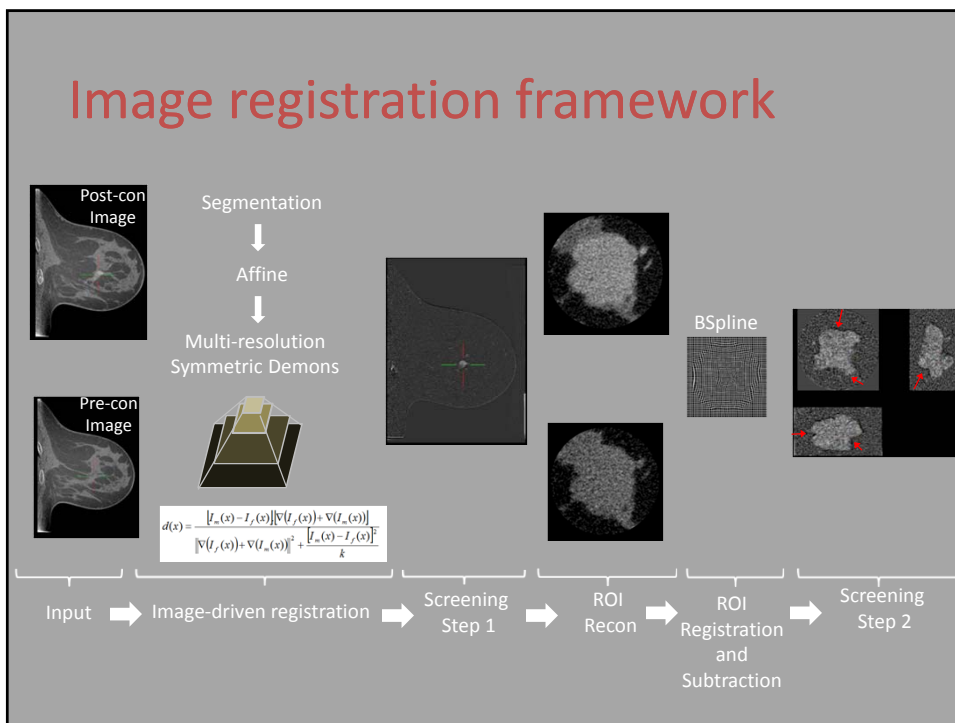
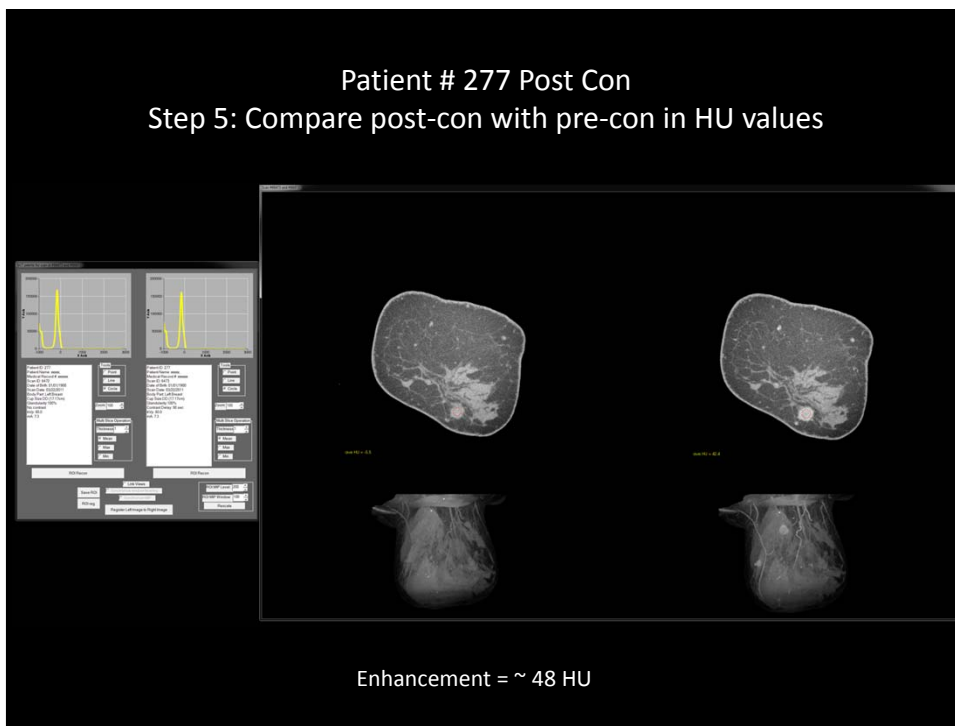


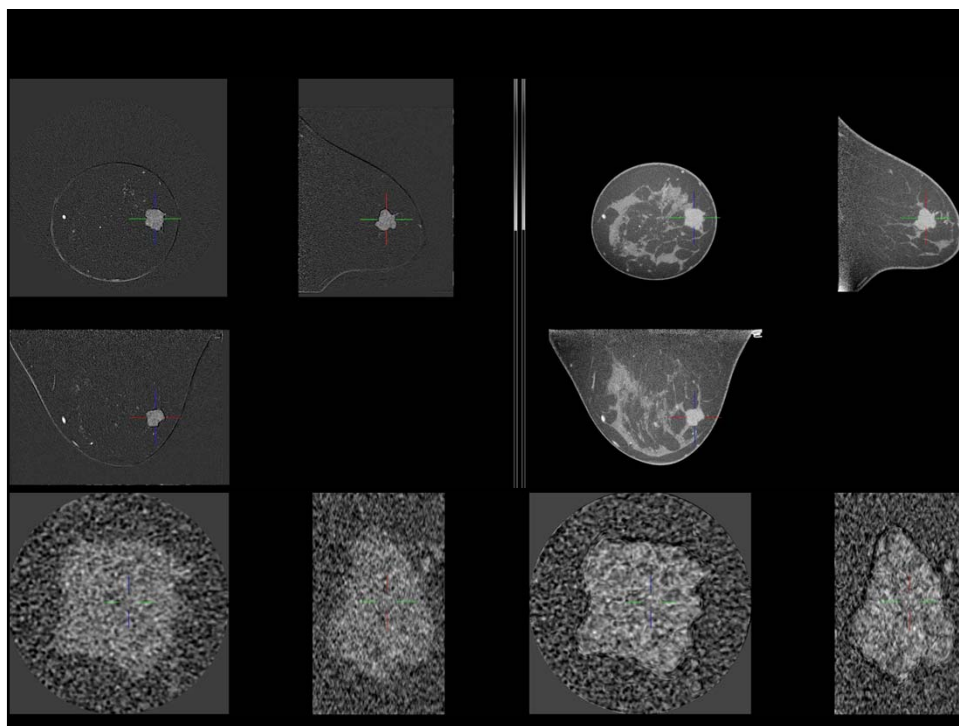
Patient # 277 Post Con Step 1: Initial observation-post con

The image displays a software interface for breast imaging analysis. On the left, there is a data panel with a graph showing a peak. The graph has a y-axis labeled 'Counts' and an x-axis labeled 'Energy (keV)'. Below the graph, there is a table of data:

Parameter	Value
Patient ID	277
Study ID	10000000000000000000
Case ID	10000000000000000000
Exam ID	10000000000000000000
Series ID	10000000000000000000
Image ID	10000000000000000000
Image Name	10000000000000000000
Image Date	10000000000000000000
Image Time	10000000000000000000
Image User	10000000000000000000
Image Modality	10000000000000000000
Image Protocol	10000000000000000000
Image Series	10000000000000000000
Image Subseries	10000000000000000000
Image Frame	10000000000000000000
Image Frame Count	10000000000000000000
Image Frame Rate	10000000000000000000
Image Frame Size	10000000000000000000
Image Frame Type	10000000000000000000
Image Frame Subtype	10000000000000000000
Image Frame Subseries	10000000000000000000
Image Frame Subseries Count	10000000000000000000
Image Frame Subseries Rate	10000000000000000000
Image Frame Subseries Size	10000000000000000000
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Image Frame Subseries Subseries Type	10000000000000000000
Image Frame Subseries Subseries Subtype	10000000000000000000

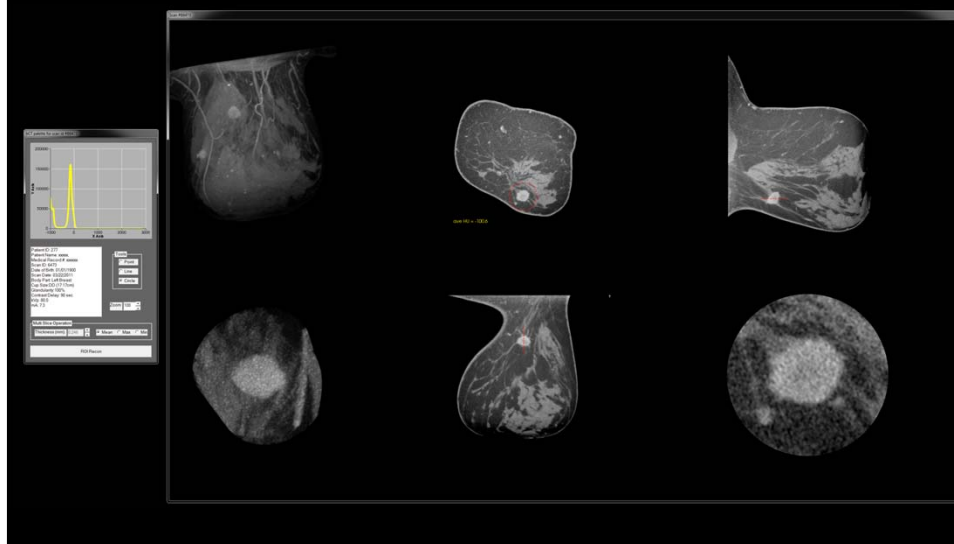
The main area of the interface shows four different views of the breast specimen: a 3D reconstruction, a top-down view, a side view, and a bottom-up view. The views show the internal structure of the breast, including the vascular network and the tumor. The background is black.





Patient # 277 Post Con
Step 2: Compare with registered/subtracted dataset

Patient # 277 Post Con Step 3: ROI Recon



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Detector Performance

➔ Noise (texture) Analysis (NPS)

Spatial Resolution Analysis (MTF)

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Detector Performance (noise)

total noise

anatomical noise

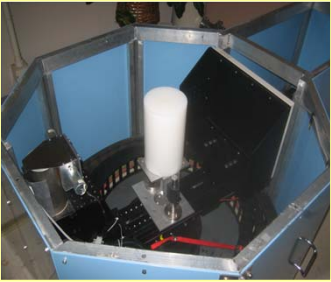
quantum noise

$$\text{NPS}(f) = \text{NPS}_a(f) + \text{NPS}_q(f)$$

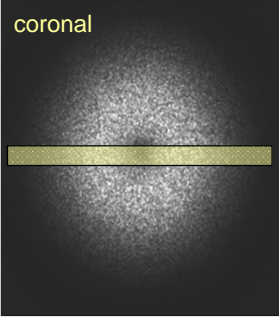
The diagram illustrates the decomposition of total noise into anatomical and quantum noise. A vertical arrow points from 'total noise' down to the equation. Two curved arrows point from 'anatomical noise' and 'quantum noise' to the terms $\text{NPS}_a(f)$ and $\text{NPS}_q(f)$ in the equation, respectively.

