Beam Shaping: Dynamic Fluence Field Modulation Techniques

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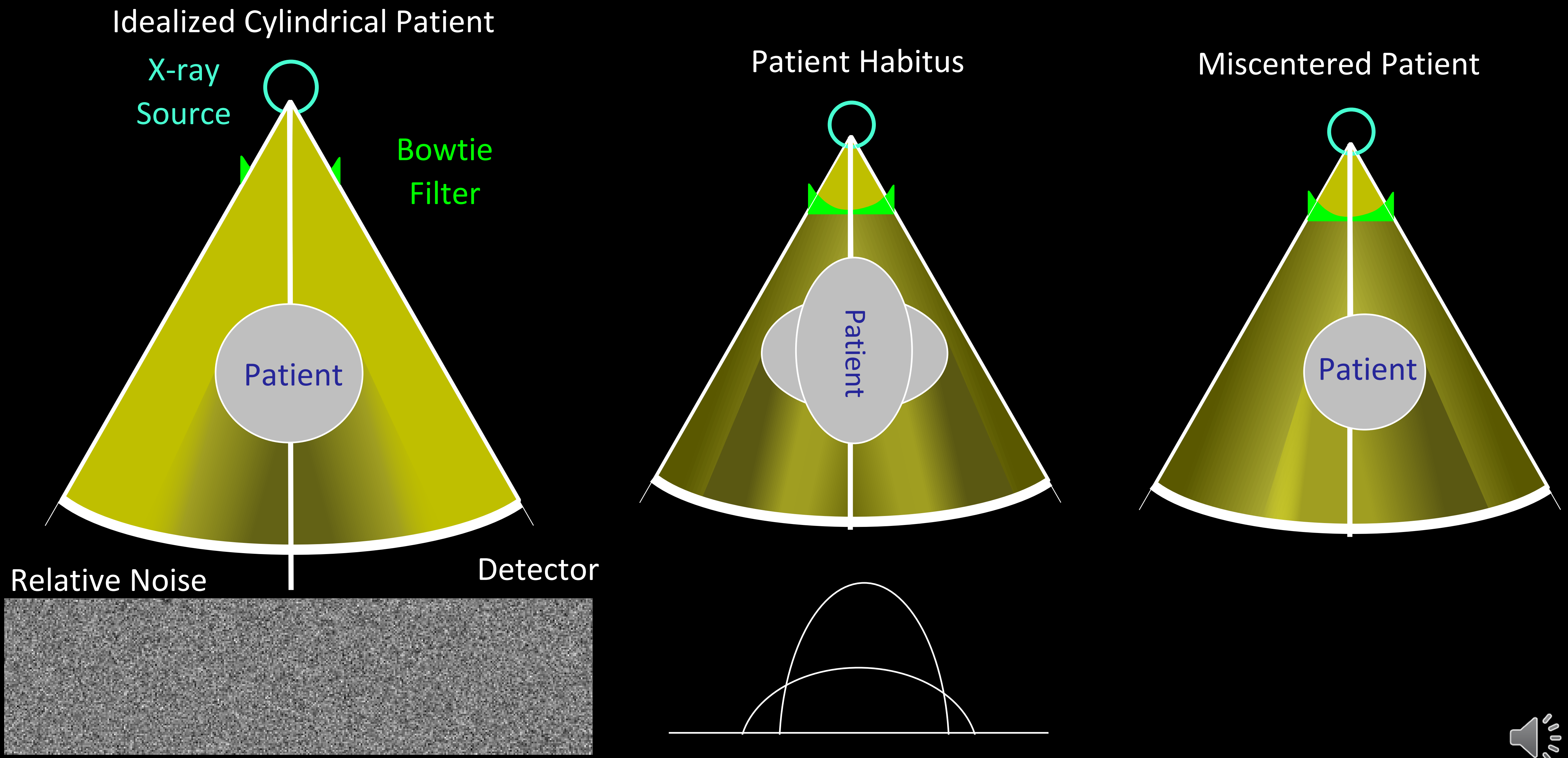
Spatial Filtering in CT



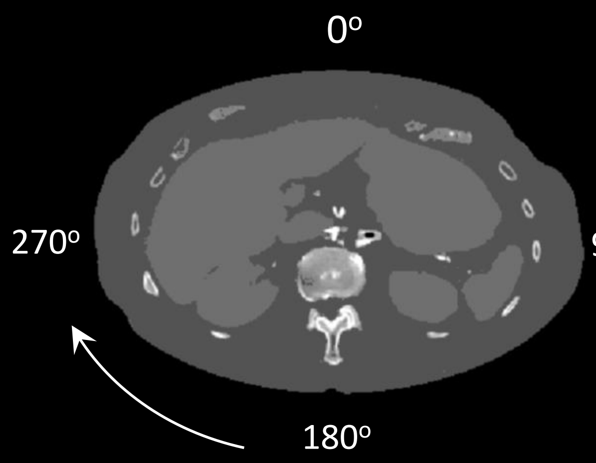
Optimal Fluence Field Modulation

$$I_0(u,\theta) = e^{\alpha l(u,\theta)} \frac{I_0^{tot}}{\sum_{u,\theta} e^{\alpha l(u,\theta)}}$$

Barebeam Fluence

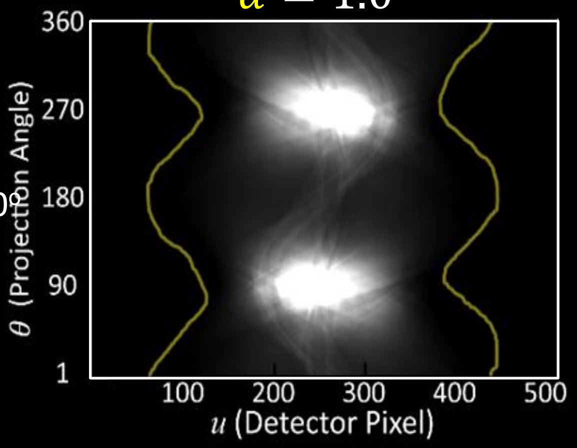
Normalization to total bare beam fluence, I_0^{tot}

l: Line integral
θ: projection angle
u: horizontal detector pixel



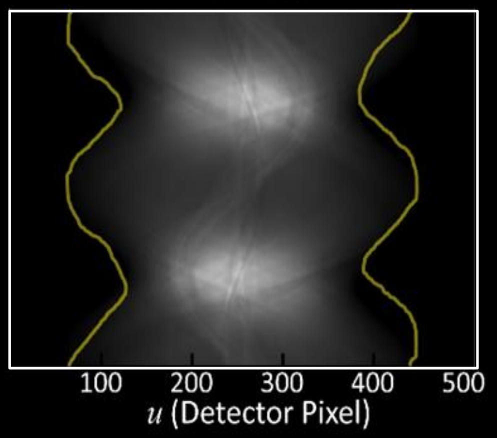
Perfect Bowtie

$\alpha = 1.0$



Minimize mean σ^2 in FBP

$\alpha = 0.5$



Harpen, Michael D. "A simple theorem relating noise and patient dose in computed tomography." *Medical Physics* 26.11 (1999): 2231-2234.

Noise and Dose Simulations

	Unmodulated	Static Bowtie	Perfect Bowtie $\alpha = 1.0$	Minimize mean σ^2 $\alpha = 0.5$	Minimize peak σ^2

Noise maps

	Unmodulated	Static Bowtie	Perfect Bowtie	Minimize mean σ^2	Minimize peak σ^2
% dose to achieve the same mean σ^2:	146%	100%	109%	85.7%	99.4%
% dose to achieve the same peak σ^2:	178%	100%	58.9%	73.8%	54.8%

	Unmodulated	Static Bowtie	Perfect Bowtie	Minimize mean σ^2	Minimize peak σ^2
% dose to achieve the same mean σ^2:	119%	100%	102%	83.0%	93.6%
% dose to achieve the same peak σ^2:	142%	100%	36.2%	46.8%	34.7%

Hsieh, Scott S., and Norbert J. Pelc. "Algorithms for optimizing CT fluence control." *Medical Imaging 2014: Physics of Medical Imaging*. Vol. 9033. International Society for Optics and Photonics, 2014.

Dynamic Beam Filters

Design considerations

Produce a wide range of modulation profiles

Rapidly changing modulation due to fast gantry rotation

→ fast actuation / small range of motion

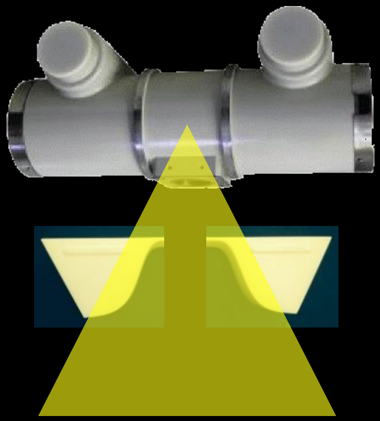
→ operate under high G conditions

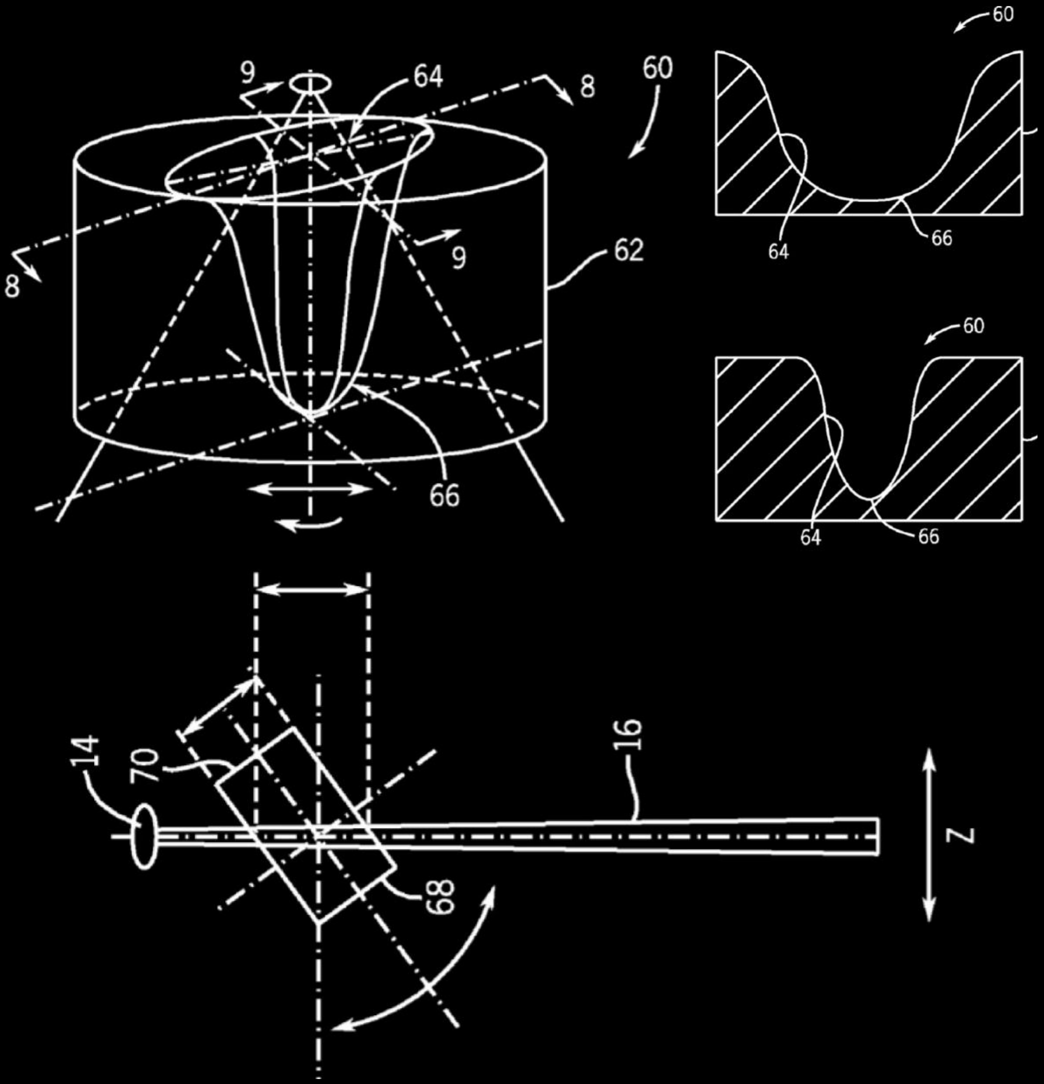
Limited space in the CT gantry

→ small form factor

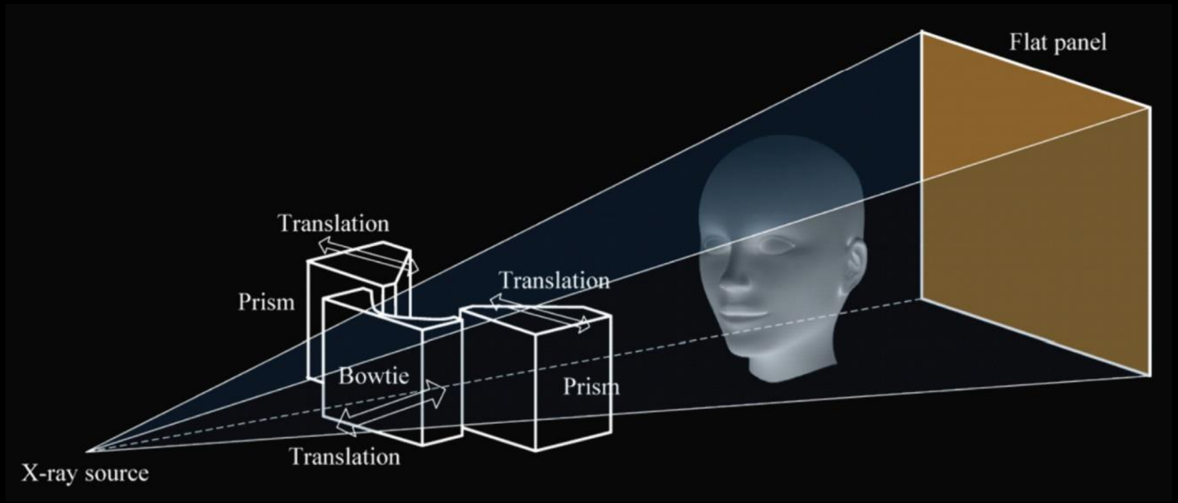
Dynamic Bowties

Split bowtie





Toth, Thomas L., Eric J. Tkaczyk, and Jiang Hsieh. "Method and apparatus of radiographic imaging with an energy beam tailored for a subject to be scanned." U.S. Patent No. 7,076,029. 11 Jul. 2006.



