Radiographic Tomosynthesis: Image Quality and Artifacts Reduction

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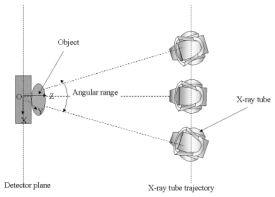
Background

- Linear Trajectory Tomosynthesis
  - Retrospective reconstruction of tomographic planes from multiple low-dose projections (21-61) acquired over a limited angular range (<60°) along a linear trajectory.

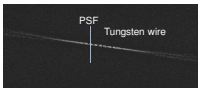


Outline

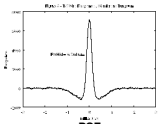
- Image quality metrics: methods and results
  - Spatial resolution
    - In-plane (x-y plane)
    - Slice sensitivity profile (SSP) (z-dimension)
  - Low contrast detectability
    - Pulmonary nodule detection
- Artifacts and remedies
  - Out of focus objects
  - Ripples
  - Edge fall off

In-plane MTF

- Measure MTF using a slanted wire (Flynn et. al, SPIE 2007)
  - 50-80 um tungsten wire suspended in air.
  - Slant angle of 6 degree.
  - Obtain point-spread-function in the scanning direction.
  - MTF = FFT(PSF) normalized to 1.



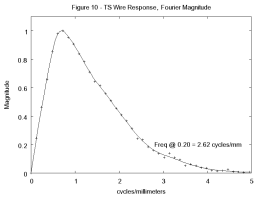
A tomo image



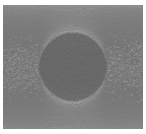
PSF

In-plane MTF

- Mid-frequency "hump" – shape of edge enhancing filters
- MTF(0) – some vendors add a small DC component, others don't.



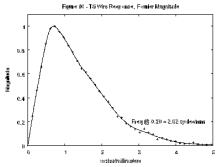
MTF

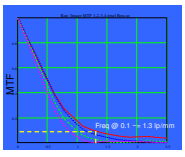


Tomo image of a spherical object

In-plane MTF

- Tomosynthesis vs. digital linear tomography





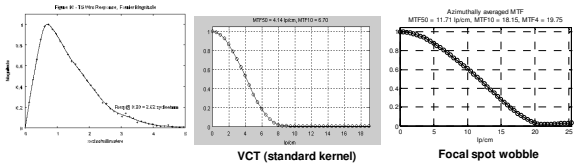
lp/mm

MTF	Tomosynthesis (150 um x 150 um)	Linear Tomography (200 um x 200 um)
50% MTF	~1.8 lp/mm	~0.5 lp/mm
10% MTF	~3.5 lp/mm	~1.3 lp/mm

The in-plane resolution of Tomosynthesis is 3x of digital linear tomography

In-plane MTF

- Tomosynthesis vs. CT



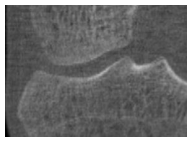
VCT (standard kernel) | Focal spot wobble

MTF	Tomosynthesis (150 um x 150 um)	MDCT (0.65 mm) (standard kernel)	MDCT (0.65 mm) (FS wobble)
50% MTF	~1.8 lp/mm	~0.4 lp/mm	~1.2 lp/mm
10% MTF	~3.5 lp/mm	~0.7 lp/mm	~1.8 lp/mm

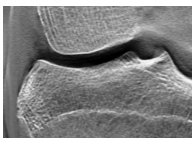
The in-plane resolution of Tomosynthesis is 2-4x of CT

In-plane MTF

- Comparison of clinical images (Flynn et. al, SPIE 2007)



CT (coronal reformat)



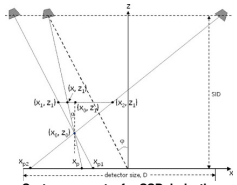
Tomosynthesis (150 um x 150 um)

In-plane MTF

- Summary
  - The in-plane resolution of tomosynthesis is ~3x of digital linear tomography
  - The in-plane resolution of tomosynthesis is ~2-4x of CT

Slice Sensitivity Profile

- SSP is reconstruction algorithm dependent
- For Filtered backprojection, the relationship is derived (Li et. al, Med Phys 2008)



System geometry for SSP derivation

$$f(x_0,z_0)=\int_{-\theta/2}^{\theta/2}d\varphi\int_{-D/2}^{D/2}q(x',\varphi)h(x_p(\varphi,x_0,z_0)-x')dx'$$

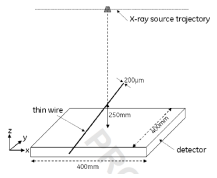
$$=\int_{-\theta/2}^{\theta/2}d\varphi\int_{-D/2}^{D/2}q(x',\varphi)h\left(x_0+z_0\frac{SID\tan(\varphi)-x_0}{SID-z_0}-x'\right)dx'$$

