AAPM 2012 Annual Meeting

Radiographic Tomosynthesis II: reconstruction algorithms

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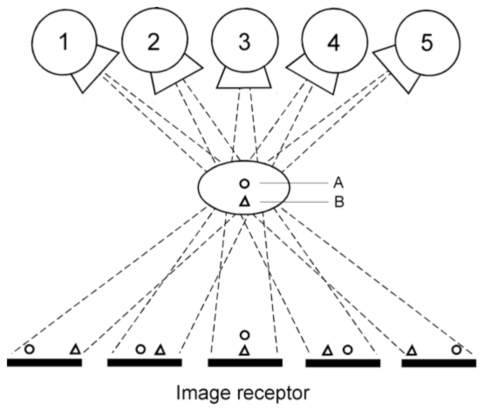
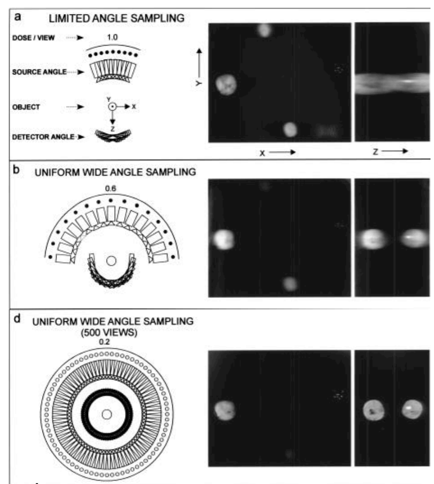
Acknowledgments and financial disclosure

James Dobbins:
Grant support from NIH (ROI CA80409) and GE Healthcare.
Patent jointly held by GE and Duke; JTD is co-inventor.
Has spoken at GE sponsored events.
Unpaid participant at GE Medical Advisory Board mtgs.

FDA statement: discussion will include off-label uses and applications not yet approved

Tomosynthesis: section imaging from multi-projection image reconstruction (limited angle tomography)

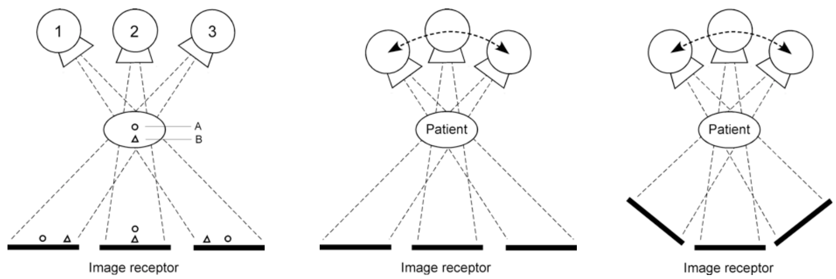




Tao Wu et al, *Med Phys* 30(3), 2003

Geometry of tomosynthesis image acquisition

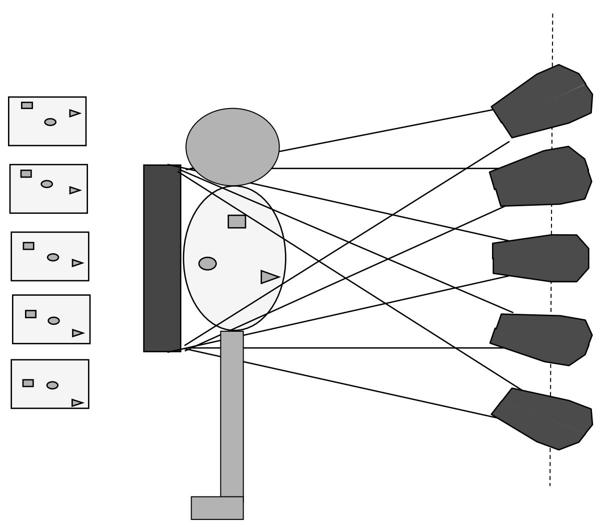
Geometries of motion



Parallel path	Partial isocentric	Isocentric
Chest tomosynthesis	Breast tomosynthesis	CBCT, RadOnc tomosynthesis

3D Chest Radiography (Tomosynthesis)

- **Vertical tube motion**
- **Total tube angle: 20-35°**
- **Number of Projected Images: 60 - 71**
- **Exam length: 10-11 sec (single breath-hold)**
- **Slice thickness: 4-5 mm**