54

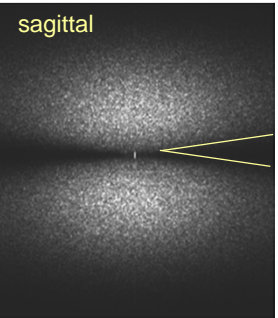
Contrast Resolution: NPS measurements

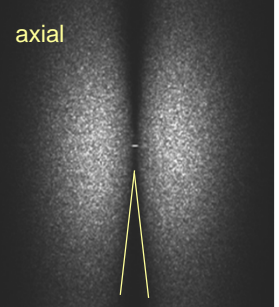


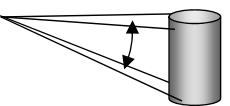
coronal



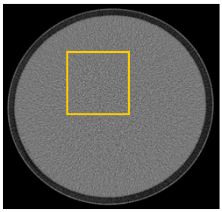
sagittal



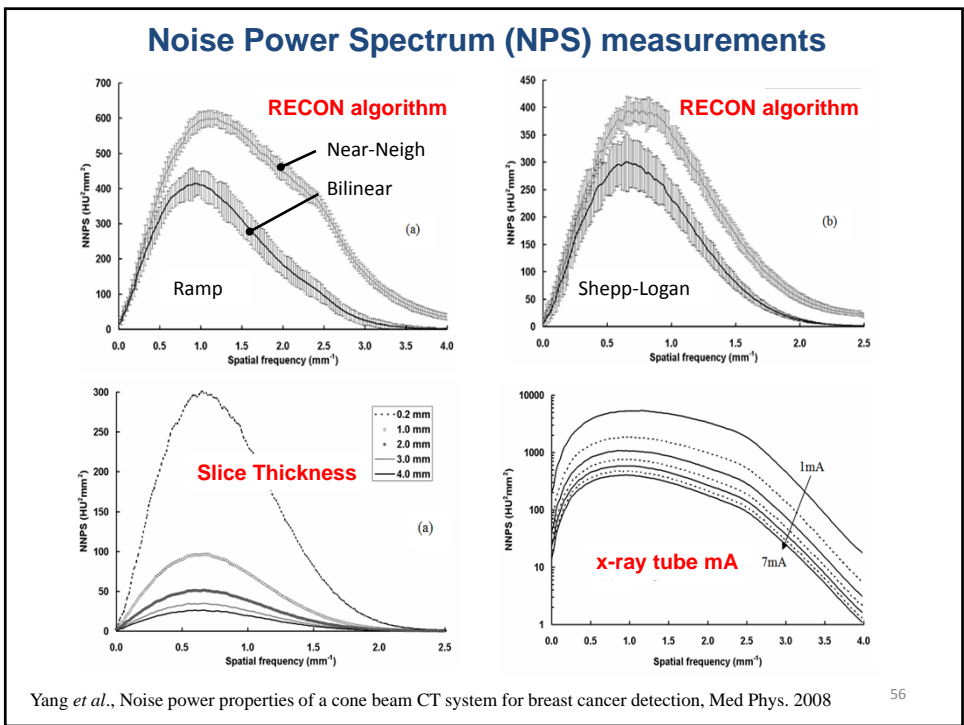




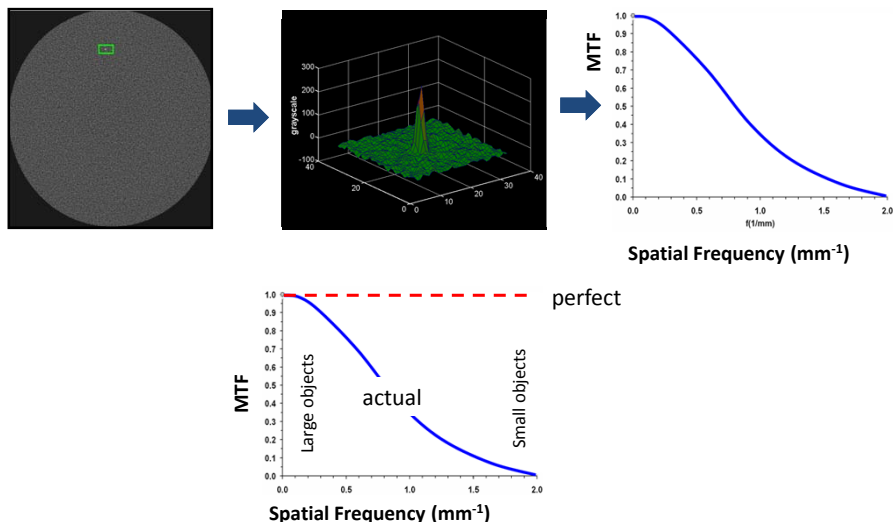
cone angle



$$NPS(u,v) = \frac{|F(u,v)|^2}{N_x N_y} \Delta_x \Delta_y$$

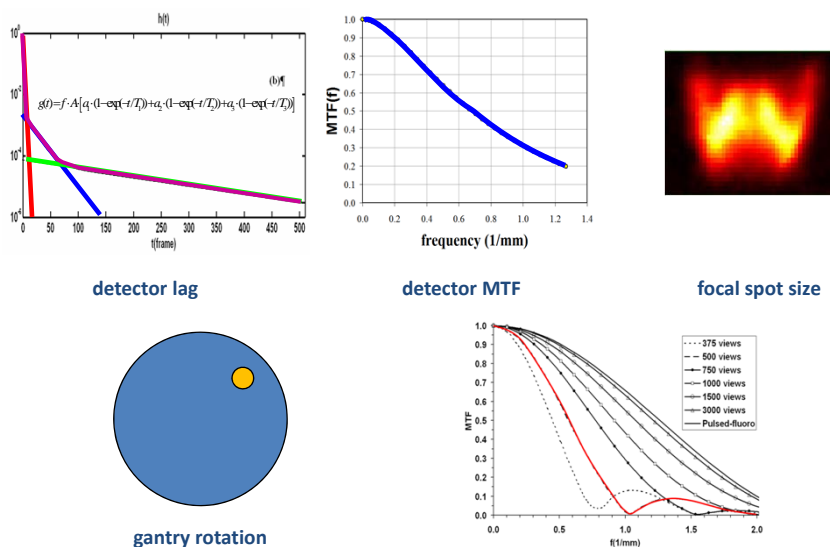


Detector Performance (resolution)

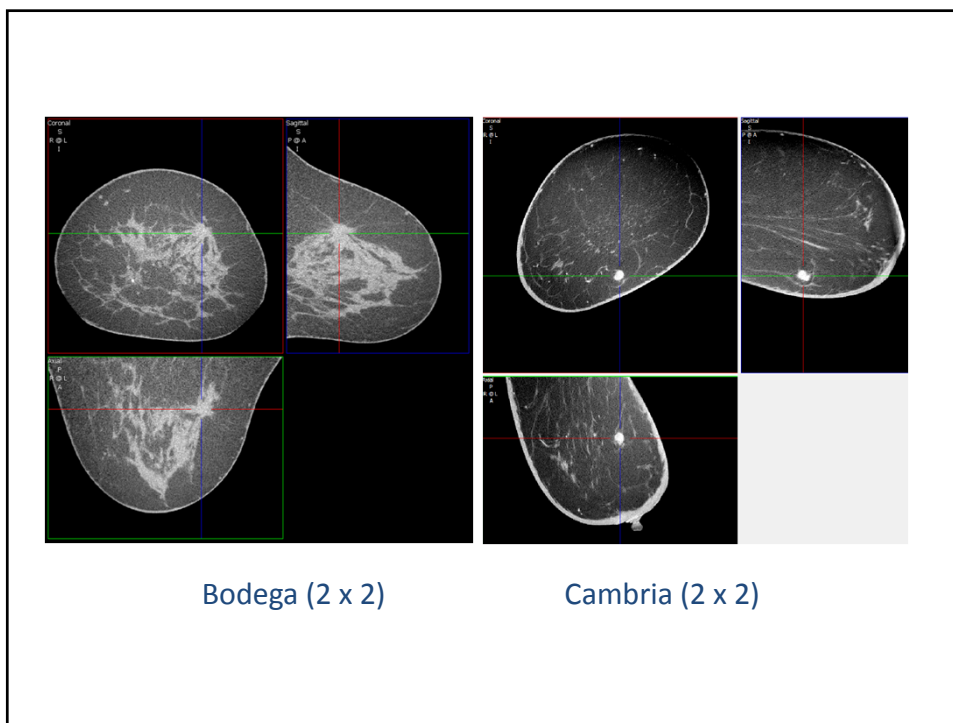
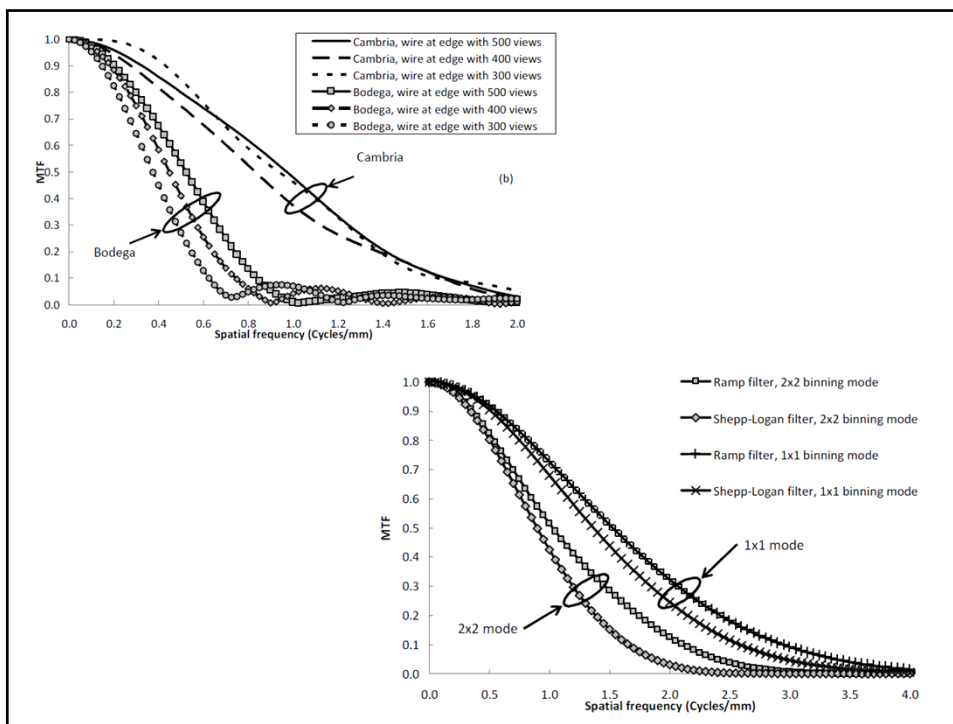


Kwan *et al.*, Evaluation of the spatial resolution characteristics of a cone beam breast CT scanner, Med Phys 2005

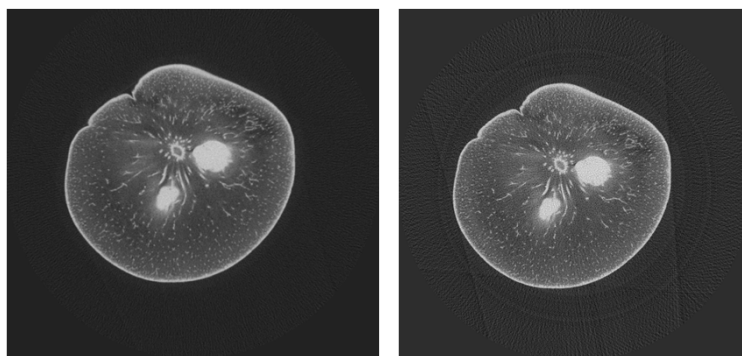
Spatial Resolution: Computer Modeling MTF