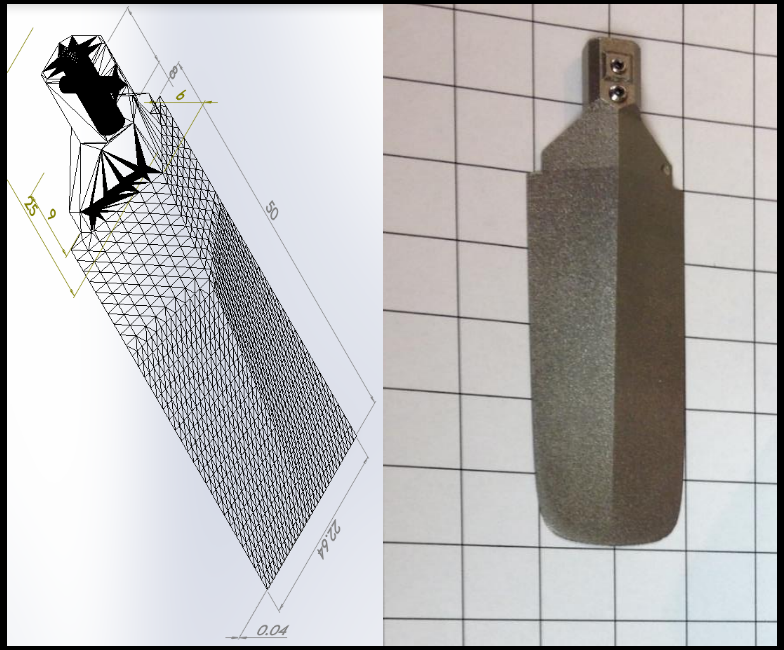
Liu, Fenglin, et al. "Dynamic bowtie for fan-beam CT." *Journal of X-ray Science and Technology* 21.4 (2013): 579-590.

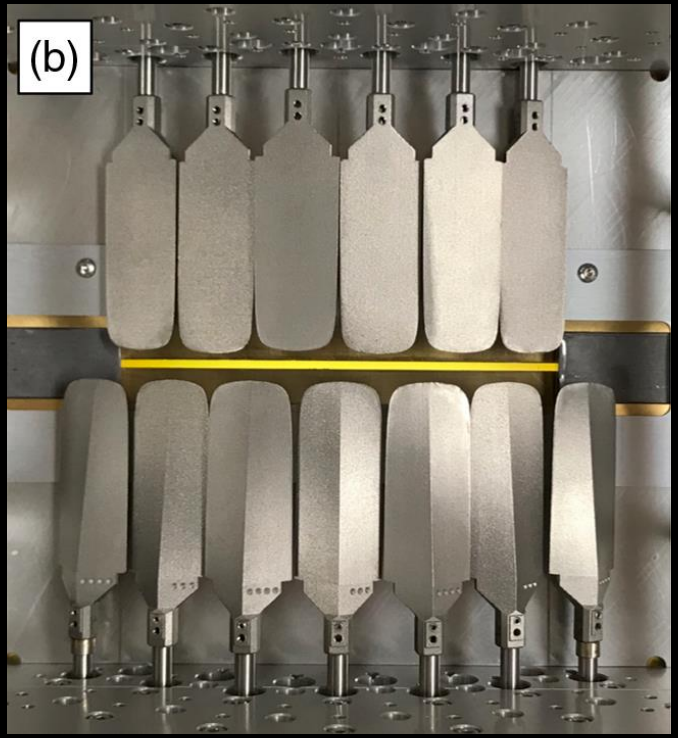
Arenson, Jerome Stephen, et al. "X-ray flux management device." U.S. Patent No. 8,199,883. 12 Jun. 2012.

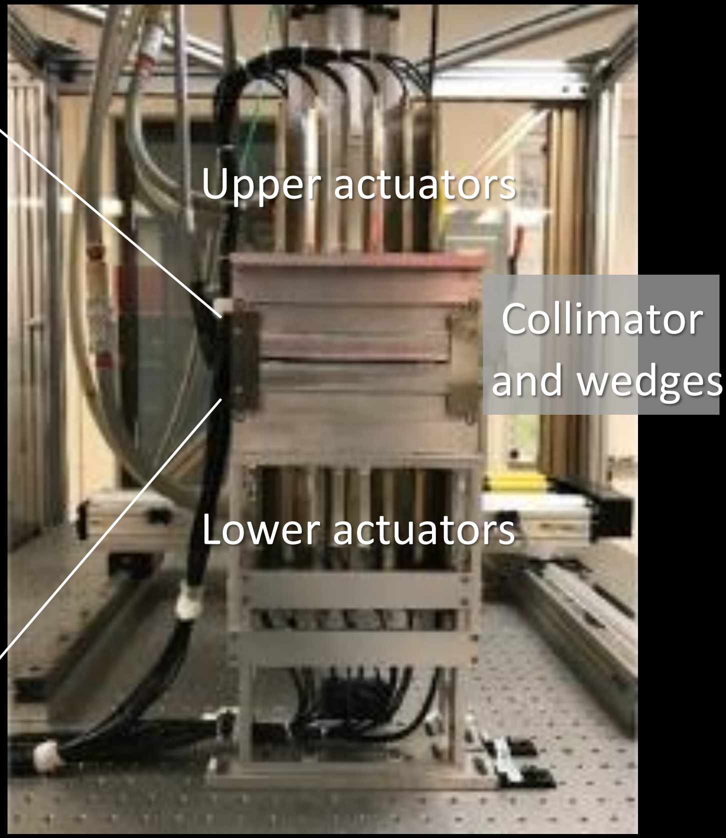
Dynamic Bowties

Piecewise-Linear Dynamic Attenuator*

3D-printed Stainless Steel
Wedge Attenuator



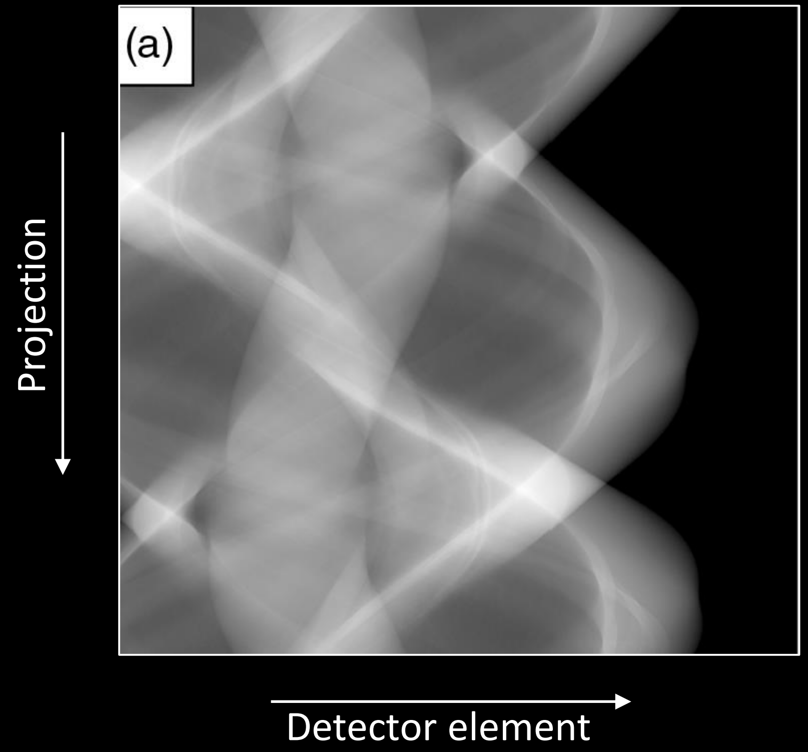




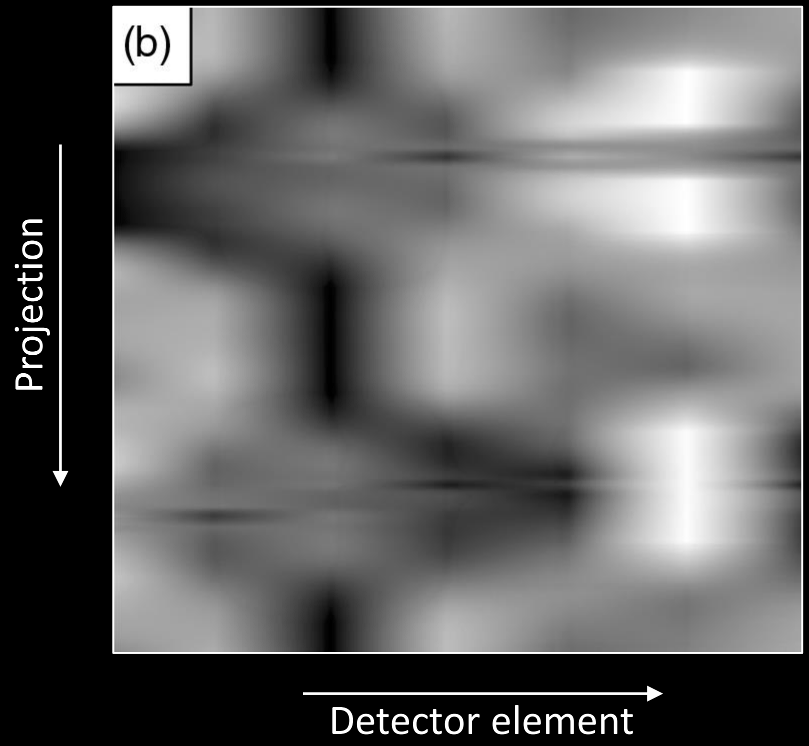
*Shunhavanich, P., Bennett, N. R., Hsieh, S. S., & Pelc, N. J. (June 2019) Implementation of a piecewise-linear dynamic attenuator. *Journal of Medical Imaging*, **6**(2), 023502.
Szczykutowicz, Timothy P., and Charles A. Mistretta. "Design of a digital beam attenuation system for computed tomography: Part I. System design and simulation framework." *Medical physics* 40.2 (2013): 021905.

