Physical Principles and Design of Advanced Applications for Digital Mammography

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AAPM SPRING CLINICAL MEETING

Disclosures and Acknowledgements

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Employees of GE Healthcare

Thanks to: Gerhard Brunst
Luc Katz
Remy Klaus
Serge Muller
Henry Souchay
and
Our clinical collaborators for providing example cases

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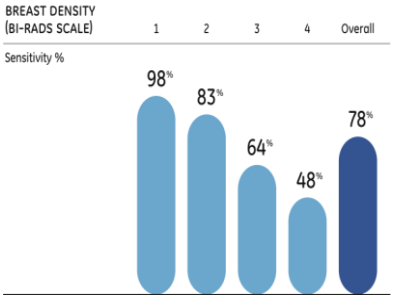
Mammography: A reliable tool with limitations

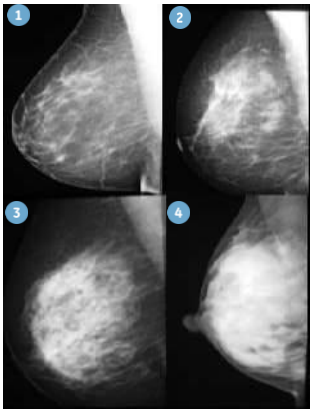
Dense breast tissue can overlap with lesions

Lesions are not always visible with x-ray

Interpretation of images can vary among radiologists



Kolb et al. *Radiology* 2002; 225:165-175.



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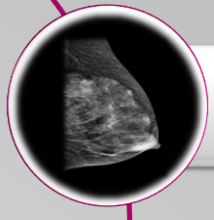
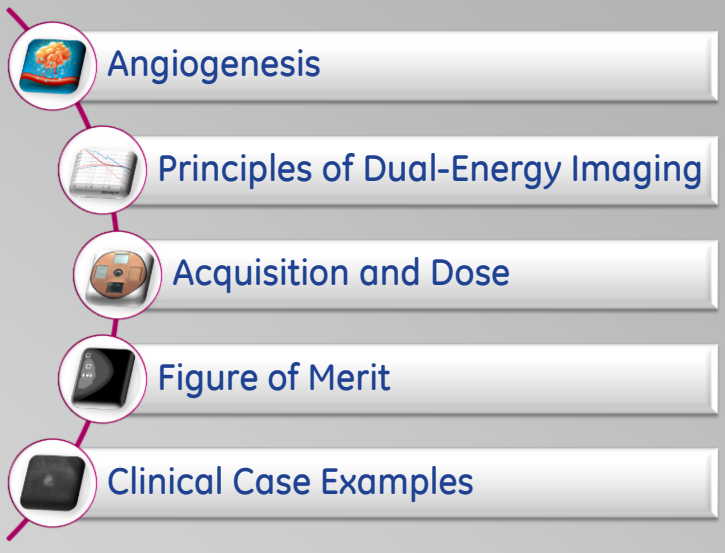
Digital Mammography - Advanced Applications



Contrast Enhanced Spectral Mammography

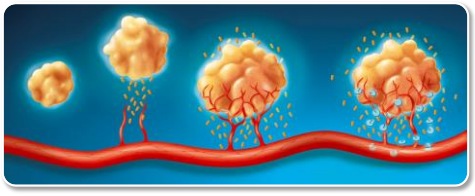
Digital Breast Tomosynthesis

Contrast Enhanced Spectral Mammography



Contrast Enhanced Spectral Mammography

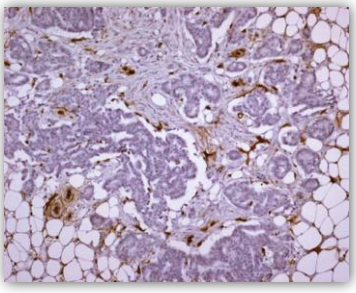
The growth of tumors often requires a dedicated blood supply.



Idea: Use contrast agents in digital mammography to provide contrast-enhanced images

Challenge: Dense overlapping tissue obscures detection of contrast enhancement

Solution: Use multiple x-ray exposures to reduce background signal, effectively highlighting contrast enhanced areas.



Dromain, Clarisse, *et al.* "Evaluation of tumor angiogenesis of breast carcinoma using contrast-enhanced digital mammography." **AJR 187(**5) (2006): W528-W537

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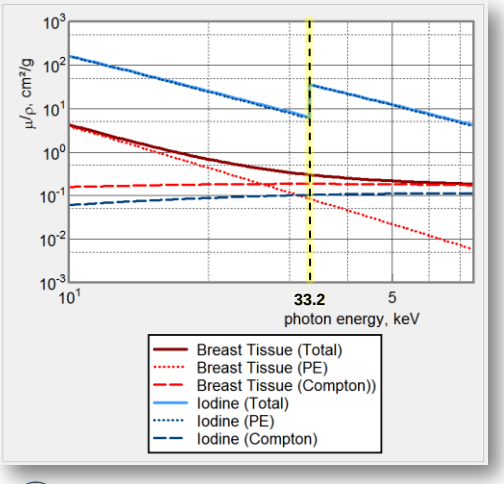
General Principle of Dual-Energy Imaging

Assume:
- Breast is made of 50-50 breast tissue and Iodine contrast agent
- Take two images at two different energies



$$I_L = I_{o,L} \cdot e^{-(\mu_{C,L} \cdot x_C + \mu_{50/50,L} \cdot x_{50/50})}$$

$$I_H = I_{o,H} \cdot e^{-(\mu_{C,H} \cdot x_C + \mu_{50/50,H} \cdot x_{50/50})}$$

Solve for x_C and $x_{50/50}$

Make image of iodine contrast thickness

Exploit energy dependent differences in photoelectric and Compton interaction cross sections

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Principles of CESM

Three components: fibroglandular, adipose, iodine

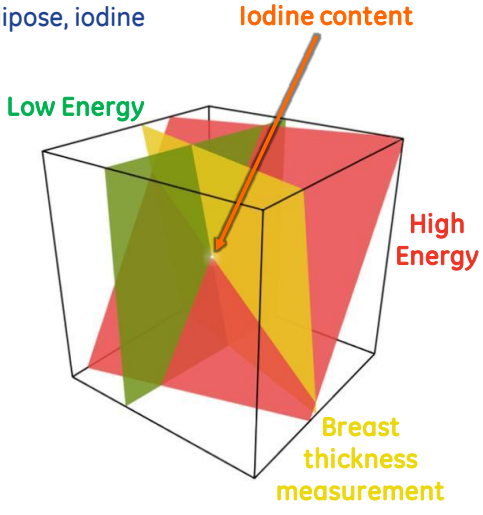
Two objectives for CESM images:

Demonstrate the iodine uptake

Cancel the anatomical texture

→ Iodine content image

Two spectra
+ breast thickness measurement
is needed to reach these two objectives



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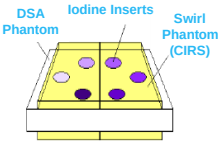
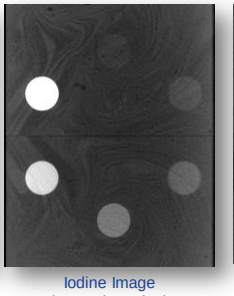
Background Signal Suppression



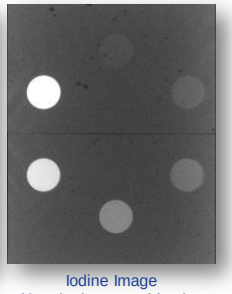
Quadratic recombination of high and low energy images improves subtraction of breast structures that are not enhanced by the contrast medium.

Low Energy
(Rh/Rh, 28 kVp)

High Energy Image
(Rh/Cu, 44 kVp)



Iodine Image
(Log subtraction)



Iodine Image
(Quadratic Recombination Algorithm)

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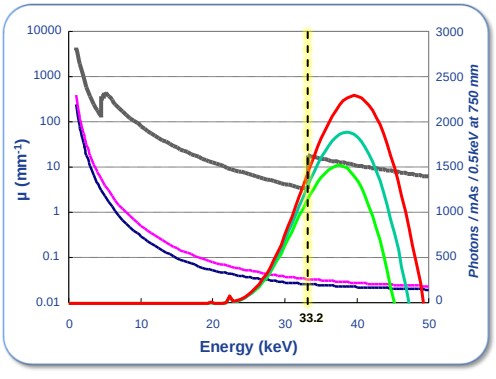
High Energy Acquisition



A high energy x-ray spectrum (mean energy above 33.2 keV – the K edge of iodine) is used to take advantage of the differential attenuation of iodine relative to the soft tissues.