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



Cambria: Detector binning mode 1x1 versus 2x2 mode

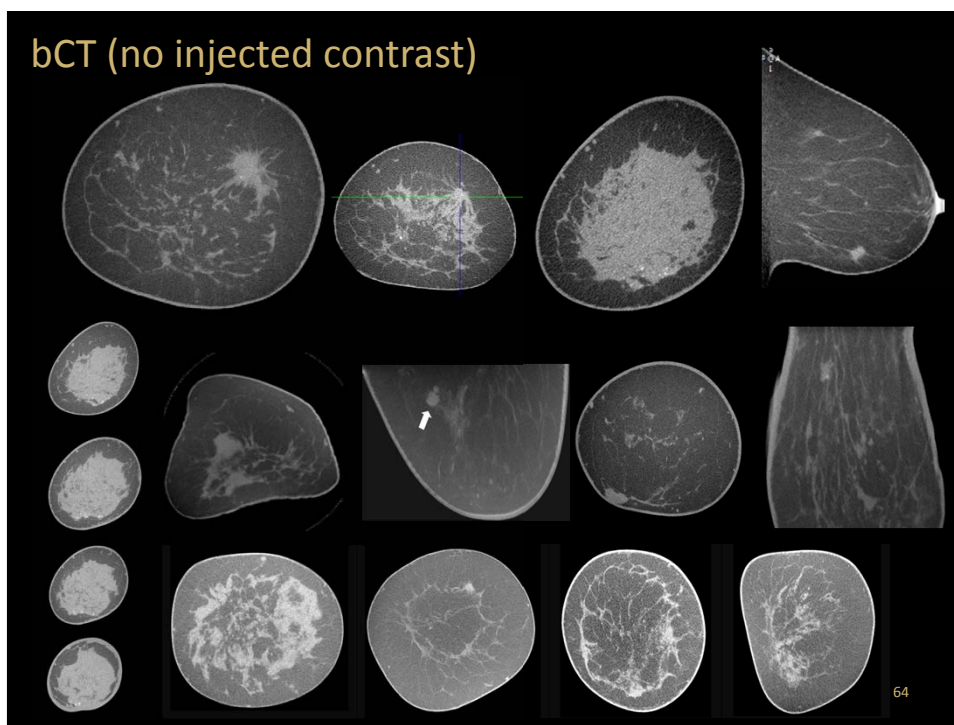
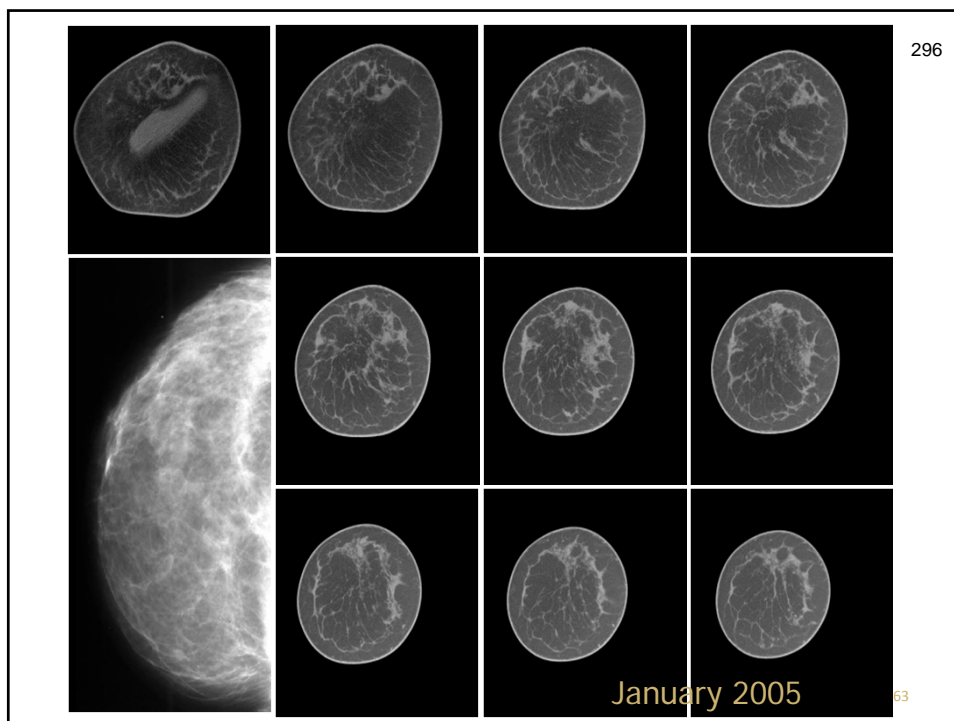


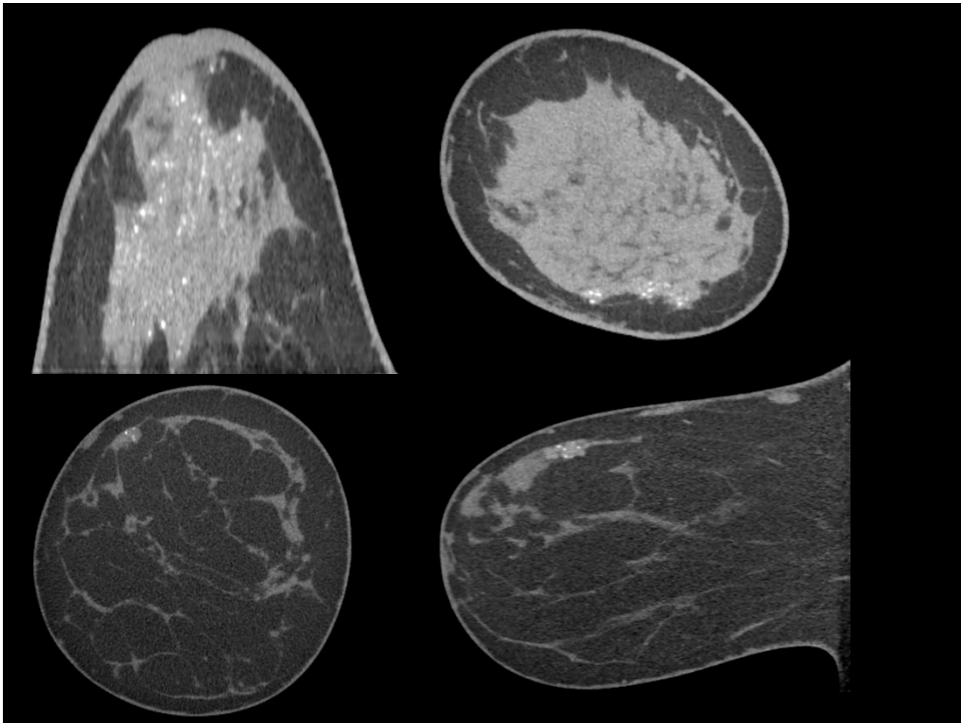
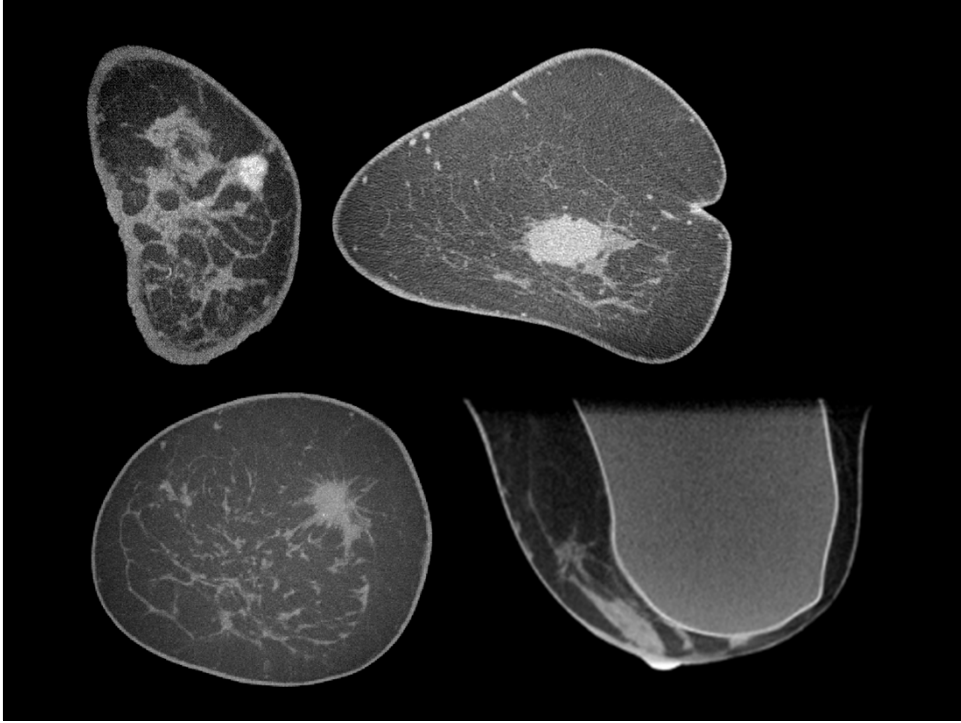
2x2 mode: 500 views

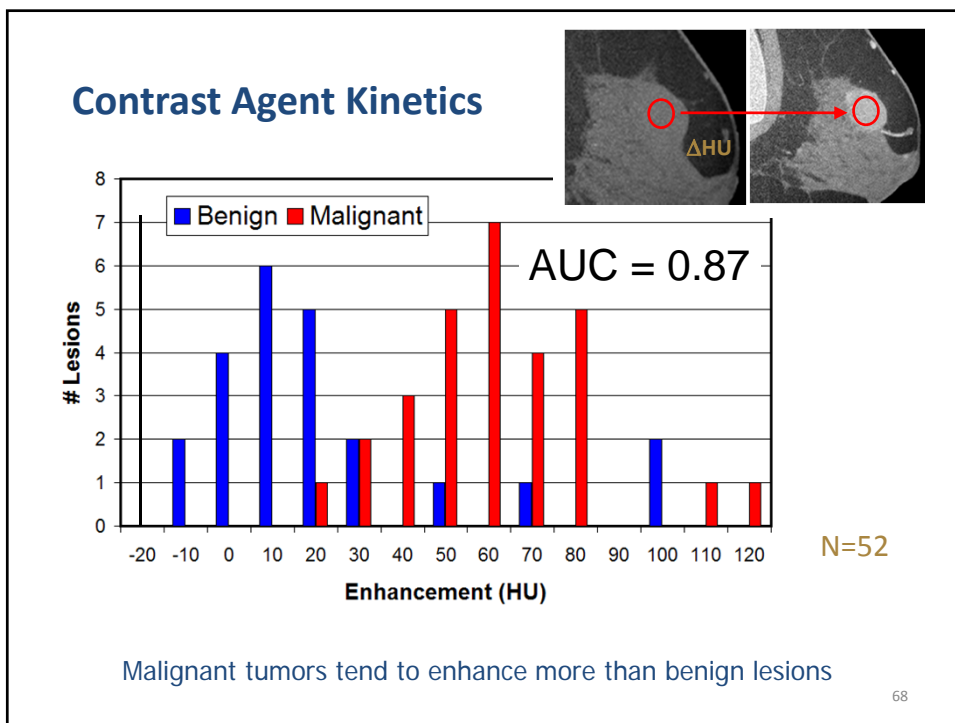
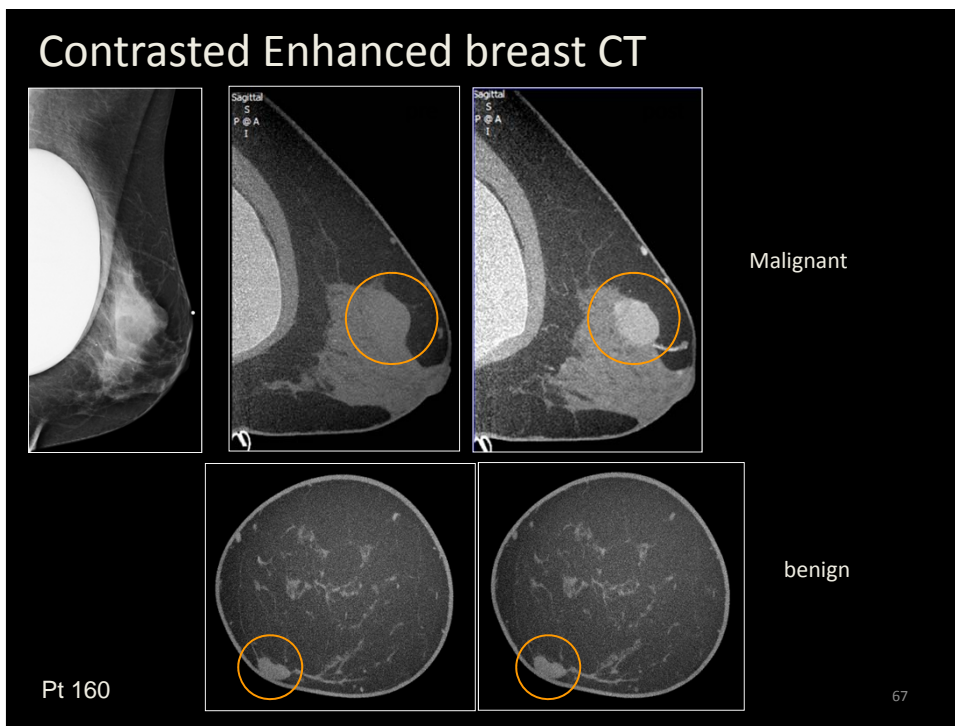
1x1 mode: 285 views

Clinical Imaging

- Over 600 women on UC Davis scanners
- Image women with suspicion of BC
- Informed consent / HIPAA compliant
- 16 second scan (breath hold)
- 500 projection images (1024 x 768)
- 30 frame / sec acquisition rate
- About 200 have had contrast injection
- Radiation dose same as 2V mammography
- Image reconstruction 512³ or better







Radiology

Dedicated Breast CT: Initial Clinical Experience¹

2008

Karen K. Lindfors, MD
John M. Boone, PhD
Thomas R. Nelson, PhD
Kai Yang, MS
Alexander L. C. Kwan, PhD²
DeWitt F. Miller, BE

Purpose: To prospectively and intraindividually compare dedicated breast computed tomographic (CT) images with screen-film mammograms.