Dynamic Bowtie

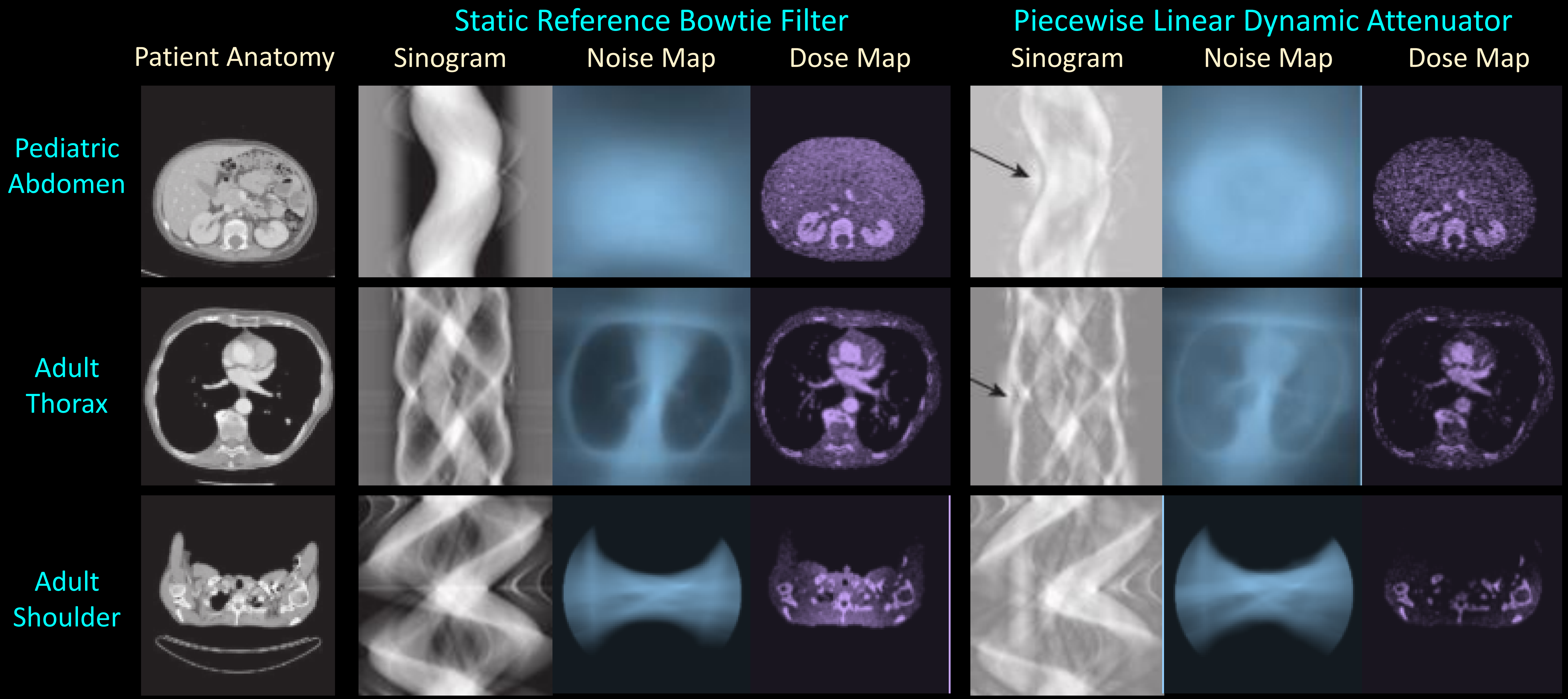
Sinogram of Chest Phantom



Piecewise-Linear Attenuator Sinogram

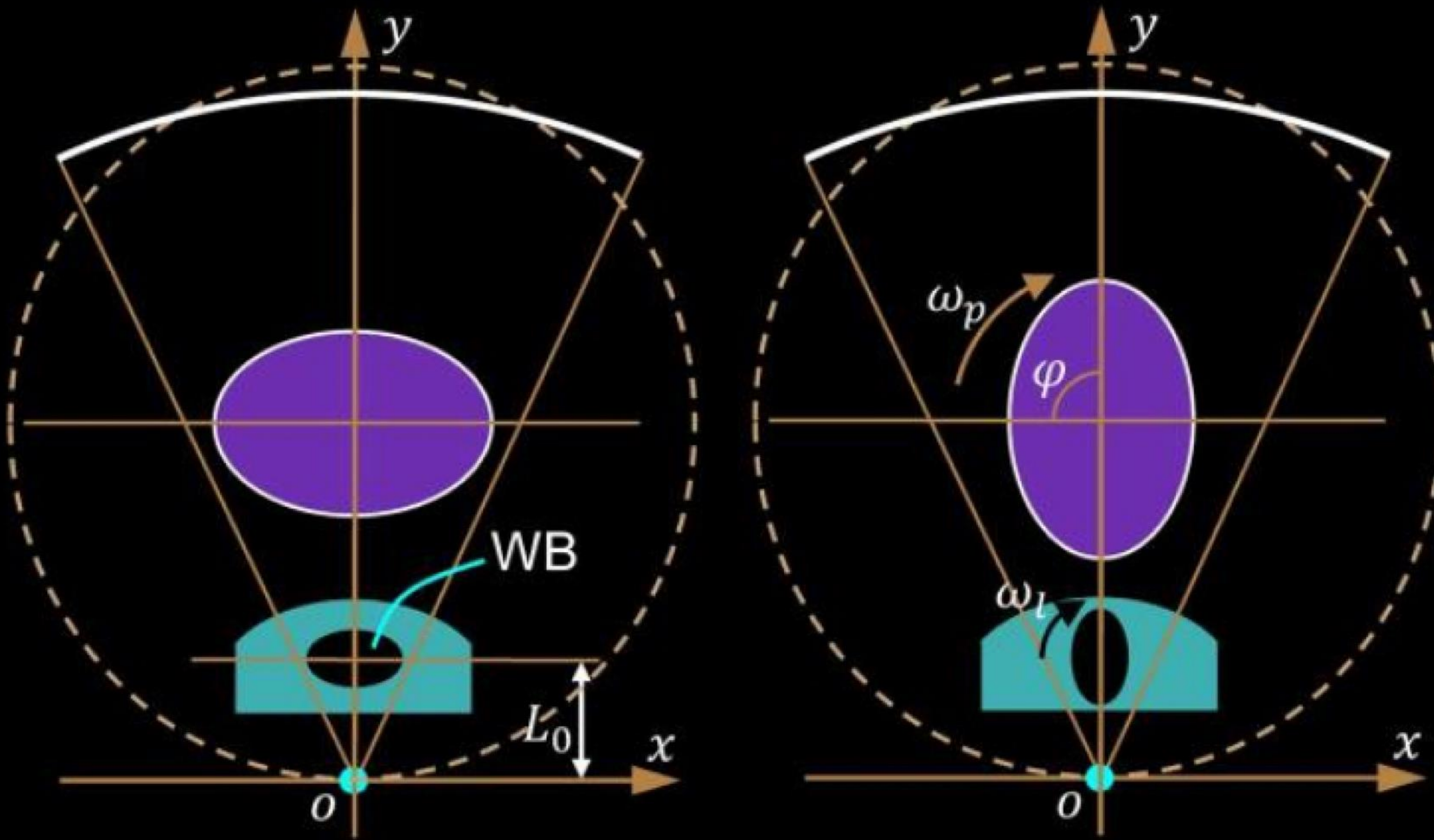


Dynamic Bowtie – Dynamic Range Reduction



Hsieh S S and Pelc N J 2013 The feasibility of a piecewise-linear dynamic bowtie filter. *Med. Phys.* **40** 31910

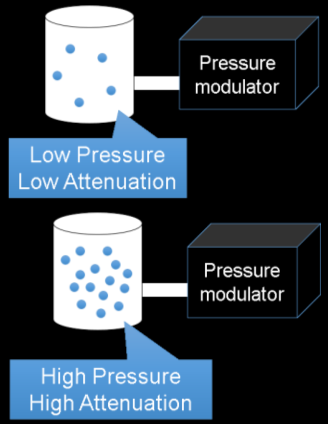
Fluid-Filled Dynamic Bowties

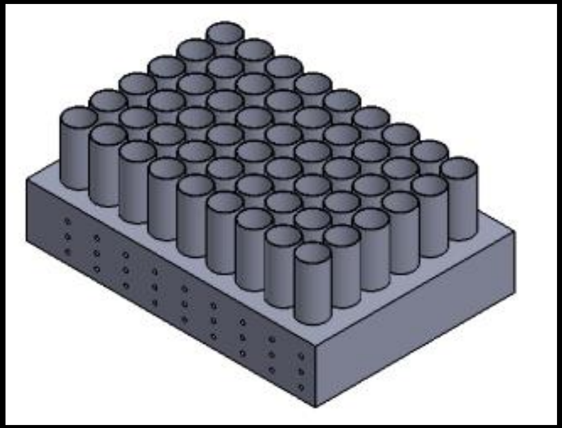


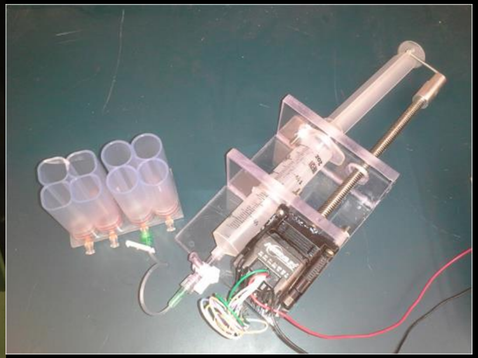
Liu, Fenglin, et al. "Dynamic bowtie filter for cone-beam/multi-slice CT." *PloS one* 9.7 (2014).

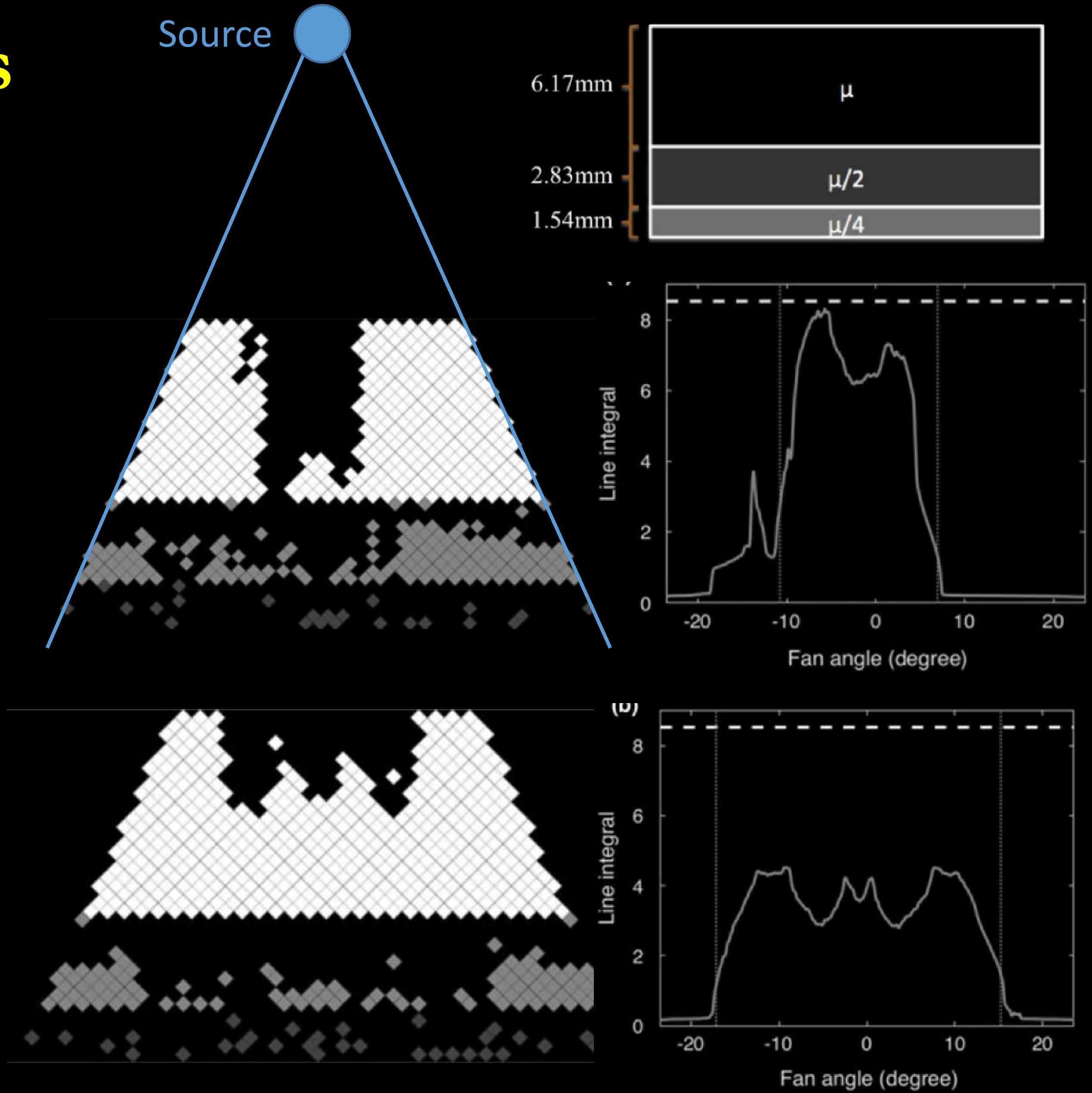
Tkaczyk, J. Eric, et al. "X-ray filter having dynamically displaceable x-ray attenuating fluid." U.S. Patent No. 7,308,073. 11 Dec. 2007.

Fluid-Filled Dynamic Bowties





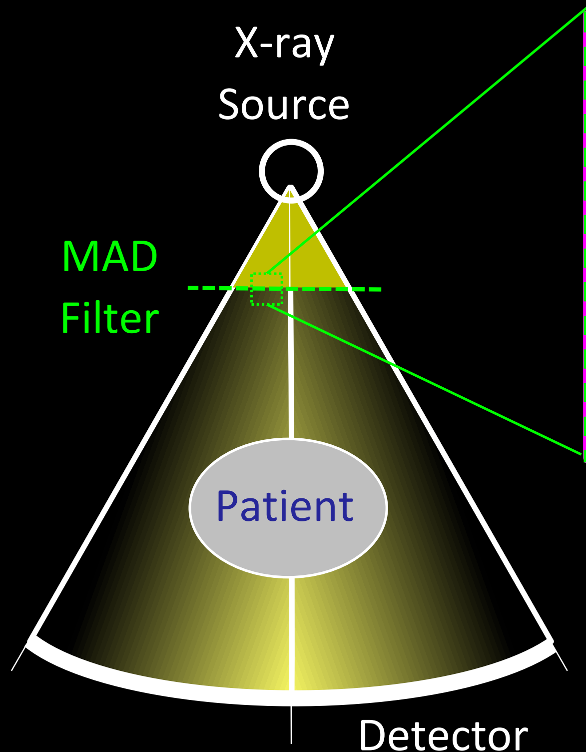


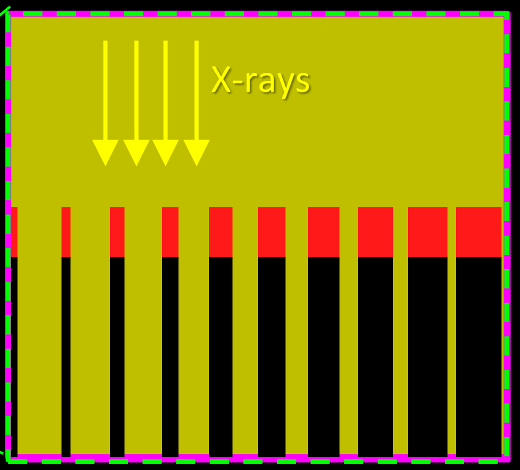


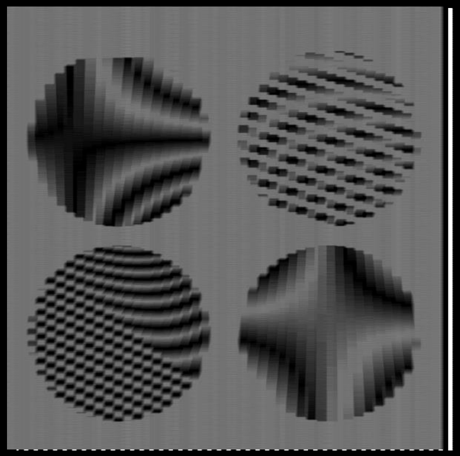
Hermus, James R., and Timothy P. Szczykutowicz. "Two-dimensional dynamic fluid bowtie attenuators." *Journal of Medical Imaging* 3.1 (2016): 013502.

Shunhavanich, Picha, Scott S. Hsieh, and Norbert J. Pelc. "Fluid-filled dynamic bowtie filter: Description and comparison with other modulators." *Medical physics* 46.1 (2019): 127-139.

Structured Filters





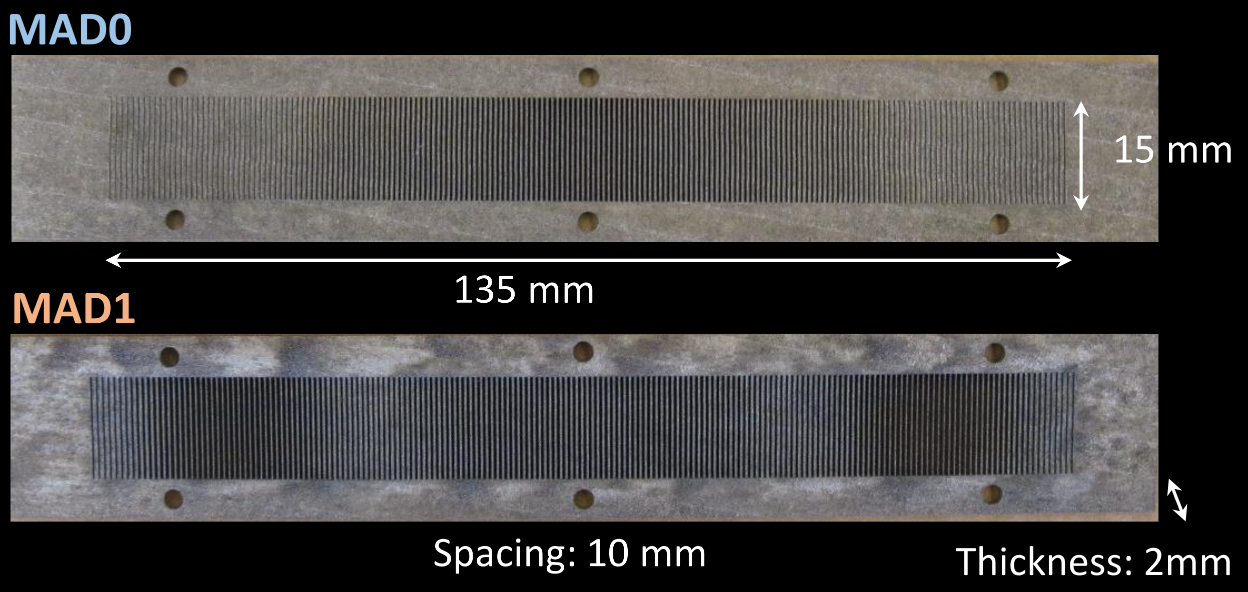


Moiré patterns
Mathijs Delbaere, behance.net

Multiple Aperture Devices (MADs)

