Dose reduction using cuts in the data set

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Outline

1. Data requirements in CT: old beliefs
2. New understanding (> 2002)
   - Super short-scans
   - Region-of-interest imaging
   - Dose savings through data collimation
3. Full FOV imaging with reduced number of views

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Data requirements in CT:
old beliefs

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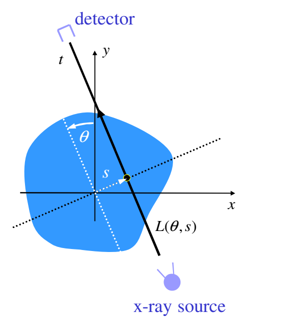
Problem

What set of measurements is sufficient to achieve accurate reconstruction of a given region-of-interest (ROI)?

Note: By accurate, we mean “theoretically-exact” and “stable”.

Mathematical formulation



Unknown:

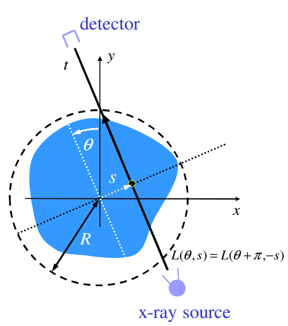
linear attenuation coefficient μ in a given region of interest

Data model (Radon transform):

$$g(\theta,s)=(R\mu)(\theta,s)=\int_{L(\theta,s)}\mu(\vec{x})\,dL$$

Problem:

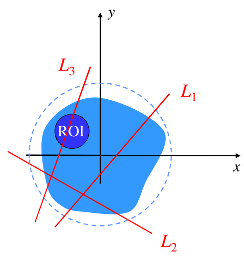
Over which (θ, s) - range do we need to know the data to achieve accurate reconstruction of μ in a given ROI?



A priori information:

$$g(\theta,s)=g(\theta+\pi,-s)$$
$$g(\theta,s)=0 \quad \text{if} \quad |s|\geq R$$

Hence, we only need measurements for $(\theta,s)\in[0,\pi)\times(-R,+R)$



Can we deal without measurements on lines L_1 and L_2 ?

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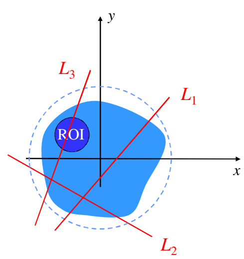

Can we deal without measurements on lines L_1 and L_2 ?

Learning from the classical FBP reconstruction formula:

"every line integral though the object is needed for accurate reconstruction at any location"

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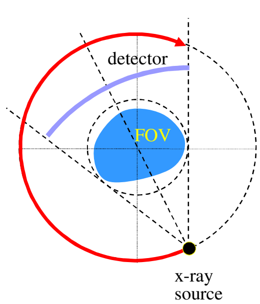
In fan-beam geometry, the requirement to measure on all lines through the object leads to the concept of short-scan range.

Short-scan = 180 degrees plus fan-angle
Full-scan = 360 degrees



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Relaxing the data requirement …

- Limited-angle problem
- Exterior problem
- Interior problem

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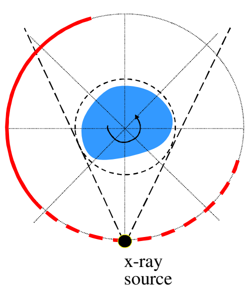
Limited-angle Problem



Theoretically-exact reconstruction is possible, but not in a stable way.