Materials and Methods: All patient studies were performed according to protocols approved by the institutional review board and Radiation Use Committee.

2010

Contrast-enhanced Dedicated Breast CT: Initial Clinical Experience¹

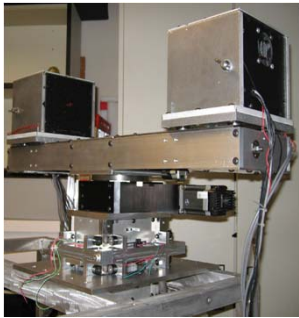

Radiology

Nicolas D. Prionas, MS
Karen K. Lindfors, MD
Shonket Ray, MS
Shih-Ying Huang, BS
Laurel A. Beckett, PhD
Wayne L. Monsky, MD, PhD
John M. Boone, PhD

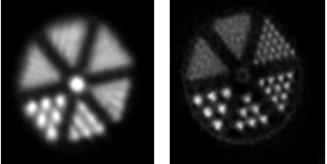
Purpose: To quantify contrast material enhancement of breast lesions scanned with dedicated breast computed tomography (CT) and to compare their conspicuity with that of unenhanced breast CT and mammography.

Materials and Methods: Approval of the institutional review board and the Radiation Use Committee and written informed consent were obtained from all patients.

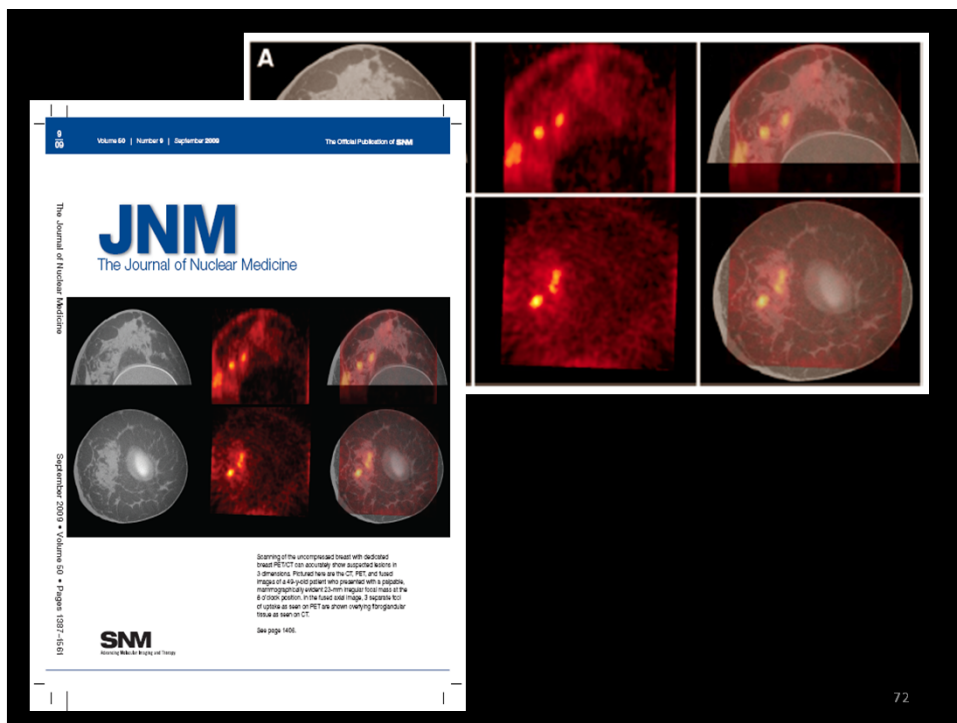
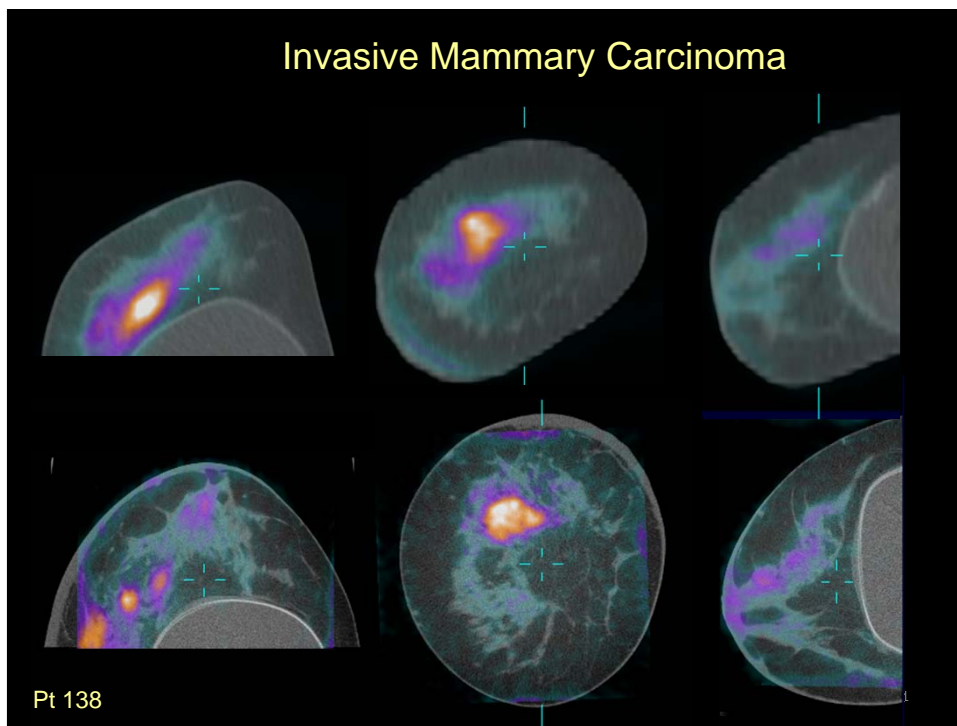
PET / CT for dedicated breast imaging

ramsey badawi
simon cherry
abhijit chaudhari
spencer bowen



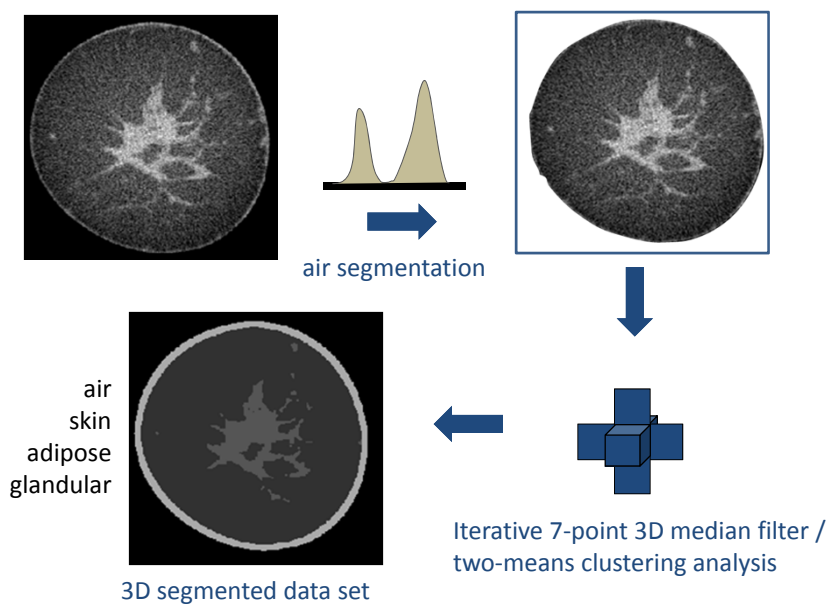
70



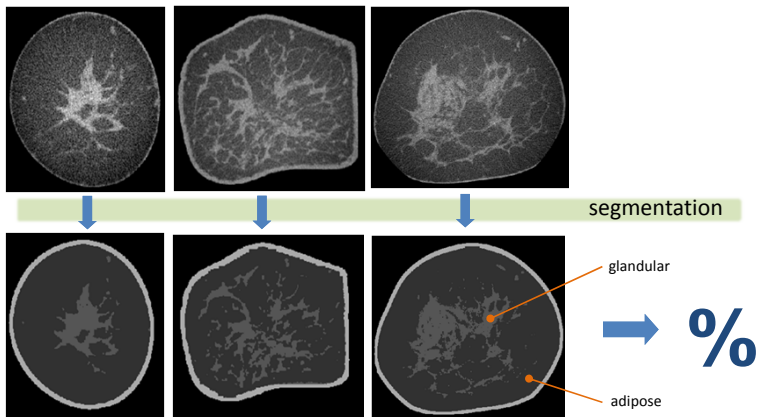
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Image Segmentation



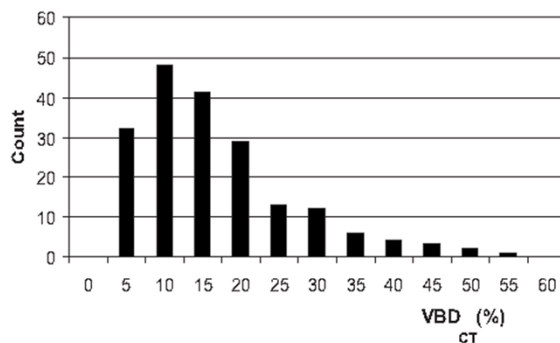
Breast Density Analysis



risk assessment & dosimetry
validation of 2D approaches (M. Yaffe)

75

$N = 138$
 $\bar{x} = 12.3\%$
 $\sigma = 8.5\%$

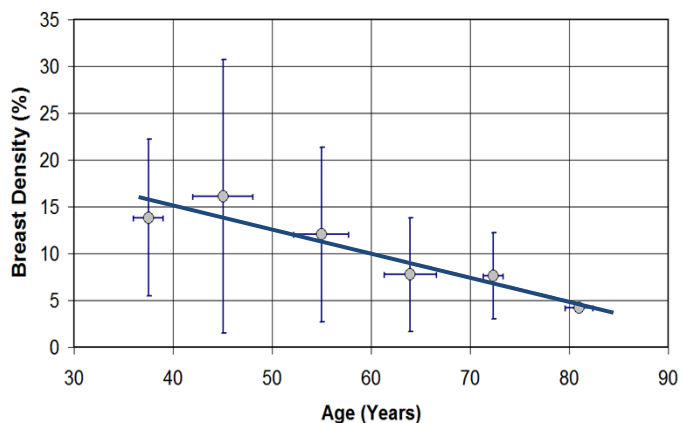


The myth of the 50-50 breast

- M. J. Yaffe^{a)}
Sunnybrook Health Sciences Centre, University of Toronto, Toronto, Ontario M4N 3M5, Canada
- J. M. Boone and N. Packard
UC Davis Medical Center, University of California-Davis, Sacramento, California 95817
- O. Alonzo-Proulx
Sunnybrook Health Sciences Centre, University of Toronto, Toronto, Ontario M4N 3M5, Canada
- S.-Y. Huang
UC Davis Medical Center, University of California-Davis, Sacramento, California 95817
- C. L. Peressotti
Sunnybrook Health Sciences Centre, University of Toronto, Toronto, Ontario M4N 3M5, Canada
- A. Al-Mayah and K. Brock
University Health Network, University of Toronto, Toronto, Ontario M5G 2M9, Canada