Manufacturing:

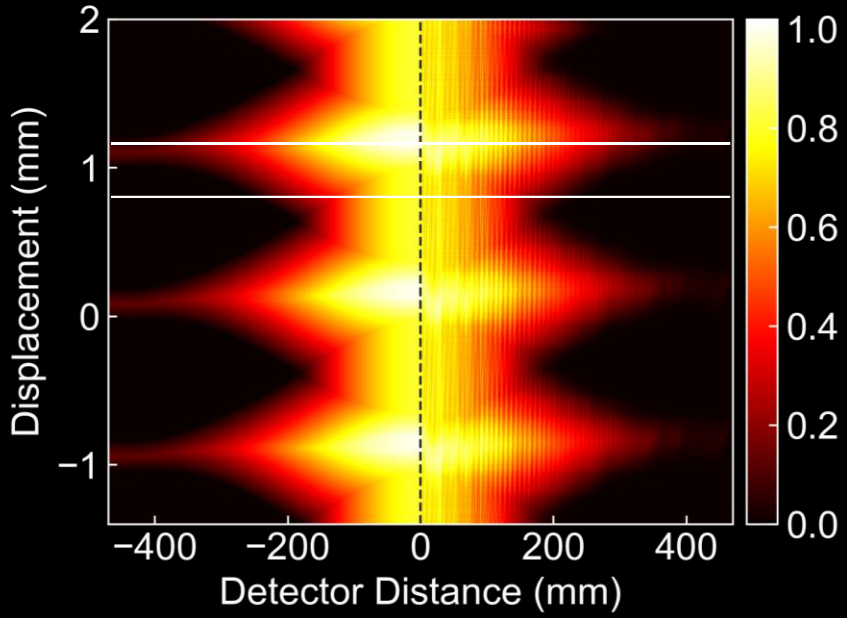
3D-printed metal
Tungsten powder laser sintering



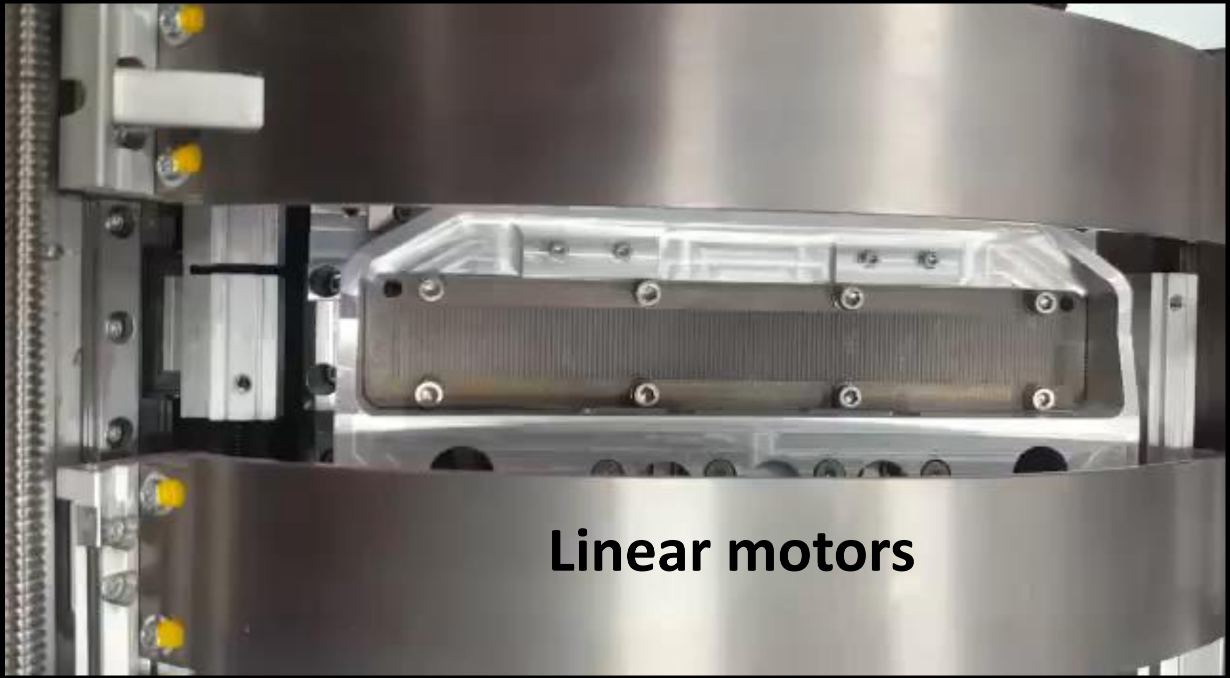
Gang, Grace J., et al. "Dynamic fluence field modulation in computed tomography using multiple aperture devices." *Physics in Medicine & Biology* 64.10 (2019): 105024.

Diagnostic CT Scanner

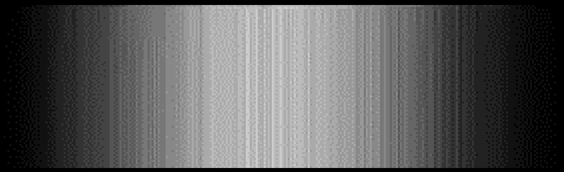
Achievable Modulation Profiles



Motion system on CT gantry



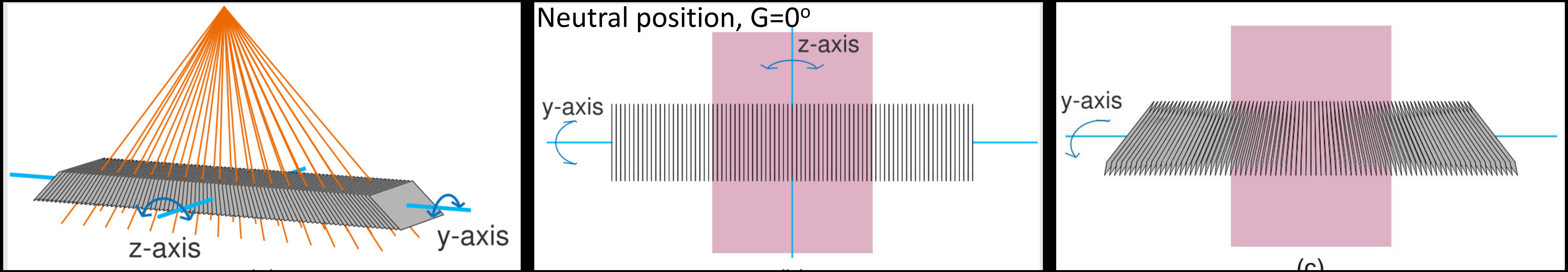
Dynamic Fluence Pattern (Relative Motion)

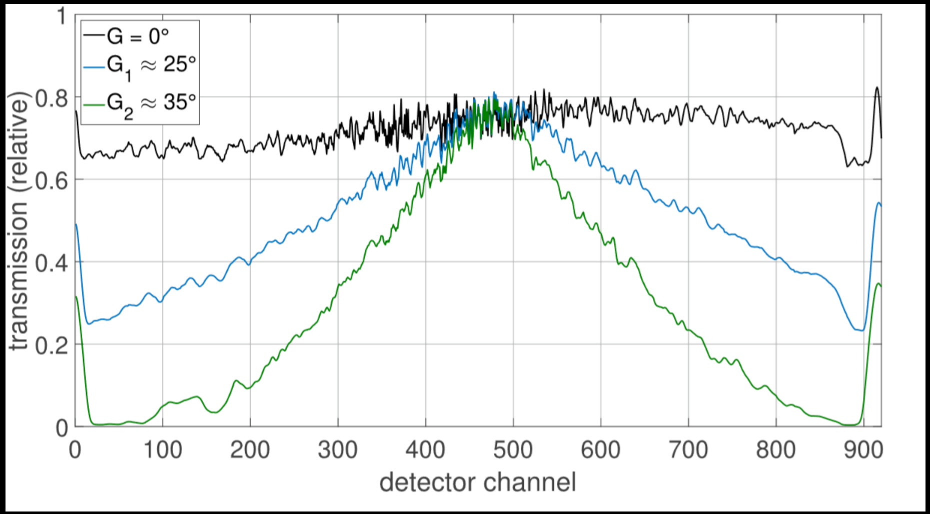


Gang G, Mao A, Wang W, Siewerdsen JH, Mathews A, Kawamoto S, Levinson R, Stayman JW (May 2019) Dynamic fluence field modulation in computed tomography using multiple aperture devices *Physics in Medicine and Biology* **64**(10)

Structured Filters

Sheet-based Dynamic Beam Attenuator (sbDBA)

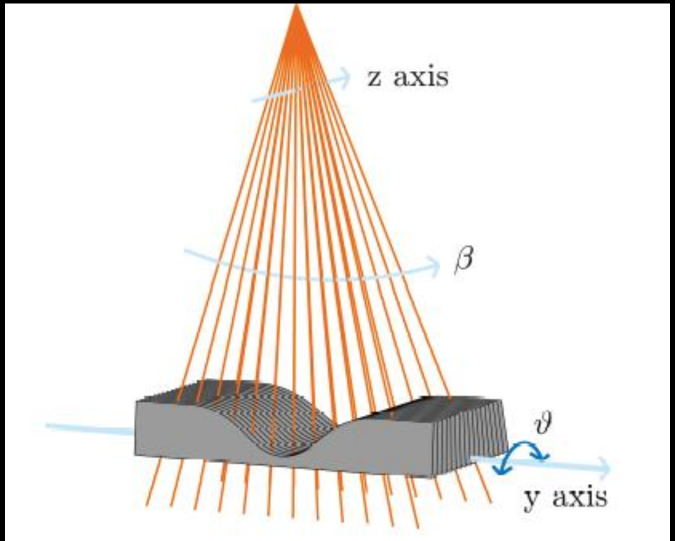


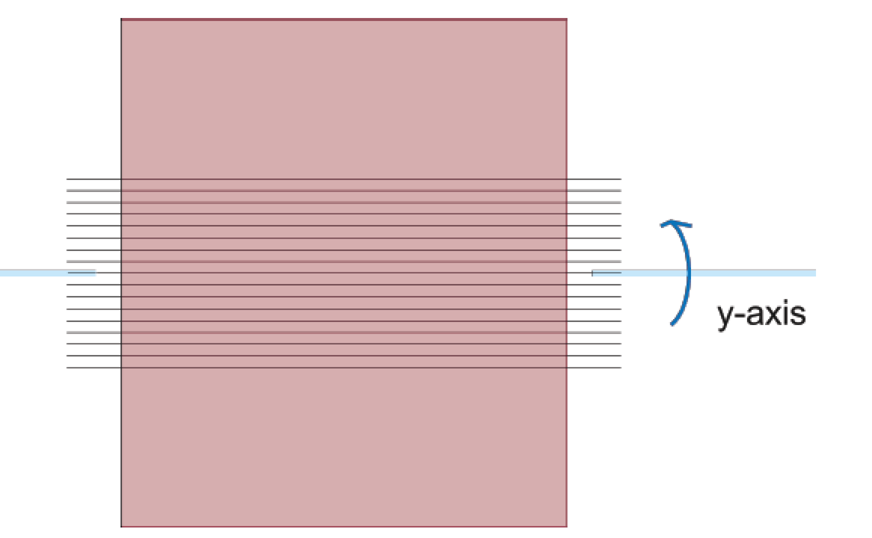


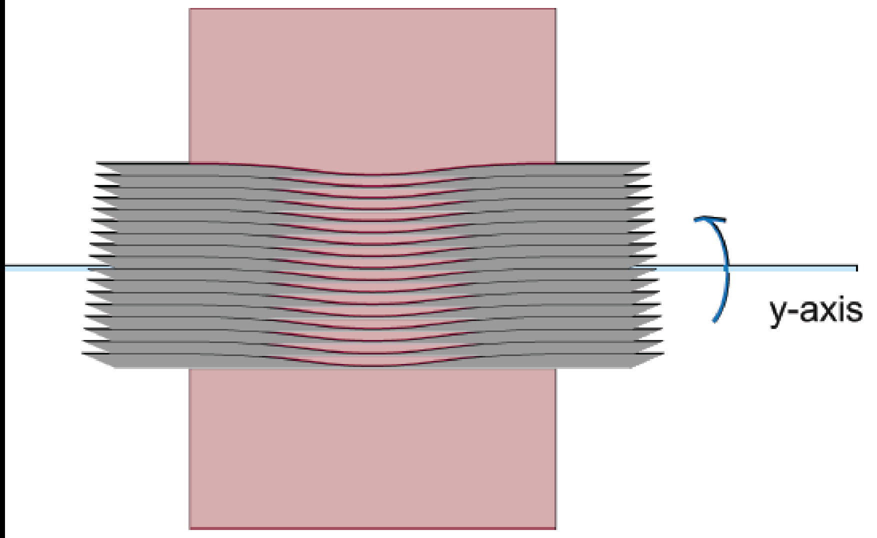
Huck, Sascha Manuel, et al. "Sheet-based dynamic beam attenuator–A novel concept for dynamic fluence field modulation in x-ray CT." *Medical physics* 46.12 (2019): 5528-5537.

