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Resolution Modeling for Digital Breast Tomosynthesis

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Overview

- Digital Breast Tomosynthesis
- Acquisition Model
- Grouped Coordinate Ascent Algorithm
- Evaluation
  - Acceleration
  - Observer Study
  - (Model Observers)
- Conclusion & Future Work

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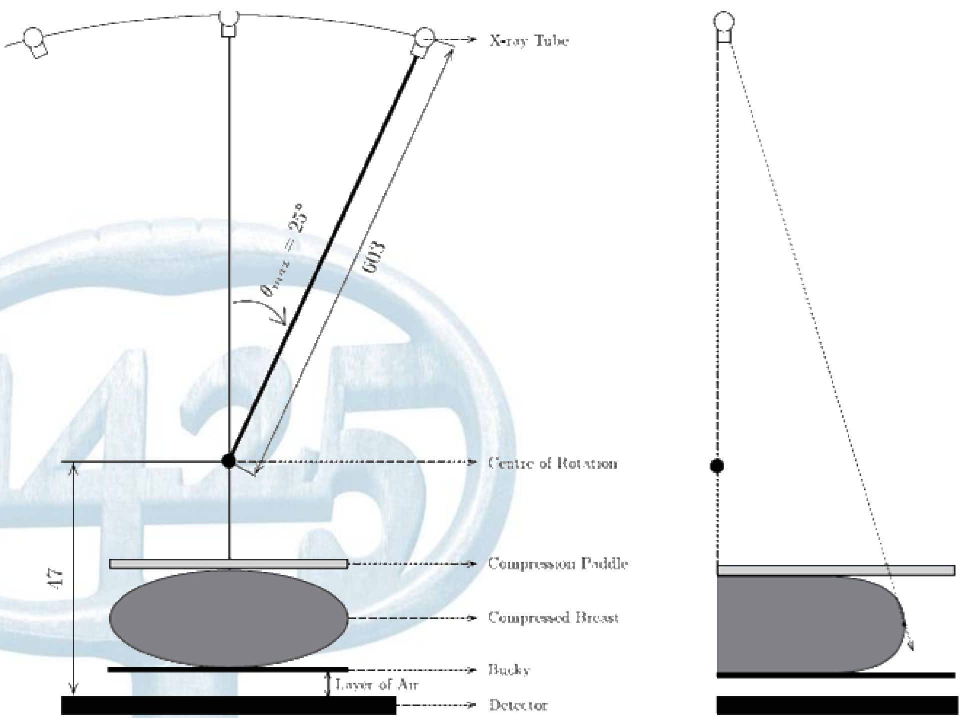
Digital Breast Tomosynthesis

- Limited angle tomography: (depending on the vendor)
  - 11 to 25 exposures
  - Angular range: 15 to 50 degrees

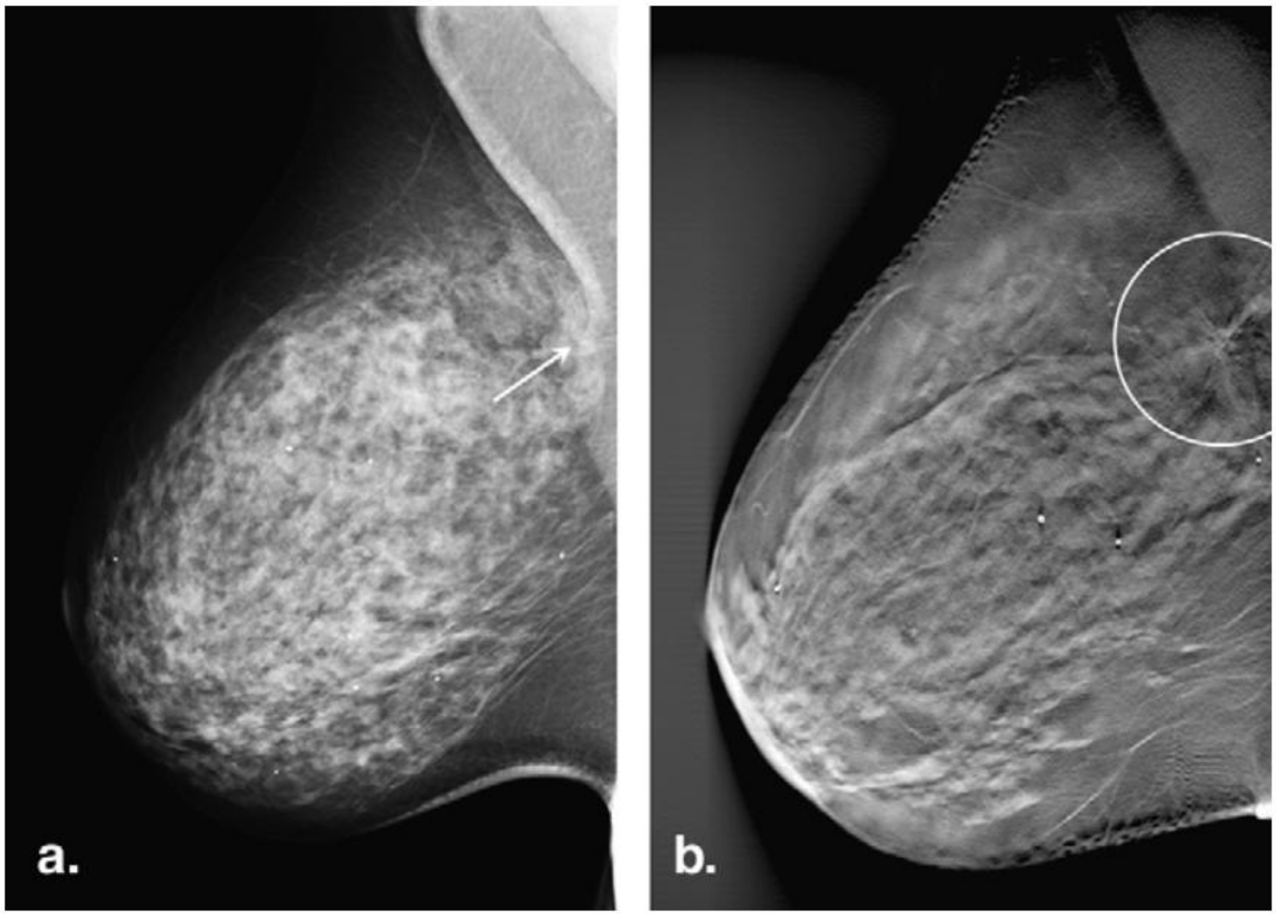


Digital Breast Tomosynthesis

- Limited angle tomography: (depending on the vendor)
  - 11 to 25 exposures
  - Angular range: 15 to 50 degrees
- X-ray doses between 1x and 2x dose of normal mammogram
- High resolution flat panel detector (70-100 µm pixel spacing)
- Reconstructed in 1mm planes parallel to detector surface

Digital Breast Tomosynthesis

Main strength: removing interference from overlapping anatomical structures



J. A. Baker and J. Y. Lo, “Breast tomosynthesis: state-of-the-art and review of the literature.,” *Academic Radiology*, vol. 18, no. 10, pp. 1298-1310, Oct. 2011.

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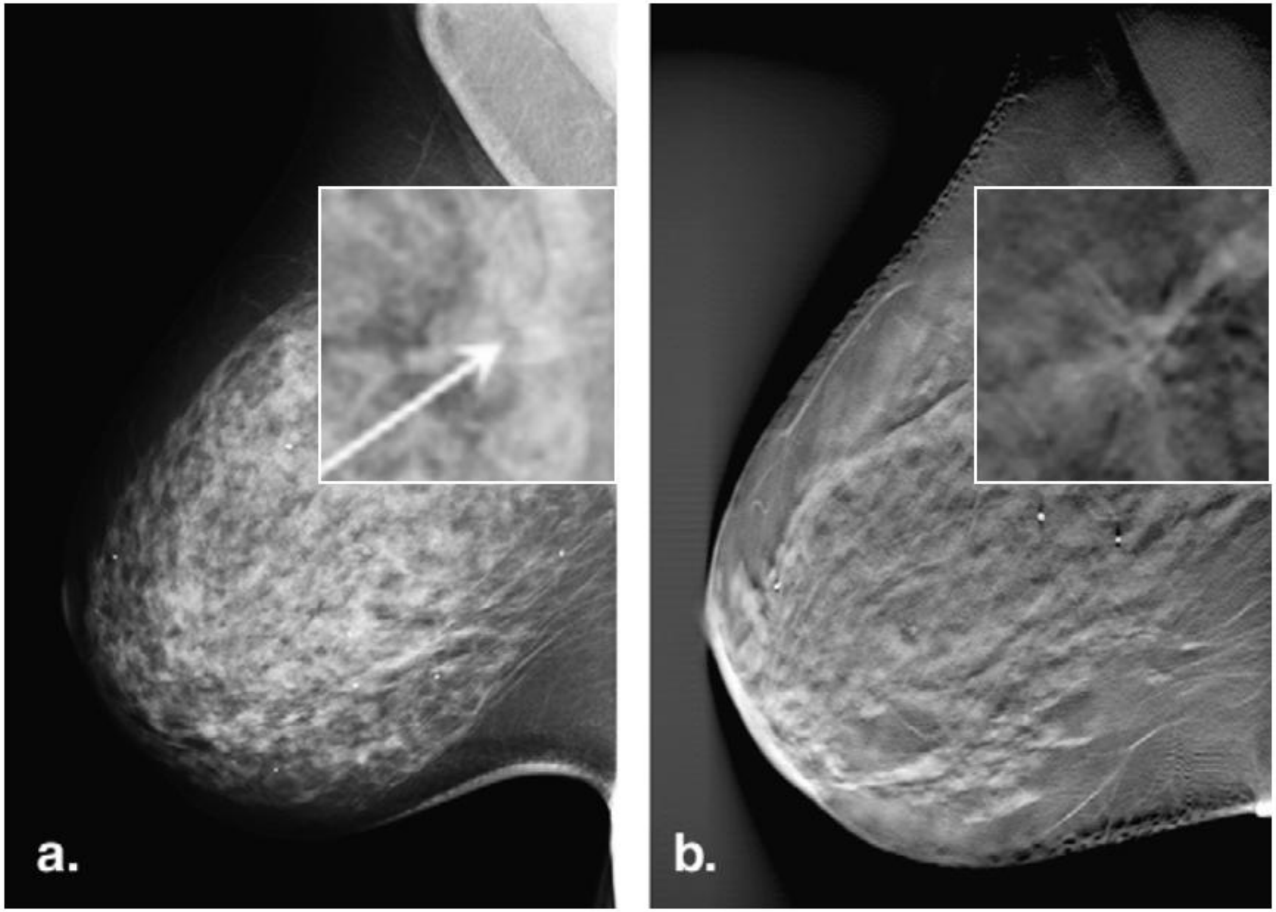

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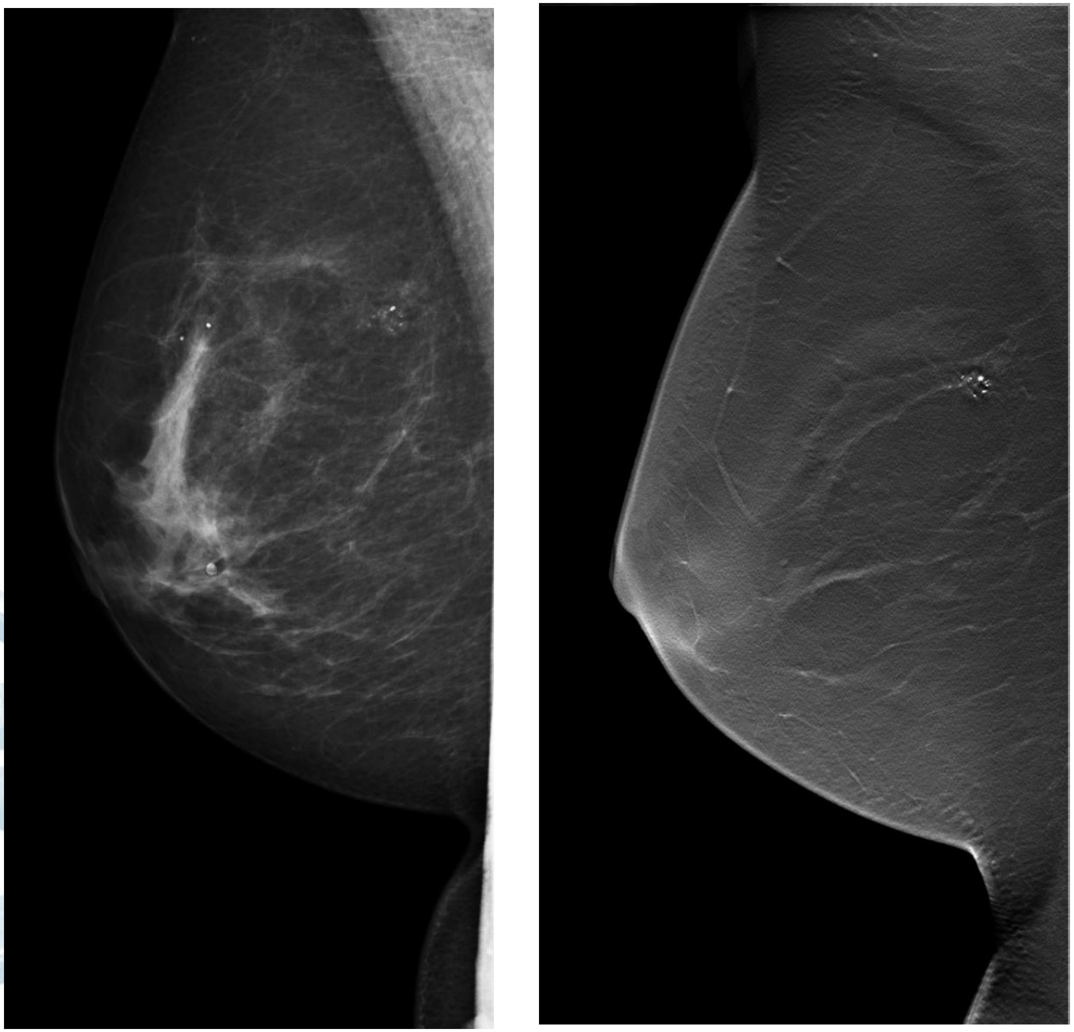
Digital Breast Tomosynthesis