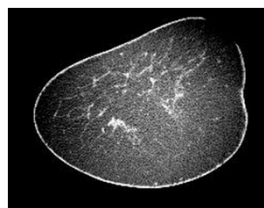
76

2.5% loss in breast density every decade

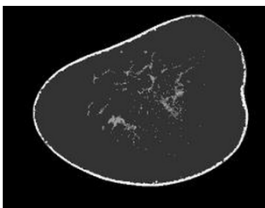


77

Mathematical Flat Fielding of Breast CT images



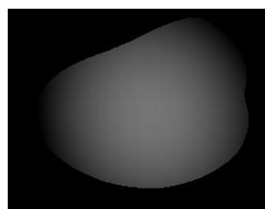
original image



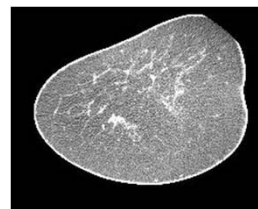
segmented image

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

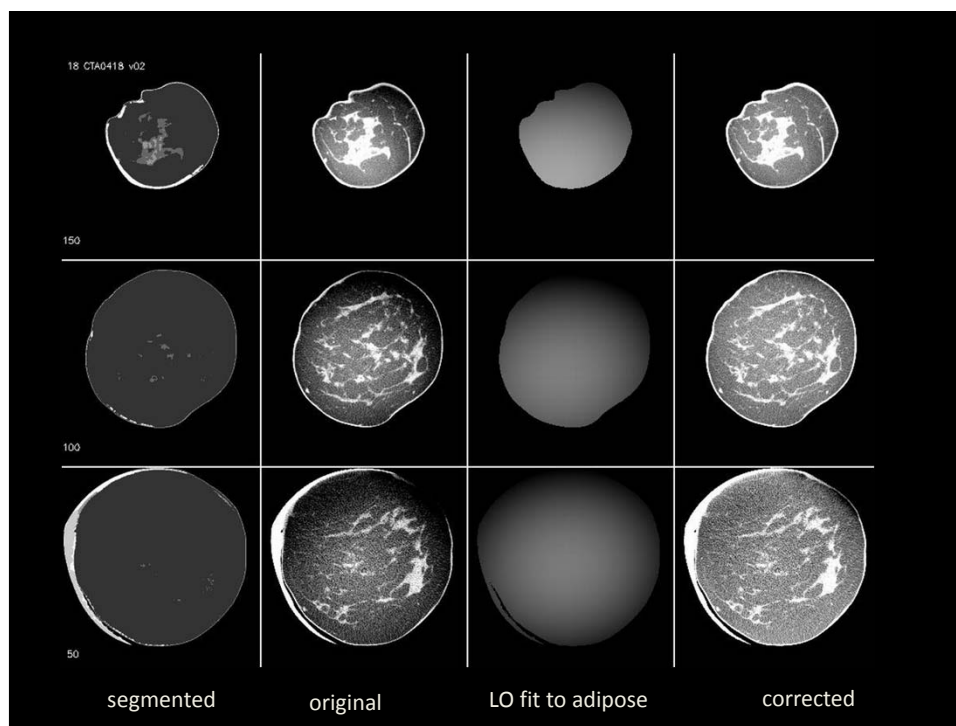
$$\mathbf{Q}_A = \begin{bmatrix} 1 & x_A & y_A & z_A & x_A y_A & x_A z_A & y_A z_A & x_A^2 & y_A^2 & z_A^2 \end{bmatrix}$$



low order fit

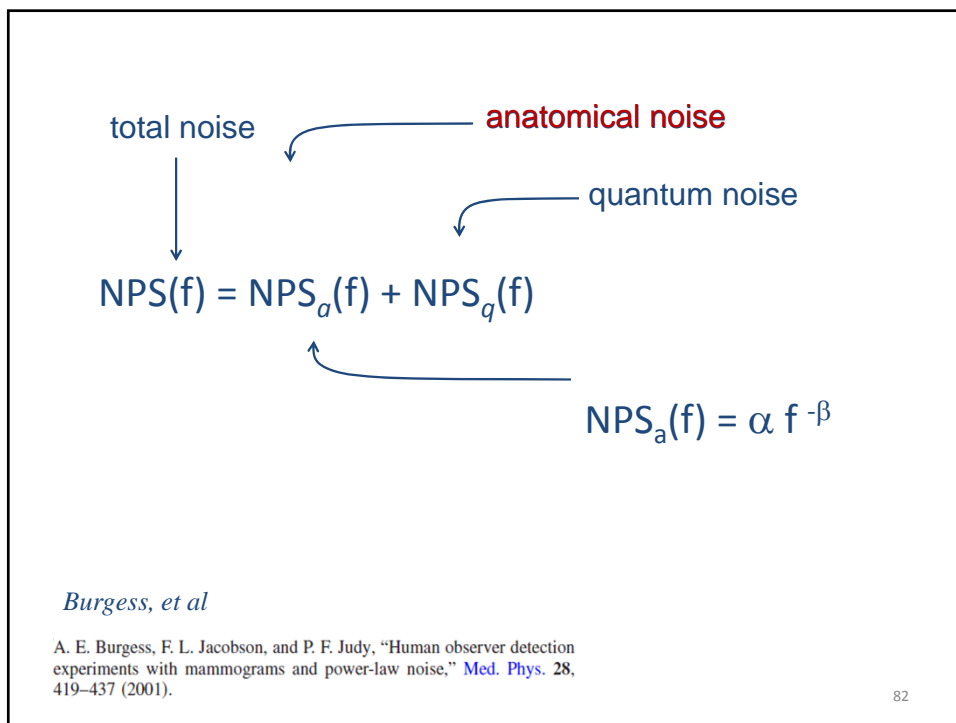
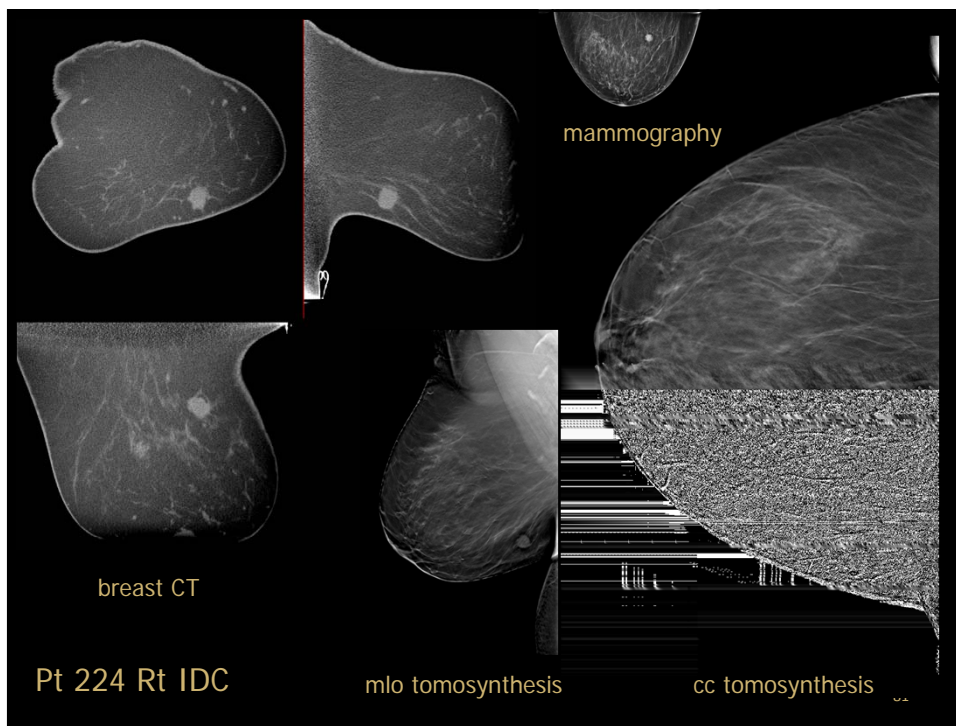


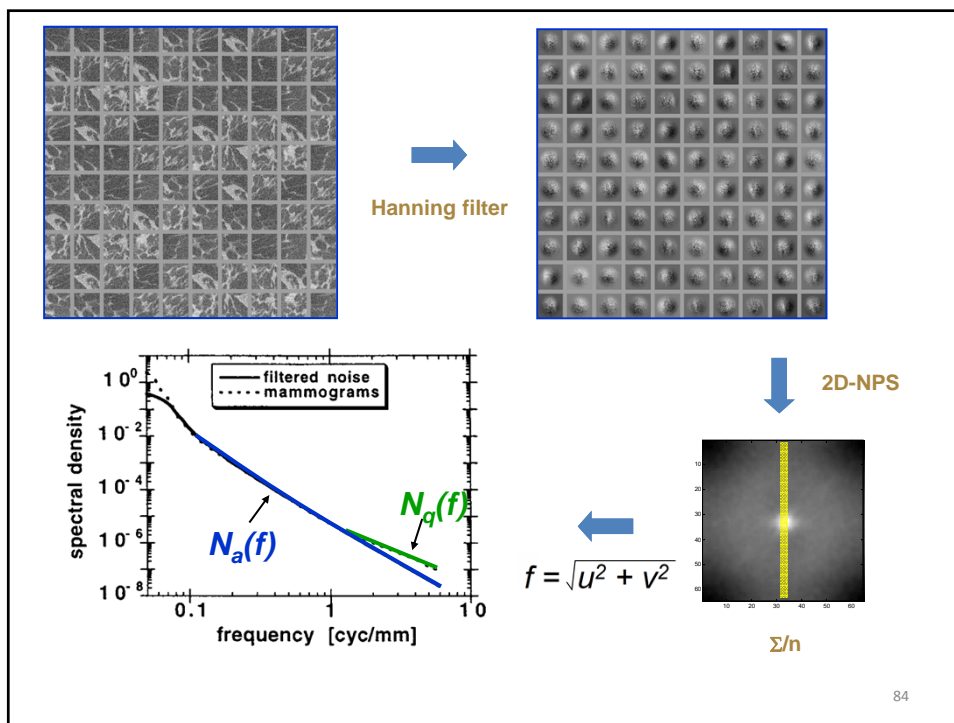
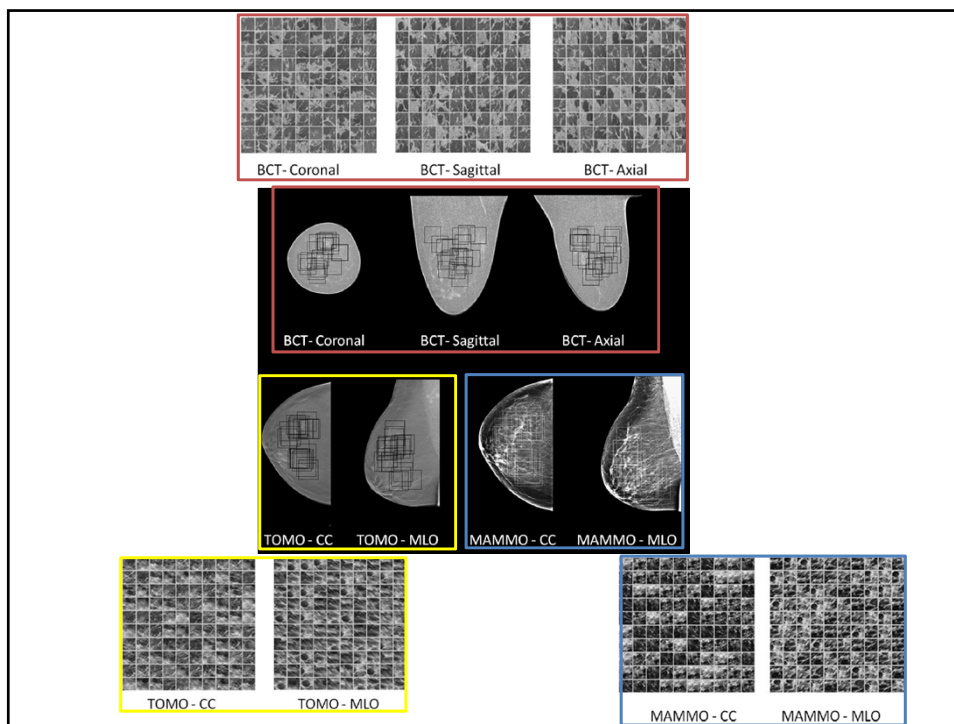
corrected image