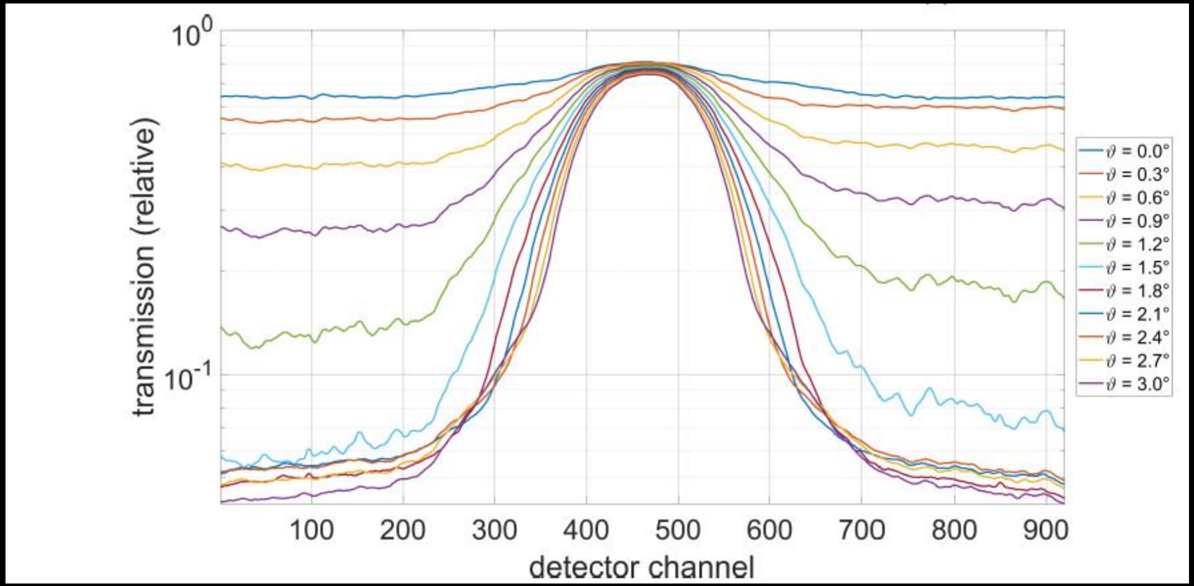
Structured Filters

Z-Aligned Sheet-based Dynamic Beam Attenuator (z-sbDBA)



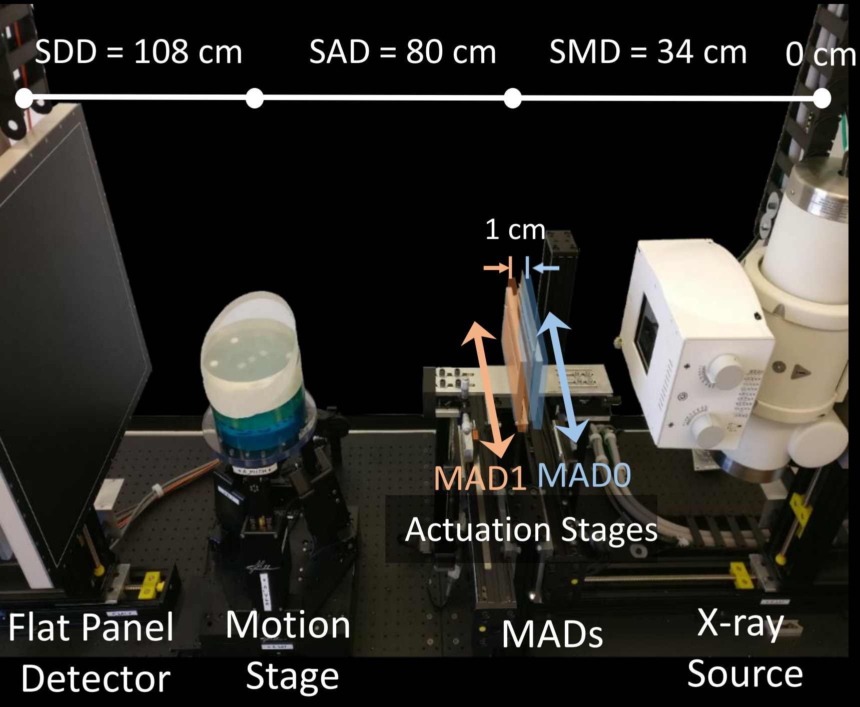




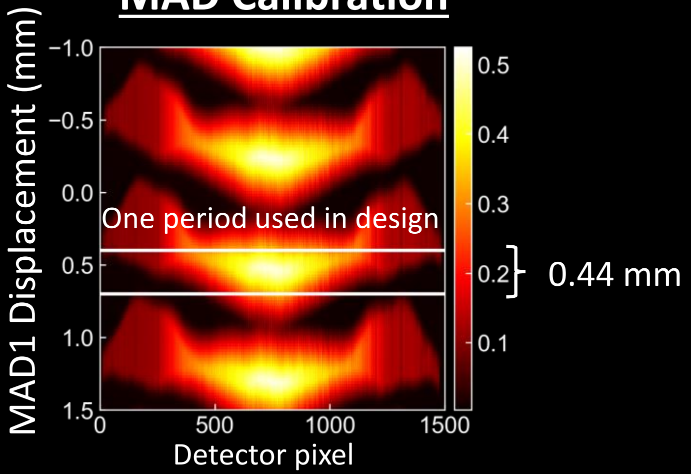


Huck, Sascha Manuel, et al. "A new concept for fluence field modulation in x-ray CT: the z-sbDBA." *Medical Imaging 2020: Physics of Medical Imaging*. Vol. 11312. International Society for Optics and Photonics, 2020.

Patient-Specific Dynamic FFM Design

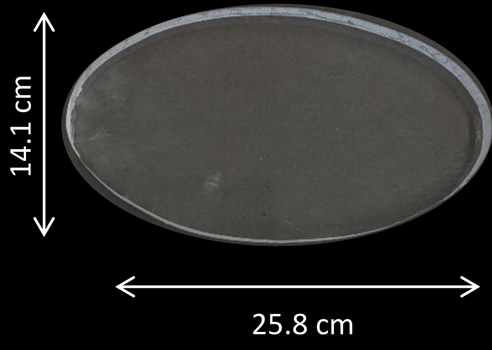


MAD Calibration

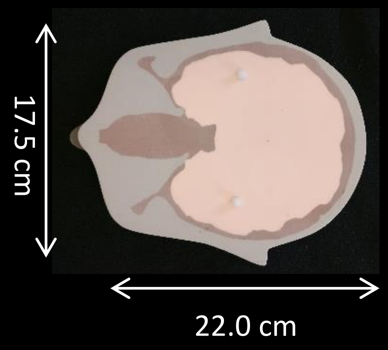


Phantoms

PMMA Ellipse



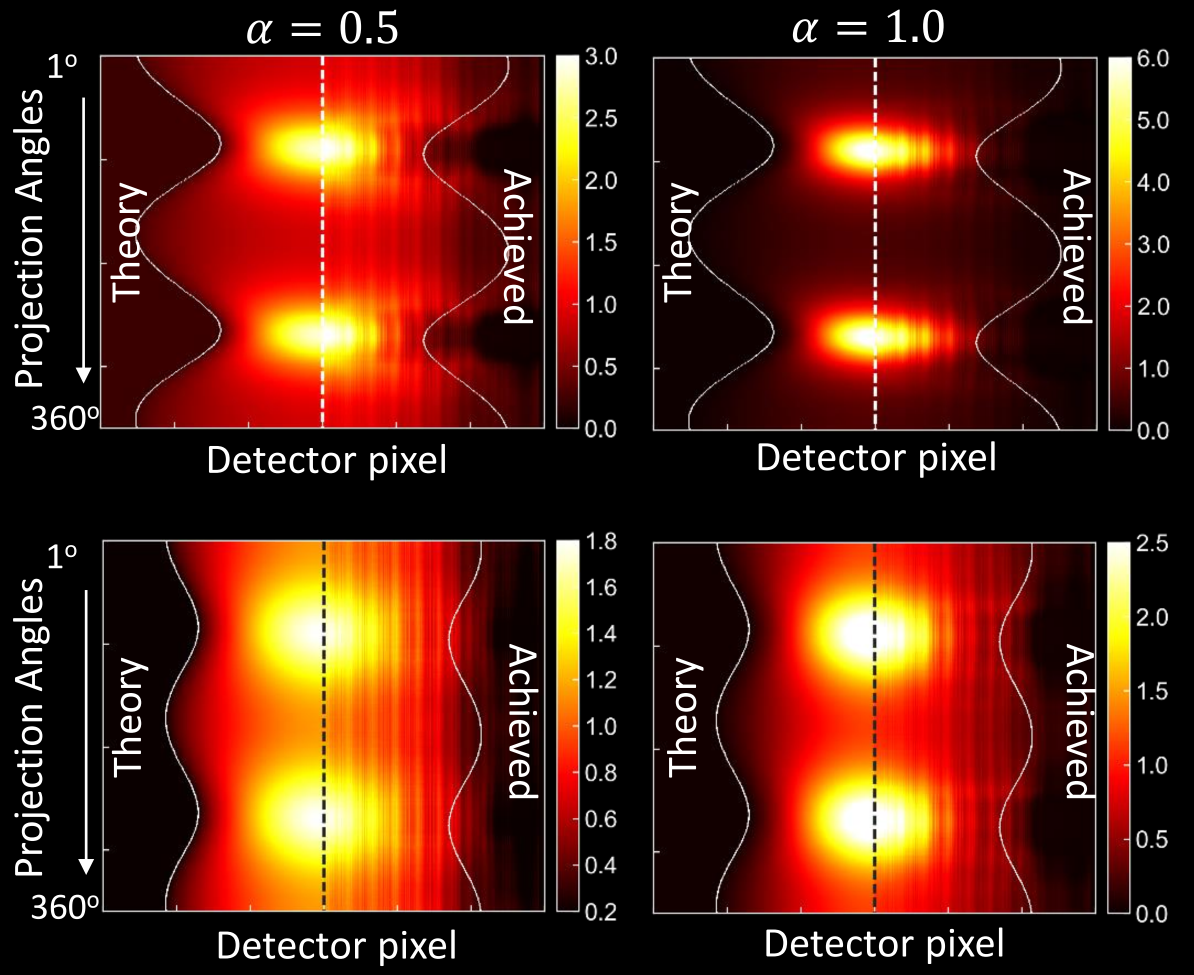
Atom Head



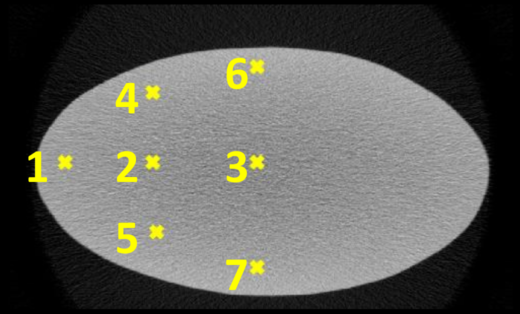
Imaging Objectives

Minimize mean variance in FBP

Flat fluence behind object



Phantom Specific, Task Specific FFM Design

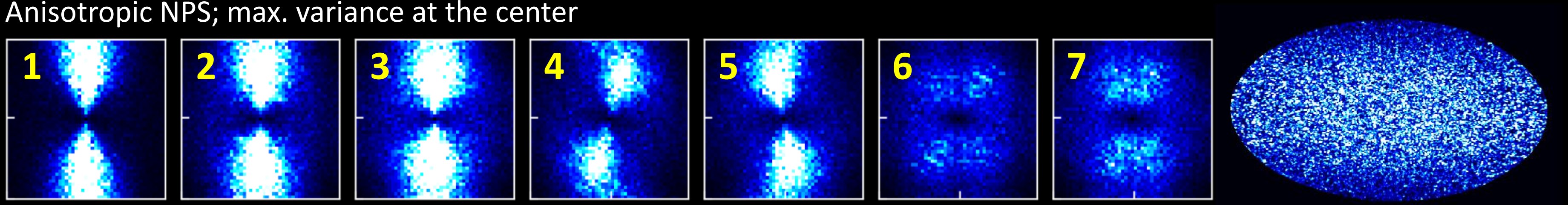


Local Noise Power Spectrum

Variance Maps

Unmodulated:

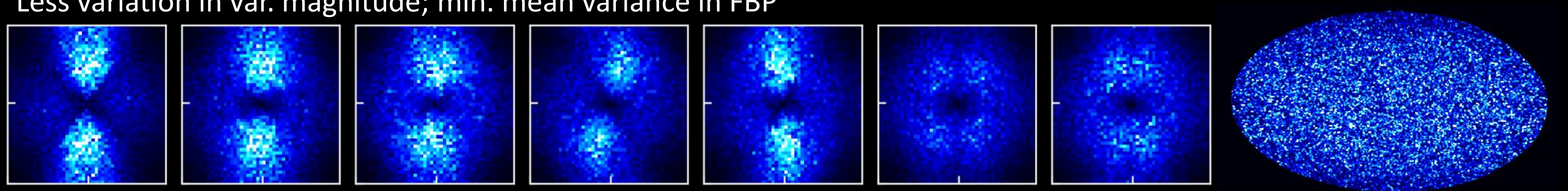
Anisotropic NPS; max. variance at the center



Mean Var = 1.05e-5

$\alpha = 0.5$: Minimize mean variance in FBP

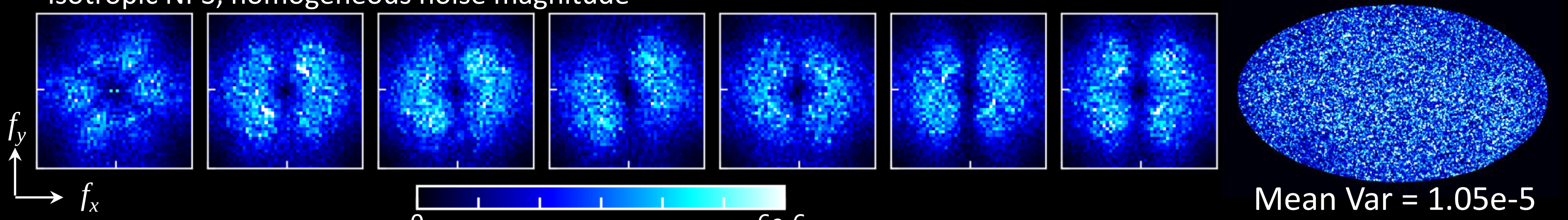
Anisotropic NPS; max. variance at the center;
Less variation in var. magnitude; min. mean variance in FBP