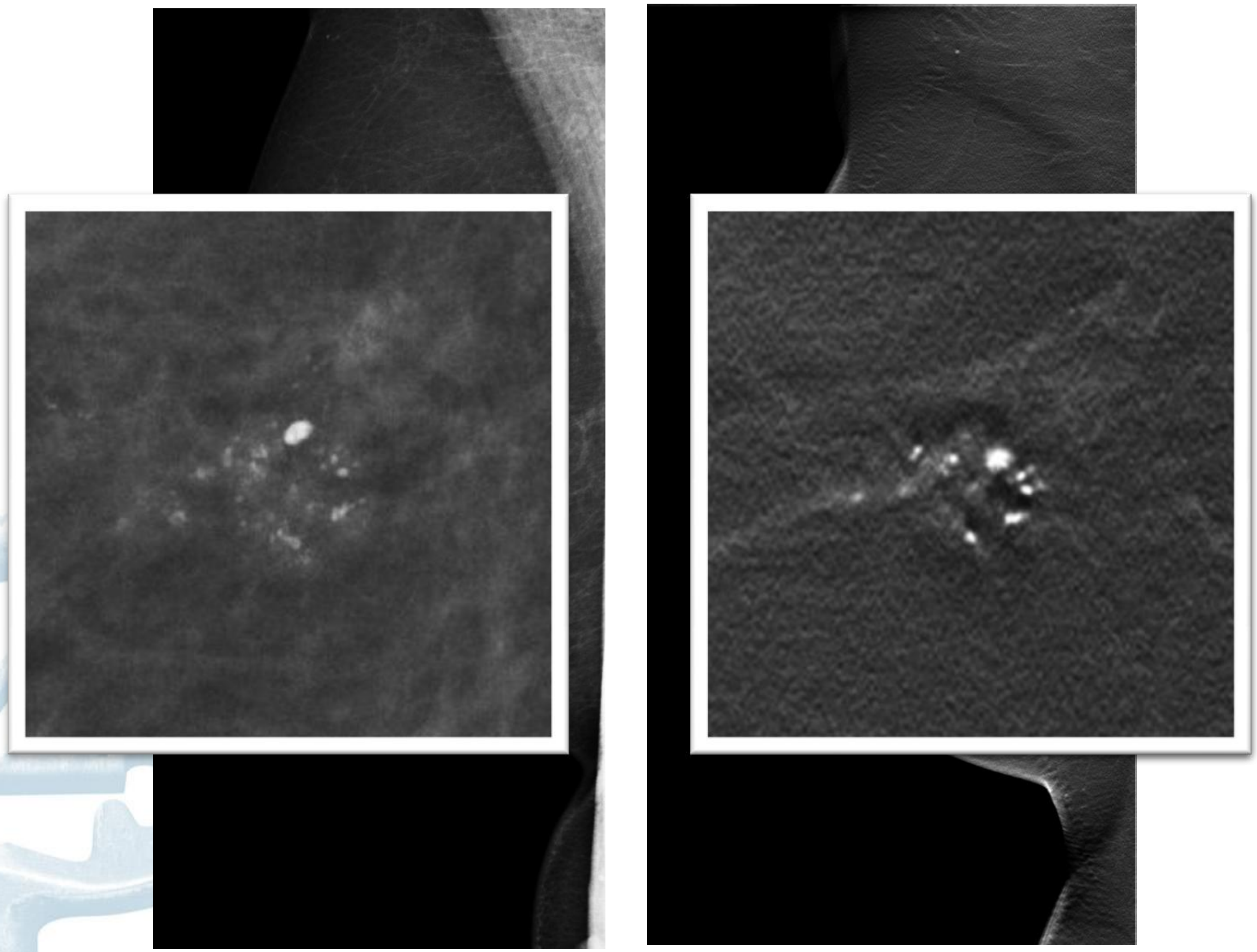
Less accurate visualizing micro-calcifications



Figures courtesy of Lesley Cockmartin, Dept. of Radiology, KU Leuven

Digital Breast Tomosynthesis

Less accurate visualizing micro-calcifications



Figures courtesy of Lesley Cockmartin, Dept. of Radiology, KU Leuven

Digital Breast Tomosynthesis

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Less accurate visualizing micro-calcifications

Our goal:

Apply a maximum-likelihood reconstruction to improve visualization of micro-calcifications in digital breast tomosynthesis

Figures courtesy of Lesley Cockmartin, Dept. of Radiology, KU Leuven

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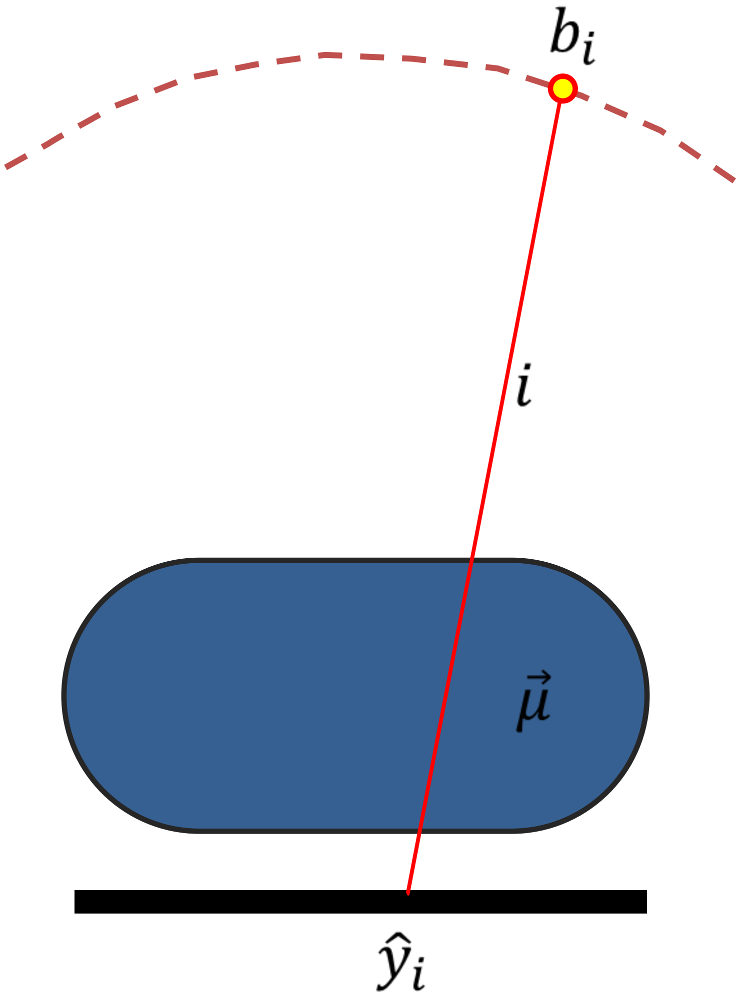
Acquisition Model

- Model for measured data in a transmission scan:

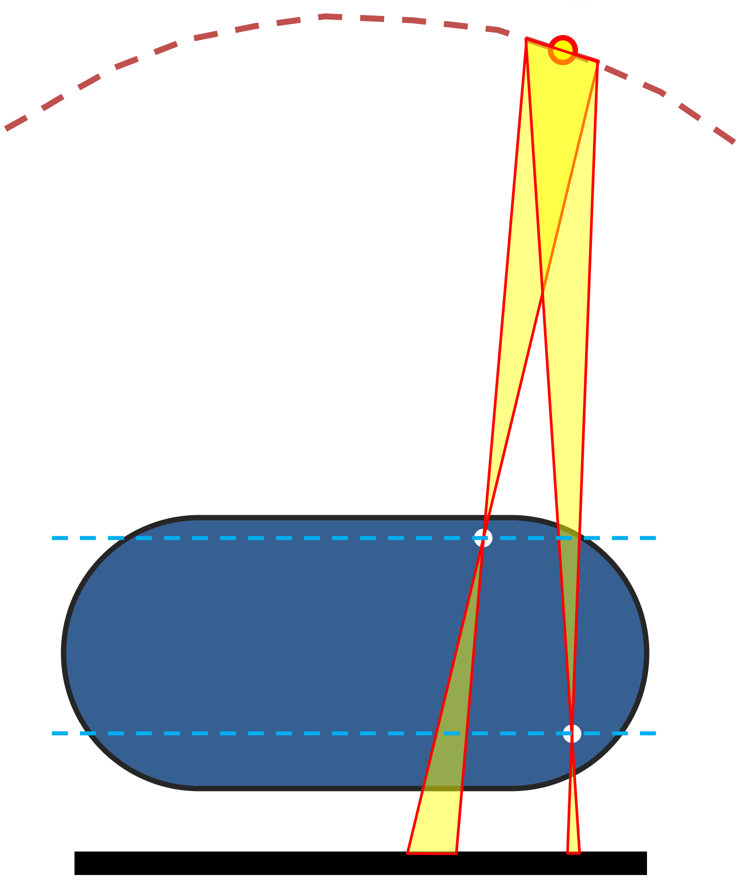
$$\hat{y}_i = b_i e^{-\sum_j l_{ij}\mu_j}$$



Resolution Model

- Two options for acquisition sequence:
  - Step and shoot
  - Continuous motion
    (with pulsed exposures)

    $\Rightarrow$ Motion Blur



We model continuous motion for Siemens Mammomat Inspiration*

* Breast tomosynthesis with Siemens MAMMOMAT Inspiration is an investigational practice and is limited by U.S. law to investigational use. It is not commercially available in the U.S. and its future availability cannot be ensured.