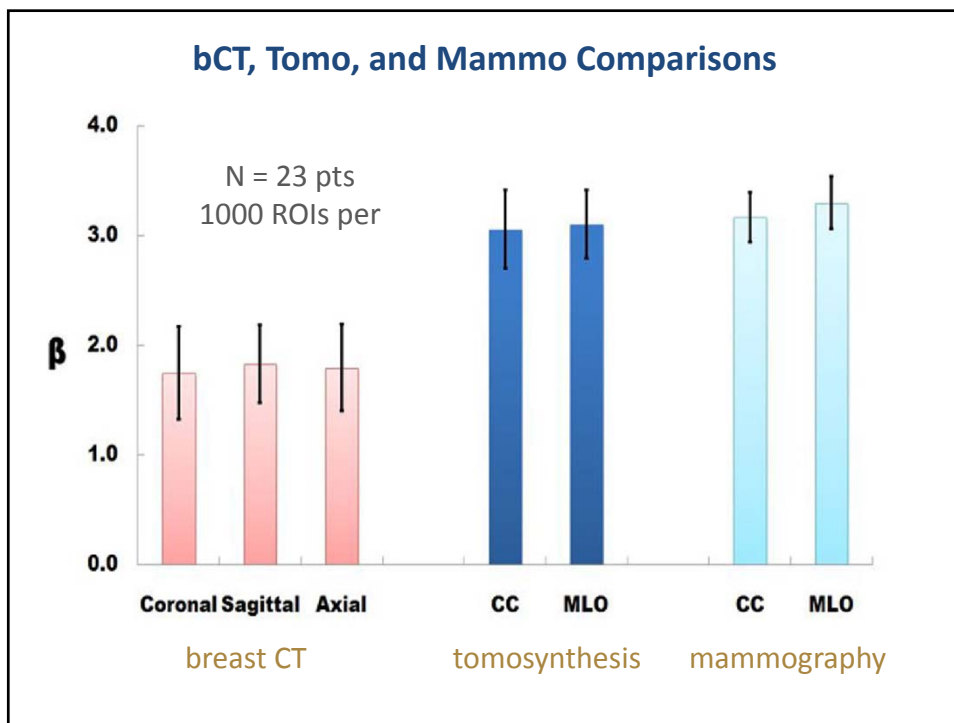
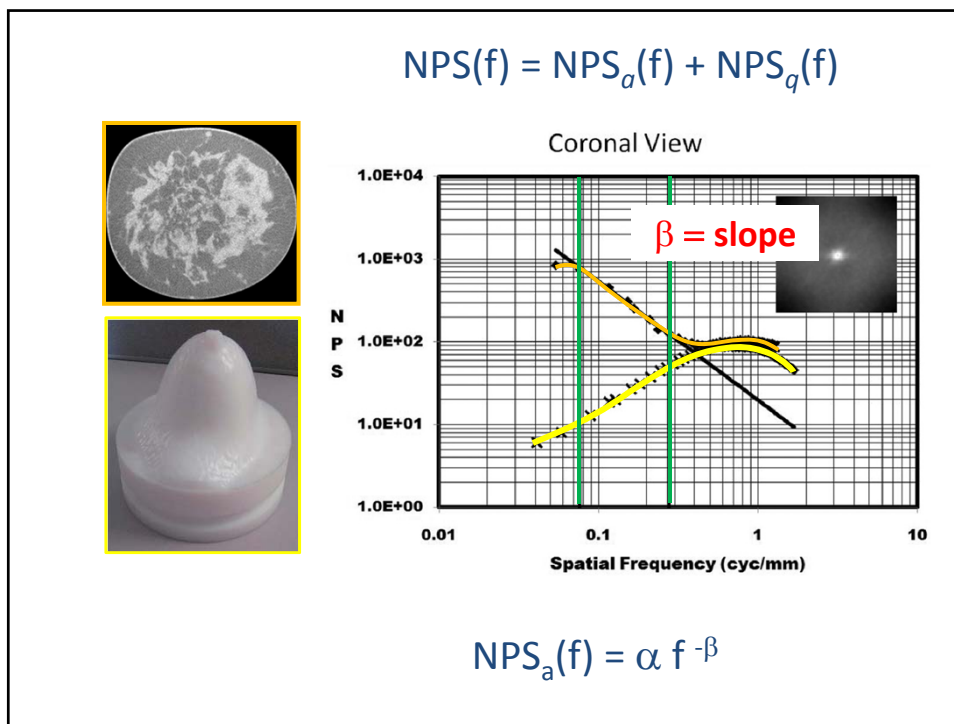


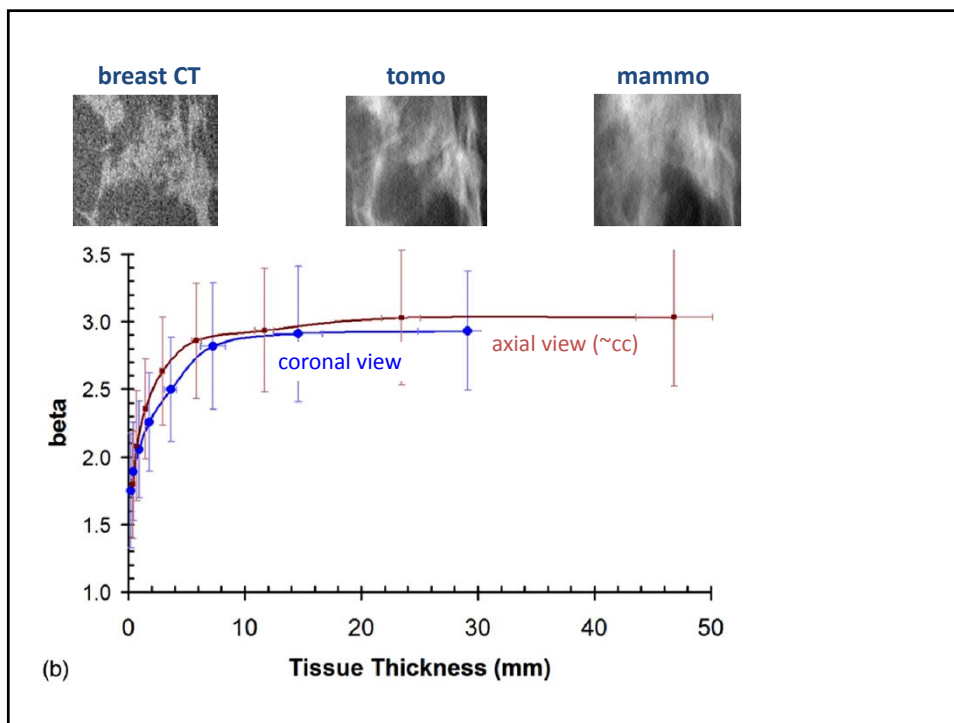
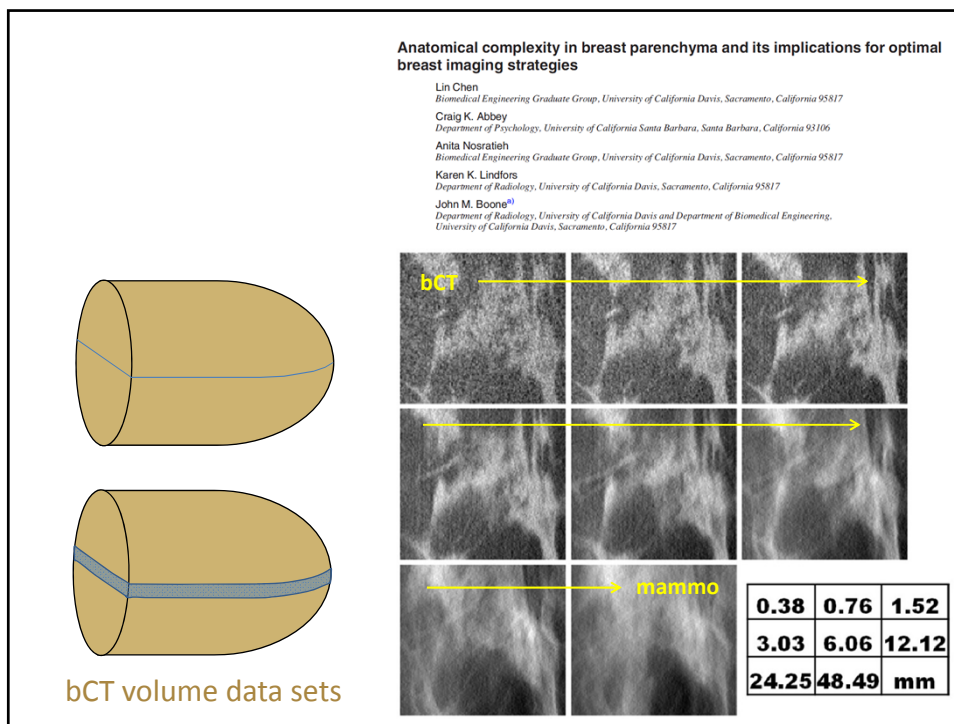
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PWMF Observer Performance Analysis

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

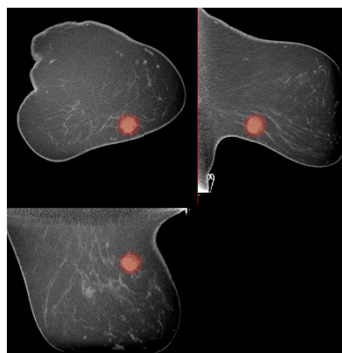
Nathan J. Packard
Carestream Health Inc., Rochester, New York 14615