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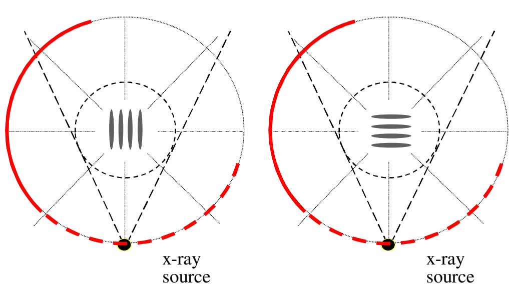

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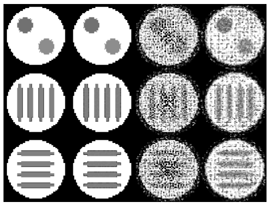
SVD analysis

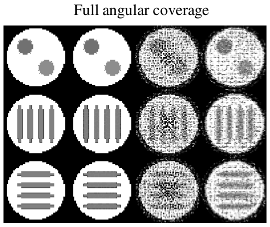
Full angular coverage



Truth | Noise free | 3% noise | Dropping the last 275 terms

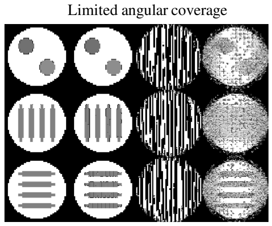
SVD analysis

Full angular coverage



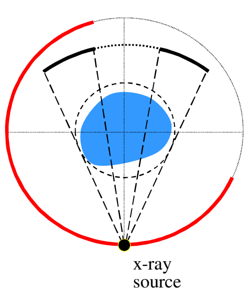
Truth | Noise free | 3% noise | Dropping terms

Limited angular coverage



Truth | Noise free | 3% noise | Dropping terms

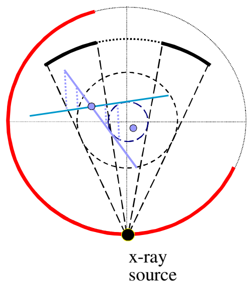
Exterior problem (peripheral imaging)



Theoretically-exact reconstruction is possible, but not in a stable way.

Exterior problem (cont'd)

For points inside the small inner disk we have no data, and for points outside we have a limited angle problem that depends on the point location.



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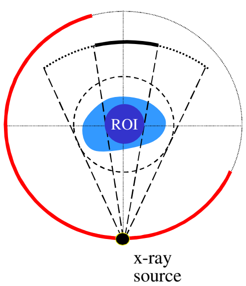
Interior problem



Theoretically-exact reconstruction of the ROI is not possible.

Ghosts can be added to the reconstructed image without affecting consistency with the data.

Note that the ghosts are low-frequency images!

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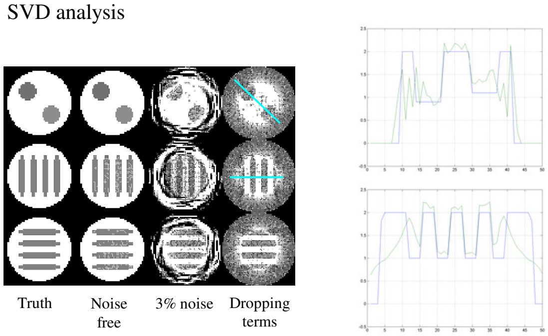
SVD analysis



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Conclusion:

Tomography is “all or nothing” ???

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Data requirements in CT:
new understanding (> 2002)

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Theory of super short-scans

New data completeness condition*

Given non-truncated fan-beam projections, accurate reconstruction of a given ROI is possible whenever every line passing through the ROI intersects the trajectory of the x-ray source

*Noo F, Defrise M, Clackdoyle R, H. Kudo, “Image reconstruction from fan-beam projections on less than a short-scan”, Phys. Med. Biol., 2002.

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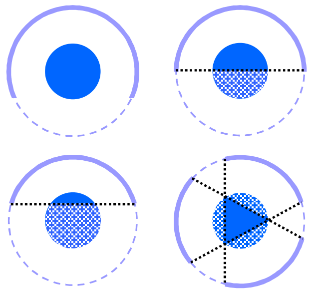
Theory of super short-scans (cont'd)