Resolution Model

Effect is clearly visible in the measured Modulation Transfer Function

Example:

Angular speed: 50°/25s
Exposures: 25
Exposure time: 120ms
Radius: 608.5 mm
Tube motion: 2.5mm
Focus size: (0.3 mm)²

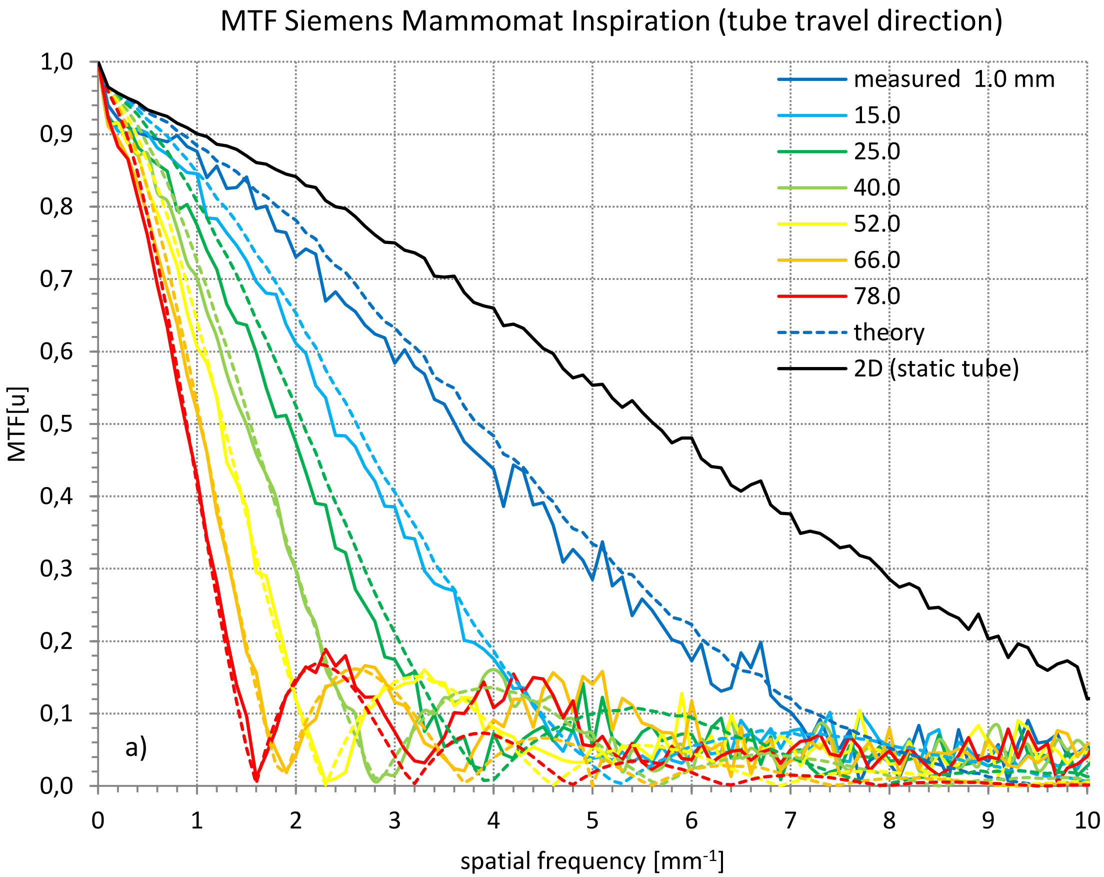


Figure courtesy of Nicholas Marshall, Dept. of Radiology, UZ Leuven

Resolution Model

$$\hat{y}_{s\theta} = \int_{\theta-\frac{\alpha}{2}}^{\theta+\frac{\alpha}{2}} b_s(\phi)\; e^{-\sum_p \sum_k l_{skp}(\phi)\;\mu_{kp}}\; d\phi \qquad (1)$$

Model of image acquisition with continuous tube motion

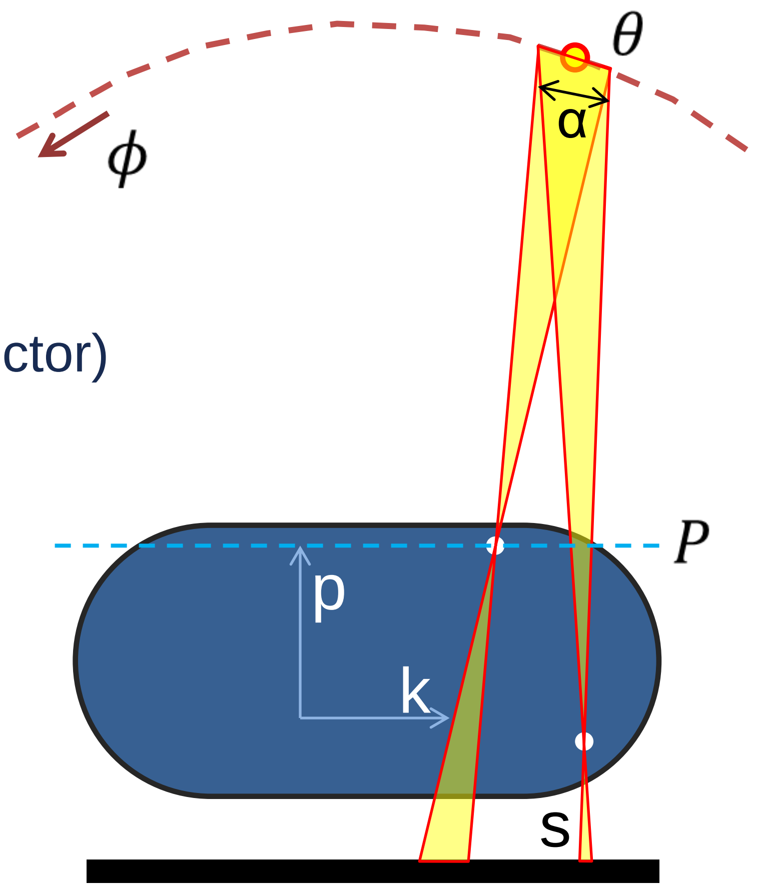
Sinogram coordinates:

- s detector pixel index
- θ x-ray source position

Volume coordinates:

- p plane number (parallel to detector)
- k in plane coordinate

Angular motion α during acquisition

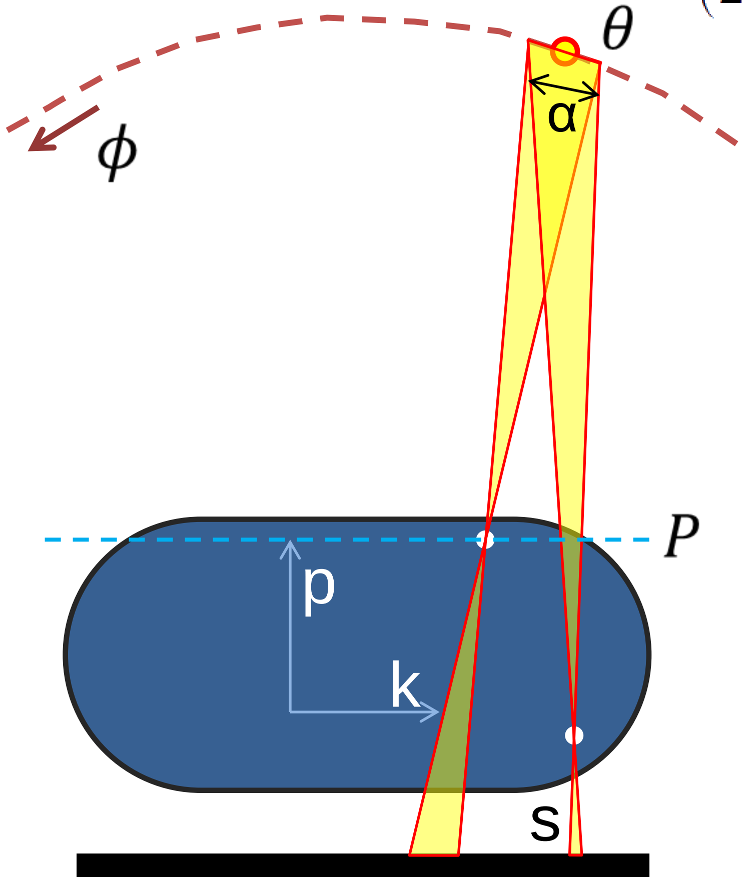


Resolution Model

$$\hat{y}_{s\theta} = \int_{\theta-\frac{\alpha}{2}}^{\theta+\frac{\alpha}{2}} b_s(\phi)\ e^{-\sum_p \sum_k l_{skp}(\phi)\ \mu_{kp}}\ d\phi \quad (1)$$

$$\hat{y}_{s\theta} = \sum_{\phi=\theta-\frac{\alpha}{2}}^{\theta+\frac{\alpha}{2}} b_{s\phi}\ e^{-\sum_p \sum_k l_{s\phi kp}\ \mu_{kp}} \quad (2)$$

Step 1: create a discrete model



Resolution Model

Step 2: Assume volume is smooth, except plane P

$$\hat{y}_{s\theta} = \sum_{\phi=\theta-\frac{\alpha}{2}}^{\theta+\frac{\alpha}{2}} b_{s\phi}\ e^{-\sum_p \sum_k l_{s\phi kp}\ \mu_{kp}} \tag{2}$$

$$= \sum_{\phi=\theta-\frac{\alpha}{2}}^{\theta+\frac{\alpha}{2}} b_{s\phi}\ e^{-\sum_{p\neq P} \sum_k l_{s\phi kp}\ \mu_{kp}} e^{-\sum_k l_{s\phi kP}\ \mu_{kP}} \tag{3}$$

Resolution Model

Step 2: Assume volume is smooth, except plane P

$$\hat{y}_{s\theta} = \sum_{\phi=\theta-\frac{\alpha}{2}}^{\theta+\frac{\alpha}{2}} b_{s\phi} \; e^{-\sum_p \sum_k l_{s\phi kp} \; \mu_{kp}} \quad (2)$$

$$= \sum_{\phi=\theta-\frac{\alpha}{2}}^{\theta+\frac{\alpha}{2}} b_{s\phi} \; e^{-\sum_{p\neq P} \sum_k l_{s\phi kp} \; \mu_{kp}} e^{-\sum_k l_{s\phi kP} \; \mu_{kP}} \quad (3)$$

$$\approx b_{s\theta} \; e^{-\sum_{p\neq P} \sum_k l_{s\theta kp} \; \mu_{kp}} \sum_{\phi=\theta-\frac{\alpha}{2}}^{\theta+\frac{\alpha}{2}} w_{\theta\phi} e^{-\sum_k l_{s\phi kP} \; \mu_{kP}} \quad (4)$$

Resolution Model

Step 3: We prefer smoothing over s rather than θ

$$\hat{y}_{s\theta} = \sum_{\phi=\theta-\frac{\alpha}{2}}^{\theta+\frac{\alpha}{2}} b_{s\phi}\ e^{-\sum_p \sum_k l_{s\phi kp}\ \mu_{kp}} \quad (2)$$

$$= \sum_{\phi=\theta-\frac{\alpha}{2}}^{\theta+\frac{\alpha}{2}} b_{s\phi}\ e^{-\sum_{p\neq P} \sum_k l_{s\phi kp}\ \mu_{kp}} e^{-\sum_k l_{s\phi kP}\ \mu_{kP}} \quad (3)$$

$$\approx b_{s\theta}\ e^{-\sum_{p\neq P} \sum_k l_{s\theta kp}\ \mu_{kp}} \sum_{\phi=\theta-\frac{\alpha}{2}}^{\theta+\frac{\alpha}{2}} w_{\theta\phi} e^{-\sum_k l_{s\phi kP}\ \mu_{kP}} \quad (4)$$

$$\approx b_{s\theta}\ e^{-\sum_{p\neq P} \sum_k l_{s\theta kp}\ \mu_{kp}} \sum_n w_{sn}^P e^{-\sum_k l_{n\theta kP}\ \mu_{kP}} \quad (5)$$

Resolution Model

Step 4: Repeat the previous argument for all planes

$$\hat{y}_{s\theta} = \sum_{\phi=\theta-\frac{\alpha}{2}}^{\theta+\frac{\alpha}{2}} b_{s\phi}\ e^{-\sum_p \sum_k l_{s\phi kp}\ \mu_{kp}} \tag{2}$$

$$= \sum_{\phi=\theta-\frac{\alpha}{2}}^{\theta+\frac{\alpha}{2}} b_{s\phi}\ e^{-\sum_{p\neq P} \sum_k l_{s\phi kp}\ \mu_{kp}} e^{-\sum_k l_{s\phi kP}\ \mu_{kP}} \tag{3}$$

$$\approx b_{s\theta}\ e^{-\sum_{p\neq P} \sum_k l_{s\theta kp}\ \mu_{kp}} \sum_{\phi=\theta-\frac{\alpha}{2}}^{\theta+\frac{\alpha}{2}} w_{\theta\phi} e^{-\sum_k l_{s\phi kP}\ \mu_{kP}} \tag{4}$$

$$\approx b_{s\theta}\ e^{-\sum_{p\neq P} \sum_k l_{s\theta kp}\ \mu_{kp}} \sum_n w_{sn}^P e^{-\sum_k l_{n\theta kP}\ \mu_{kP}} \tag{5}$$

$$\approx b_{s\theta} \prod_p \sum_n w_{sn}^p e^{-\sum_k l_{n\theta kp}\ \mu_{kp}} \tag{6}$$

Resolution Model

Verification of the resolution model in projections:

Motion Blur approximated
with Gaussian smoothing

Range:

A: [0.841 – 1.000]

B: [0.842 – 1.000]

Ratio A/B:

0.991 < A/B < 1.009

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Update equation

- Model for measured data in a transmission scan:

$$\hat{y}_i = b_i e^{-\sum_j l_{ij}\mu_j}$$

- Likelihood (Poisson distribution):

$$P = \prod_i e^{-\hat{y}_i} \frac{\hat{y}_i^{\,y_i}}{y_i!}$$

- Log-Likelihood:

$$L = \sum_i (y_i \ln \hat{y}_i - \hat{y}_i - \ln y_i!)$$

Update equation

- Update Step:
  - maximize log-likelihood
  - Newton update step:

$$\Delta\mu_j = \frac{-\frac{\partial L}{\partial \mu_j}}{\sum_k \frac{\partial^2 L}{\partial \mu_j \partial \mu_k}}$$

$$\Delta\mu_j = \frac{\sum_i l_{ij}(\hat{y}_i - y_i)}{\sum_i l_{ij}(\sum_k l_{ik})\hat{y}_i}$$

→ Maximum Likelihood for Transmission (MLTR)

Grouped Coordinate Ascent* updates

- New update step:

$$\Delta\mu_j = \frac{\alpha_j \sum_i l_{ij}(\hat{y}_i - y_i)}{\sum_i l_{ij}(\sum_k l_{ik}\alpha_k)\hat{y}_i}, \qquad with\ \hat{y}_i = b_i e^{-\sum_j l_{ij}\mu_j}$$

- Choose $\alpha_j = 1$ in ROI, $\alpha_j = 0$ outside, for GCA updates
- Choose α_j to minimize denominator

$\Rightarrow$ Update sequentially, plane by plane
for maximal update step size

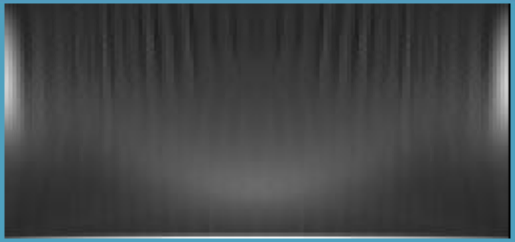
*J. A. Fessler, E. P. Ficaro, N. H. Clinthorne, and K. Lange, “Grouped-coordinate ascent algorithms for penalized-likelihood transmission image reconstruction.,” *IEEE Transactions on Medical Imaging*, vol. 16, no. 2, pp. 166-175, Apr. 1997.

Grouped Coordinate Ascent updates

Maximum likelihood update step, applied plane by plane (bottom to top) for limited angle tomography

- Homogeneous phantom
- Axial slices

Grouped Coordinate Ascent updates

1 

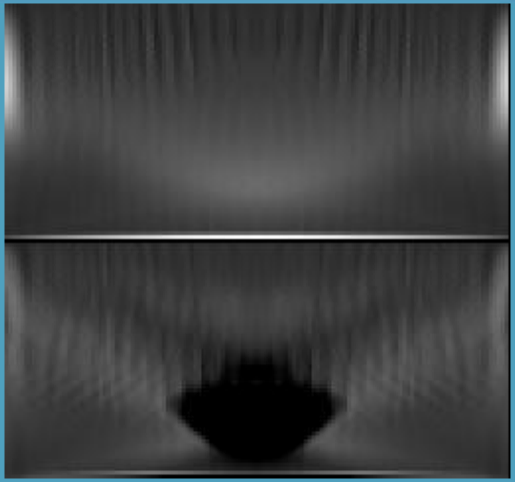
Maximum likelihood update step, applied plane by plane (bottom to top) for limited angle tomography

$\Rightarrow$ Severe inhomogeneity in reconstruction

Grouped Coordinate Ascent updates

1

2

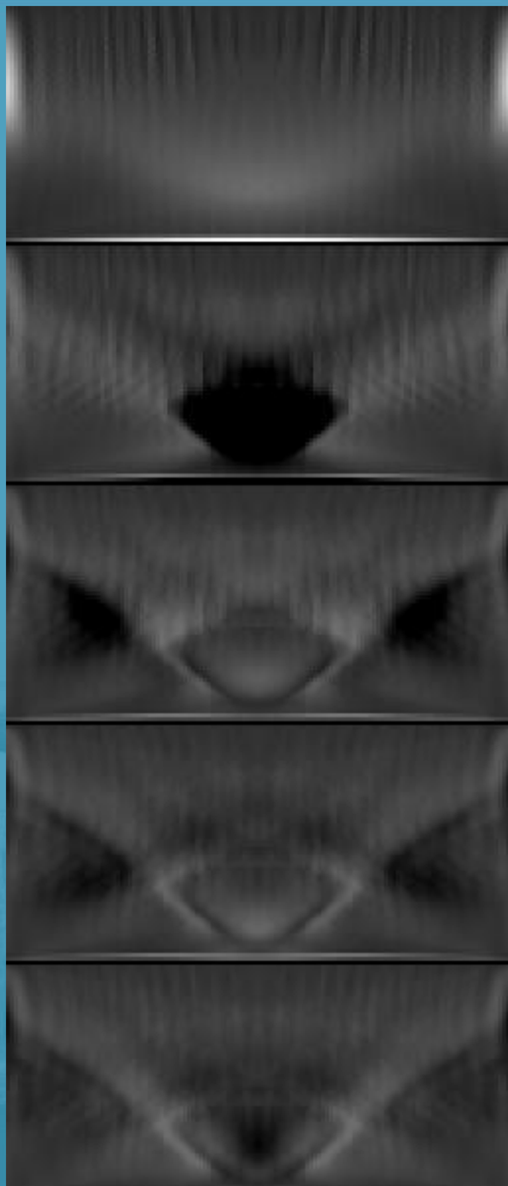


Maximum likelihood update step, applied plane by plane (bottom to top) for limited angle tomography

⇒ Severe inhomogeneity in reconstruction

Grouped Coordinate Ascent updates

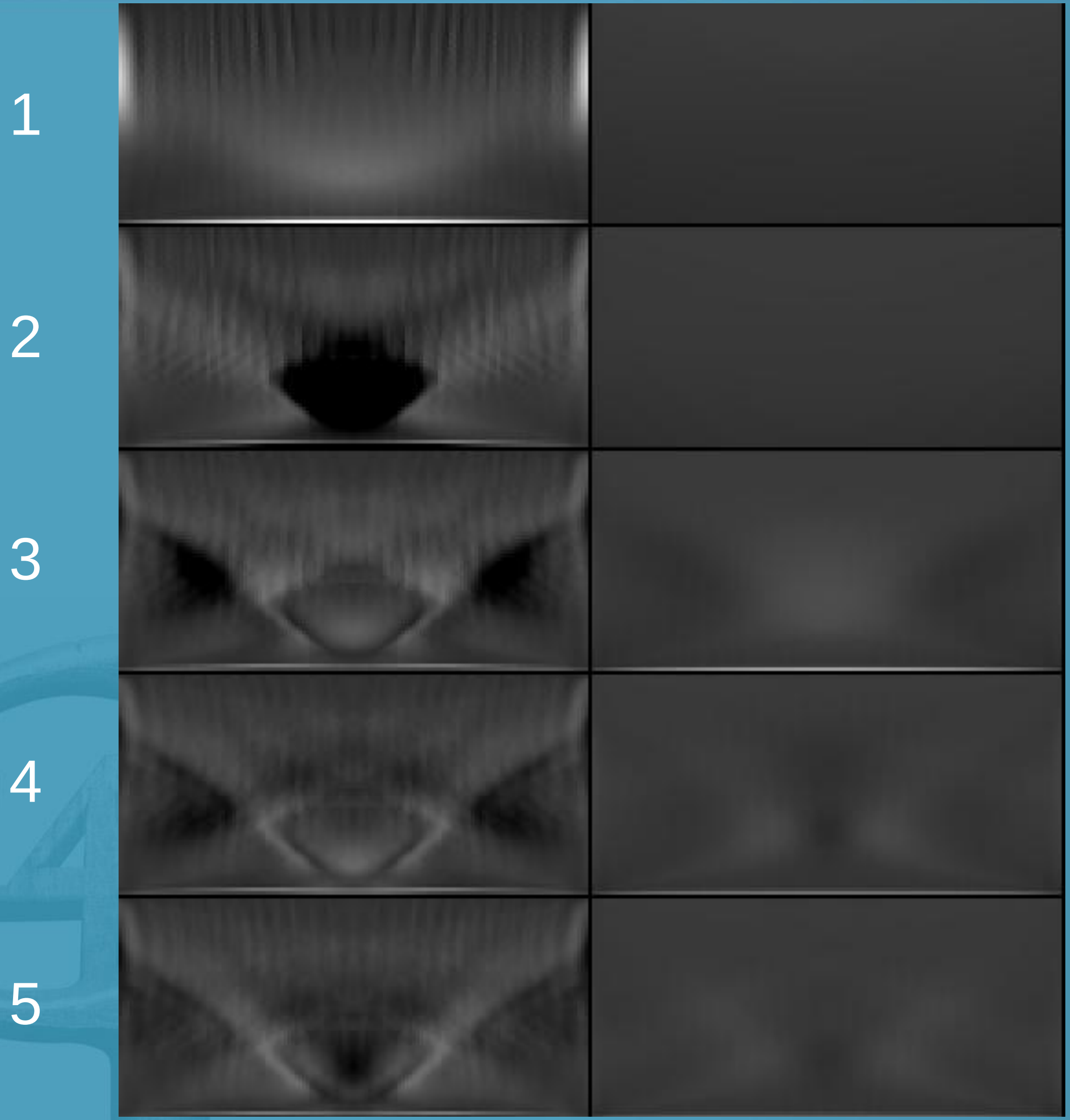
1
2
3
4
5



Maximum likelihood update step, applied plane by plane (bottom to top) for limited angle tomography

⇒ Severe inhomogeneity in reconstruction

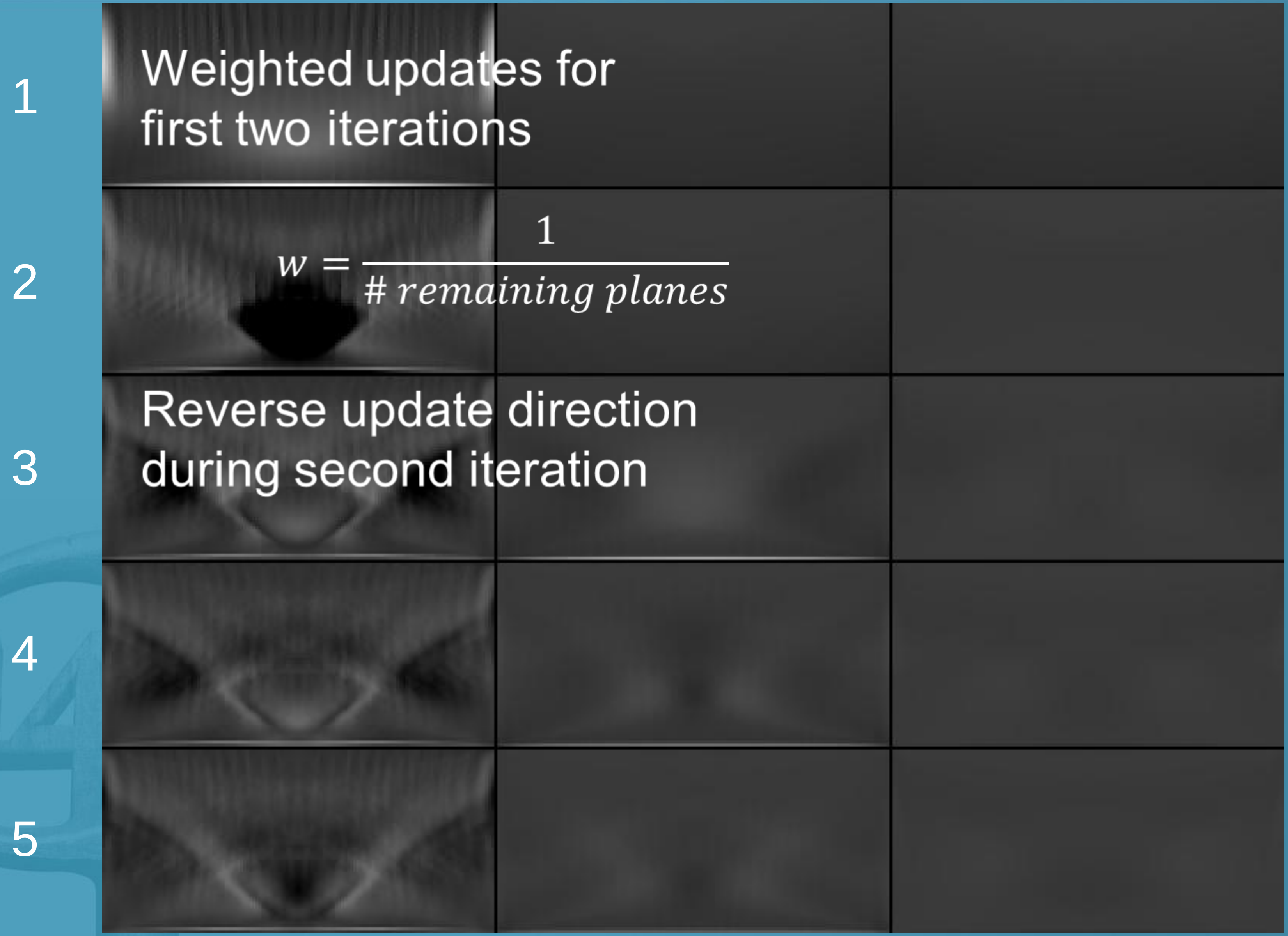
Grouped Coordinate Ascent updates



Weighted updates for first two iterations

$$w = \frac{1}{\#\ remaining\ planes}$$

Grouped Coordinate Ascent updates



Patchwork with Resolution Model

Grouped Coordinate Ascent Updates

+

Plane by Plane Resolution Model

=

Patchwork reconstruction
with resolution modeling

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Evaluation

1. Proof of concept: Does the combination of GCA updates and resolution model work?

2. Acceleration

3. Observer study: Is there an improvement in the visualization of micro-calcifications?
    a. Is there improved detection?
    b. Is there improved classification?