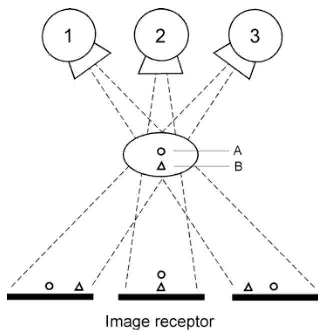


Tomosynthesis image formation

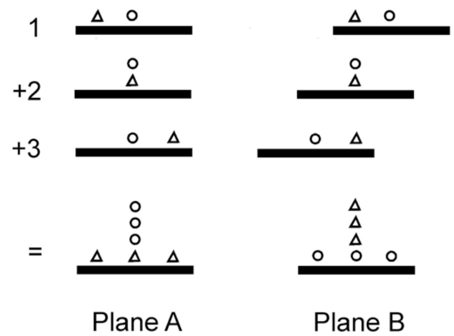
Tomosynthesis algorithms

- Shift-and-add
- ART (algebraic reconstruction techniques)
- Tuned aperture computed tomography (TACT)
- Iterative methods (MLEM)
- Matrix inversion tomosynthesis (MITS)
- Filtered backprojection (FBP)
- Feldkamp (limited angle CBCT)

Shift-and-add reconstruction (simple backprojection)

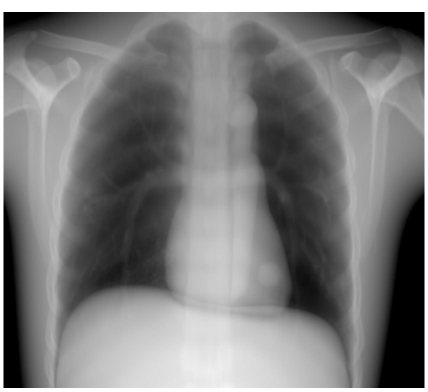


Acquisition geometry

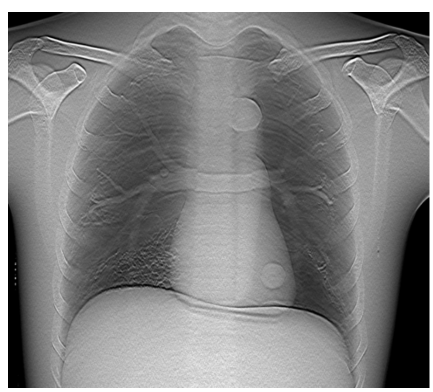


Shift-and-add image formation

The importance of deblurring



Conventional tomo section



After deblurring

Development of deblurring methods

Self-masking subtraction tomosynthesis
Chakraborty et al, 1984

Selective plane removal
Ghosh Roy et al, 1985

Matrix inversion tomosynthesis
Dobbins, 1986

TACT and image restoration
Webber, Ruttimann,1990s

Filtered backprojection
2000s

Matrix Inversion Tomosynthesis (MITS)

Removing the blur with MITS

Direct solution using linear algebra and the known acquisition geometry

- Much faster computationally than iterative deblurring
- Better performance at narrow tube angles than filtered backprojection
- However…. susceptible to noise at the lowest spatial frequencies (< ~ 0.1 cycles/mm)

Conventional tomosynthesis planes

$$t_1 = s_1 \otimes f_{11} + s_2 \otimes f_{12} + \cdots + s_n \otimes f_{1n}$$
$$t_2 = s_1 \otimes f_{21} + s_2 \otimes f_{22} + \cdots + s_n \otimes f_{2n}$$
$$\vdots$$
$$t_n = s_1 \otimes f_{n1} + s_2 \otimes f_{n2} + \cdots + s_n \otimes f_{nn}$$

In the frequency domain…

$$
\begin{aligned}
T_1 &= S_1 \times F_{11} + S_2 \times F_{12} + \cdots + S_n \times F_{1n} \\
T_2 &= S_1 \times F_{21} + S_2 \times F_{22} + \cdots + S_n \times F_{2n} \\
&\vdots \\
T_n &= S_1 \times F_{n1} + S_2 \times F_{n2} + \cdots + S_n \times F_{nn}
\end{aligned}
$$

Removing the blur with MITS

- Matrix form (freq space)

$$
\begin{pmatrix} T_1 \\ T_2 \\ \vdots \\ T_n \end{pmatrix} = \begin{pmatrix} F_{11} & F_{12} & \cdots & F_{1n} \\ F_{21} & & & \\ \vdots & & \ddots & \\ F_{n1} & & & F_{nn} \end{pmatrix} \times \begin{pmatrix} S_1 \\ S_2 \\ \vdots \\ S_n \end{pmatrix}
$$