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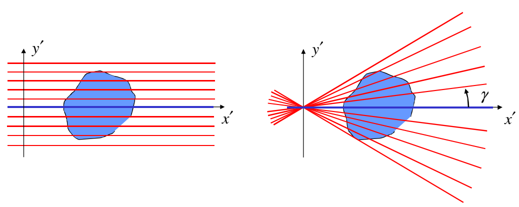
Key result behind the theory of super short-scans



$$\int_{-\infty}^{+\infty} dy' \frac{1}{\pi y'} g_{PB}(y') = \int_{-\pi}^{\pi} \frac{1}{\pi \sin \gamma} g_{FB}(\gamma) d\gamma$$

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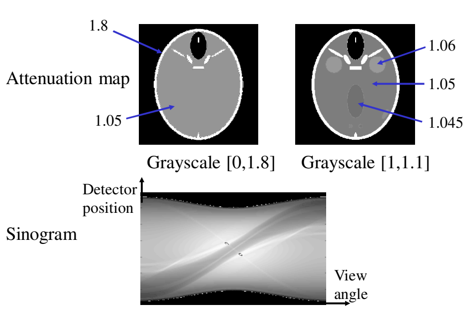
Simulations using the FORBILD head phantom



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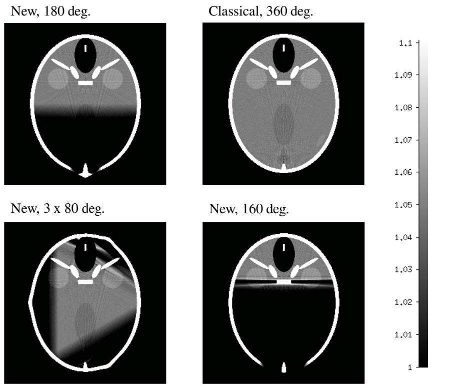

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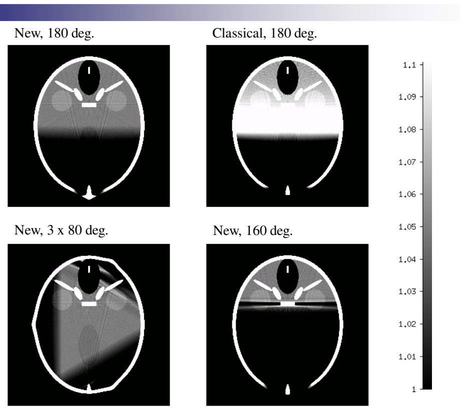

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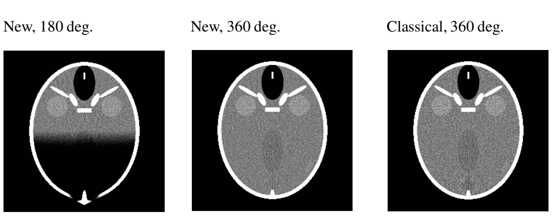
With noisy data …



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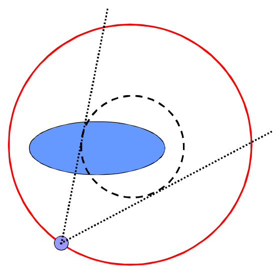
Can we extend the result to truncated projections ?



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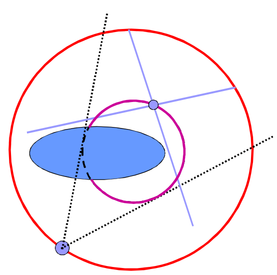
Trick*: rearrange the ray-sums in non-truncated virtual fan-beam projections, then apply the super short-scan theory



*Clackdoyle R, Noo F, Guo J, Roberts J A, "Quantitative reconstruction from truncated projections in classical tomography", IEEE Trans. Nuc. Sci., 2004.

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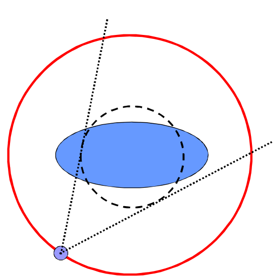
How about with truncation on two sides?