Evaluation: Reconstructions

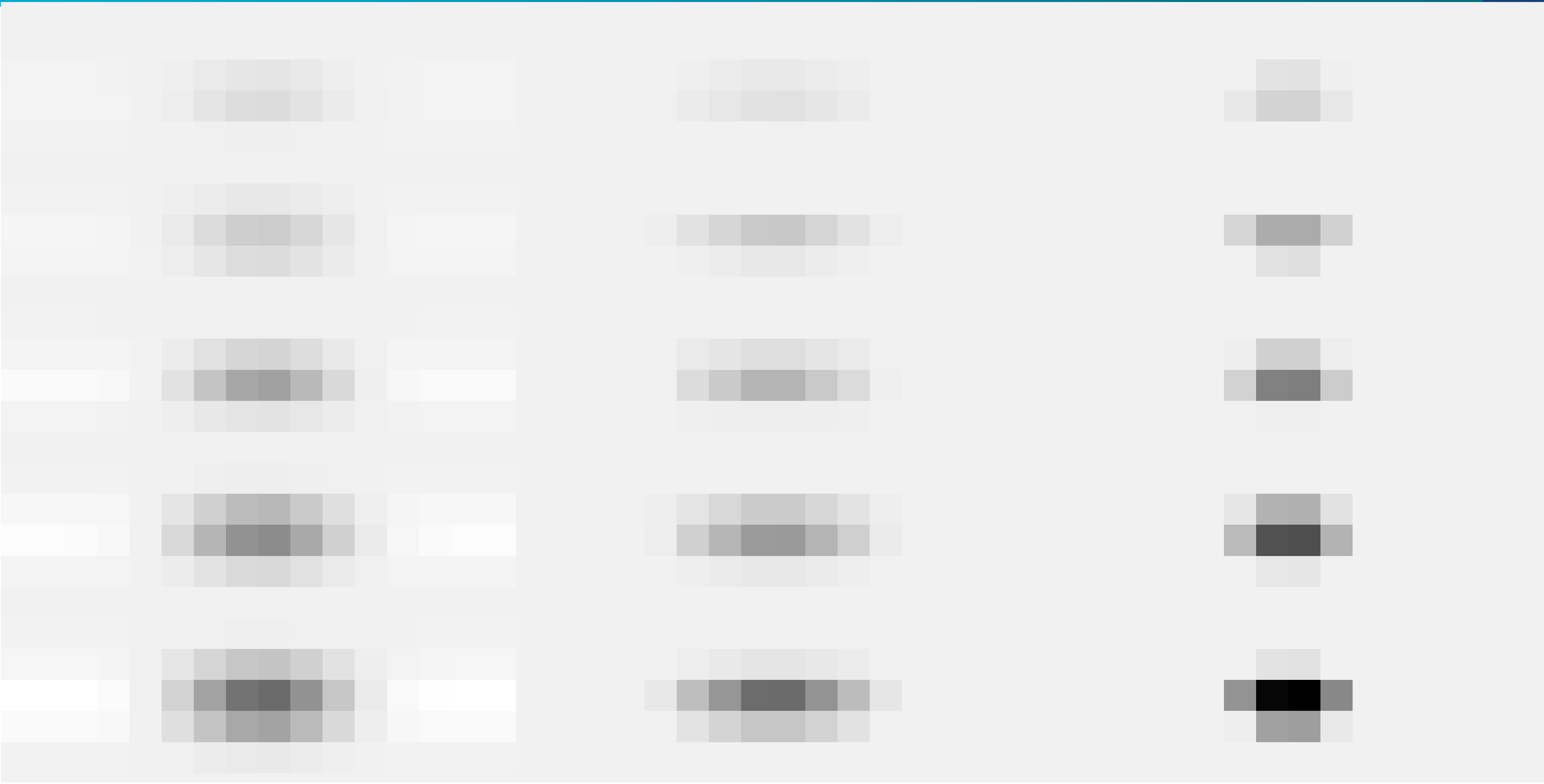
1. Basis point of reference: Siemens iFBP*

2. Other iterative methods:
   – Maximum likelihood (MLTR)
   – Maximum a posteriori (MAPTR)
   – Gradient coordinate ascent (GCA)

3. Our methods:
   – Patchwork (Patch MLTR)
   – Patchwork + smoothing prior (Patch MAPTR)

*J. Ludwig, T. Mertelmeier, H. Kunze, and W. Harer, "A Novel Approach for Filtered Backprojection in tomosynthesis Based on Filter Kernels Determined by Iterative Reconstruction Techniques," in *LNCS Proceedings of the IWDM*, 2008, pp. 612–620.

Evaluation: Proof of Concept



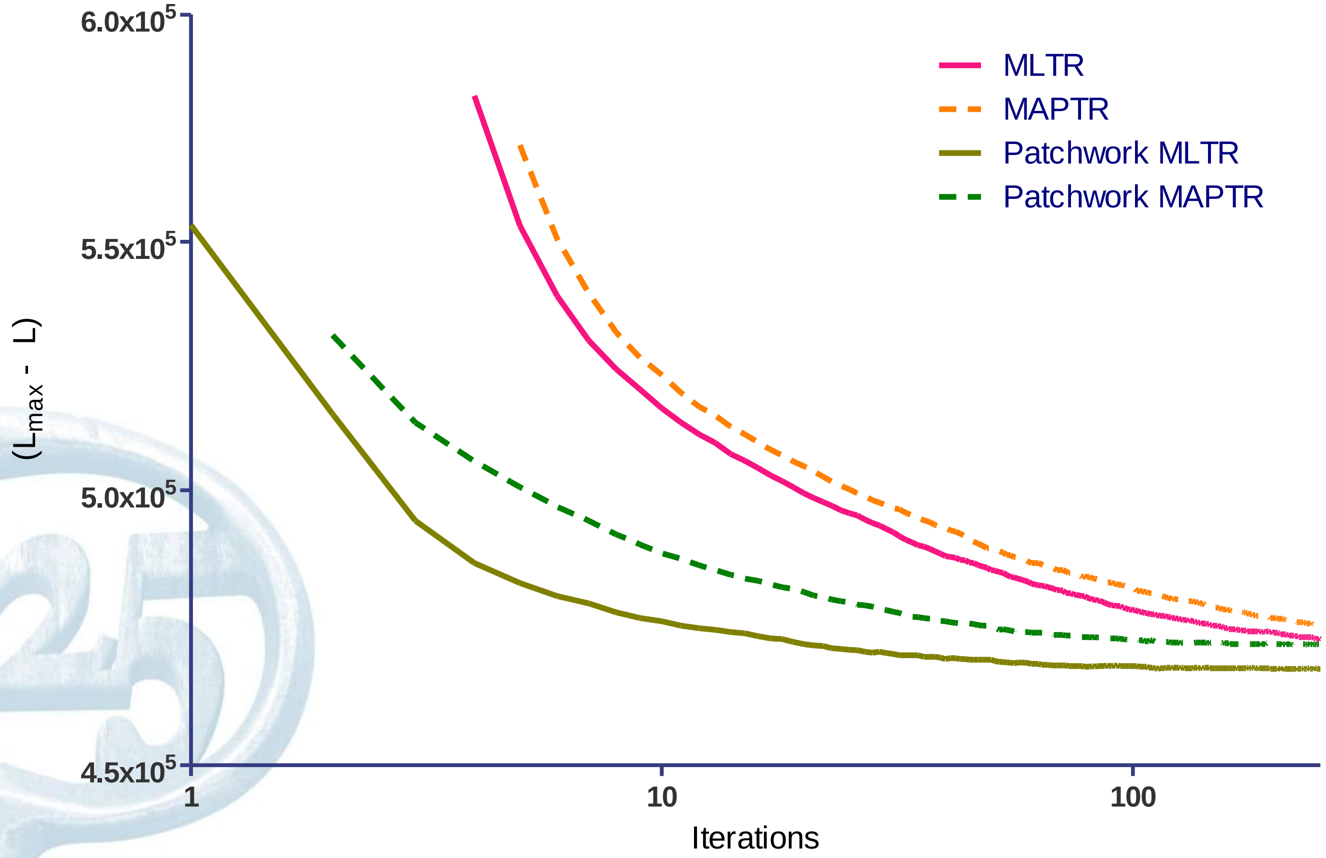
Siemens iFBP*

GCA
(50 iterations)

Patch MLTR
(50 iterations)

Evaluation: Acceleration

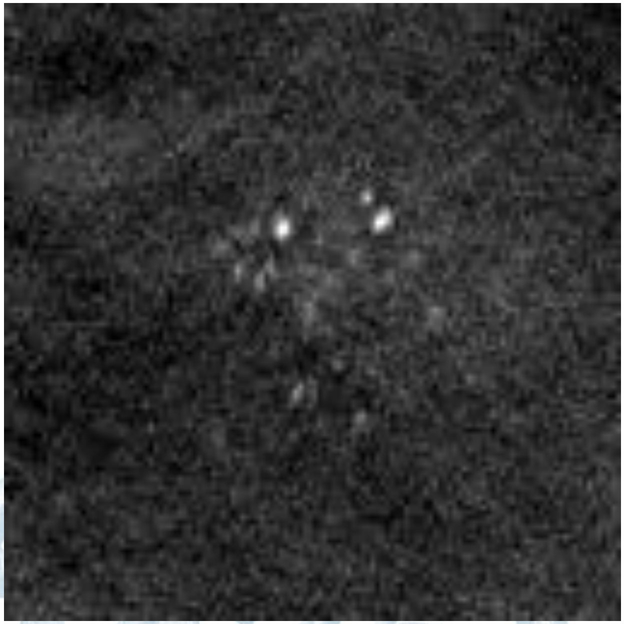
- Log-Likelihood:



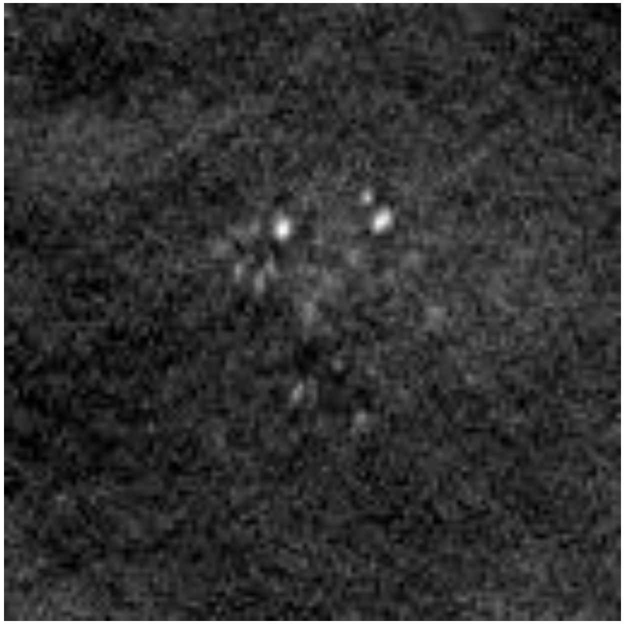
Evaluation: Acceleration

- Visual Evaluation:

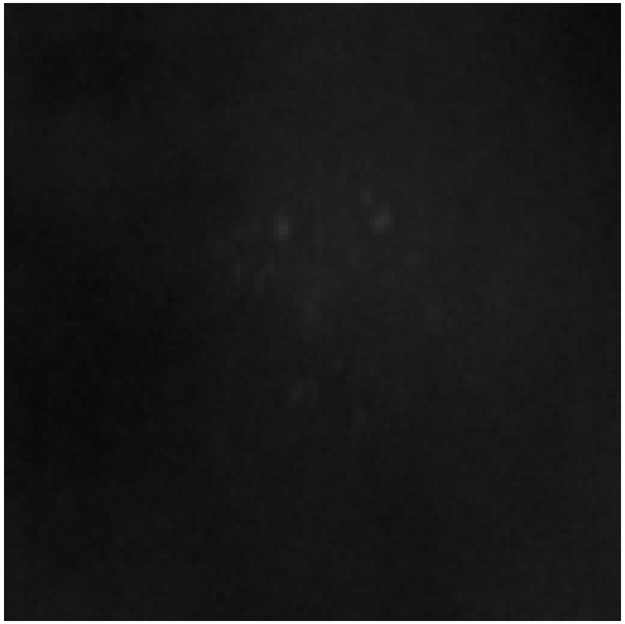
MAPTR (20 it)



Patch MAPTR (3 it)



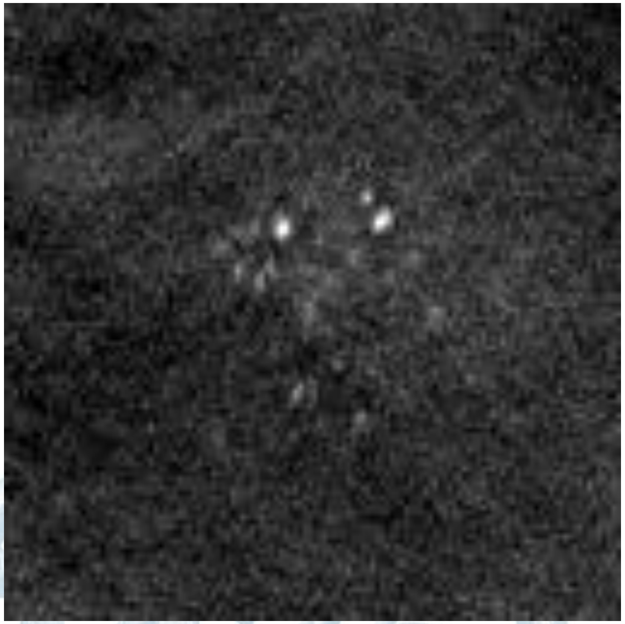
MAPTR (3 it)



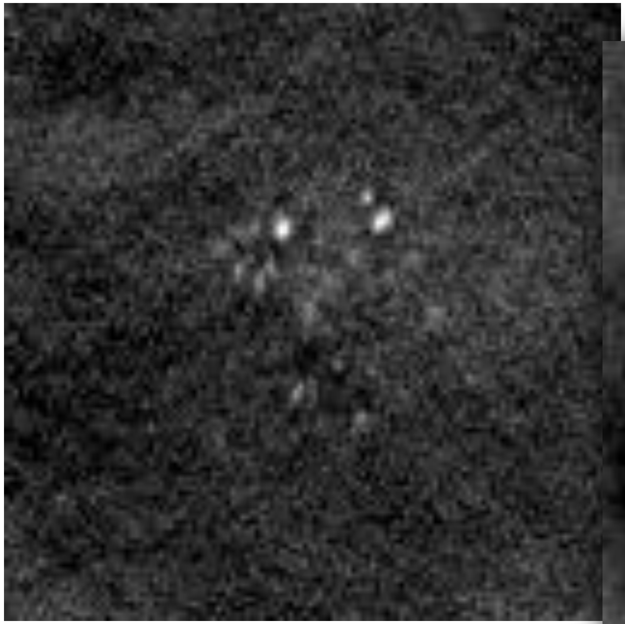
Evaluation: Acceleration

- Visual Evaluation:

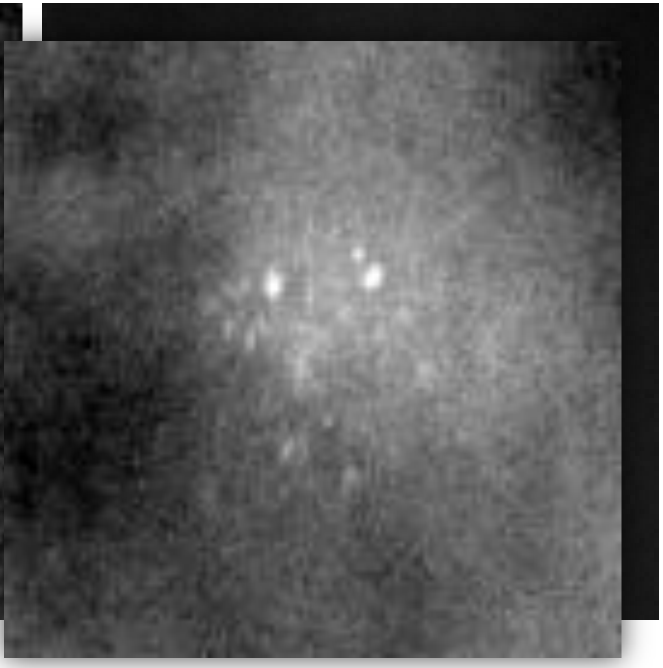
MAPTR (20 it)



Patch MAPTR (3 it)



MAPTR (3 it)

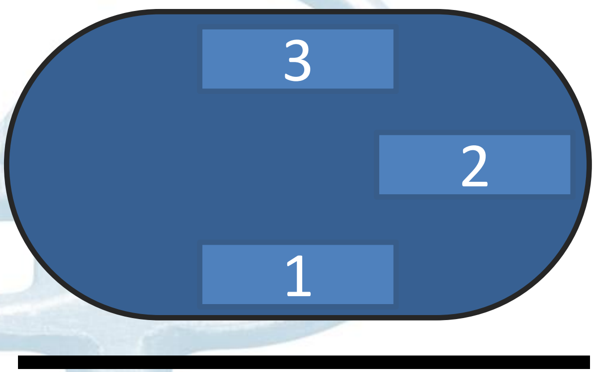


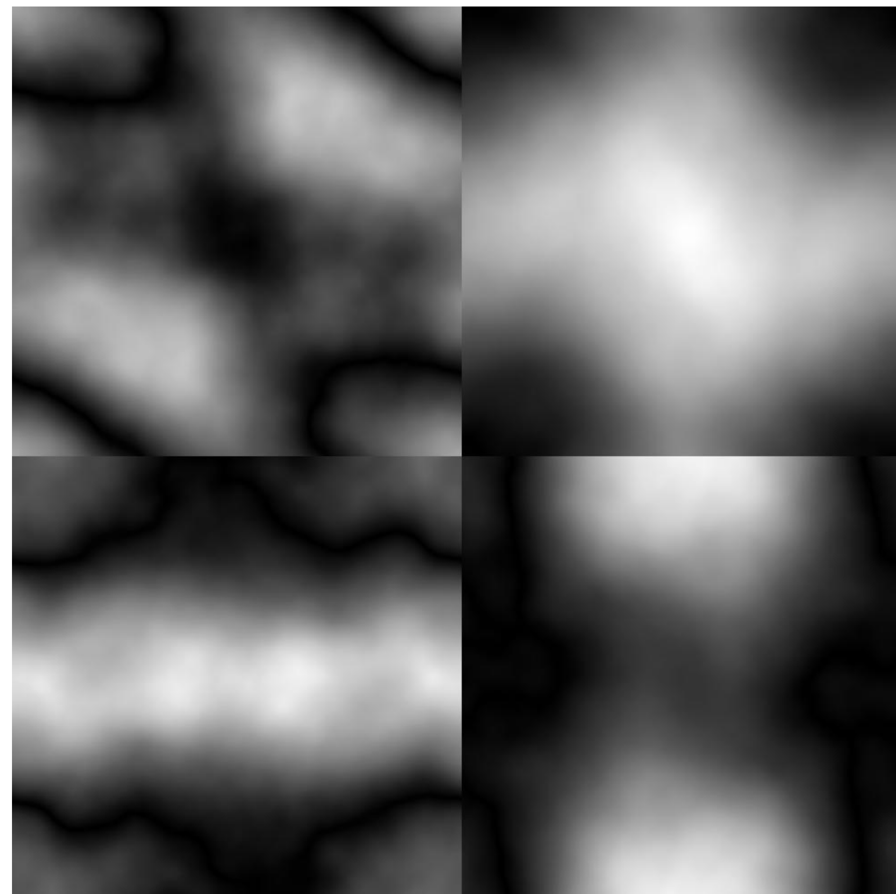
Evaluation: Observer Study

- Background images for both studies:
  - white noise filtered by power law

$$f(\nu) = \kappa/\nu^{\beta}$$
$$\beta = 3, \kappa = 10^{-5} mm^{-1}$$

  - Placed at 3 locations:

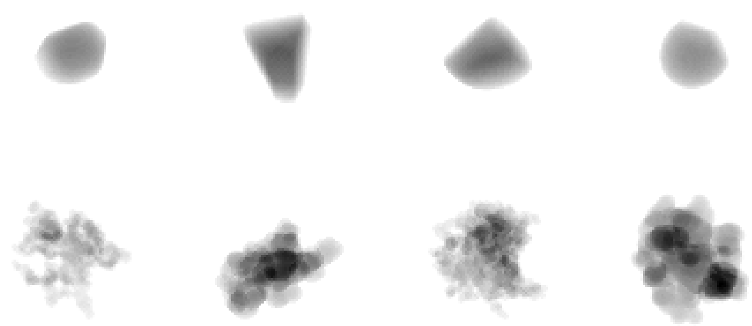




Evaluation: Observer Study

- Lesions
  - Detection: spherical calcifications in clusters, 100 – 200 µm

  - Classification: smooth and irregular calcifications, 200 – 600 µm



Evaluation: Observer Study

- Simulation
  - 9 source positions for each angle (120ms exposure time)
  - 5x detector super sampling (85µm → 17µm pixel pitch)
  - Voxel size:
    - Background: $(85\mu m)^3$
    - small spherical calcs $(5\mu m)^3$
    - smooth and irregular calcs $(6 – 18\mu m)^3$
  - 1500 photons @ 20 keV per pixel (~ 12.5 µGy)

Evaluation: Observer Study

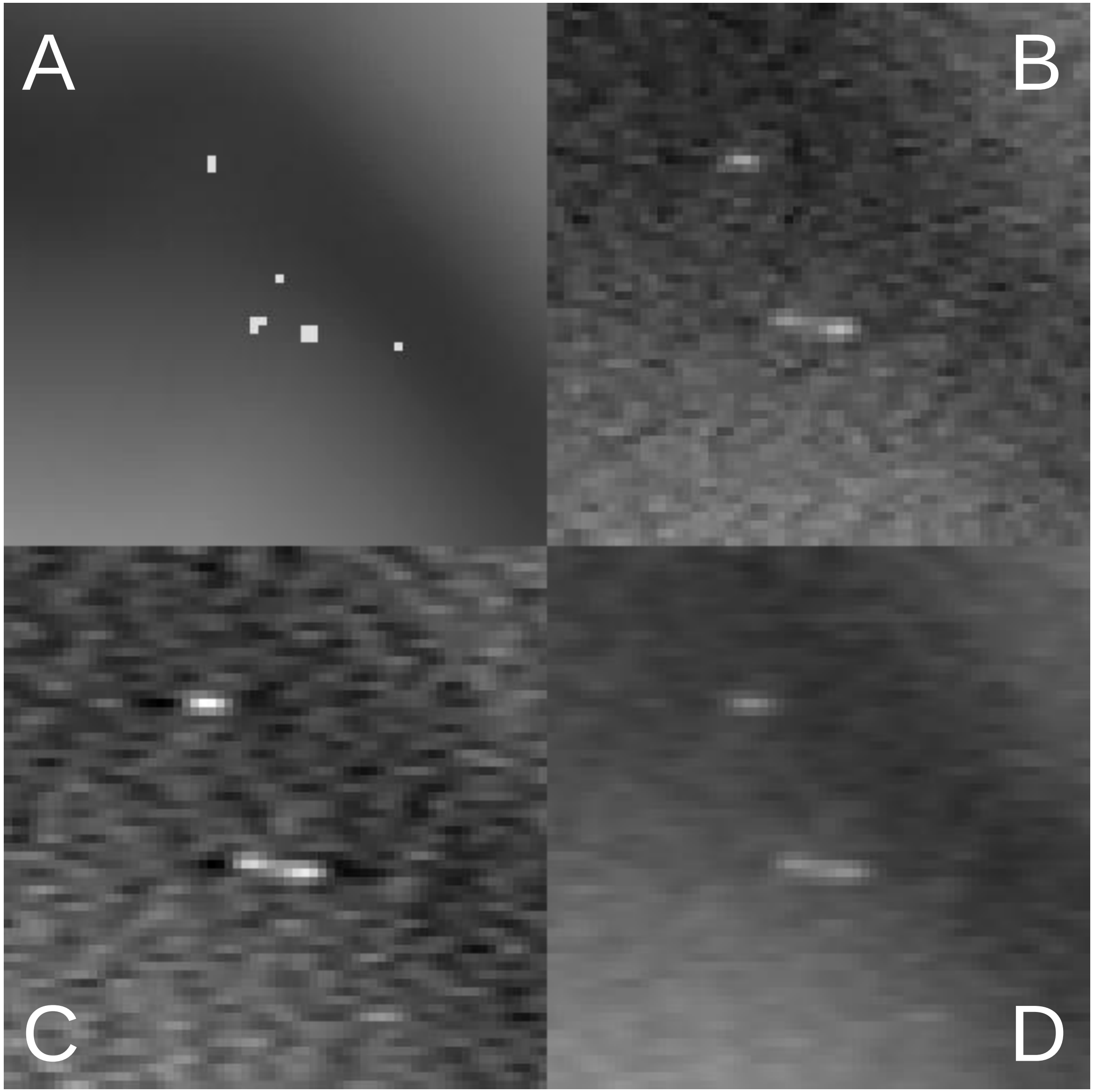
Reconstructions:

A. phantom

B. Siemens iFBP

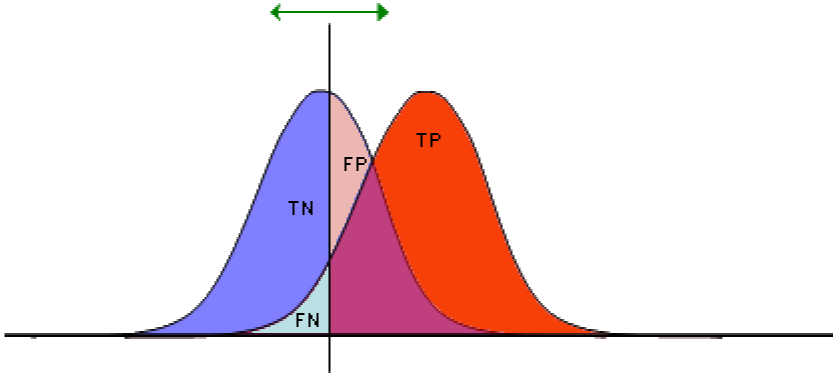
C. 3 iterations patch MLTR

D. 3 iterations patch MAPTR



Evaluation: Observer Study

- ROC analysis:
  - Binary decision per case (benign / malignant) + certainty



TP	FP
FN	TN
1	1

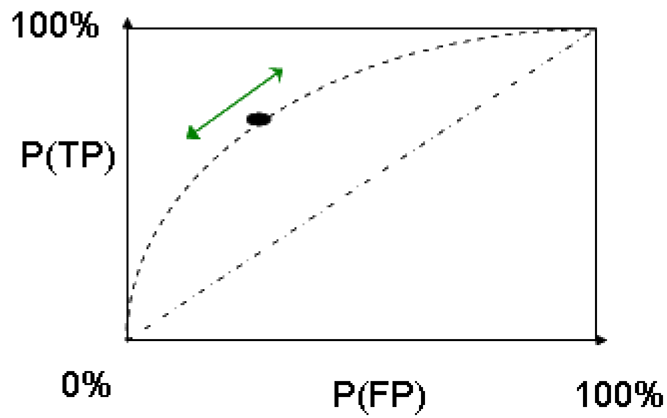


Figure: wikipedia.org

Evaluation: Observer Study

- ROC analysis

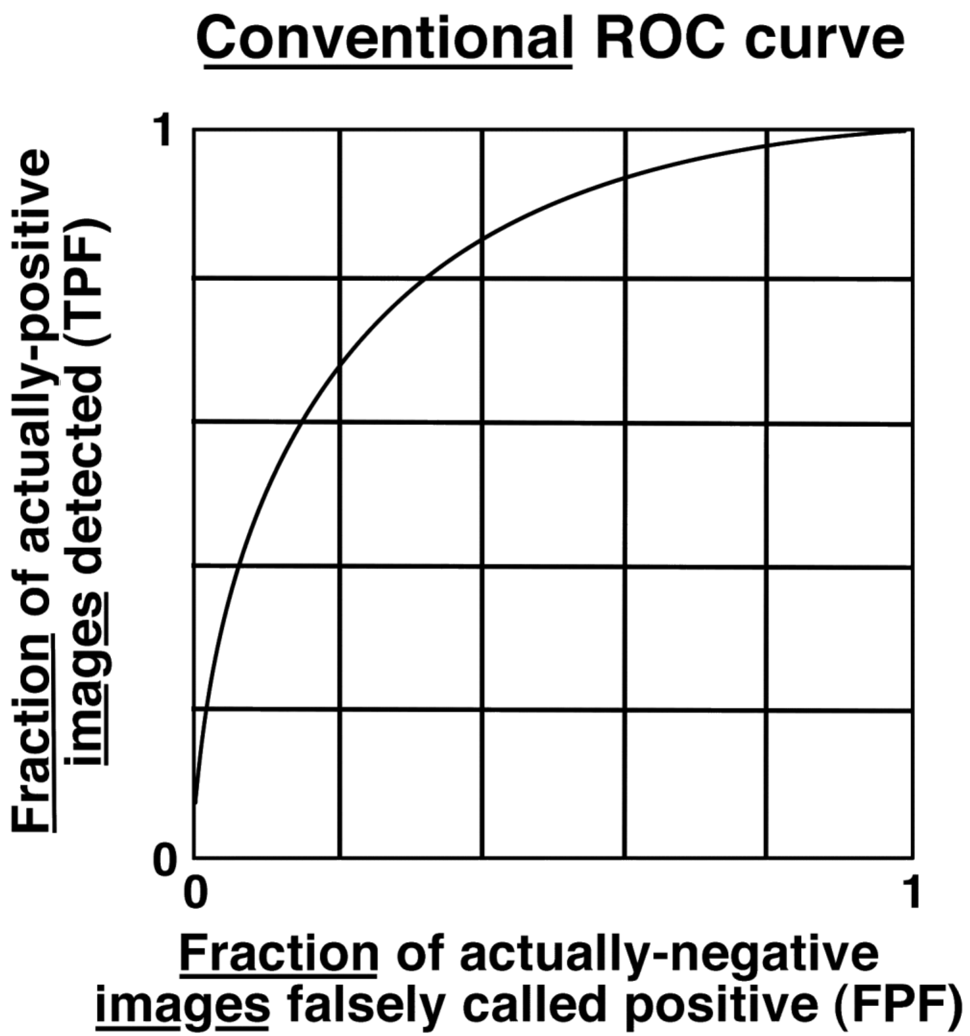


Figure: Metz, C.E., ‘Receiver Operating Characteristic Analysis: A Tool for the Quantitative Evaluation of Observer Performance and Imaging Systems’, Journal of the American College of Radiology, Vol 3, Issue 6, 2006, 413–422

Evaluation: Observer Study

- FROC analysis
  - Multiple decisions per case (malignant lesion is here) + certainty

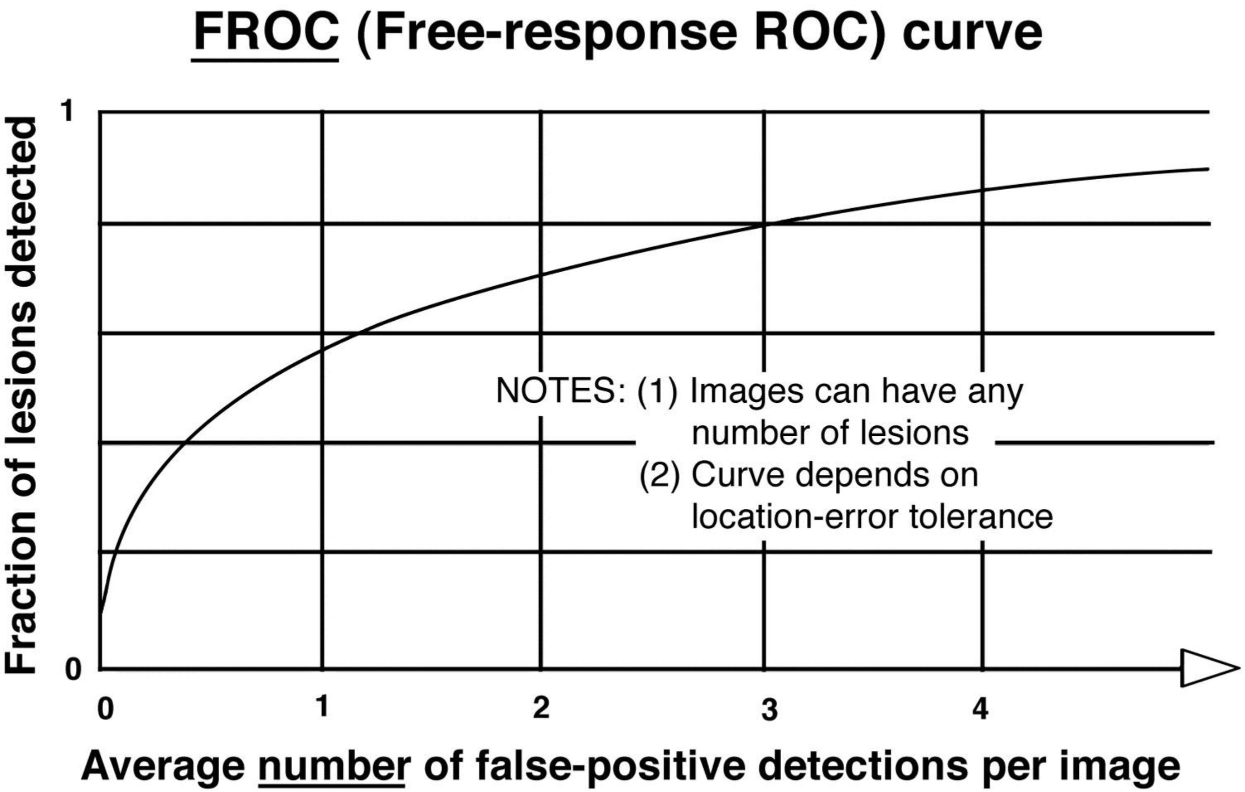


Figure: Metz, C.E., 'Receiver Operating Characteristic Analysis: A Tool for the Quantitative Evaluation of Observer Performance and Imaging Systems', Journal of the American College of Radiology, Vol 3, Issue 6, 2006, 413–422

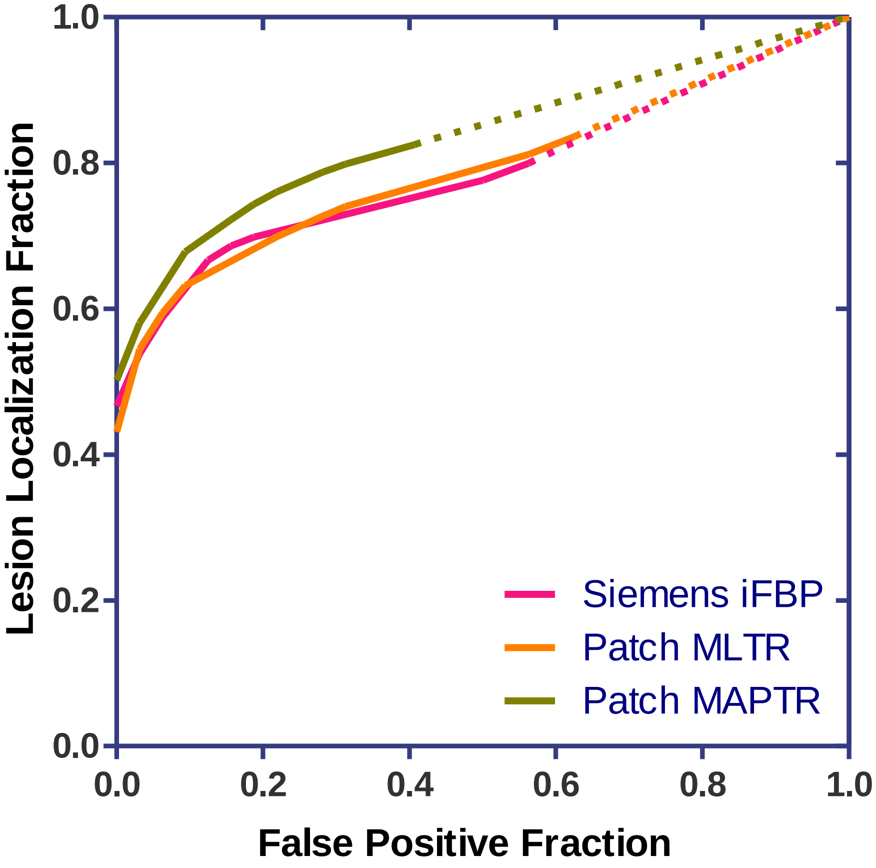
Evaluation: Observer Study

- Detection Study
  - Free search model
  - 80 cases (+ 40 training) for ~~7~~ 6 readers
  - Scores:
    1. I see a hint of a calcification
    2. This might be a calcification
    3. This is probably a calcification
    4. I am sure this is a calcification
  - Analysis with weighted JAFROC* software

*D. P. Chakraborty, “Analysis of location specific observer performance data: validated extensions of the jackknife free-response (JAFROC) method.,” *Academic Radiology*, vol. 13, no. 10, pp. 1187-1193, Oct. 2006.