Mean Var = 0.94e-5

$\alpha = 1.0$: Flat fluence behind object

Isotropic NPS; homogeneous noise magnitude



Mean Var = 1.05e-5

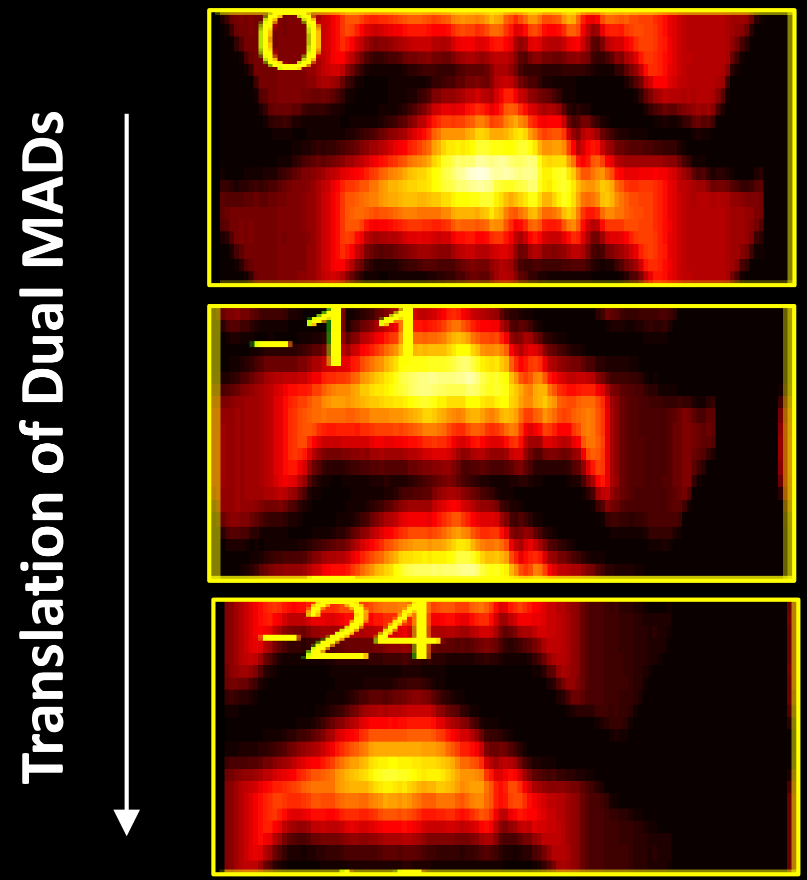
Gang G, Mao A, Wang W, Siewerdsen JH, Mathews A, Kawamoto S, Levinson R, Stayman JW (May 2019) Dynamic fluence field modulation in computed tomography using multiple aperture devices *Physics in Medicine and Biology* **64**(10)

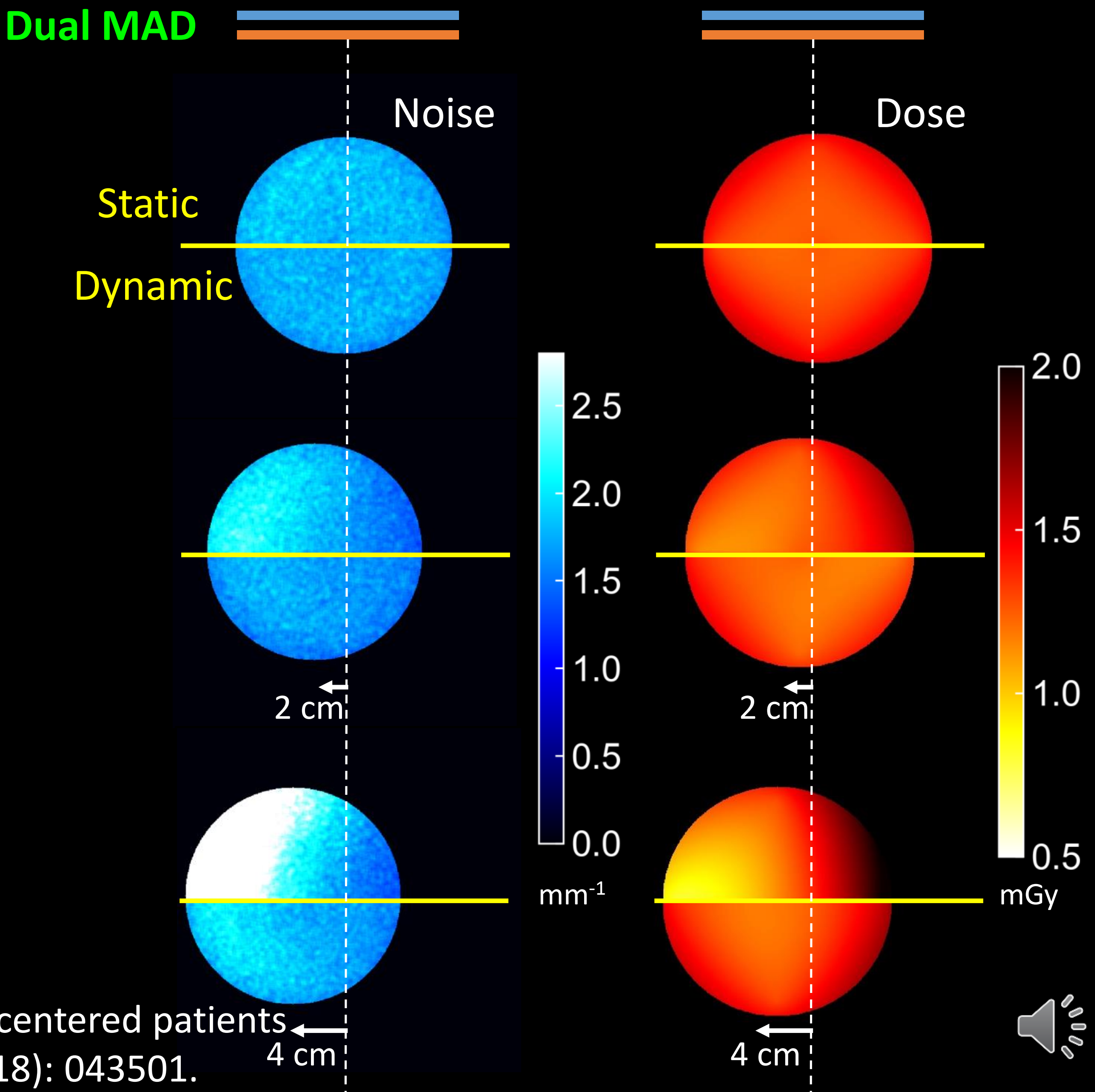
Patient Mis-Centering

AP/LAT Scouts → Patient Position

↓

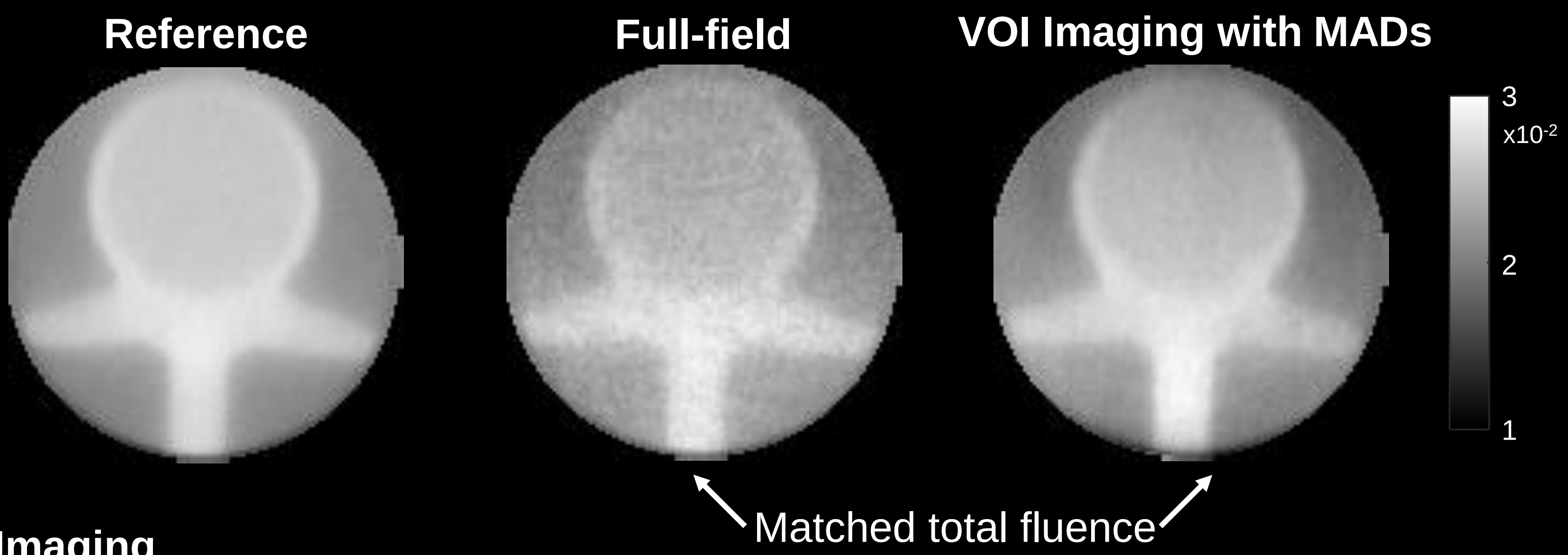
Patient-specific FFM from 2D MAD Calibration

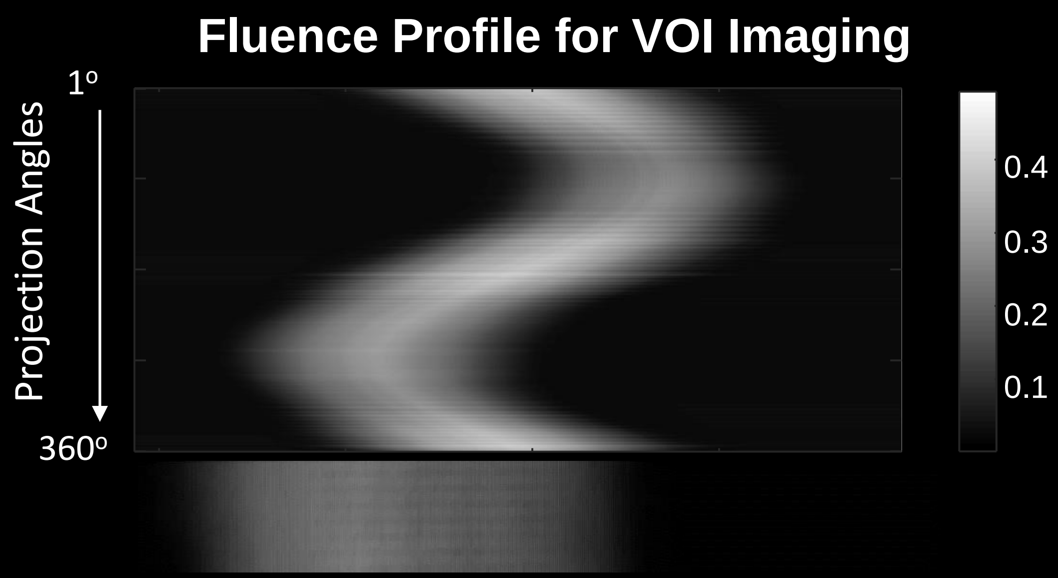




Mao, Andrew, et al. "Dynamic fluence field modulation for miscentered patients in computed tomography." *Journal of Medical Imaging* 5.4 (2018): 043501.

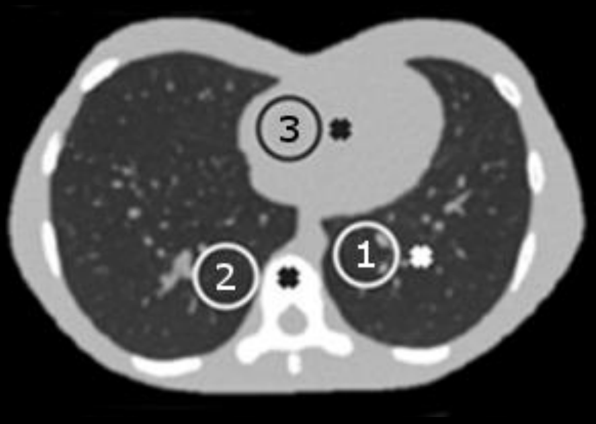
Volume of Interest Imaging

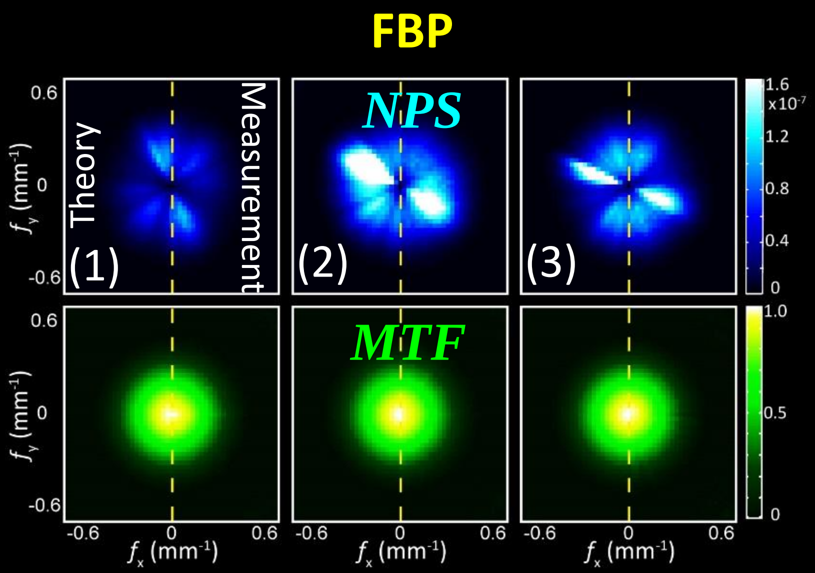


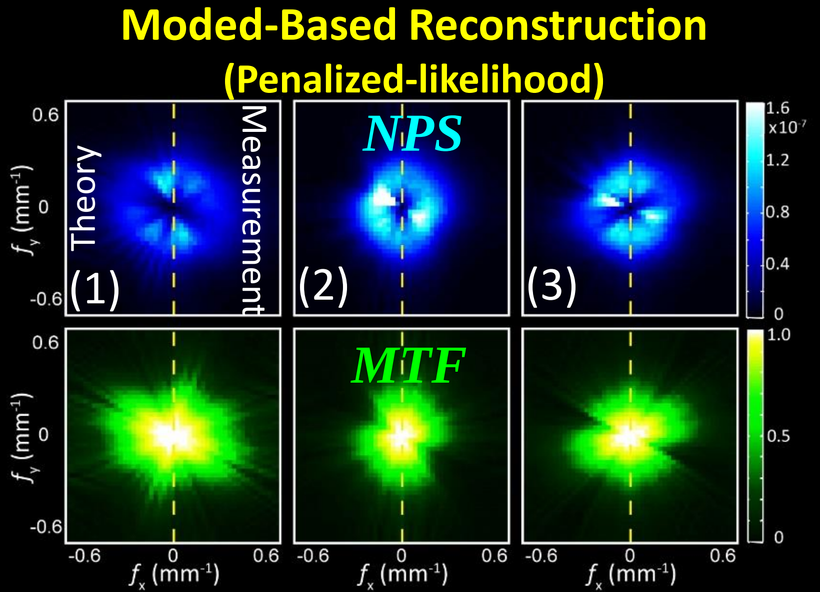


Wang, Wenying, et al. "Volume-of-interest imaging with dynamic fluence modulation using multiple aperture devices." *Journal of Medical Imaging* 6.3 (2019): 033504.