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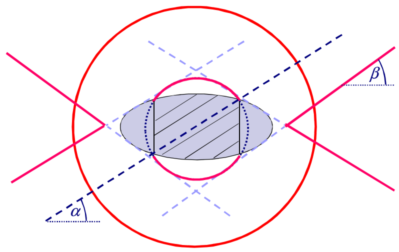

If the area of the ellipse body is smaller than the FOV area, the shaded region can be accurately reconstructed

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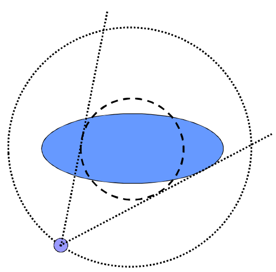
Other theory: the BPF/DBP method*



*Zhou Y and Pan X, PMB, 2004; Noo F et al., PMB 2004; other works by Chen GH; and by Wang G.

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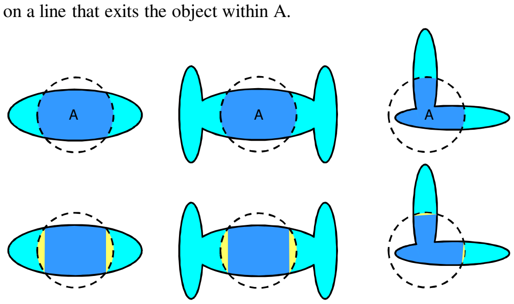
Let region A be such that all lines passing through a point of A are measured. Accurate reconstruction is possible at any point of A that lies on a line that exits the object within A.



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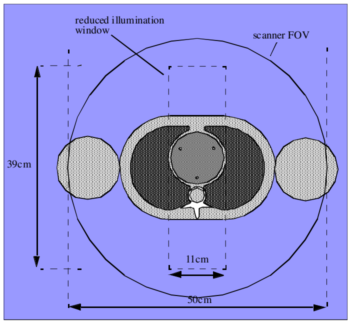
Experiment with the QRM phantom



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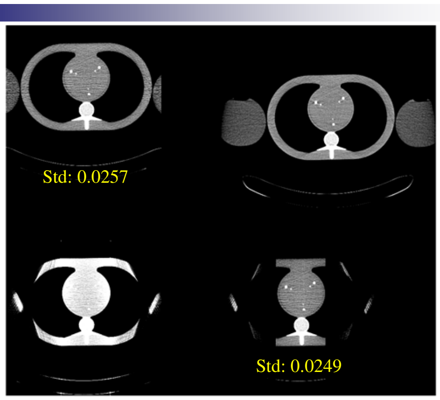

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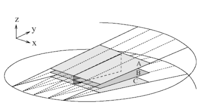
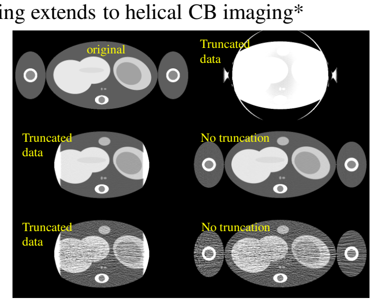
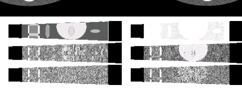
Axial truncation handling extends to helical CB imaging*



Left: M-line DBP
Right: Katsevich





*Pack J D, Noo F, Clackdoyle R, IEEE TMI, 2005.

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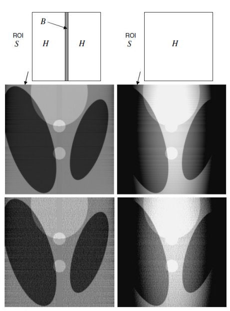
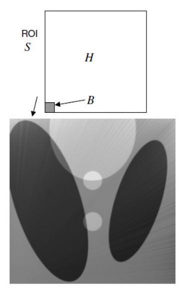
Pushing the limits: towards "solving" the interior problem*

- Tiny a priori knowledge solves the interior problem*
- Compressed-sensing based interior tomography**

*Ye Y et al., 2007; Kudo H et al., 2008; Courdurier et al., 2008
**Yu H. and Wang G., 2009