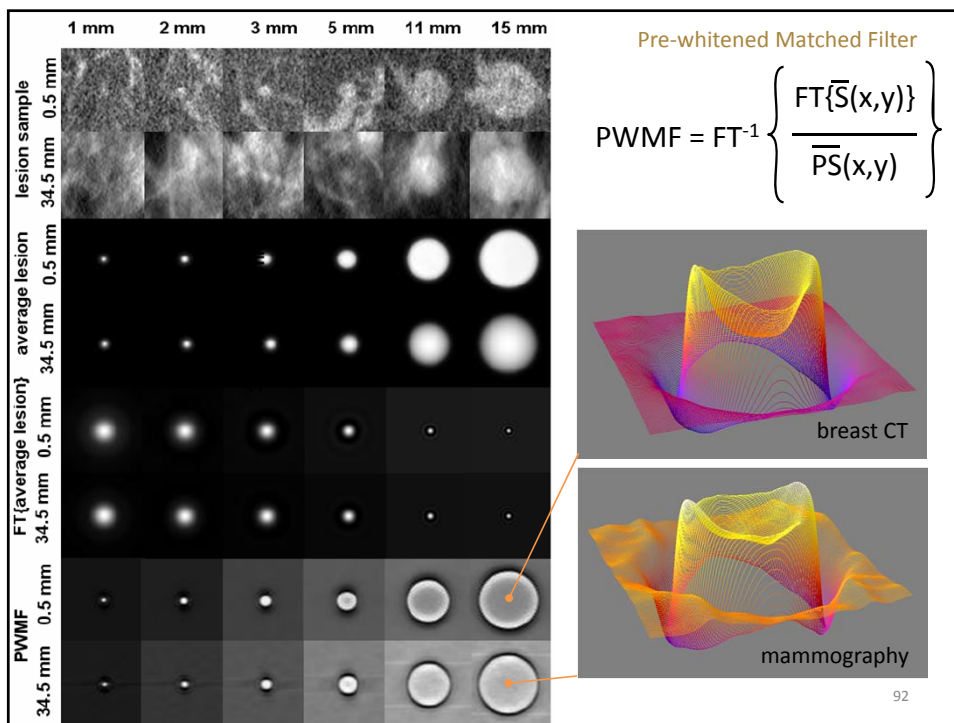
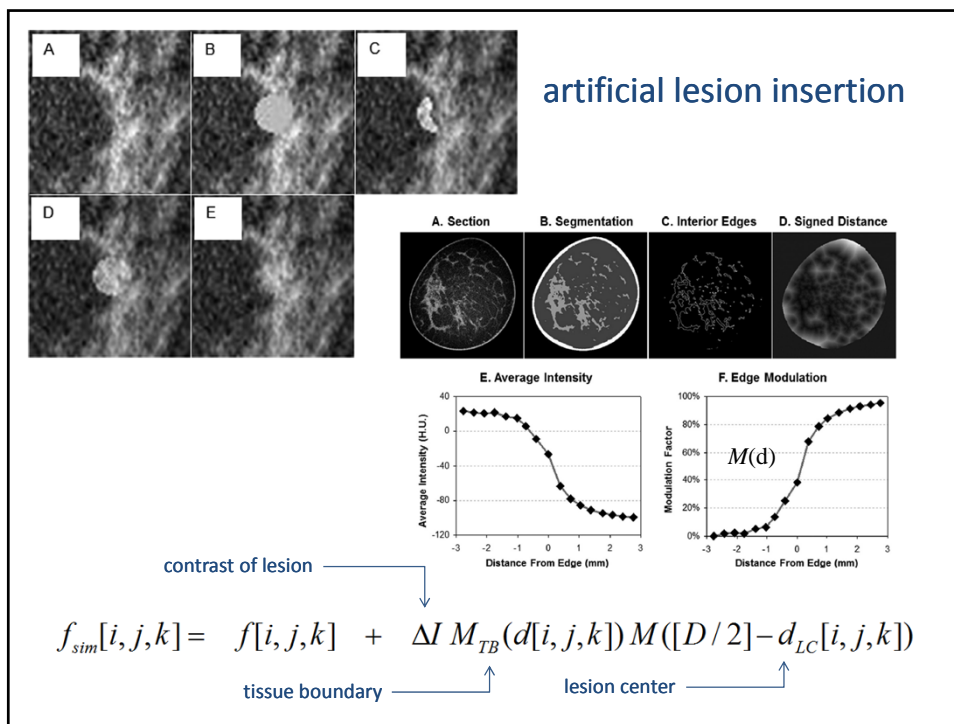
Craig K. Abbey
Department of Psychology, University of California, Santa Barbara, California 93106

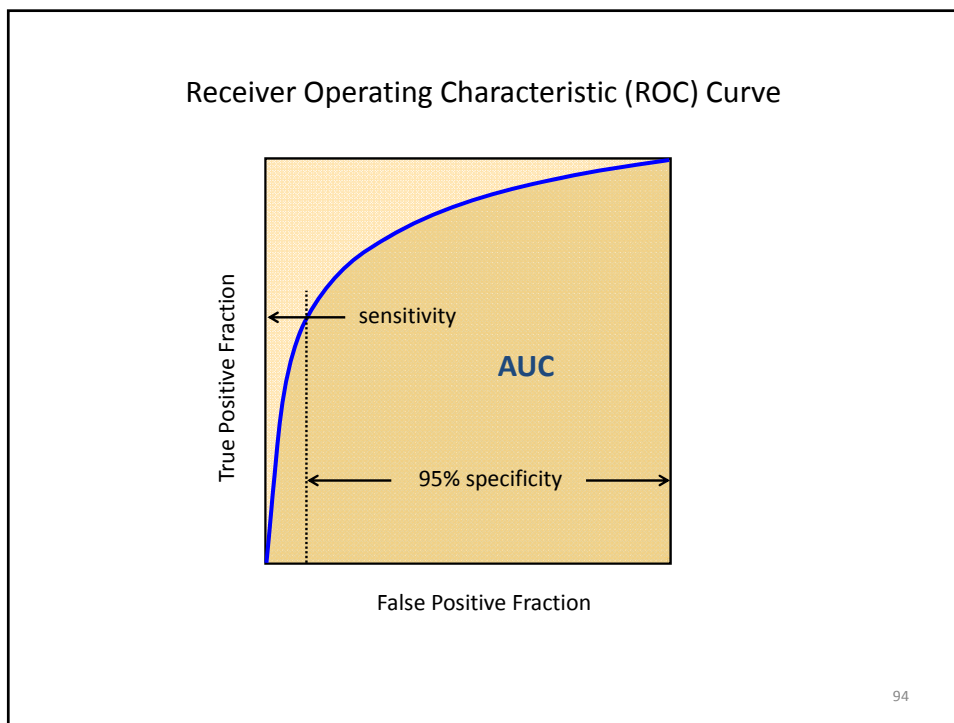
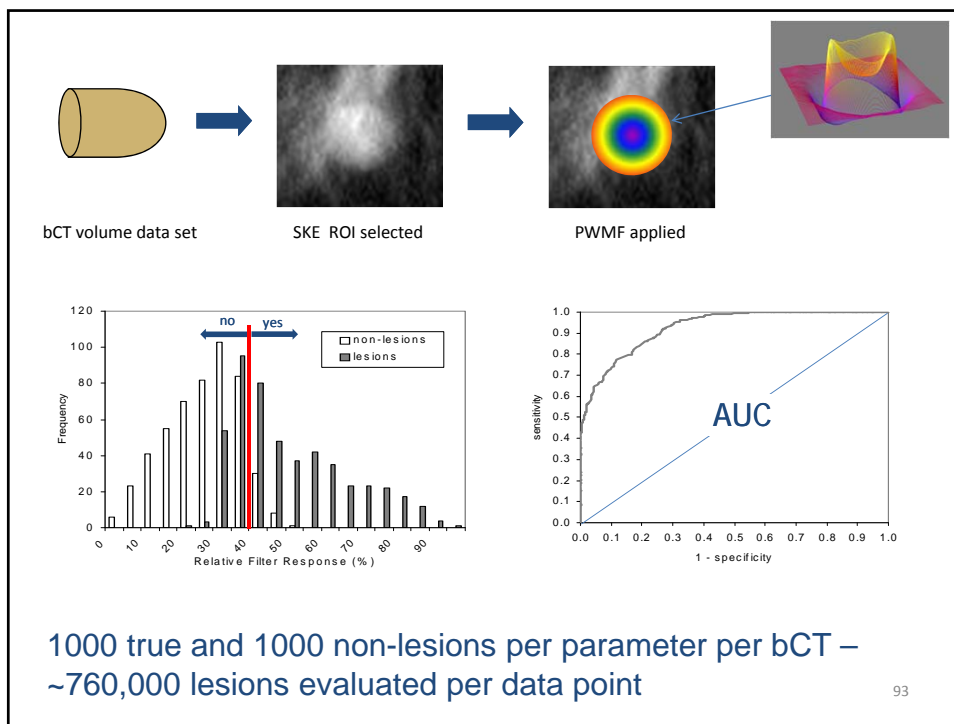
Kai Yang
Department of Radiology, University of California Davis Medical Center, Sacramento, California 95817

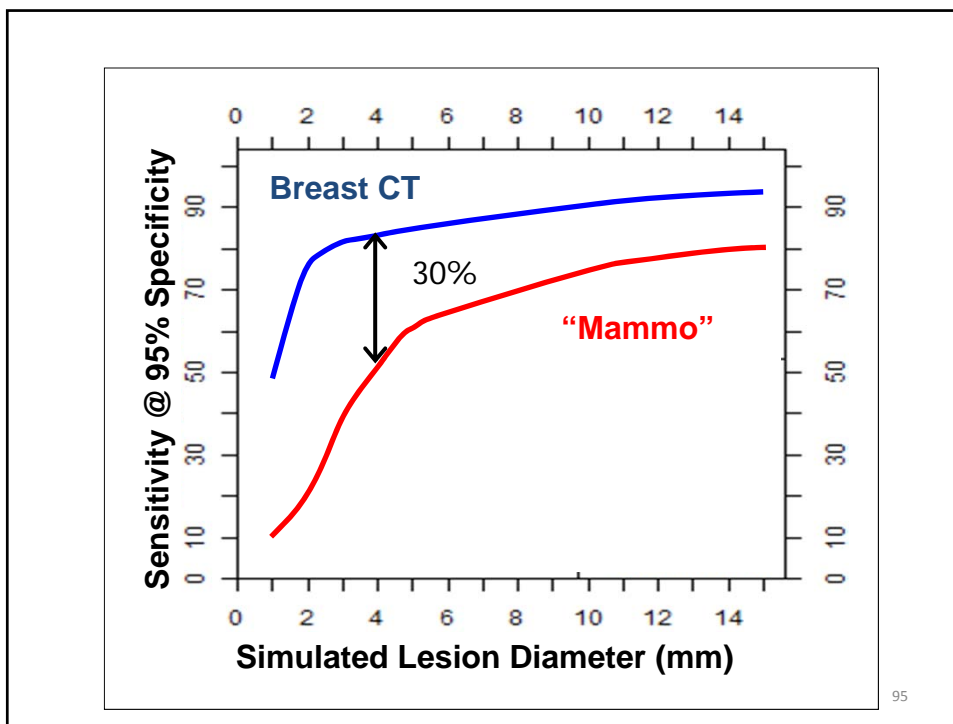
John M. Boone[¶]
Department of Radiology, University of California Davis Medical Center, Sacramento, California 95817 and
Department of Biomedical Engineering, University of California, Davis, California 95616