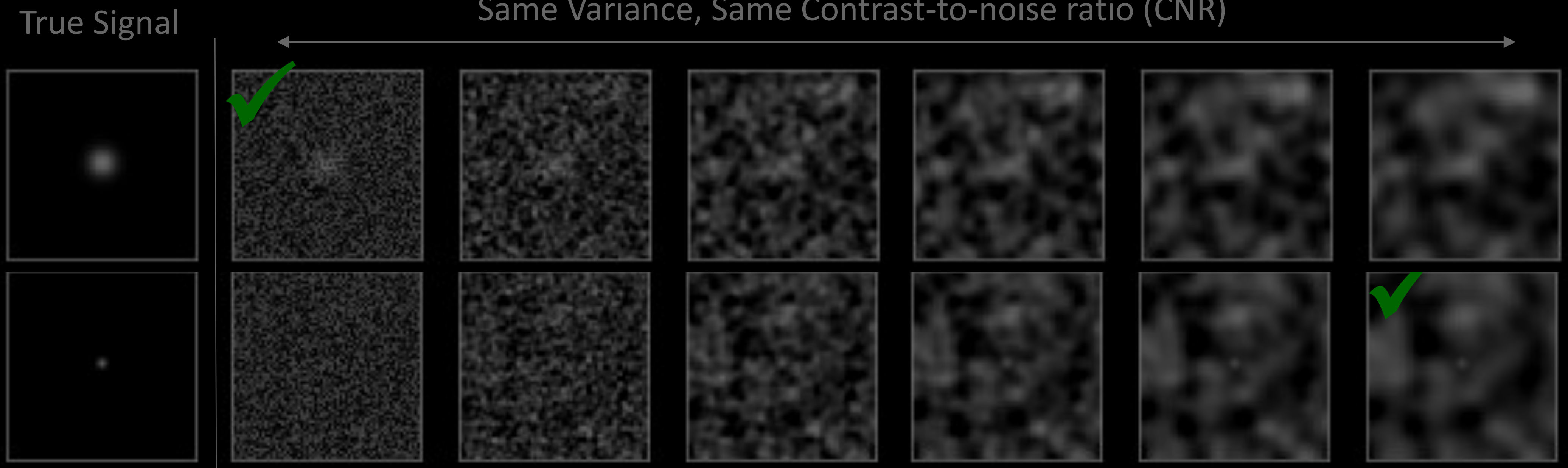
Optimal Fluence Field Modulation (Revisited)



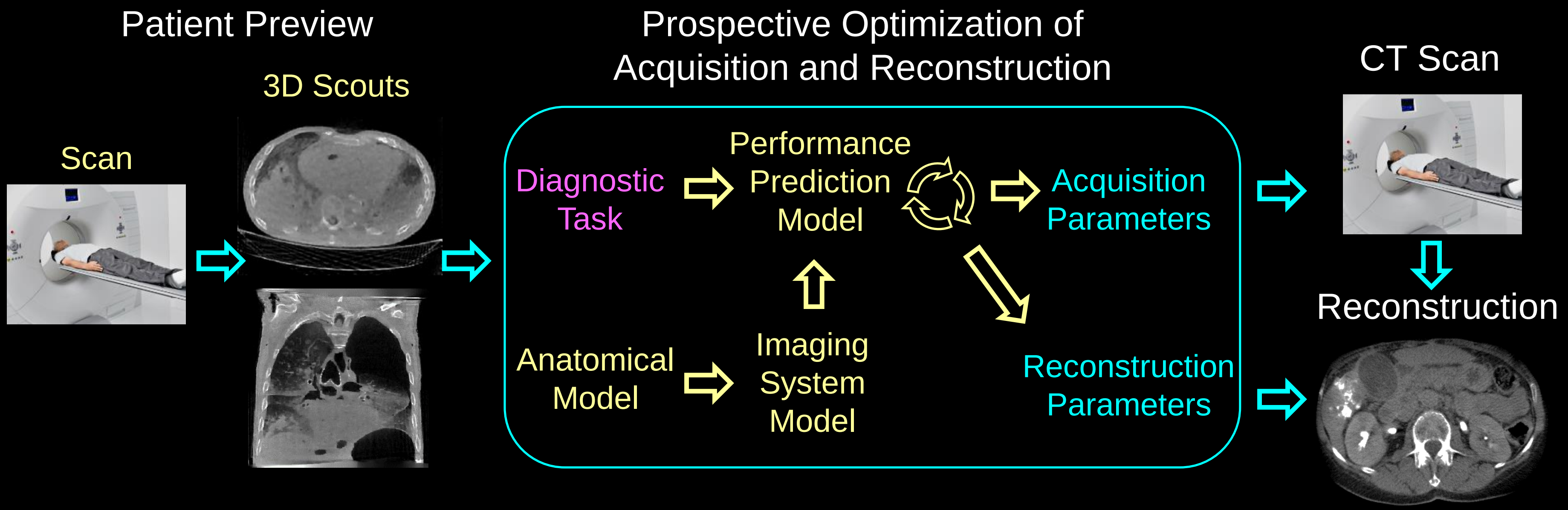




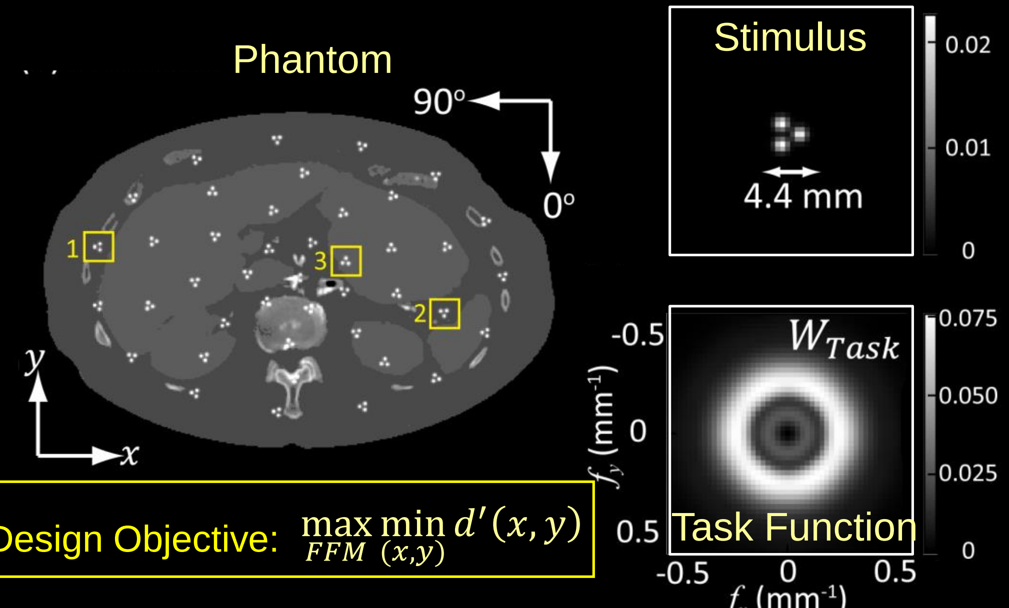
Gang et al., Med Phys 41(8) 2014



Optimal Fluence Field Modulation (Revisited)

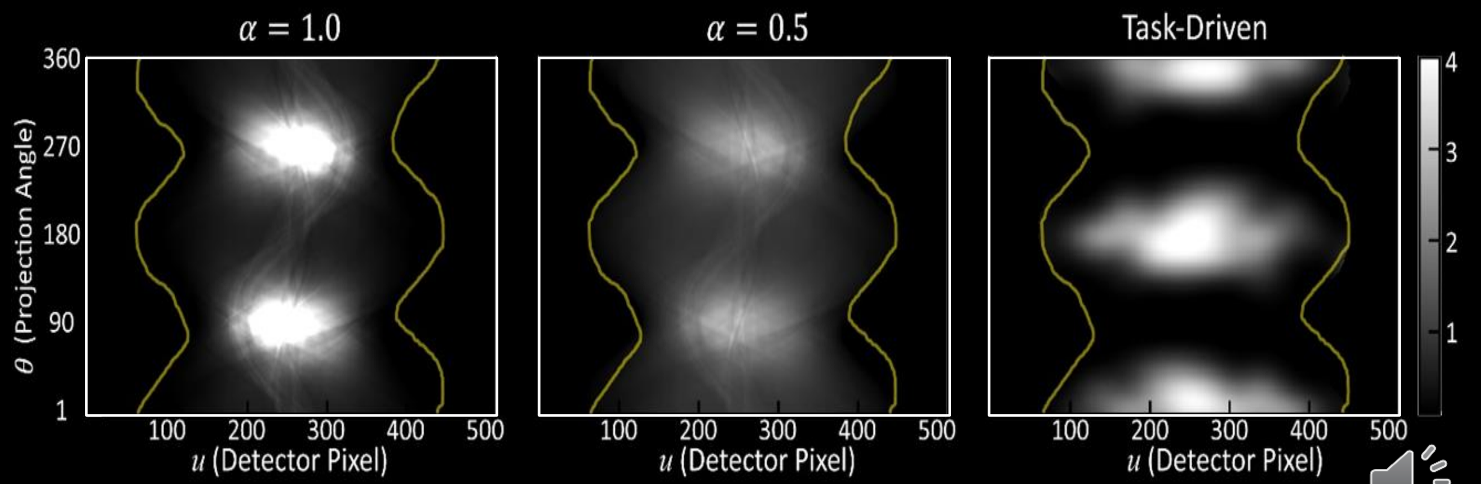


Task and Phantom Definition

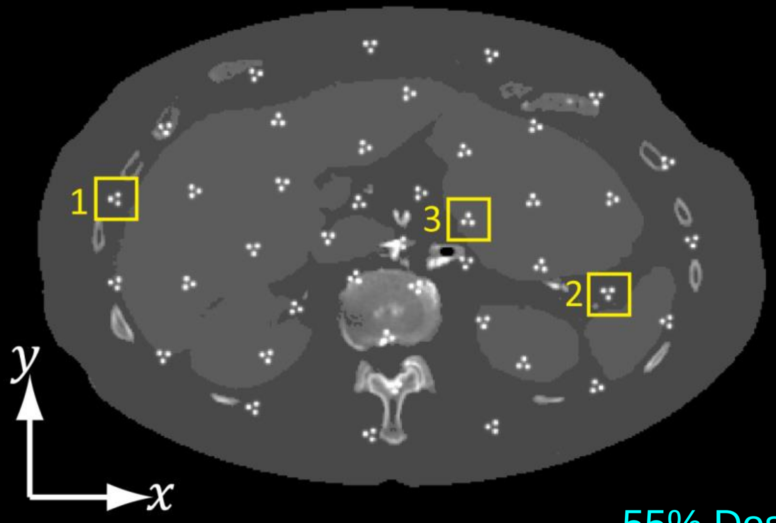


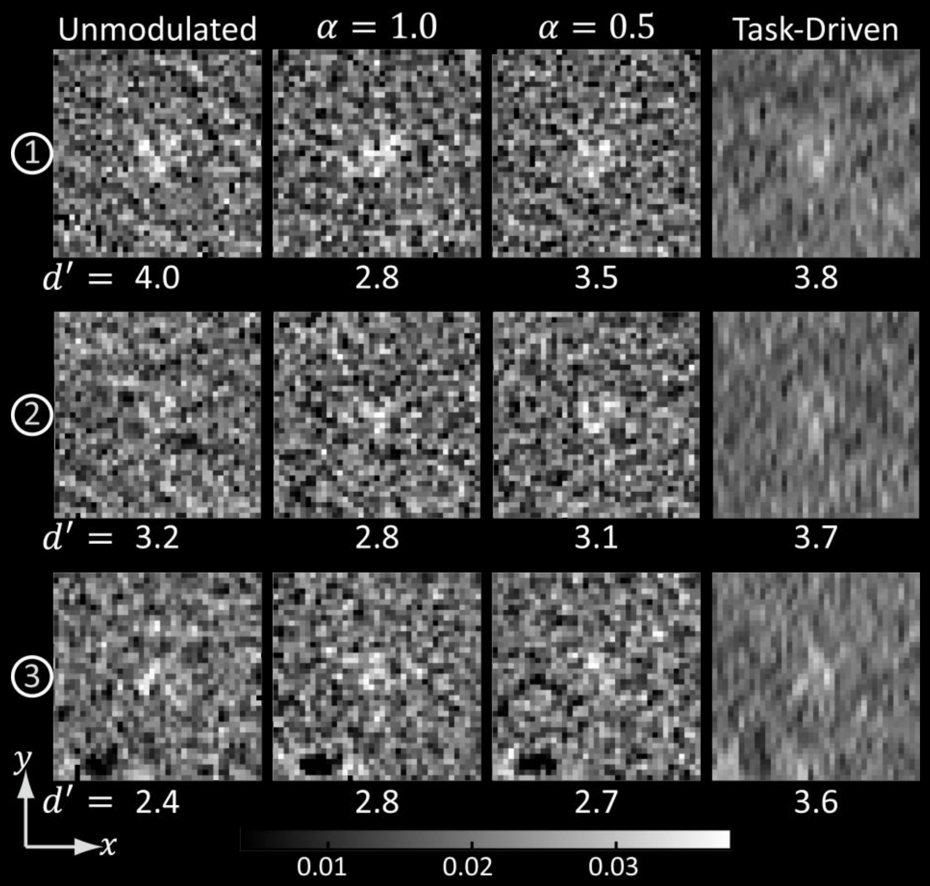
Design Objective: $\max_{FFM} \min_{(x,y)} d'(x,y)$

