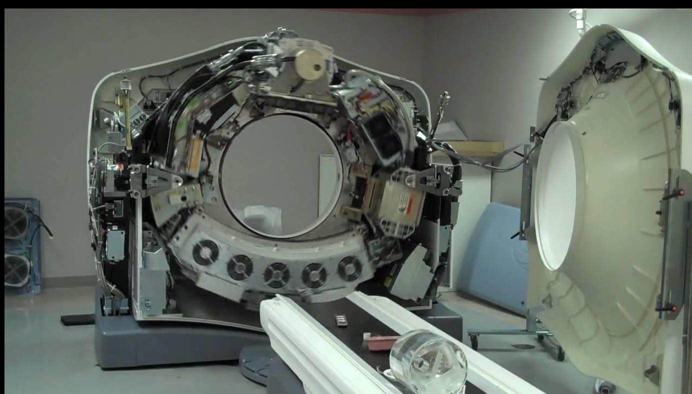
Low Dose CT Technologies: Hardware Strategies



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Disclosures

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R01EB017226 (Siewerdsen)

Current Academic-Industry Partnerships:
Carestream Health
Elekta AB
Medtronic
Philips Healthcare
Siemens Medical

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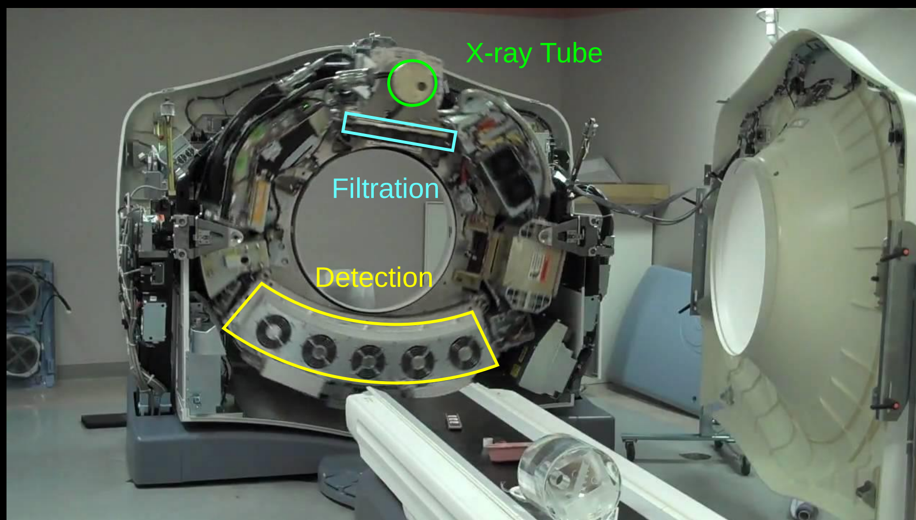
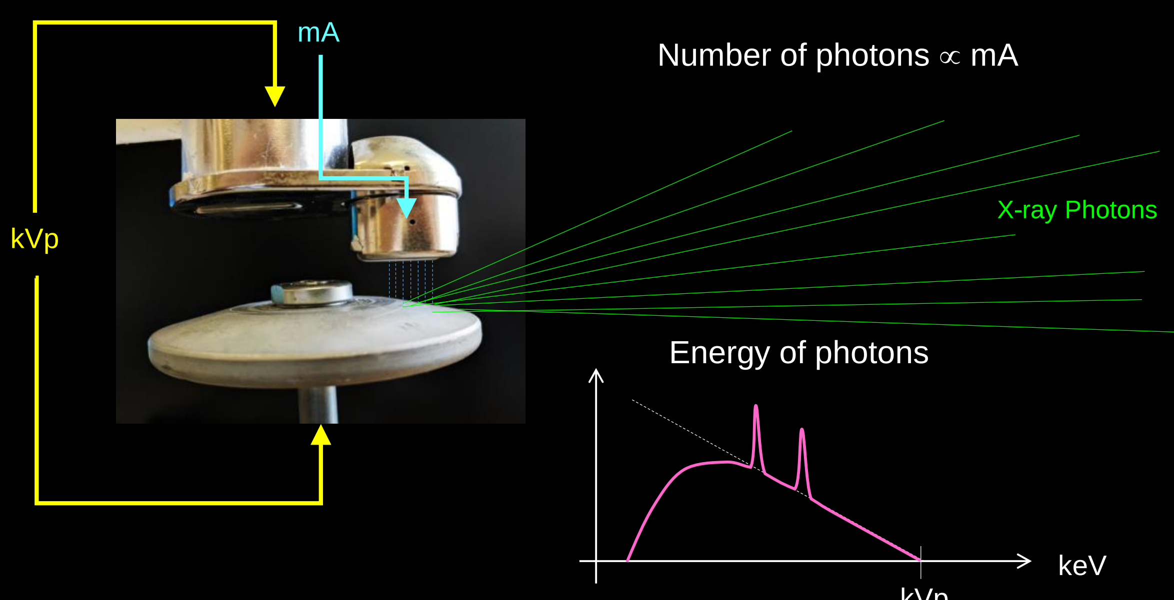
Introduction – Hardware Targets for Better Dose Utilization