High Energy Image

- Use 45 - 49 kVp
- Cu filtration
- 0.15 – 0.7 mGy per exposure
- Exact dose depends on breast thickness
- About 1/5 of conventional mammogram dose

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CESM Acquisition

Image acquisition – unilateral or bilateral

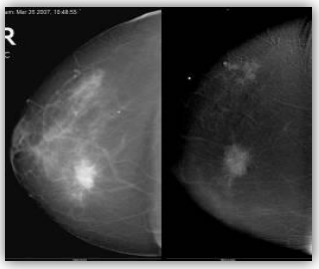
One image with low kVp (→ Low Energy, LE)

One image with high kVp (→ High Energy, HE)

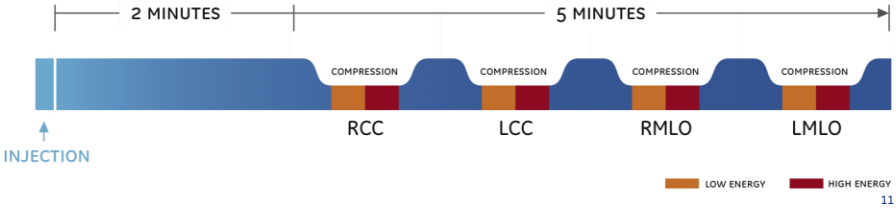
Low and high-energy images acquired successively within short time

Image processing

Low and high-energy image combination



Conventional MX **CESM image**



Dose in SenoBright CESM

Average Glandular Dose (AGD) for 4.2 cm 50/50 breast:

Low Energy (Conventional View) is 1.6 mGy per view

AGD to the population of women* of CESM (LE + HE):

~ 1.2 times the dose of AOP† Contrast‡ mode

AGD to 4.2 cm compressed breast is ~50% AGD of single magnification view (1.8-times mag, using AOP)

* "To Population": AGD averaged over breast thickness and composition in a representative population of women

† AOP: "Automatic Optimization of Parameters", AEC-like control of the Target (Mo or Rh), filtration, kVp, mAs

‡ Contrast Mode: Selects exposure technique to give priority to maximize the Contrast-to-Noise-Ratio, delivers higher dose than "Standard" and "Dose" modes.

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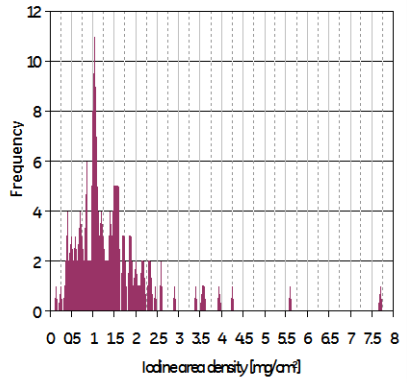
Figure of Merit: Visibility of Iodine



From clinical data:

In 93% of cases:

Iodine content > 0.5 mg cm^{-2}

QC process is designed to ensure 0.5 mg/cm² iodine is more visible than the residual breast texture

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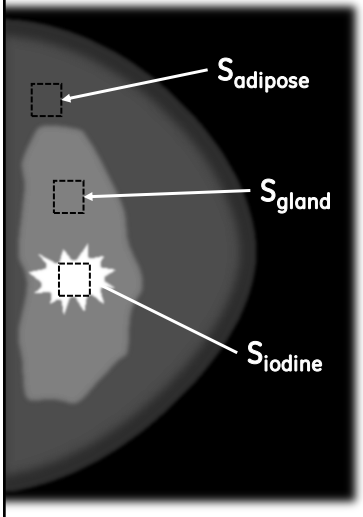
Measurement Method For Iodine Visibility



Texture cancellation in recombined image

$C_{texture} = S_{adipose} - S_{gland}$

Iodine contrast in recombined image

$C_{iodine} = S_{iodine} - S_{gland}$

Tested for iodine concentration of 0.5 mg cm^{-2}

Ratio between residual texture and iodine contrast

$R_{iodine} = C_{texture} / C_{iodine}$

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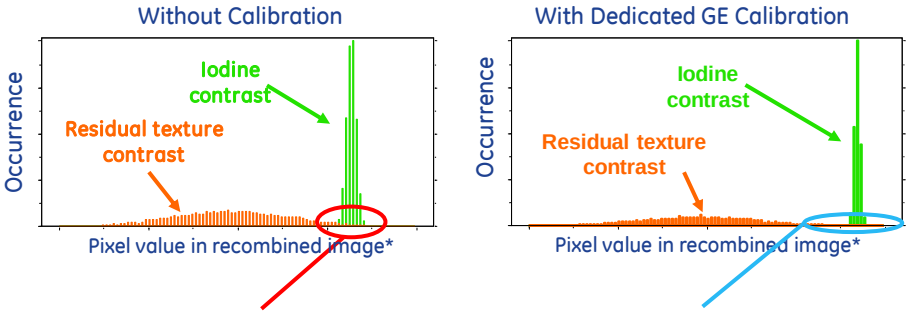
Dedicated Calibration



Residual texture and 0.5 mg/cm² iodine not separated
Target met in 93% of cases

Separation of iodine from residual texture in more than 99% of cases

Dedicated calibration ensures that the combination algorithm parameters are tuned for the real system

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** Simulated data*

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CESM: Indication for use

Contrast Enhanced Spectral Mammography (CESM) is an extension of the existing indication for diagnostic mammography with the Senographe Essential or Senographe DS.

The CESM application shall enable contrast enhanced breast imaging using a dual energy technique.

This imaging technique can be used as an adjunct following mammography and ultrasound exams to localize a known or suspected lesion

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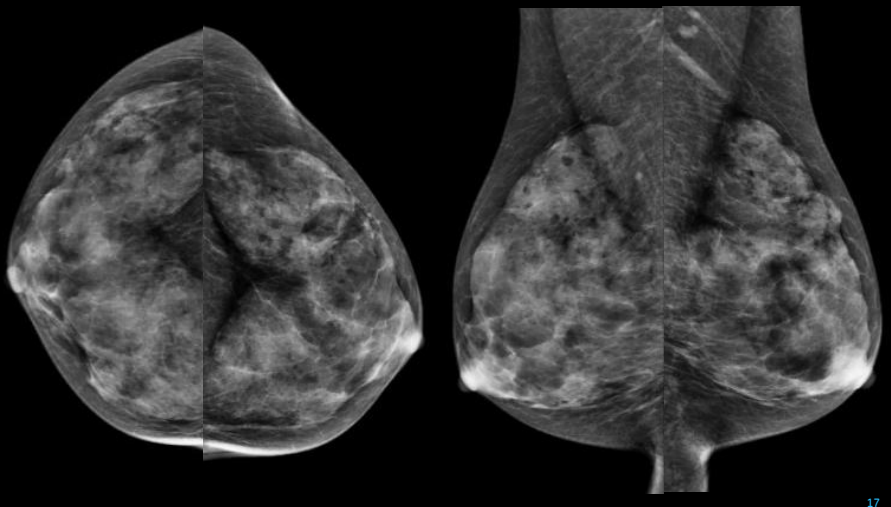
SenoBright – Case 1

79 yo with palpable mass on left breast, original mammography



Images courtesy of Mikawa Breast Center, Mikawa, Japan

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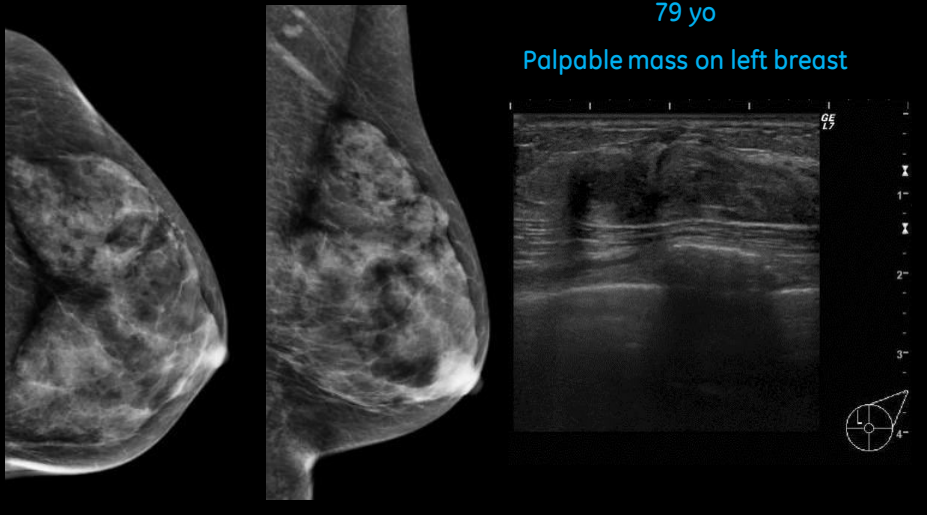
SenoBright – Case 1