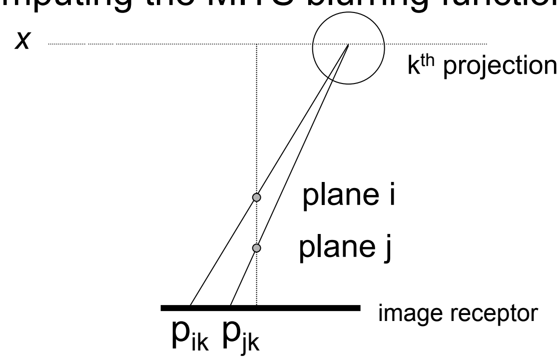
- Rewritten

$$T = M \times S$$

- Solving for true structures

$$s = \mathrm{FT}^{-1}\left(M^{-1} \times T\right)$$

Computing the MITS blurring functions



Shift for kth projection image to tomosynthesize jth plane: $-p_{jk}$

Blurring function for δ-function in i^{th} plane when j^{th} plane is tomosynthesized:

$$f_{ij} = \sum_k \delta(x - p_{ik} + p_{jk})$$

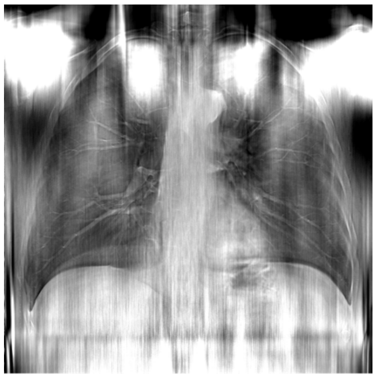
MITS requires a correction for low-frequency noise susceptibility

1. High pass MITS planes (Gaussian filter, σ ~.1 cycles/mm)
1. Low pass conventional planes (Gaussian filter, σ ~.1 cycles/mm)
2. Add 1.25% of the filtered conventional spectra to the high-passed MITS spectra, to restore lung opacity in chest images

$$MITS_{fb}(f) = \left[1 - \exp\left(\frac{-f^2}{2\sigma^2}\right)\right] \cdot MITS(f) + FW \cdot \exp\left(\frac{-f^2}{2\sigma^2}\right) \cdot CONV(f)$$

Frequency blending with MITS

20-degree tube motion, 61 proj images, 59 planes recon, 5 mm plane spacing



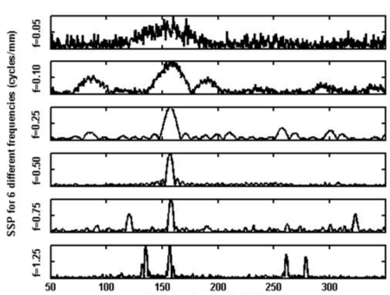
σ=0.01 mm^{-1}

σ=0.1 mm^{-1}

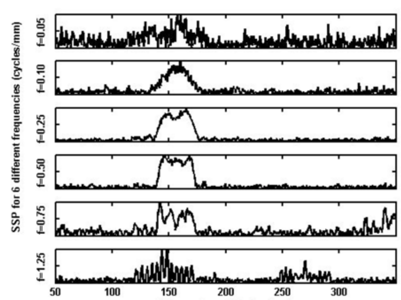
$$MITS_{fb}(f) = \left[1 - \exp\left(\frac{-f^2}{2\sigma^2}\right)\right] \cdot MITS(f) + FW \cdot \exp\left(\frac{-f^2}{2\sigma^2}\right) \cdot CONV(f)$$