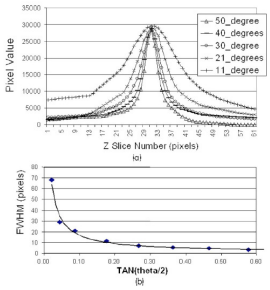
$$f(x_0,z_i)\propto\frac{f(x_0,z_0)}{\tan(\vartheta/2)}\approx\frac{f(x_0,z_0)}{\vartheta}$$

1. For FBP, the SSP is inversely proportional to angular range θ.
2. SSP is spatially varying as a function of z_0.

Slice Sensitivity Profile

- Simulation study

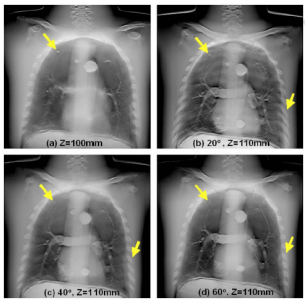




The reduction in SSP is less and less pronounced beyond 40°

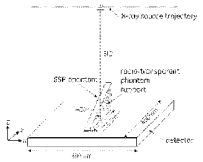
Slice Sensitivity Profile

- Anthropomorphic phantom (Li et. al, Med Phys 2008)
  - (a) In-focus plane containing a 8.8 mm nodule
  - (b)–(d) Off-focus plane at z=110 mm with increasing angular range from 20° to 60°
  - **Confirming:**
    - **A decrease in slice thickness as angular range increases**
    - **Diminishing returns beyond 40°**

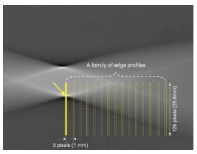


Slice Sensitivity Profile

- Measure MTF using a slanted wedge (Li et. al, Med Phys 2008)
  - Tungsten ruler on a foam support. Slant angle of 30 degree
  - Obtain a family of line-spread-functions in the scanning direction
  - PSFs = Differentiate(LSFs)
  - Obtain FWHMs from the family of PSFs as function of z



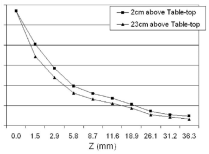
PSF

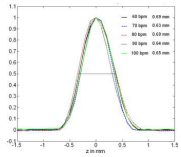


A tomo image

Slice Sensitivity Profile

- Tomosynthesis vs. CT





SSP	Tomosynthesis (300 um x 300 um)	MDCT	MDCT (xFFS)
FWHM	~ 3 mm	~ 0.6 mm	~ 0.3 mm

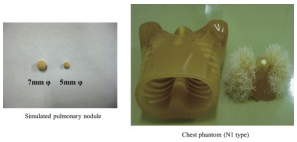
The slice thickness of Tomosynthesis is ~ 5-10x of CT

Slice Sensitivity Profile

- Summary
  - For FBP, the SSP is inversely proportional to angular range ϑ; diminishing returns beyond 40°
  - The slice thickness of Tomosynthesis is ~5-10x of CT i.e., highly anisotropic voxel
  - SSP of tomosynthesis is spatially varying

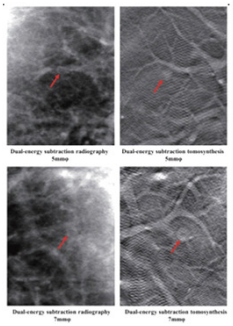
Low Contrast Detectability

- Simulated pulmonary nodule – DES vs DES-Tomosynthesis (Gomi et. al, Acad. Radiol. 2011)



Simulated pulmonary nodule

Chest phantom (N1 type)


Dual-energy subtraction radiography 5mmφ

Dual-energy subtraction tomosynthesis 5mmφ

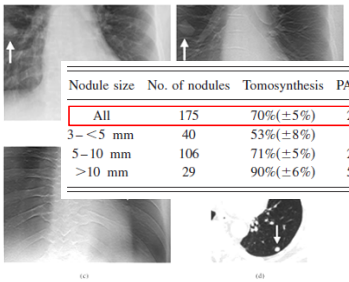
Dual-energy subtraction radiography 7mmφ

Dual-energy subtraction tomosynthesis 7mmφ

The area under ROC curve was ~90% and ~60% for DES-T and DES, respectively (P < .003).