79 yo

Palpable mass on left breast



Images courtesy of Mikawa Breast Center, Mikawa, Japan

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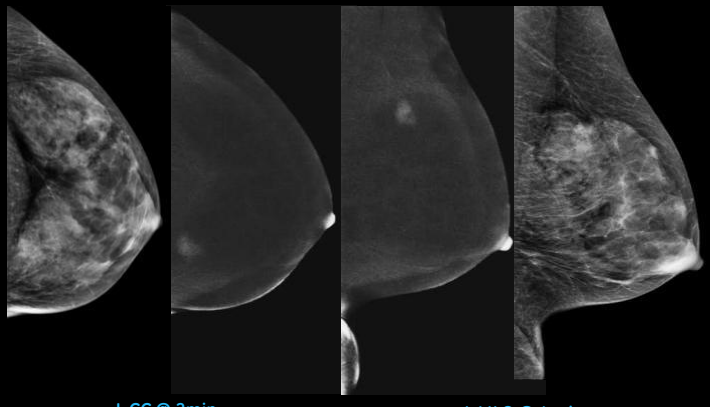
SenoBright – Case 1

79 yo w palpable mass on left breast

SenoBright contrast-enhanced images clearly localize the lesion



L CC @ 2min

Low Energy Contrast-Enhanced

L MLO @ 4 min

Contrast-Enhanced Low Energy

Images courtesy of Mikawa Breast Center, Mikawa, Japan

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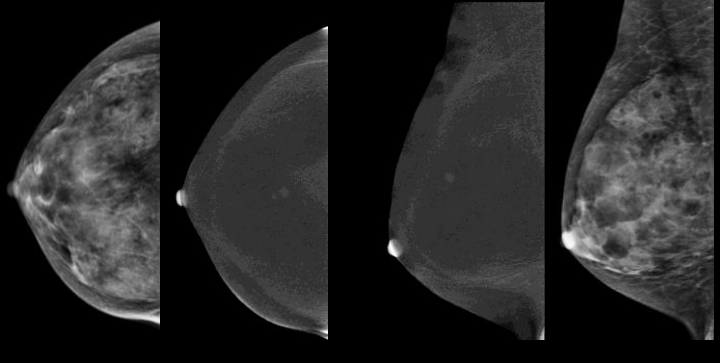
SenoBright – Case 1

79 yo w palpable mass on left breast

Unsuspected finding on right breast

2 small fibroadenomas



R CC @ 3min

Low Energy Contrast-Enhanced

R MLO @ 5 min

Contrast-Enhanced Low Energy

Images courtesy of Mikawa Breast Center, Mikawa, Japan

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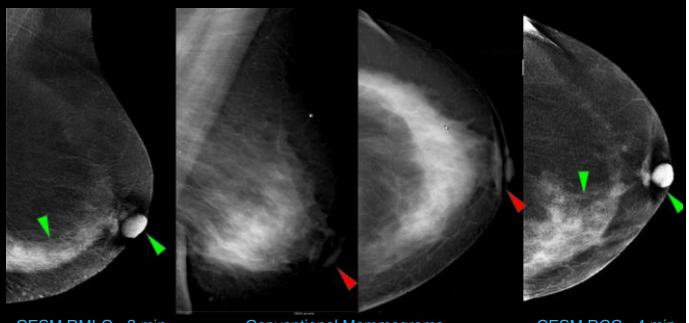
SenoBright – Case 2

Physical Examination:
Nipple stiffness for 1 year

Mammography:
Nipple & areola thickening

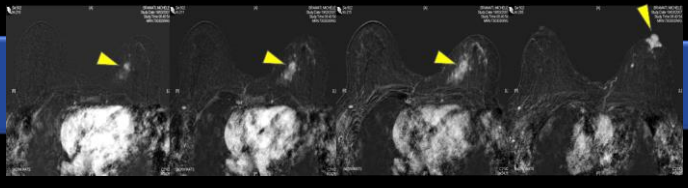
Ultrasound:
Normal

Nipple Biopsy:
Invasive lobular carcinoma



CESM RMLO - 2 min | Conventional Mammograms | CESM RCC - 4 min

Indication for MRI to assess extent of disease



Invasive Lobular Carcinoma (Surgery)

Excellent correlation between CESM and MRI images

Dr Dromain
IGR – Villejuif, France

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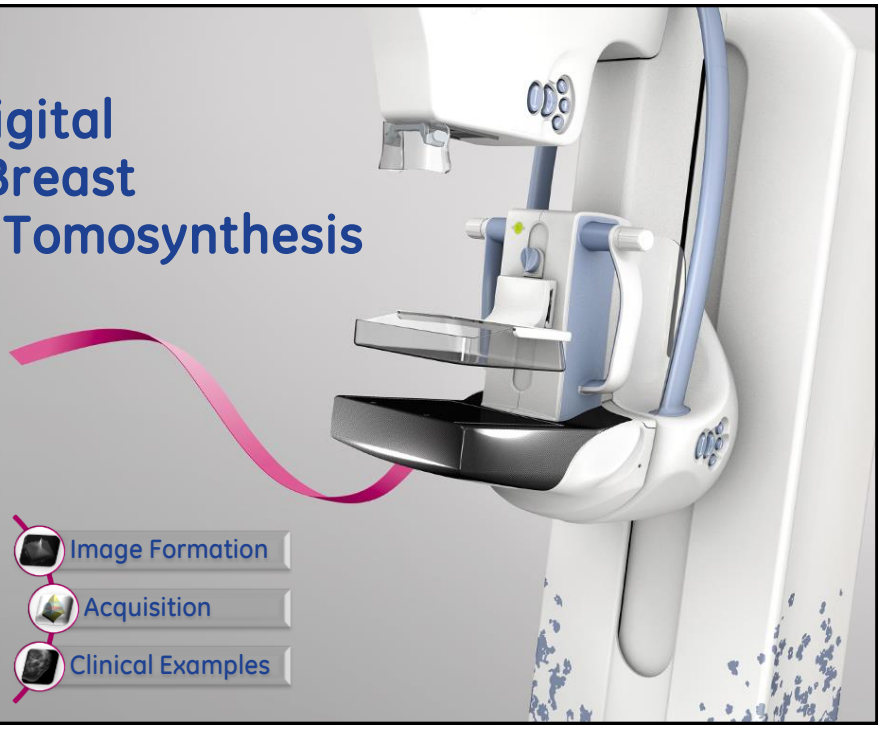
Digital Breast Tomosynthesis



- Image Formation
- Acquisition
- Clinical Examples

Digital Breast Tomosynthesis - Image Formation

- Tomosynthesis – How it's done
- Reconstruction
- Iterative Reconstruction
- Slices or Planes
- DICOM images

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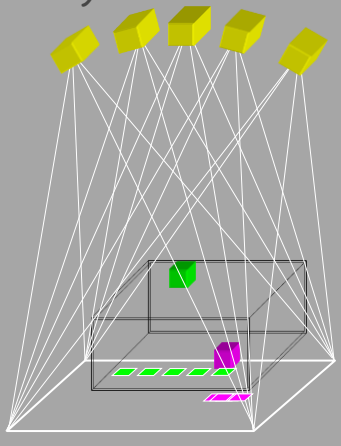
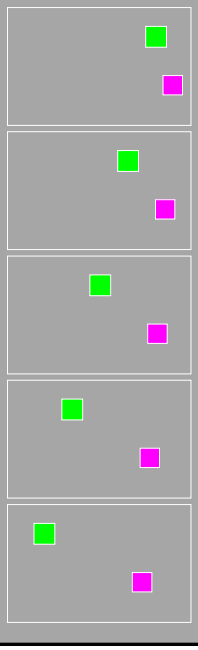
Tomosynthesis