Slice sensitivity profile

Single-slice MITS

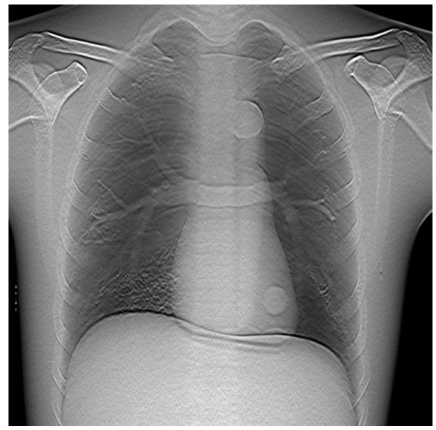


7-slice sliding average MITS



MITS provides excellent reconstruction even at very narrow tube angles

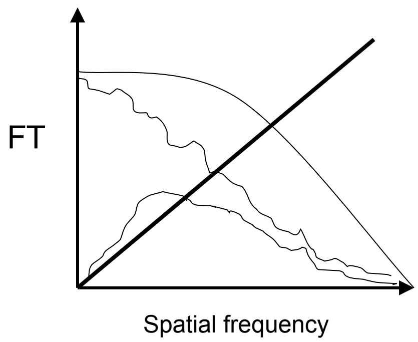
~ 12° tube movement



~ 6° tube movement

Filtered backprojection

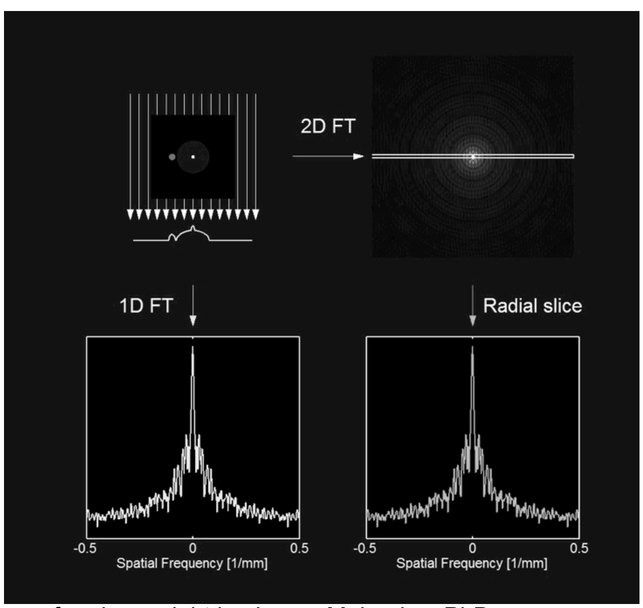
Filtered backprojection methodology



- Ramp filter corrects for the 1/f inherent point response in frequency space
- Apodization (roll-off filter) suppresses high-frequency noise enhancement following ramp filter

Acquire projection images; take Fourier transform
Multiply by ramp filter
Multiply by roll-off filter
Reconstruct by shift-and-add

Projection/Slice Theorem



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Simple Backprojection

Back Projection | Reconstructed Fourier | Original Fourier

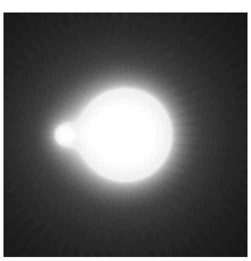
– Very blurry.
+Noise tolerant

Principles of FBP for cone-beam imaging

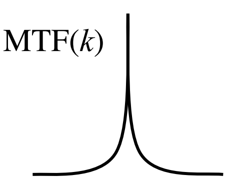
Filtered Backprojection

Intuitive Interpretation

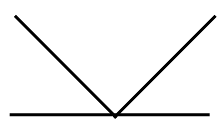
- Backprojection causes blur
- Correct the blur with an "inverse filter"



MTF(k)



Inverse filter=1/MTF(k)



Ramp Filter
Reconstruction Filter

Filtered Backprojection

Back Projection | Reconstructed Fourier | Original Fourier

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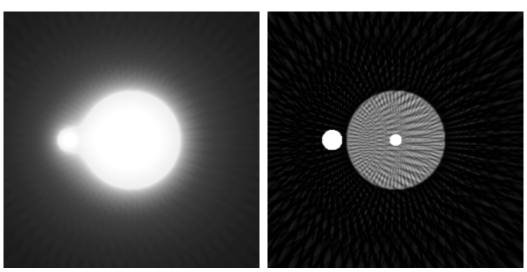
Filtered Backprojection



- Ramp filter provides exact reconstruction when:
  - Noise free
  - Sufficient samples (no missing data)