Tiny a priori knowledge solves the interior problem*





Compressed-sensing based interior tomography

An object that is piecewise polynomial can be exactly and stably reconstructed using total variation minimization

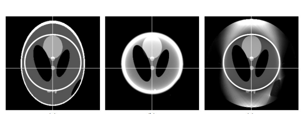
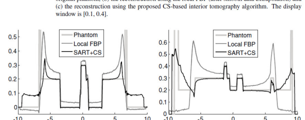
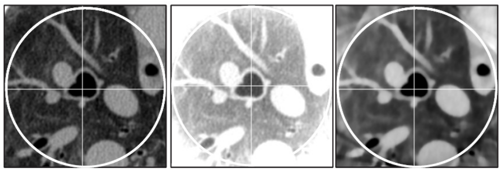


Figure 4. Reconstructed images of a modified Shepp–Logan phantom after 60 iterations. (a) The original phantom, (b) the reconstruction using the local FBP (after smooth data extrapolation) and (c) the reconstruction using the proposed CS-based interior tomography algorithm. The display window is [0.1, 0.4].



Compressed-sensing based interior tomography (cont'd)



Potential dose savings for the full interior problem*

TABLE 4. Percentage Reduction of $CTDI_{100}$ Values and $CTDI_{vol}$ for Small SFOVs as Compared to the 50-cm SFOV at 120 kVp

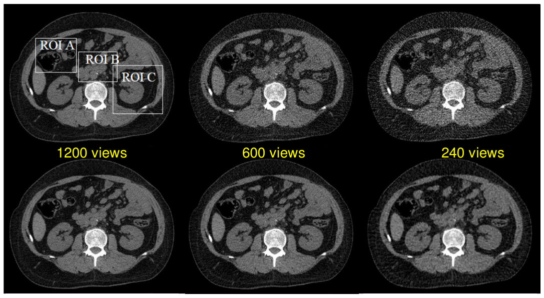
SFOV, cm	$CTDI_{100}$ at the Center		$CTDI_{100}$ at the Periphery		$CTDI_{vol}$, mGy	Percentage Reduction
	Measured, mGy	Percentage Reduction	Measured, mGy	Percentage Reduction		
8.6	13.11	36.51	14.79	63.44	16.26	57.90
13.4	16.7	19.13	21.67	46.48	22.87	40.78
16.8	18.09	12.40	26.7	33.91	27.23	29.49
20.6	19.40	6.05	31.64	21.78	31.5	18.4
50	20.65 (20.48)	0	40.45 (41.93)	0	38.62 (39.75)	0

The values in parentheses are $CTDI_{vol}$ values calculated from the CT technical manual.

*Bharkhada D et al., J Comput Assist tomogr, 2009.

Full FOV imaging using a reduced number of projections*

*Pan X et al.: "ASD POCS"; Chen GH et al.: "PICSS".



$$\mu^* = \operatorname{argmin} \|\mu\|_{TV} \quad \text{s.t.} \quad |R\mu - g| \le \varepsilon$$

*Pan X et al., "Initial experience in constrained-TV-minimization image reconstruction from diagnostic CT data", The CT meeting, 2012.

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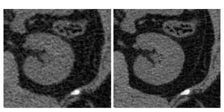
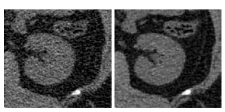
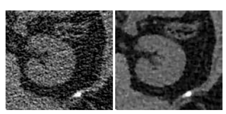


1200 views



600 views

240 views



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Conclusions

- Numerous advances in image reconstruction theory have highlighted paths to reducing the amount of data with no impact on image quality
- The interior problem can be solved by adding a priori knowledge on the attenuation coefficient, but image quality may be slightly impacted
- Dose savings for full ROI imaging may vary between 20% and 60% depending on ROI size (from 20cm to 8cm)
- TV minimization /compressed sensing may allow cutting the dose by a factor two with no impact on image quality
- Hardware developments (new collimator, fast reconstruction engine, fast tube current modulation) are needed for clinical implementation

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THANK YOU

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