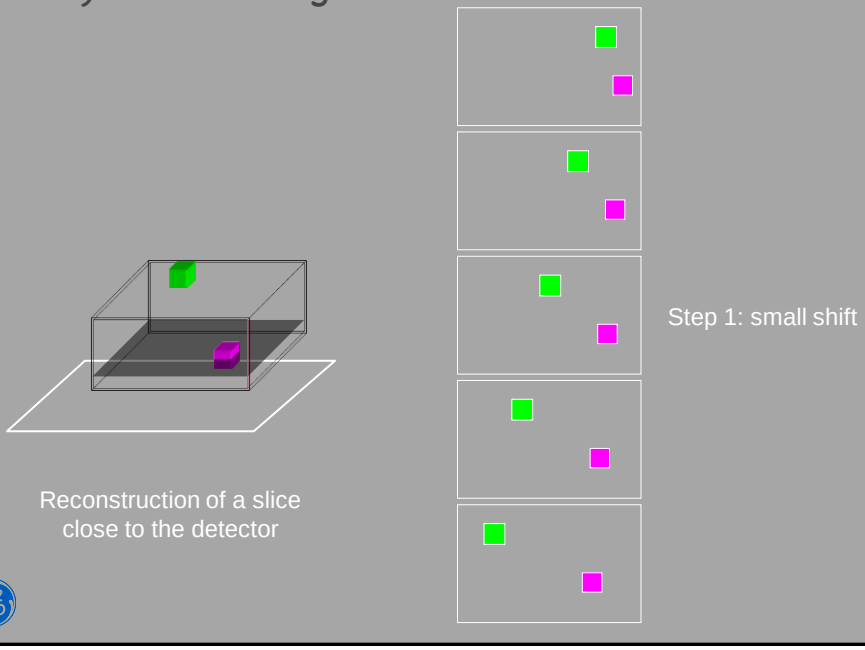


Acquisition of N projected views at different angles



N projected views

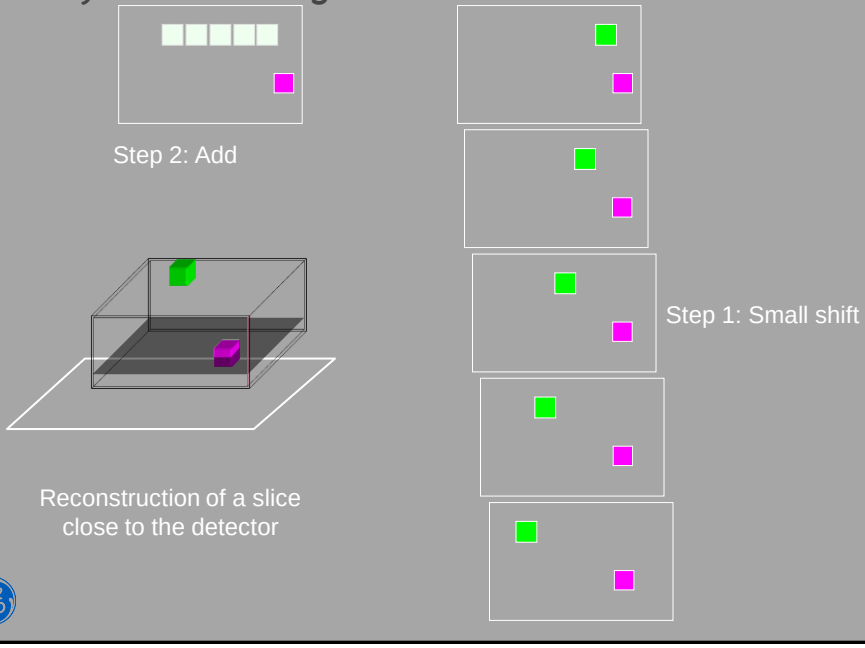
Tomosynthesis: Image Reconstruction



Reconstruction of a slice close to the detector

Step 1: small shift

Tomosynthesis: Image Reconstruction

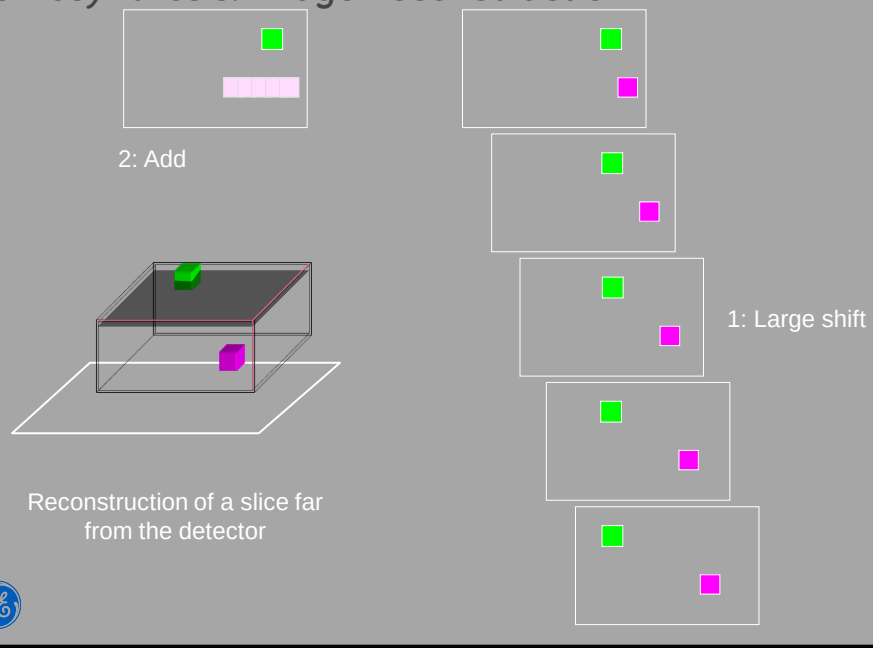


Step 2: Add

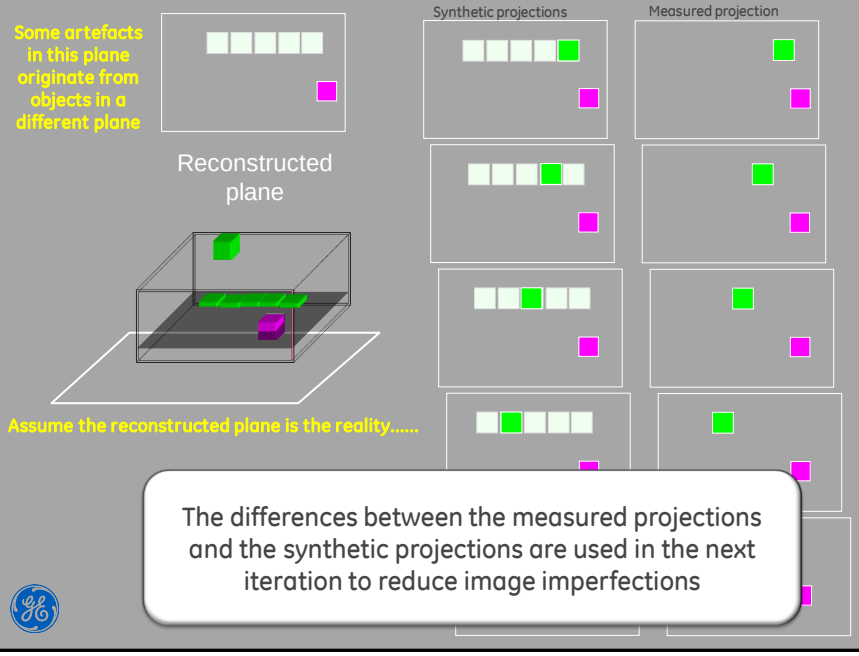
Step 1: Small shift

Reconstruction of a slice close to the detector

Tomosynthesis: Image Reconstruction

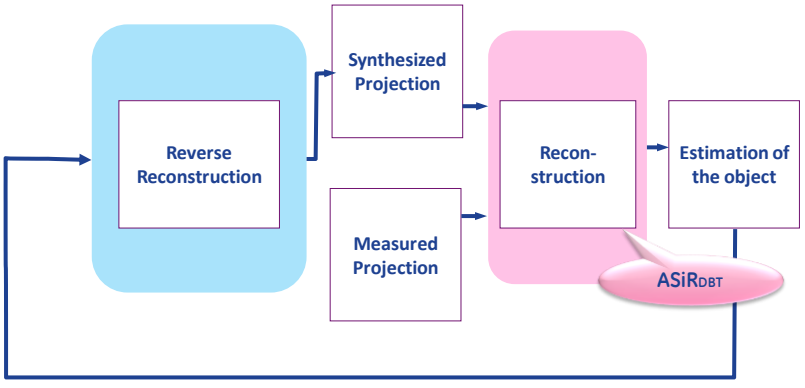


Tomosynthesis: Iterative Reconstruction



The differences between the measured projections and the synthetic projections are used in the next iteration to reduce image imperfections