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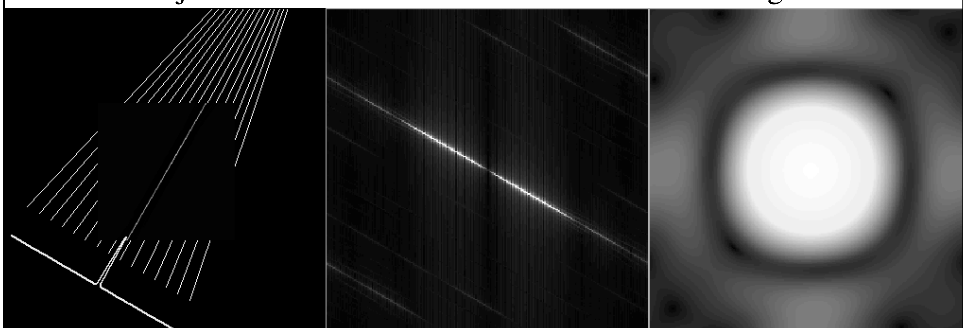
Tomosynthesis (Limited View / Limited Angle)

Back Projection   Reconstructed Fourier   Original Fourier



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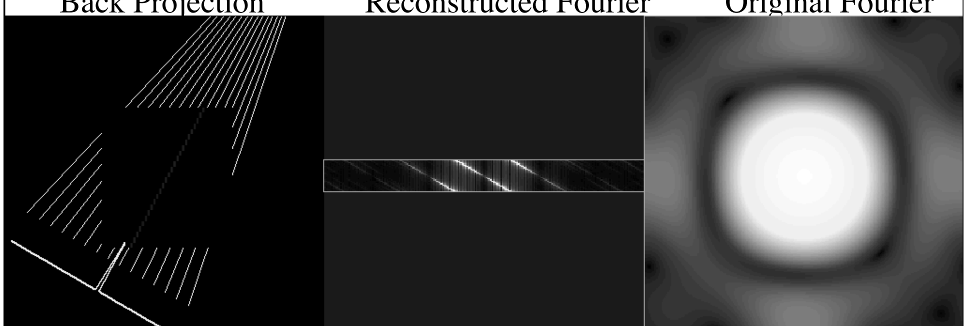
Effect of Thick Slices

Back Projection   Reconstructed Fourier   Original Fourier



Yikes! Aliasing!

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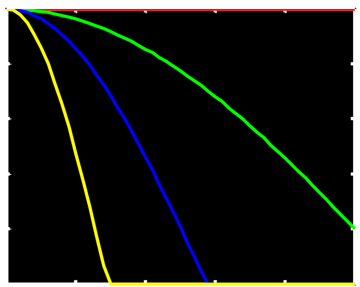
Slice Thickness Correction Filters

- View-dependent (angle) apodization

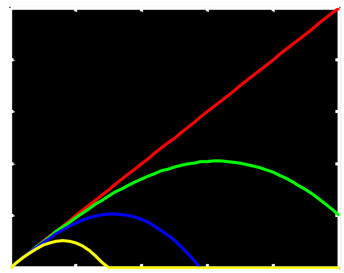
Apodizer

H(f)



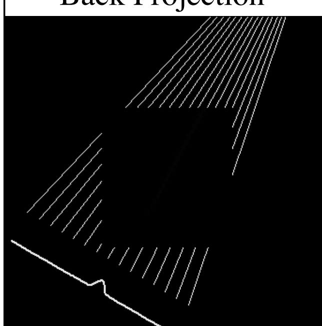
Spatial Frequency

Ramp * Apodizer

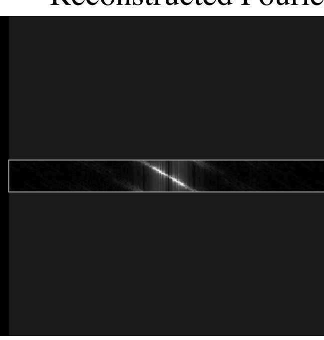


T Mertelmeier, Optimizing filtered backprojection reconstruction for a breast tomosynthesis prototype device, Proc SPIE 6142, 2006