Low Contrast Detectability

- Nodule detection clinical trial (Dobbins et. al, Med Phys 2008)



Nodule size	No. of nodules	Tomosynthesis	PA radiography	*p* value
All	175	70%(±5%)	22%(±4%)	<0.0001
3–<5 mm	40	53%(±8%)	7%(±5%)	<0.0001
5–10 mm	106	71%(±5%)	20%(±3%)	<0.0001
>10 mm	29	90%(±6%)	53%(±7%)	0.004

(c)

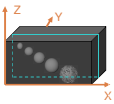
(d)

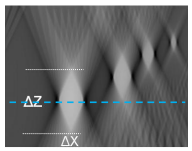
Low Contrast Detectability

- Summary
  - Low contrast detectability of Tomosynthesis is ~3x (overall) of PA radiography
  - Low contrast detectability of Tomosynthesis is size-dependent: 0.5x of CT for <5mm nodules, 0.7x of CT for 5-10mm nodules, and comparable for > 10mm nodules

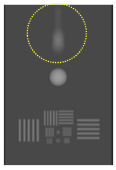
Artifacts and Remedies

- Out of focus objects
  - Highly anisotropic voxel size due to limited angular range (<60°)
  - Objects appear in adjacent slices where they do not belong
  - Out of focus objects lead to blurry image and "anatomical noise"





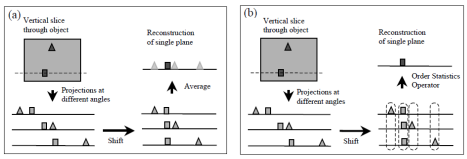
Highly anisotropic voxel size



Out of focus objects

Artifacts and Remedies

- Out of focus objects
  - Artifacts can be suppressed by software
  - Order statistics based approach (Claus et. al, SPIE 2002)

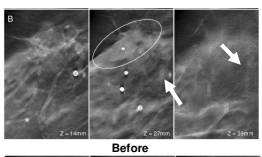


Before

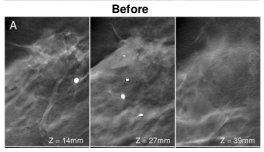
After

Artifacts and Remedies

- Out of focus objects
  - Hybrid approach combining order statistics based method with advanced image segmentation (Wu et. al, Med Phys 2006)



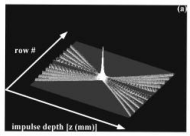
Before



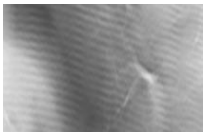
After

Artifacts and Remedies

- Ripples
  - Limited # of projection results in under-sampling of the angular range
  - Discrete impulse response is a result of angular aliasing
  - Strong edges (e.g., ribs, implants, etc.) manifests as ripples



Impulse response from N = 11

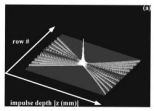


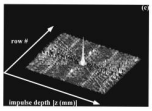
Ripples observed in phantom Images (thorax)

Artifacts and Remedies

- Ripples
  - Artifacts can be suppressed by optimization of acquisition parameters or reconstruction algorithm (Dobbins et. al, Med Phys 2008)

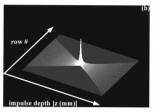
N = 11

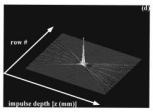




N = 11, MITS

N = 61

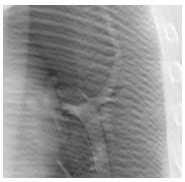




N = 61, MITS

Artifacts and Remedies

- Ripples
  - Artifacts can be suppressed by optimization of acquisition (Deller et. al, SPIE 2007)

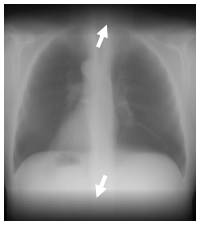


N = 21, FBP

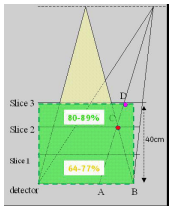
N = 61, FBP

Artifacts and Remedies

- Edge fall off
  - Uneven number of rays passing thru the planes due to truncation
  - Truncated projections cause intensity drop off



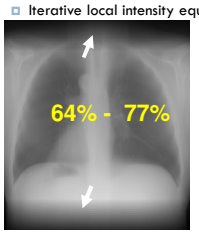
Before



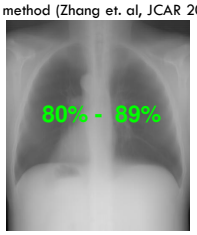
For rad tomo, source-to-image distance (SID) around 100 cm (table) or 180 cm (wall-stand)

Artifacts and Remedies

- Edge fall off
  - Artifacts can be corrected by software
  - 3-D non-uniform view-weighting technique (Li et. al, SPIE 2007)
  - Iterative local intensity equalization method (Zhang et. al, JCAR 2009)



Before



After

Conclusion

- Image quality metrics of linear-trajectory Tomo
  - In-plane resolution: 2-4x of CT or linear tomography
  - SSP: inversely proportional to θ; slice thickness: 5-10x thicker than CT
  - Low contrast detectability: >3x better than radiography, but somewhat inferior to CT (nodule size-dependent)
- Image artifacts and reduction strategies
  - Out of focus objects post the biggest image quality challenge; Order statistics based method helps, but is not perfect yet
  - Ripple artifacts can be suppressed sufficiently by optimization of acquisition parameters and/or reconstruction algorithm
  - Edge fall off can be corrected by 3-D non-uniform view-weighting or iterative intensity equalization