Reconstruction: ASiR$_{DBT}$



- Iterative reconstruction is a time consuming process.
- **ASiR$_{DBT}$** (Adaptive Statistical Iterative Reconstruction) enables **dose reduction and mitigation of artefacts**

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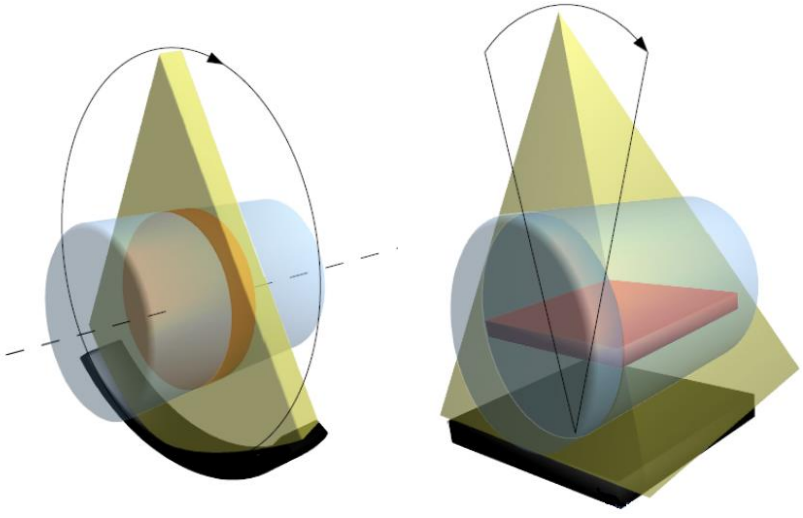
Tomosynthesis – Limited Angle Acquisition



CT-Geometry

Mammo-Tomosynthesis

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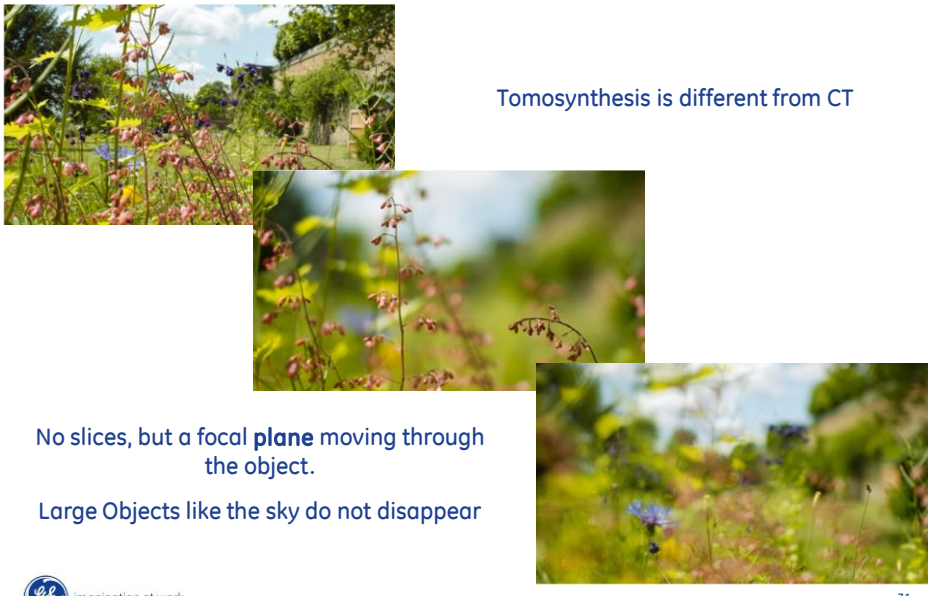
Tomosynthesis is analagous to a photography focus sweep



Tomosynthesis is different from CT

No slices, but a focal **plane** moving through the object.

Large Objects like the sky do not disappear

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Image Sequence by Henry Souchay

Finite Thickness Slices or Tomographic Planes?

- "slice" and "slice thickness" from axial transverse CT do not have the same meaning for tomosynthesis images
- Tomographic images represent strict geometric planes, with some information from the neighbor planes blurred proportionally to their distance to the tomographic plane (depth of focus)
- It is critical to sample the object volume with reconstructed planes separated by a distance consistent with the depth of focus
- Thick slices (slabs) can/should be used in addition to tomographic planes

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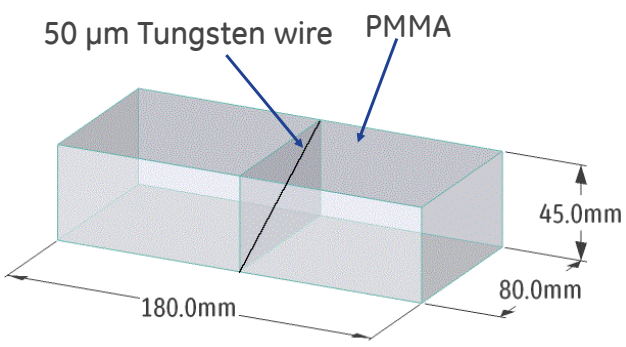
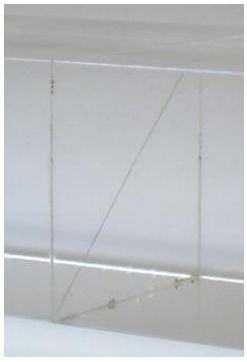
Depth of Focus – Artefacts, Slanted Wire Method





Slanted tungsten wire much smaller than the system point spread function (PSF)

Imaging a section of the wire provides this PSF

Wire angulation allows to demonstrate the plane to plane PSF variations into the tomographic plane image (Littleton, 1965…)

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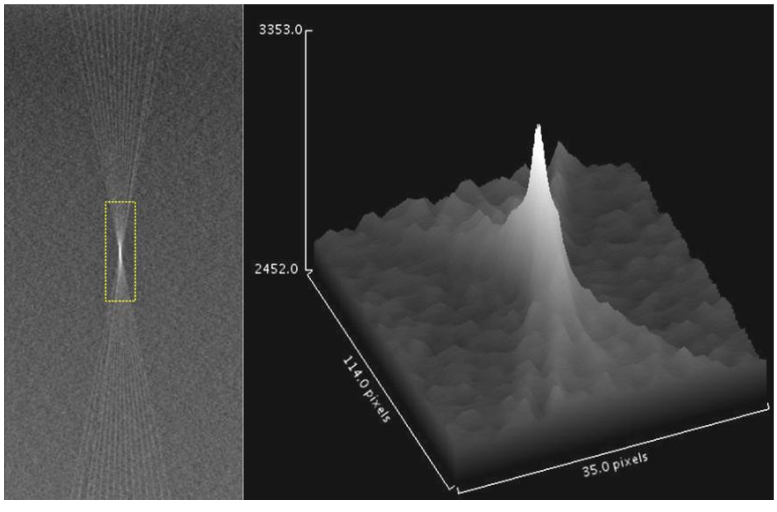
Results confirm theory:
Sharp peak/ Triangular profile



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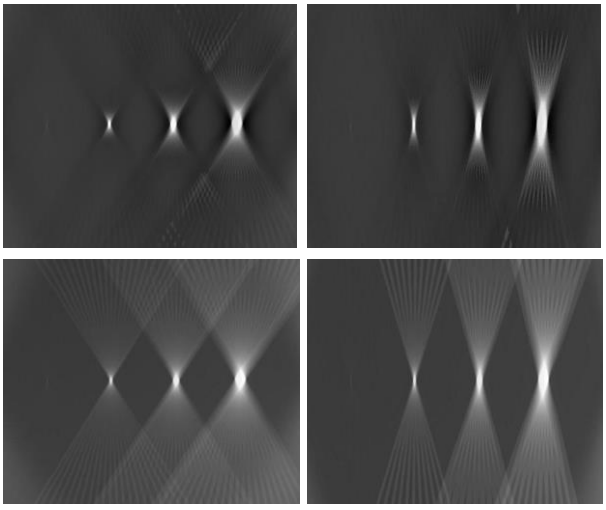
Tomosynthsisis Depth Resolution



21 Views, 60 Degrees 11 Views, 30 Degrees

- Artefact spread in z-direction depends on tomo angle and reconstruction algorithm
- "Slice thickness" determined by progressive blurring of out-of- plane structures
- Actual thickness undefined