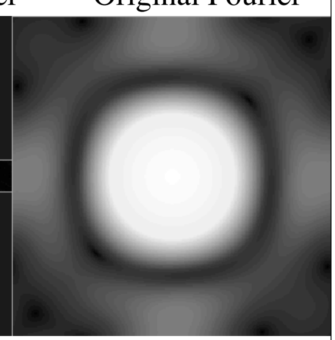
Back Projection

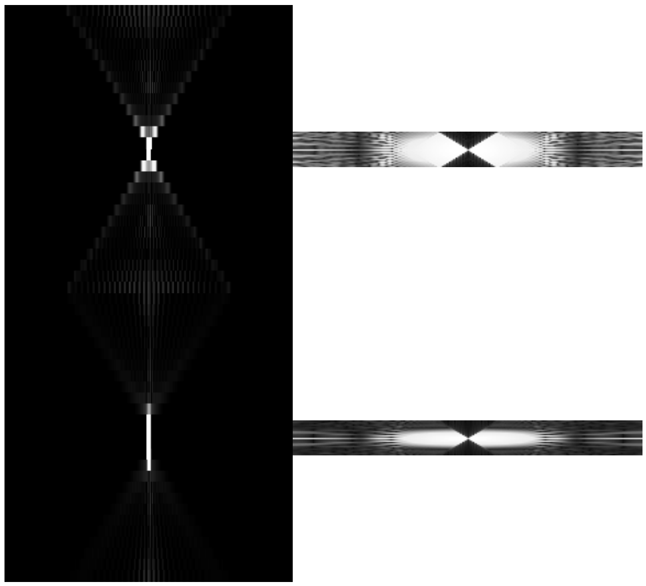


Reconstructed Fourier



Original Fourier





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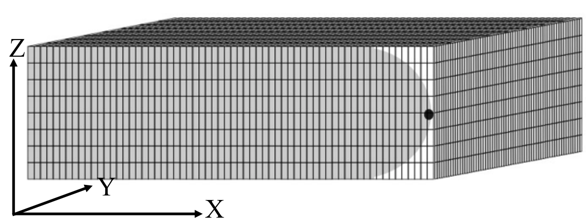
Comparison of MITS and FBP

- MITS uses direct solution using linear algebra and the known acquisition geometry (perfect rendition of in-plane structures)
- FBP uses well-known algorithm from CT
- MITS performs better at narrow tube angles
- Both are much faster computationally than iterative methods
- MITS is susceptible to noise at the lowest spatial frequencies (< ~ 0.1 cycles/mm)
- FBP must use roll-off filter to avoid noise at high-frequencies

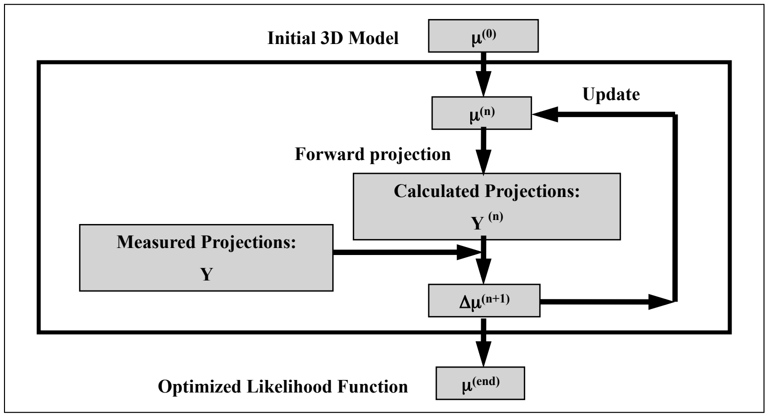
Iterative reconstruction strategies

Iterative Reconstruction Algorithm



- Breast volume is sampled using a three-dimensional matrix of elements (voxels)
- Typical voxel size: 0.1 mm   0.1 mm   1 mm
- The value of a voxel is the linear x-ray attenuation coefficient μ of that element

Maximum Likelihood Expectation Maximization (ML-EM)



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ML-EM Reconstruction: Likelihood Function

Likelihood Function

•L=P(Y|): probability of getting the measured projections Y, given a 3D model

•$\mu^{(n)}$ is updated iteratively so that $L^{(n+1)} > L^{(n)}$

•The reconstruction solution is the 3D attenuation distribution model that maximizes L

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Advantages/disadvantages of iterative methods relative to FBP/MITS

- Better modeling of system, including truncation effects
- Potentially better noise properties
- Potentially better with fewer projections
- Much slower computationally than FBP or MITS

Translational issues remaining

Reconstruction algorithms:

- Low-freq contrast in FBP (less high-pass filtered look)
- Noise improvement: MITS+FBP
- SART
- MLEM - multiple processors
- Clinical evaluation/comparison of various algorithms

Review articles:

Dobbins JT III, Godfrey DJ: Digital x-ray tomosynthesis: current state of the art and clinical potential. Physics in Medicine and Biology, 48:R65-R106, October 2003.

PDF: stacks.iop.org/PMB/48/R65

Dobbins JT III: Tomosynthesis imaging: at a translational crossroads. Medical Physics 36:1956-1967, 2009.

For questions or comments:

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