(image Credit) https://www.youtube.com/watch?v=bg0iNhw2ARw

X-ray Tube Physics and Controllable Elements



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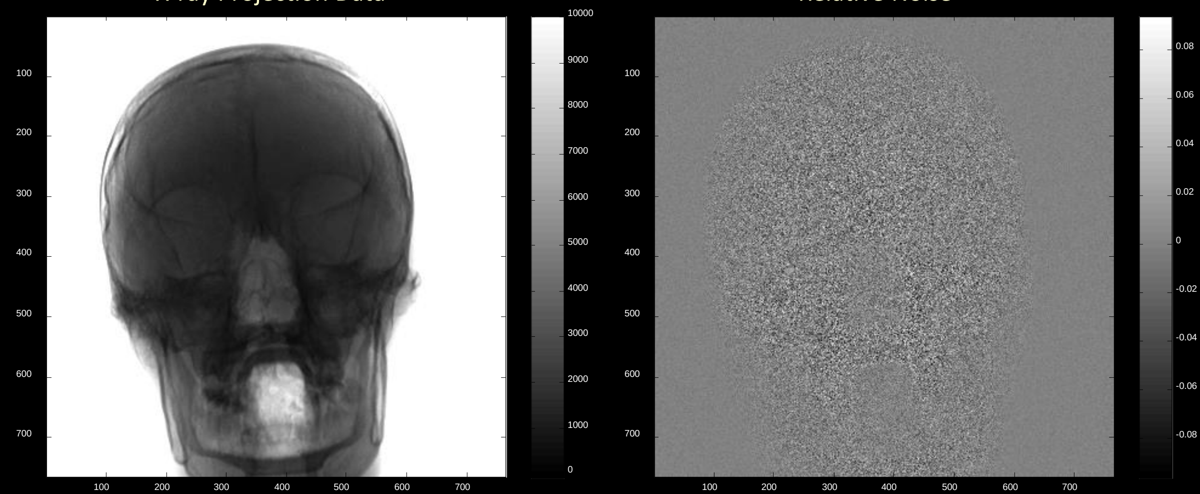
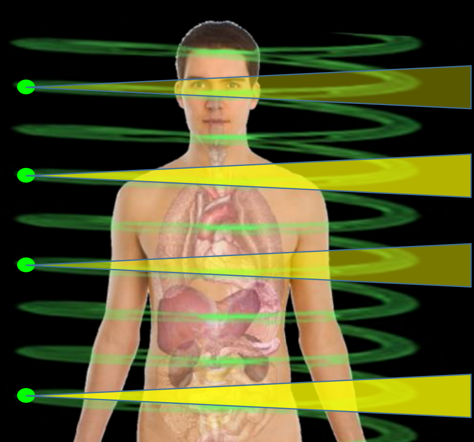
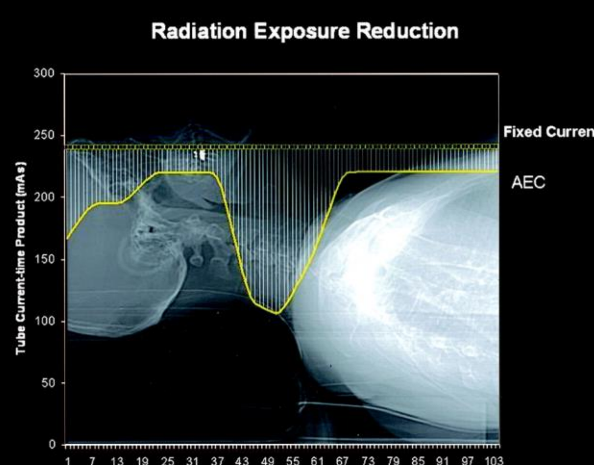
Noise in X-ray Projection Data



Modulation of X-ray Fluence as a Function of Table Position





Namasivayam S, et al. 2006 Optimization of Z-axis automatic exposure control for multidetector row CT evaluation of neck and comparison with fixed tube current technique for image quality and radiation dose *AJNR Am. J. Neuroradiol.* **27** 2221–5