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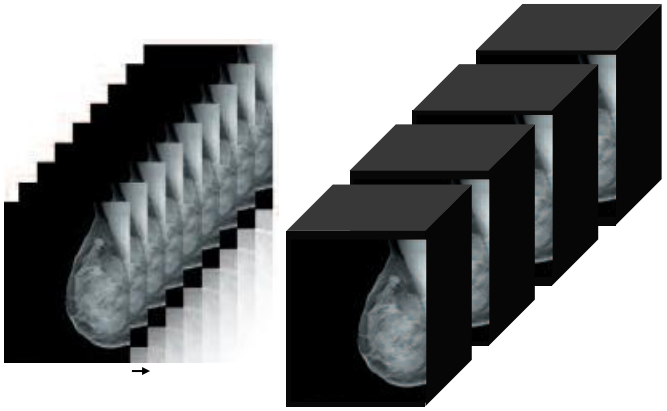
J. Eberhard, D. Albagli, A. Schmitz, B. Claus, P. Carson, M. Goodsitt, HP. Chan, M. Roubidoux, J. Thomas, J. Osland, "Mammography Tomosynthesis System for High Performance 3D Imaging" IWDM 2004, Durham, NC

Planes, Slabs, and Synthetic 2D



(Not for diagnosis only on IDI workstation)

Tomo-Planes
(0.5mm or 1.0mm distance)

Slab = 1 cm thick
5mm overlap

V-Preview
Synthetic 2D image
from 3D data

3 data files in BTO DICOM format

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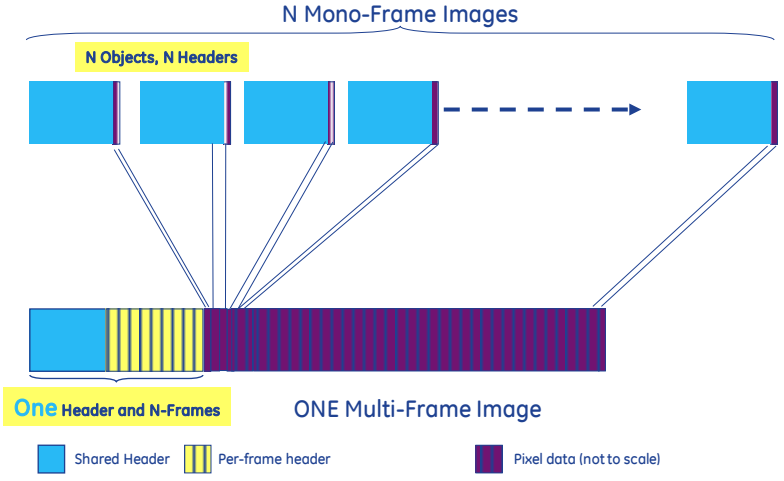
Breast Tomo Object

It is a multi frame object = *One DICOM object with several 2D images*



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SenoClaire Exam Size

Exam = (9 projections + Planes + Slabs) x 2

Size of each frame -> Cropping ratio -> Breast size

Consider 3 case examples:

	Thickness	Cropping Ratio	No. Of frames in Slabs	No. Of Frames in planes (0.5mm)	No. Of frames in planes (1mm)
Small Breast	14mm	10:1	4	39	20
Medium Breast	44mm	3:1	10	99	50
Large Breast	80mm	1:1	18	171	86

Exam size depends on:
Number of frames -> Z-Sampling (1 mm vs 0.5 mm) -> Breast thickness

Examples: Small breast 1.0 mm z-sampling 334 MB
Large Breast 0.5 mm z-sampling 5.805 MB

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Digital Breast Tomosynthesis - Acquisition

- Sweep Angle
- Number of Projections
- Step and Shoot
- Binning
- Scatter Control
- Dose

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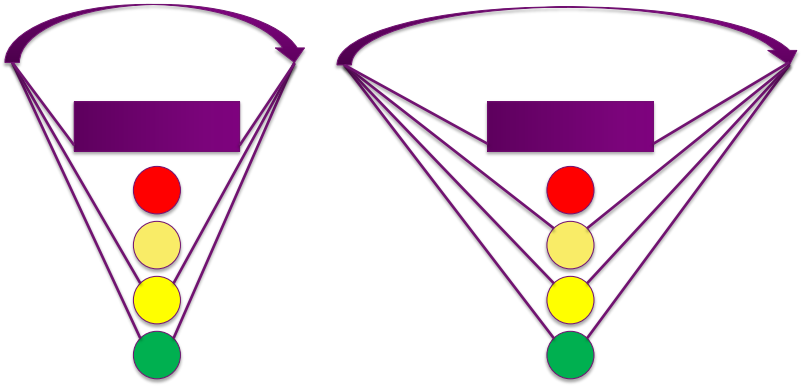
Sweep Angle



With a wider sweep angle you can separate closer objects

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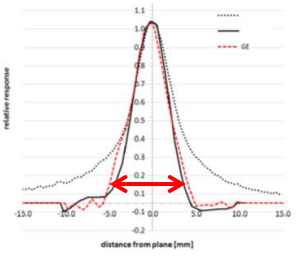
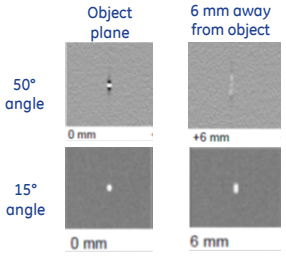
Z-Resolution: Image 1 mm Al Sphere



DBT system	FWHM (mm)
vendor b	4.6
vendor a	5.4
GE	4.8



Artefact Spread Function (ASF):

$$ASF(z) = \frac{\bar{\mu}_S(z) - \bar{\mu}_B(z)}{\bar{\mu}_S(z_0) - \bar{\mu}_B(z_0)}$$

$\bar{\mu}_S$: Mean DU values of the sphere
$\bar{\mu}_B$: Mean DU values of the background
z_0: Off-focus plane
z: Off-focus plane

- Resolution in z-direction (plane-to-plane) is poor for DBT systems with small sweep angles
- Wider sweep angle also increases blur of out-of-plane structures

N.Marshall, H.Bosmans, 29th annual meeting **of BHPA**, Feb. 2014, "Application of the draft EUREF protocol for QC of digital breast tomosynthesis (DBT) systems" http://2014.bhpa.eu/wp-content/uploads/formidable/Marshall_Nicolas.pdf

T. Wu, *et al*, "A comparison of reconstruction algorithms for breast tomosynthesis," *Med. Phys.* **31**, 2636–2647 (2004)

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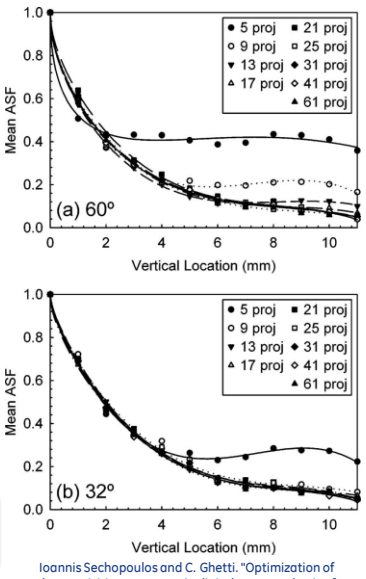
Number of Projections

Objectives:

Increase vertical resolution
Reduce artefacts

- Vertical resolution is limited by the angular range, and the number of projections should be the minimum required to obtain the best possible ASF
- Increasing the number of projections beyond that required to minimize out-of-plane artefacts does not further improve the vertical resolution
- In-plane image quality is inversely proportional to the number of projections (constant dose)

For typical DBT sweep angles, relatively few projections are required.



Ioannis Sechopoulos and C. Ghetti. "Optimization of the acquisition geometry in digital tomosynthesis of the breast." ***Medical Physics* 36**.4 (2009): 1199-1207.