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

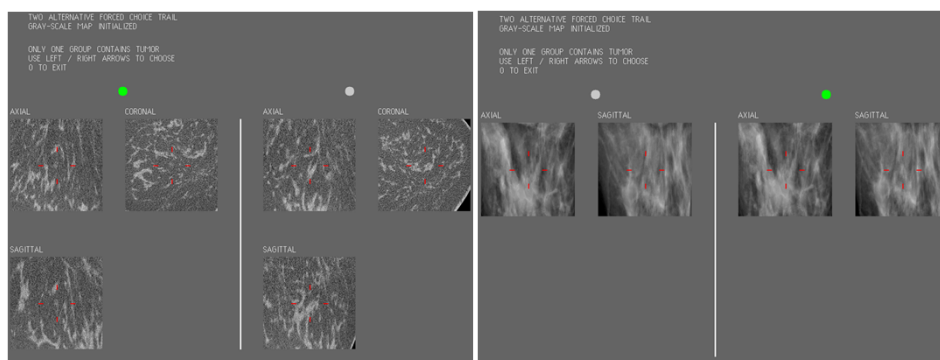






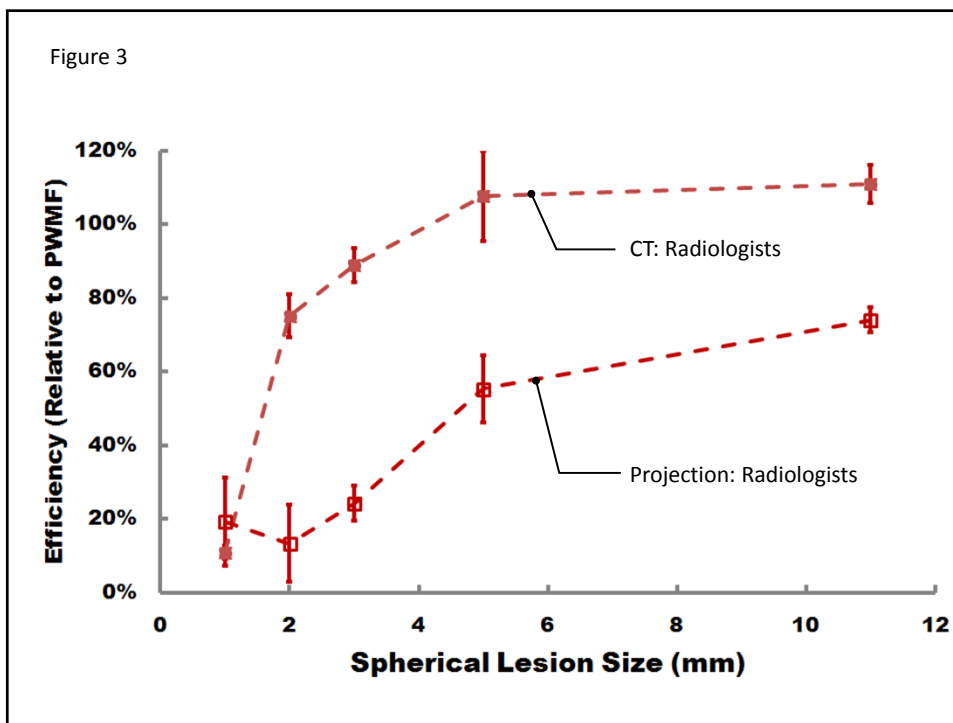
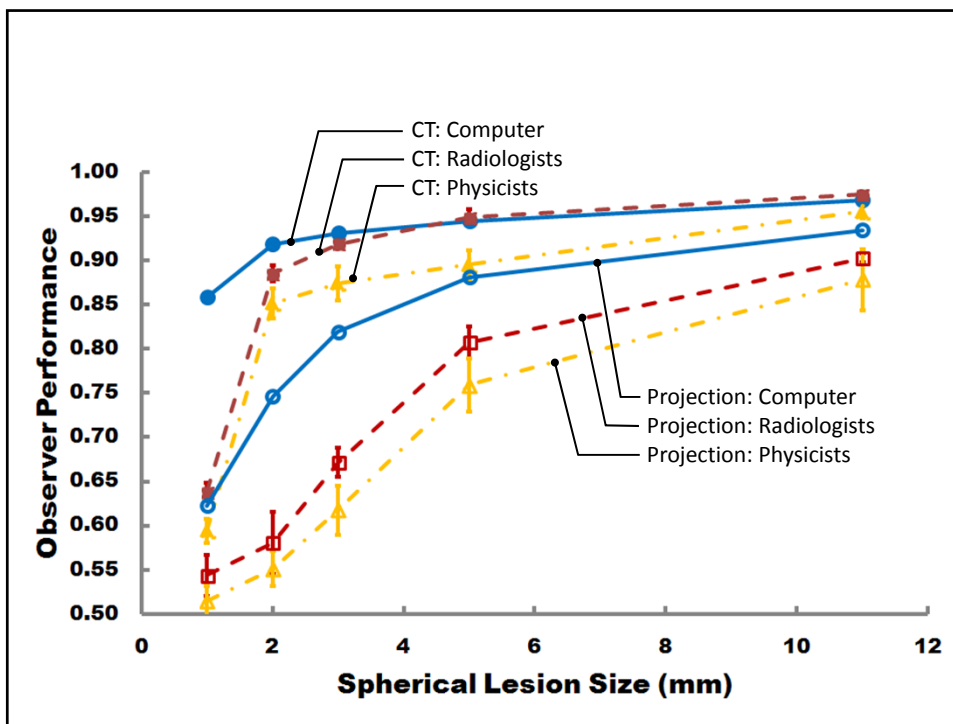


Human Observer Study: 2-Alternative Forced Choice Design



CT images

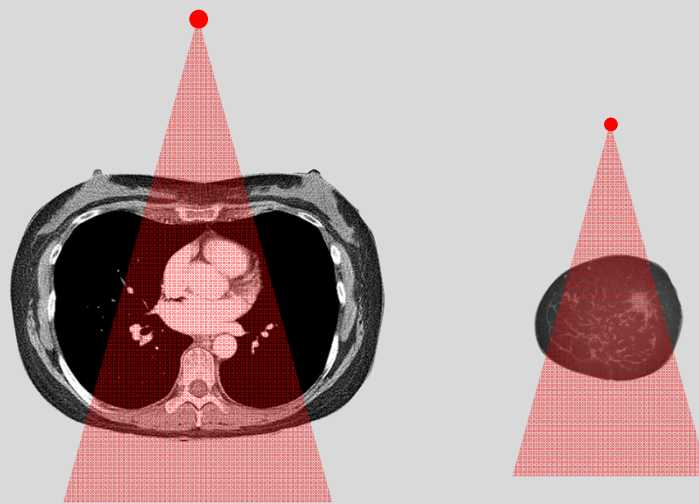
projection images



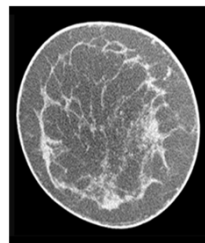
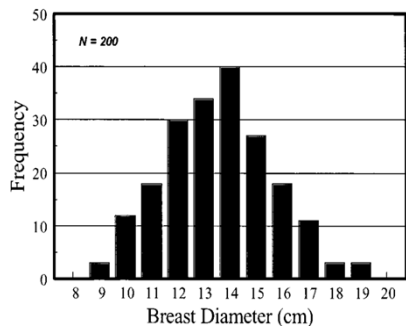
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Radiation Dose from Breast CT ?



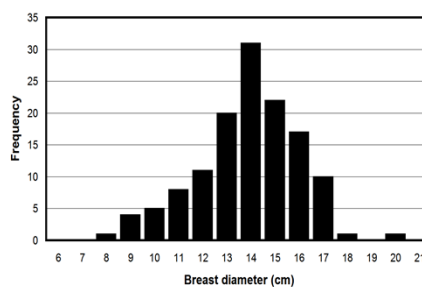
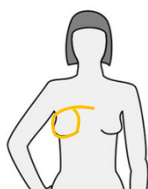
radiation dose is size dependent!



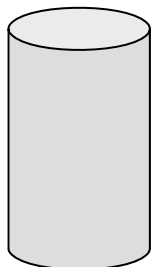
X = 13.4 cm
 σ = 2.0 cm
 Median = 13.6 cm

2008 assessment on bCT images (N = 137)

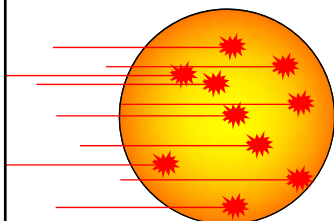
2001 tape measure results (N = 200)



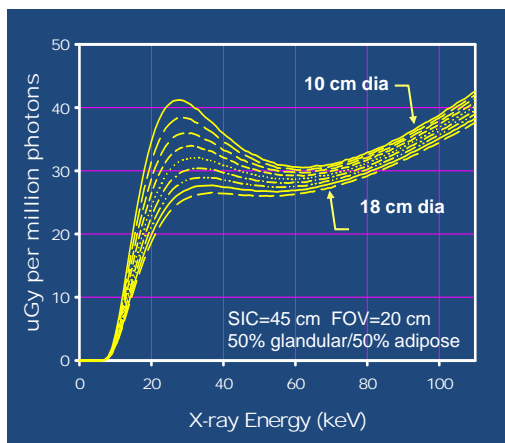
Monte Carlo Assessment of Dose Deposition



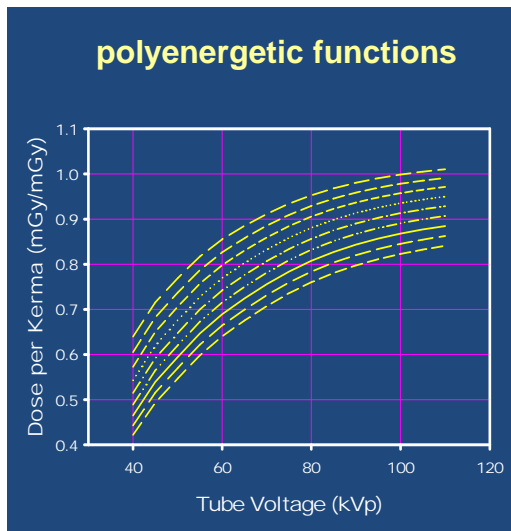
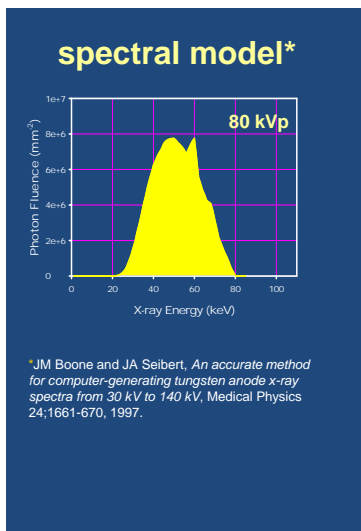
breast modeled as a cylinder



monoenergetic functions



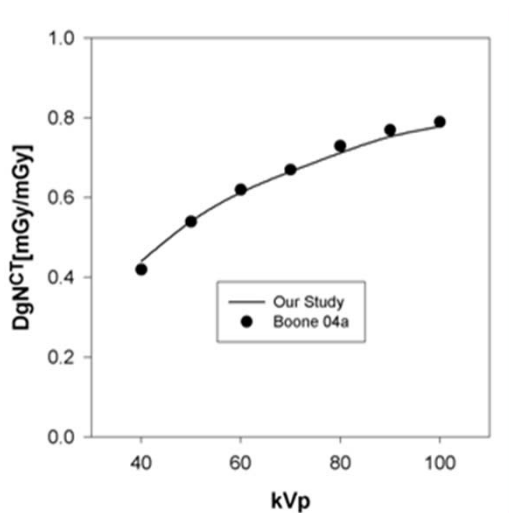
Mean Glandular Dose in Breast CT



Boone JM, *et al.*, Med Phys 2003

103

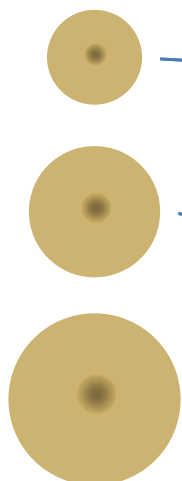
Dose assessment repeated by Thacker/Glick



Thacker S and Glick S, PMB 2004, 5433

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Breast CT technique chart



mA setting on Cambria			
Breast Diameter (cm)	0% Gland	50% Gland	1.00 Gland
10.0	37	51	72
10.5	48	67	95
11.0	59	82	117
11.5	72	100	143
12.0	87	123	175
12.5	106	150	214
13.0	130	184	263
13.5	157	224	322
14.0	189	271	389
14.5	224	323	465
15.0	262	379	548
15.5	301	437	633
16.0	340	495	719
16.5	377	550	800
17.0	409	598	872
17.5	433	636	929
18.0	447	658	964

*Dose in breast CT is set to be **EQUAL** to the dose of two-view mammography for that women.*

Evolution of the UC Davis Breast CT Scanner

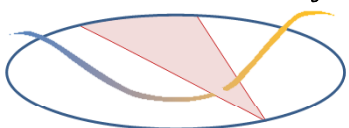
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Summary

- The Breast CT scanners at UC Davis have demonstrated that bCT has considerable potential in clinical imaging
- Hardware at UC Davis was refined over a decade
- Software continues to evolve
- The large data set of breast CT images has proven valuable in better understanding breast anatomy and has provided insight WRT breast imaging modalities
- Breast CT continues to be studied for its role in breast imaging

Evolution of the UC Davis Breast CT Scanner

Breast Tomography Project



University of California Davis



John M. Boone, Ph.D., FAAPM, FSBI, FACR
 Professor and Vice Chair (for Research) of Radiology
 Professor of Biomedical Engineering
 University of California Davis
 Sacramento, California 95817

IEEE Signal Processing Society, September 10, 2014