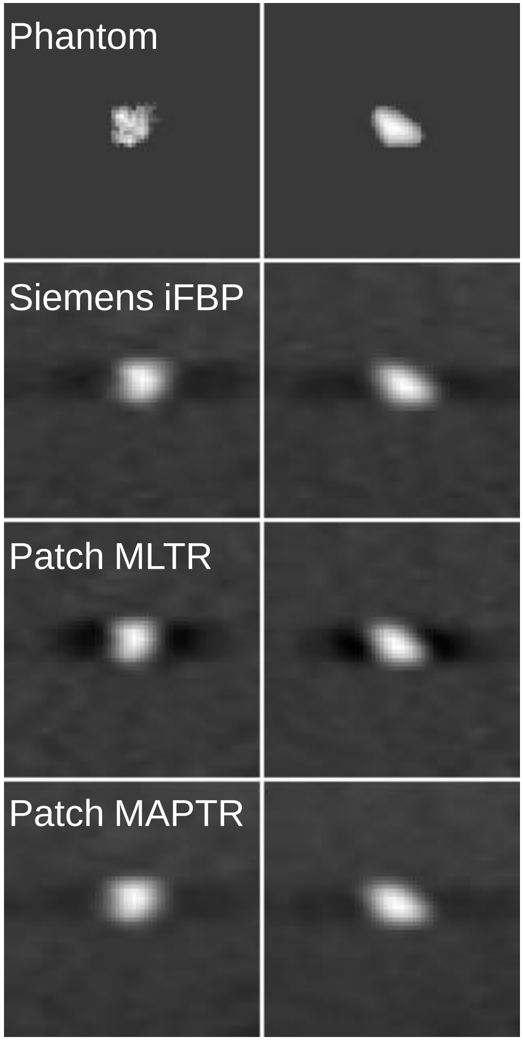
Evaluation: Observer Study

- Detection Study
  - Results
    - Siemens iFBP AUC = 0.780
    - Patch MLTR AUC = 0.778
    - Patch MAPTR AUC = 0.819
  - Differences
    - Global p = 0.036
    - iFBP vs Patch MLTR p = 0.893
    - iFBP vs Patch MAPTR p = 0.029
    - Patch (MLTR vs MAPTR) p = 0.022



Evaluation: Observer Study

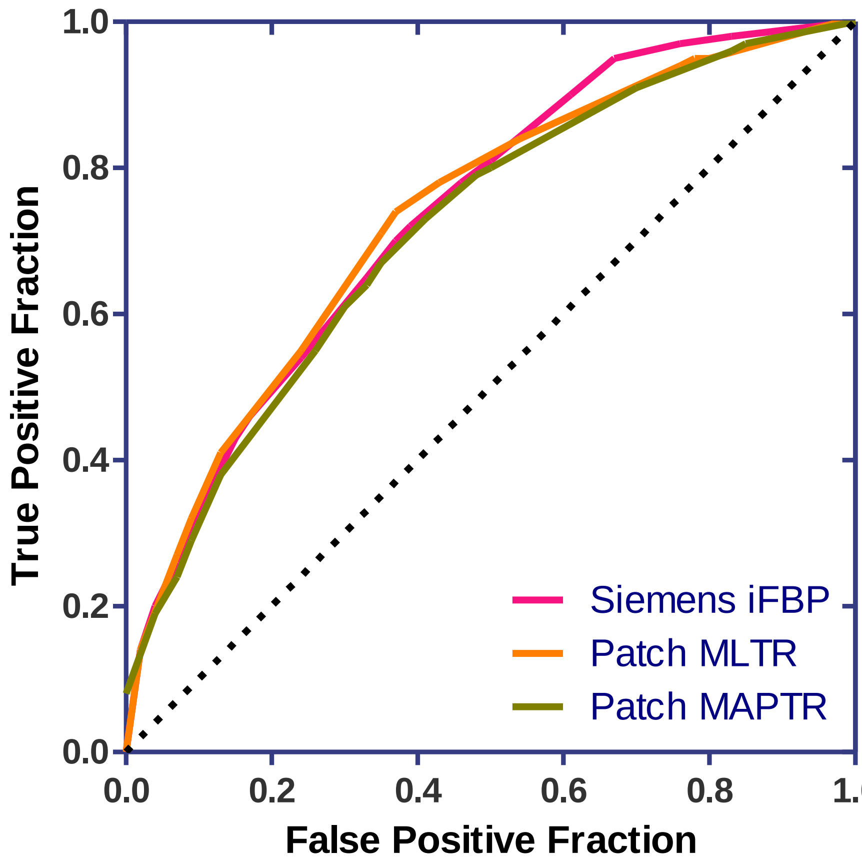
- Classification Study
  - 2 alternate forced choice model
  - 200 cases (+ 100 training) for 5 readers
  - Scores: Smooth | Irregular
    1. Low certainty
    2. Medium certainty
    3. High certainty
  - Analysis with DBM MRMC* software



*D. D. Dorfman, K. S. Berbaum, and C. E. Metz, "Receiver operating characteristic rating analysis. Generalization to the population of readers and patients with the jackknife method.," *Investigative radiology*, vol. 27, no. 9, pp. 723-731, Sep. 1992.

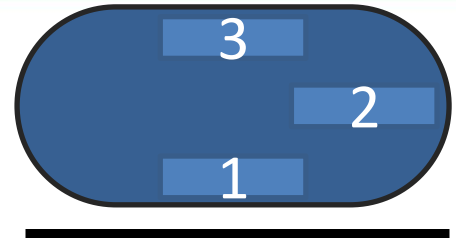
Evaluation: Observer Study

- Classification Study
  - Results
    - iFBP AUC = 0.774
    - Patchwork AUC = 0.773
    - Patchw. w Prior AUC = 0.769
  - Differences
    - Global p = 0.935



Evaluation: Observer Study

- Sub-analysis per location & lesion size

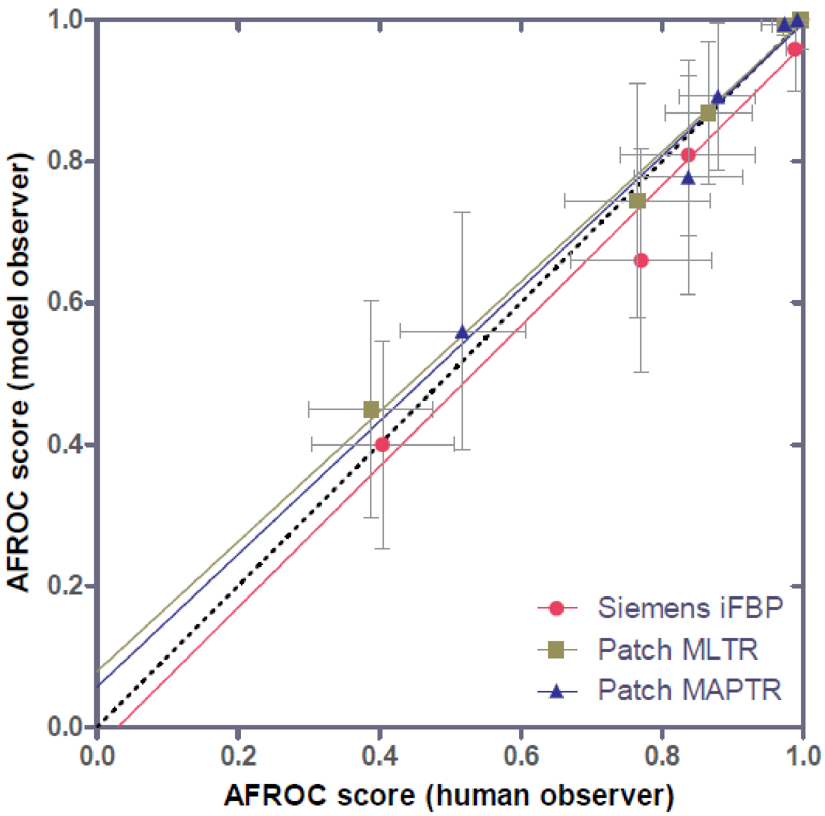


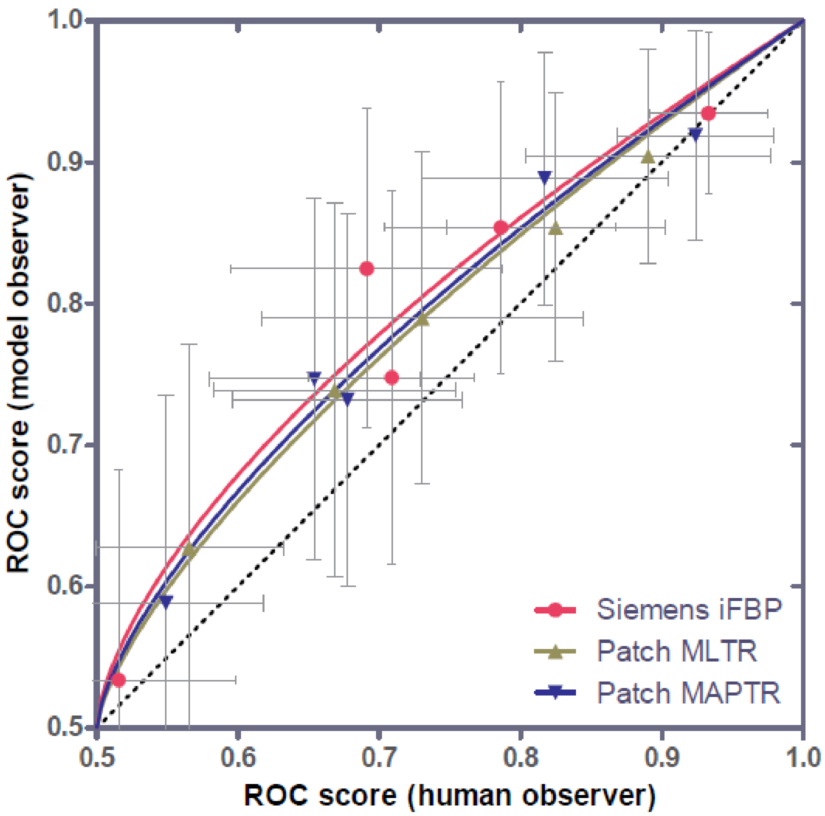
Location	Reconstruction	AUC (200 – 400 µm)	AUC (300 – 500 µm)	AUC (400 – 600 µm)
1	iFBP	0.691	0.789	0.842
	Patchwork	0.681	0.779	0.839
	Patchw. w Prior	0.726	0.803	0.844
2	iFBP	0.633	0.684	0.796
	Patchwork	0.687	0.756	0.822
	Patchw. w Prior	0.620	0.702	0.858
3	iFBP	0.685	0.779	0.870
	Patchwork	0.734	0.811	0.859
	Patchw. w Prior	0.652	0.754	0.827

⇒Indication for location dependent prior strength

Evaluation: Model Observer

- Alternative to human observers for simple tasks
  - Better correlation to human observers than contrast, SNR, CNR, …
  - Relatively easy to implement, but time is needed for initial setup
  - (Don’t complain about doing boring work)





Overview

- Digital Breast Tomosynthesis
- Acquisition Model
- Grouped Coordinate Ascent Algorithm
- Evaluation
  - Acceleration
  - Observer Study
  - (Model Observers)
- Conclusion & Future Work

Conclusions

- New reconstruction
  - Accelerated convergence
  - Improved detectability
  - Equal quality for classification

Conclusions

- New reconstruction
  - Accelerated convergence
  - Improved detectability
  - Equal quality for classification

- Future work
  - Non Gaussian approximation of smoothing
  - Location dependent smoothing prior
  - More physics:
    - Scatter correction
    - Beam hardening
  - More iterations
  - Validation on clinical data with simulated lesions

Thanks!