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Motion Blur

When the object (or the tube) moves during acquisition, the object is blurred in the direction of the motion (red arrow), but not in the direction orthogonal to the motion (blue arrow)

In the direction of motion: object is blurred – spatial resolution is reduced

Orthogonal to motion: Object not blurred – spatial resolution maintained

Stop-and-shoot avoids motion blur - Spatial resolution is maintained in all directions

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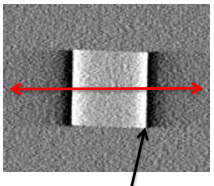
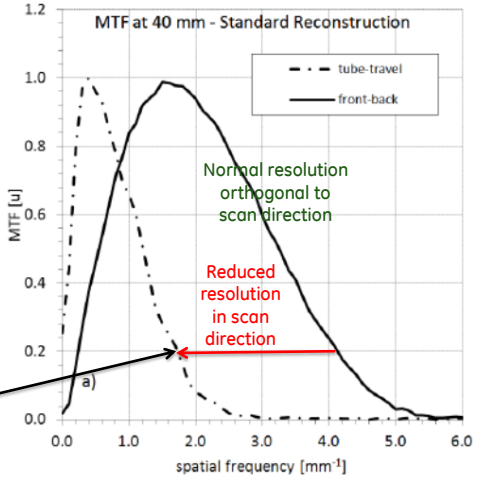
Spatial Resolution DBT

Non-isotropic spatial resolution
Objects sharp in front-back direction, unsharp in the sweep direction



Motion blur leads to reduced spatial resolution



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Step and Shoot

Step and shoot avoides motion blur

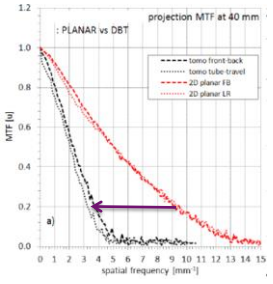
Pixel Binning

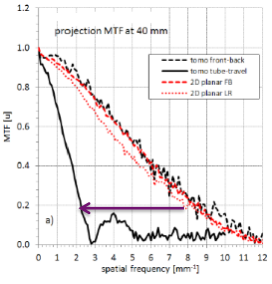
Binning 2x2 means a set of 4 pixels are fused to a single one

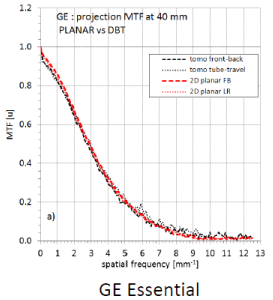
Saves reading time and/or processing time
Less data to transfer and archive

Loss of spatial resolution

Spatial Resolution – MTF of Projections







GE Essential

System A:
Loss in spatial resolution compared to 2D **in both directions**
- Result of binning

System B:
Loss in spatial resolution **in one direction** compared to 2D in sweep direction only
- No binning, but loss due to motion blurr

GE System:
No loss in spatial resolution compared to 2D in all directions
- no binning, no motion blurr due to stop-and-shoot

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Grid or no grid?

Original image

Scatter reduces image contrast

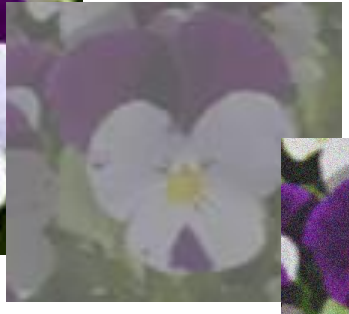

Image processing can recover the contrast, but at the expense of increased noise

For thick breasts that create a lot of scatter, image quality is deteriorated or higher dose is needed to overcome the increased noise

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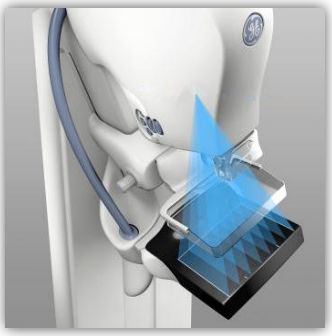
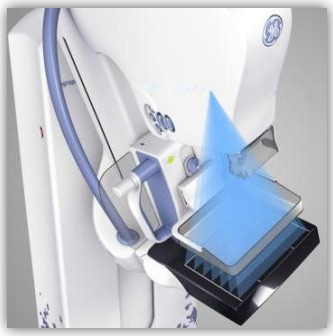
SenoClaire Grid



Traditional 2D grid
View of system positioned for a left MLO view



2D/3D grid
View of system positioned for a left MLO view

GE SenoClaire is **first DBT with an antiscatter solution**

Grid works for both 2D and 3D

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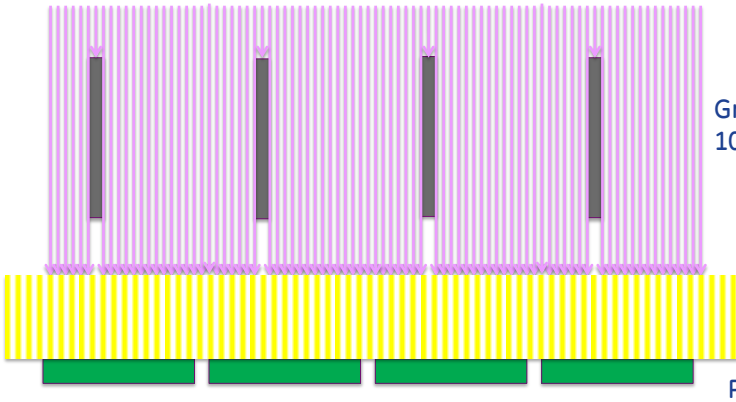
3D Grid: Grid and Pixel Matrix with same Period



Each pixel coincides with one grid line
Therefore each pixel gets the same signal
First order grid structure is eliminated in the image
Some additional oscillation will totally remove grid structure

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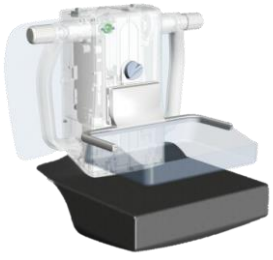
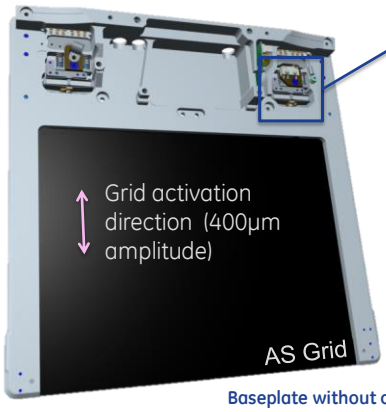
Grid Integration

Rotating the grid leaves very little space for the grid activation amplitude:

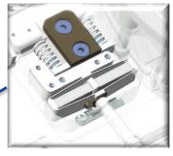
- Need for compact, high precision actuators: piezo electric transducers
- Need to match the grid lines frequency to the detector pitch: new high frequency graphite grid



Motorized Tomosynthesis Device



Baseplate without covers



Close Up of Piezo Actuator

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DBT Dose

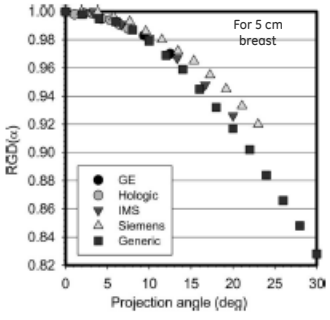
Relative Glandular Dose (RGD):

$$RGD(\alpha) = \frac{D_g N(\alpha)}{D_g N(0°)}$$

Average Relative Glandular Dose (RGD):

$$D_g N_{TOMO} = D_g N_{MAMMO} \cdot \frac{1}{N_\alpha} \cdot \sum_{\alpha=\alpha_{min}}^{\alpha=\alpha_{max}} RGD(\alpha)$$

$$D_g N_{TOMO} = D_g N_{MAMMO} \cdot \overline{RGD}$$

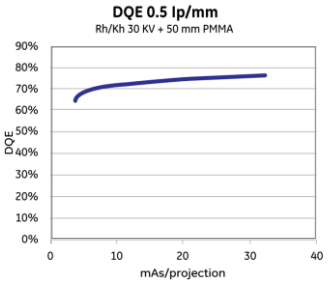


$$\overline{RGD} \cong 1\,,\ \Delta < 5\%$$

Hence, mammography (0°) glandular dose values can be used to estimate tomosynthesis acquisition dose

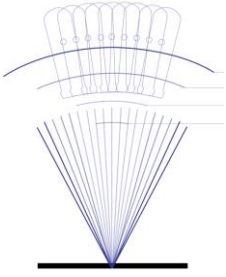
AAPM PUBLICATIONS http://www.aapm.org/pubs/reports/RPT_223.pdf

SenoCaire Acquisition – Dose Implications



High DQE even at very low exposures enables low dose projection acquisitions

The dose is equally distributed among the 9 projections



Thickness (cm)	Angle			$\overline{RGD}$
	0°	6.25°	12.5°	
2	1.000	0.996	0.982	0.994
3	1.000	0.994	0.979	0.992
4	1.000	0.993	0.974	0.990
5	1.000	0.992	0.970	0.989
6	1.000	0.993	0.969	0.989
7	1.000	0.991	0.966	0.987
8	1.000	0.991	0.963	0.986
9	1.000	0.991	0.961	0.986

Sechopoulos, I., Sabol, J. M., Berglund, J *et al*, (2014). Radiation dosimetry in digital breast tomosynthesis: Report of AAPM Tomosynthesis Subcommittee Task Group 223. ***Medical Physics*, *41***(9), 091501.