Fluence Field Design



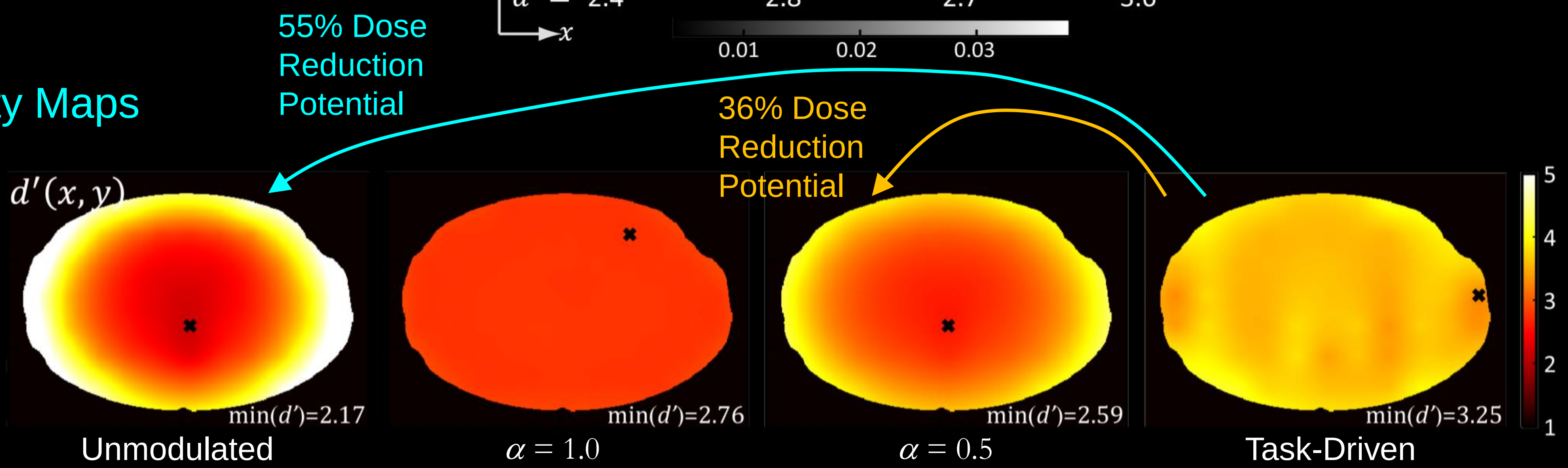
Reconstructions of Simulated FFM Data





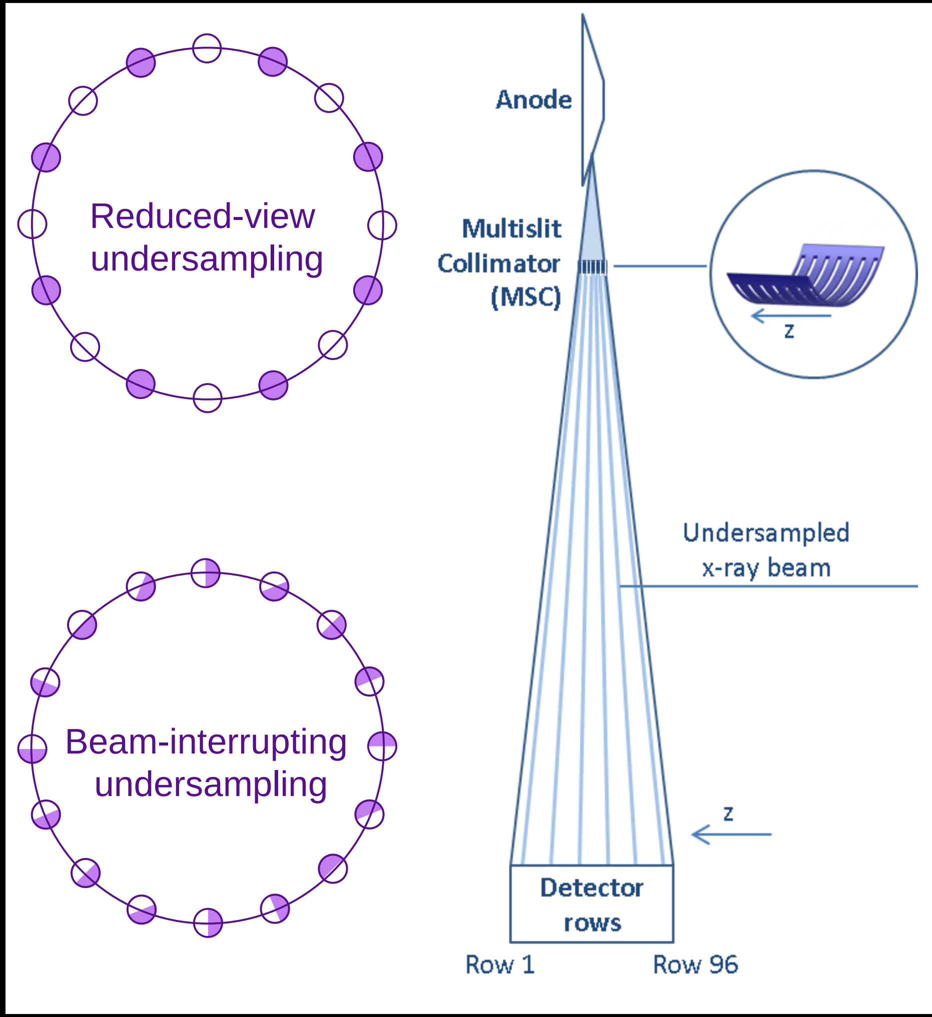
G. J. Gang, J. H. Siewerdsen, and J. W. Stayman, "Task-driven optimization of fluence field and regularization for model-based iterative reconstruction in computed tomography", *IEEE Transactions on Medical Imaging (Special Issue on Low-Dose CT)*, 36(12), 2424-35 (December 2017)

Detectability Maps

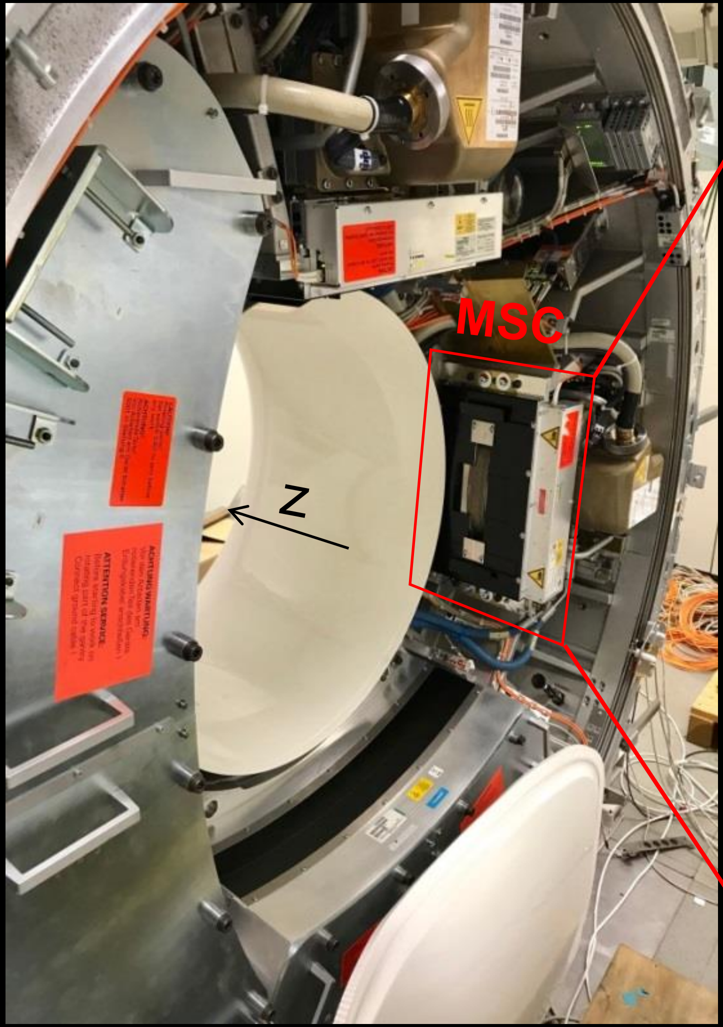


Other FFM Strategies

Sparse Data Acquisition



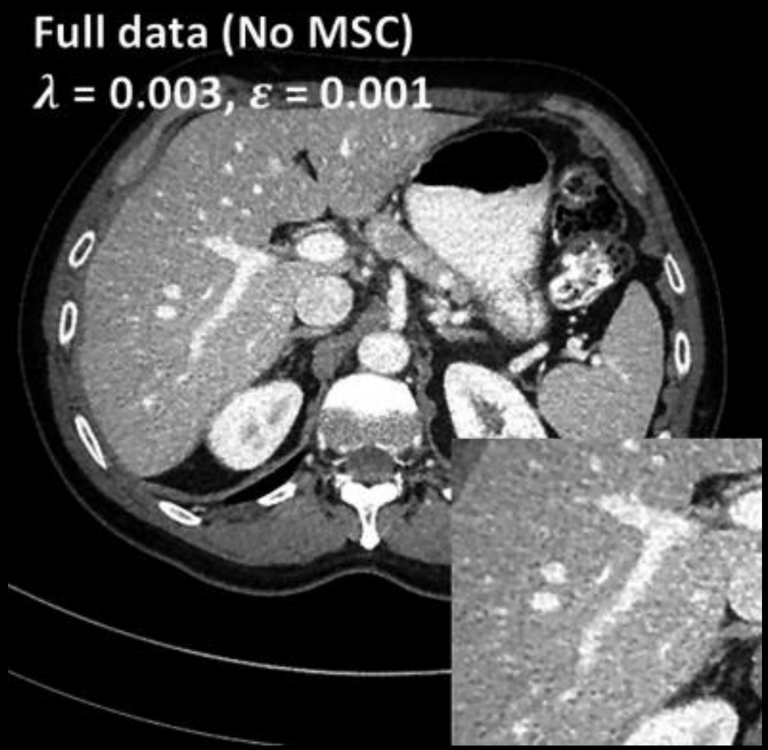
Implementation with a Moving Multislit Collimator



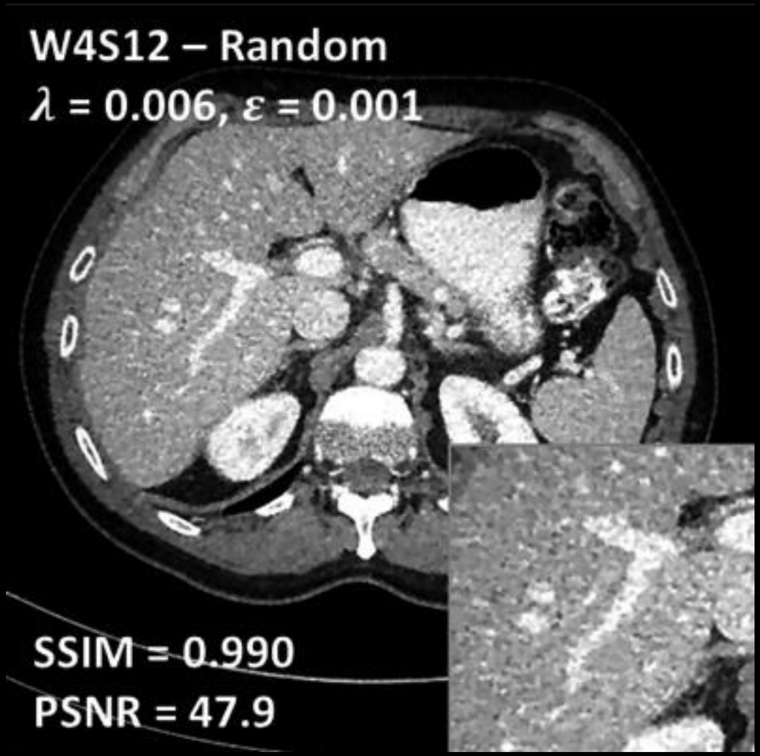
Chen, Baiyu, et al. "SparseCT: System concept and design of multislit collimators." *Medical physics* 46.6 (2019): 2589-2599.

SparseCT Data Reconstruction

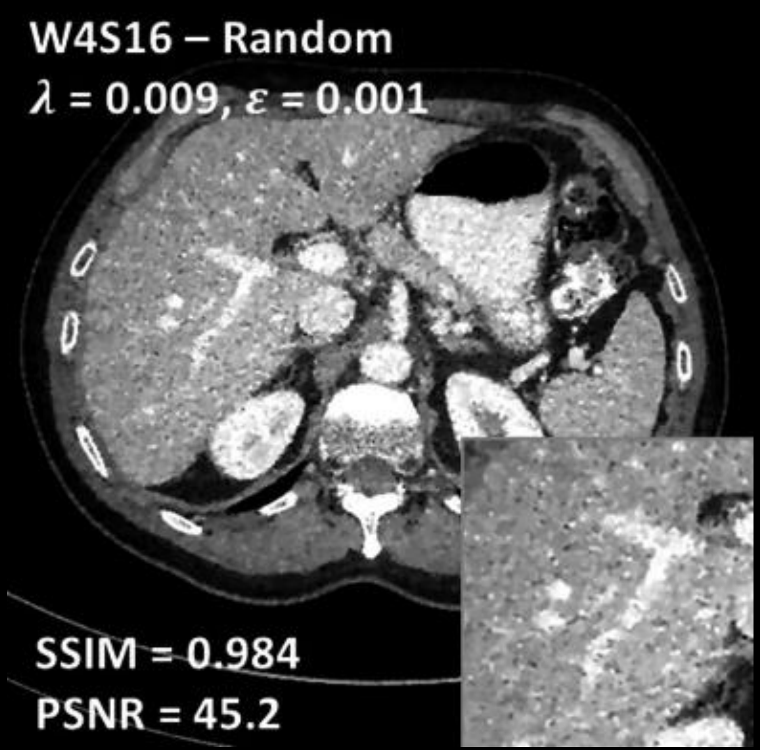
Full Dose



66.6% Dose Reduction



75% Dose Reduction



Chen, Baiyu, et al. "SparseCT: System concept and design of multislit collimators." *Medical physics* 46.6 (2019): 2589-2599.

Discussion

Motivation for dynamic beam shaping/FFM

- Reduce excessive peripheral dose
- Reduce dynamic range on detector
- Accommodate miscentered patient
- Volume of interest imaging

Hardware strategies to achieve dynamic FFM

- Design considerations: range of modulation profiles, actuation speed, form factor
- Many designs available, some are being integrated and tested on CT gantry

Optimal FFM

- Ideally patient-specific
- Depend on design objectives and reconstruction algorithms
- Advanced reconstruction enables FFM in a more general sense

Dose reduction potential

- Depends on the object, image quality objective, and imaging task
  - Full field: 15~75%
  - VOI imaging: 90%

  (For studies surveyed in this talk)

References

Theoretical FFM Design

FBP

Harpen, 1999

Bartolac et al., 2011

Hsieh and Pelc, 2013

Hsieh and Pelc, 2014

Model-based reconstruction

Gang et al., 2017

Dynamic Beam Filter Designs

Dynamic Bowties

Toth et al., 2006

Liu et al, 2013

Arenson et al., 2012

Szczykutowicz and Mistretta, 2013

Shunhavanich et al., 2019

Fluid Filled

Tkaczyk et al., 2007

Liu et al., 2007

Hermus and Szczykutowicz, 2016

Shunhavanich et al., 2019

Structured Filteres

Gang et al., 2019

Huck et al., 2019

Huck et al., 2020

Patient Miscentering

Toth et al., 2007

Mao et al., 2018

VOI imaging

Heuscher and Noo, 2011,

Bartolac and Jaffray, 2013,

Wang et al., 2019

Sparse CT

Chen et al., 2019

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