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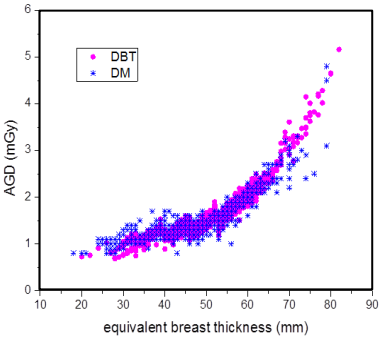
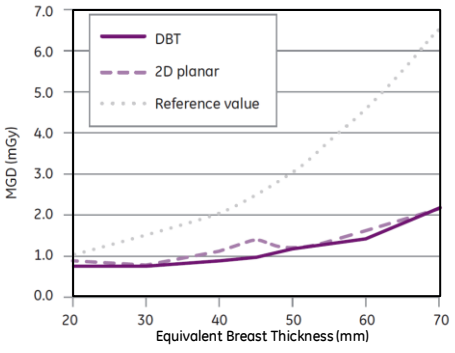
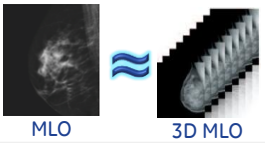
SenoClaire Dose







1-view SenoClaire DBT dose is the sames as 1-view 2D Mammography

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GE SenoClaire: Indications for use:

GE SenoClaire ...

acquires 2D images and also acquires multiple projection views to produce 3D DBT images suitable for screening and diagnosis of breast cancer. SenoClaire can be used for the same clinical applications as traditional mammographic systems for screening mammograms.

A screening examination will consist of:

- a 2D image set consisting of a craniocaudal view and a mediolateral oblique view, or
- a 2D craniocaudal view and 3D DBT mediolateral oblique image set.

The SenoClaire Digital Breast Tomosynthesis (DBT) option for the Senographe Essential FFDM system may also be used for additional diagnostic workup of the breast.

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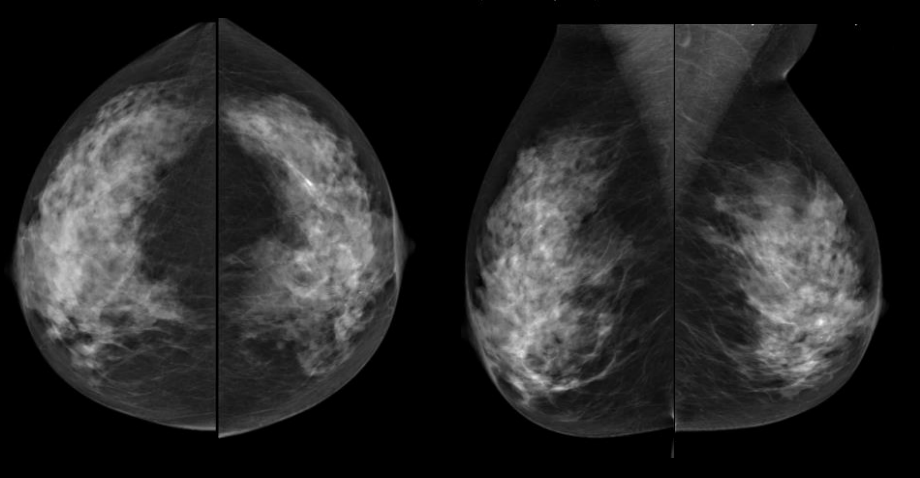
SenoClaire – Case ID 0116



SenoClaire Clinical Atlas | 2014

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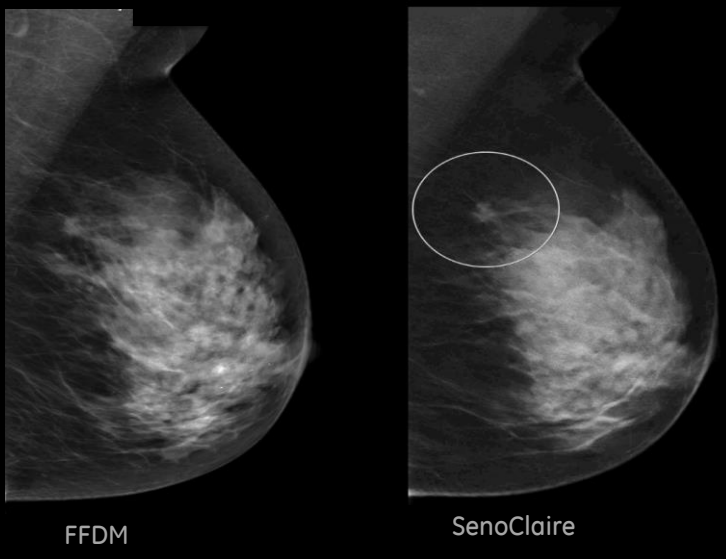
SenoClaire – Case ID 0116



SenoClaire Clinical Atlas | 2014

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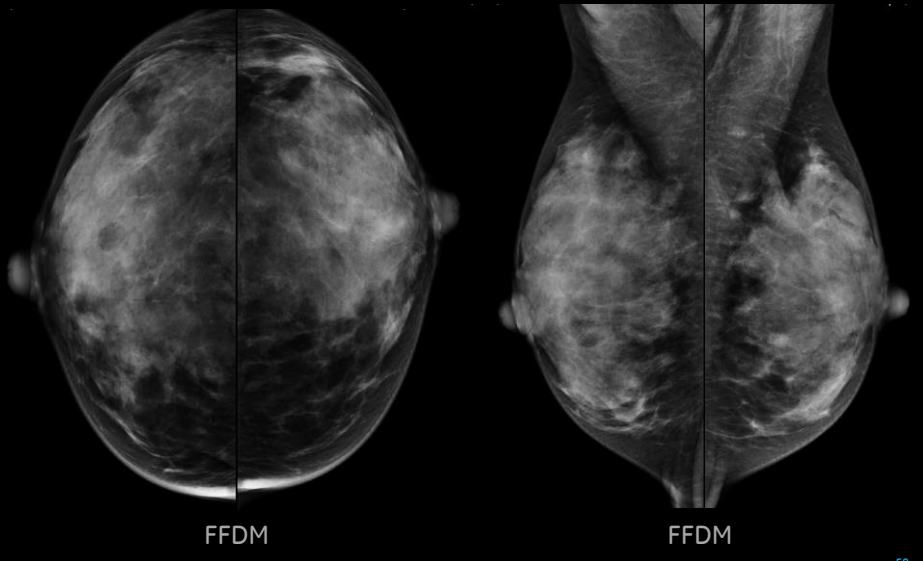
SenoClaire – Case ID 0403



SenoClaire Clinical Atlas | 2014

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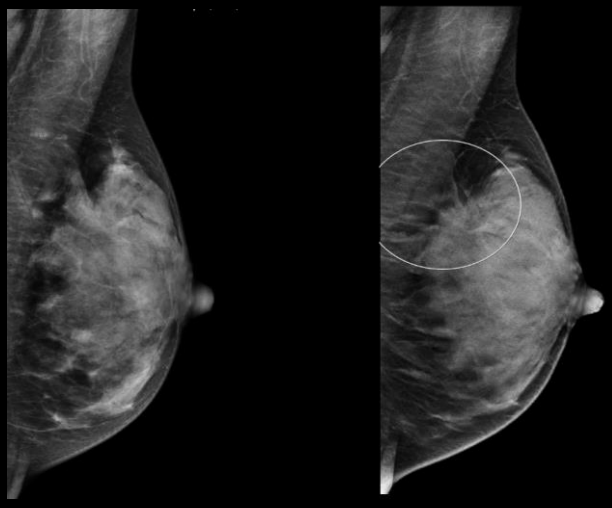
SenoClaire – Case ID 0403



FFDM SenoClaire

SenoClaire Clinical Atlas | 2014

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Volumetric Imaging helps remove overlaping tissue
SenoClaire™

SenoClaire Key Features

- 9 Projections
- Stop-and-shoot
- Sweep angle 25° (+/- 12.5)
- Sweep time <10 sec*
- No binning
- 2D/3D-grid for scatter reduction
- $ASIR_{DBT}$
  iterative Reconstruction
- 0.5mm plane distance
- No dose increase
- BTO
  Breast Tomosynthesis Object

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Thank You for your attention