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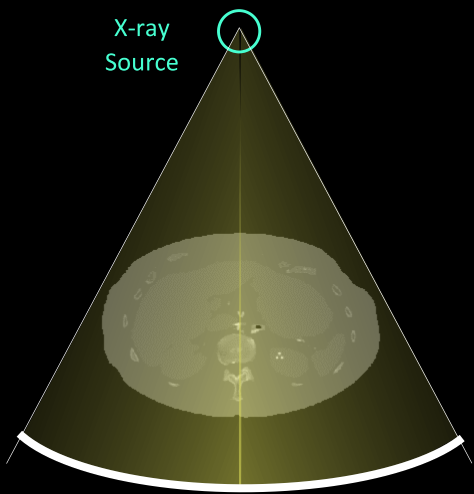
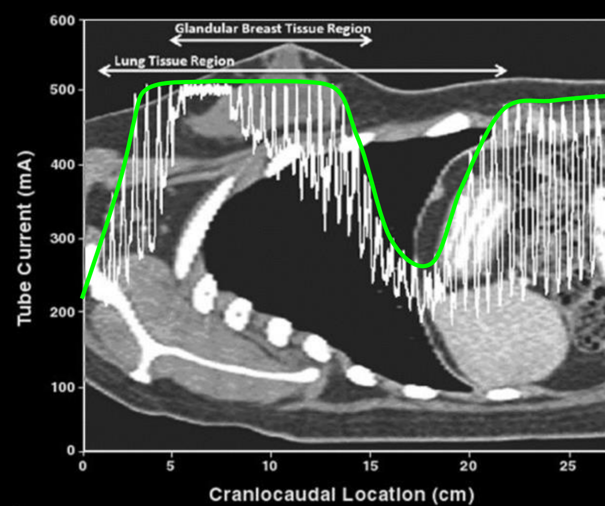
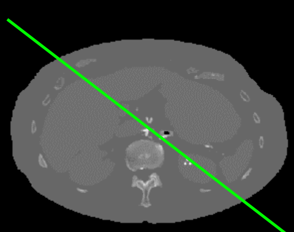
Modulation of X-ray Fluence as a Function of Rotation Angle





Angel E, et al. 2009 Dose to Radiosensitive Organs During Routine Chest CT: Effects of Tube Current Modulation *Am. J. Roentgenol.* **193** 1340–5

How to Optimally Modulate Tube Current

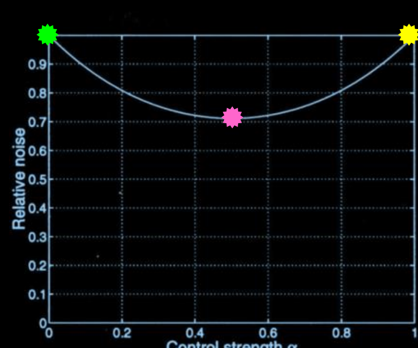


Attenuation due to Patient:

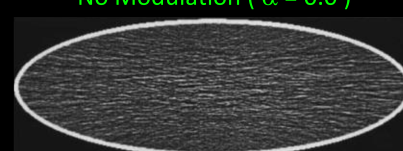
$$A = \exp(-\mu L)$$

Attenuation-based Current Modulation:

$$\exp(-\alpha\mu L) = A^{\alpha}$$

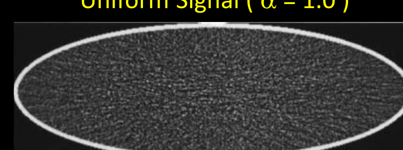


No Modulation (α = 0.0)



Optimal Modulation (α = 1/2)

Uniform Signal (α = 1.0)



Gies M, Kalender W A, Wolf H and Suess C 1999 Dose reduction in CT by anatomically adapted tube current modulation. I. Simulation studies. *Med. Phys.* **26** 2235–47

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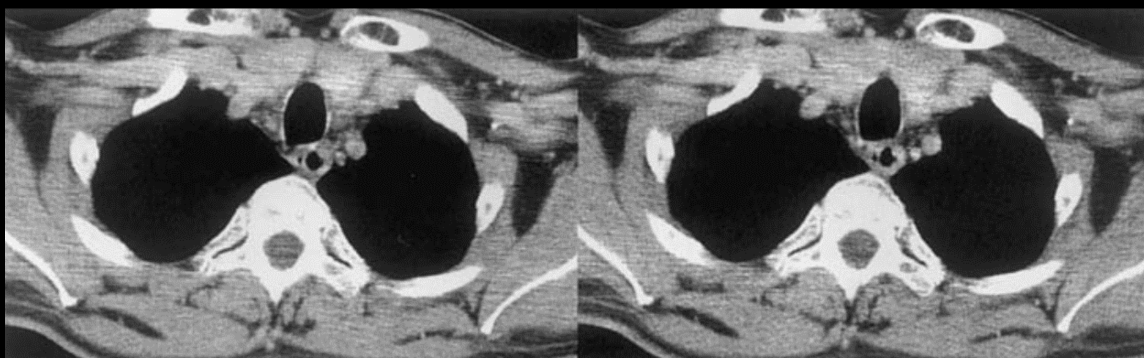
Dose Reduction in Patient Studies

Constant Current – 327 mAs

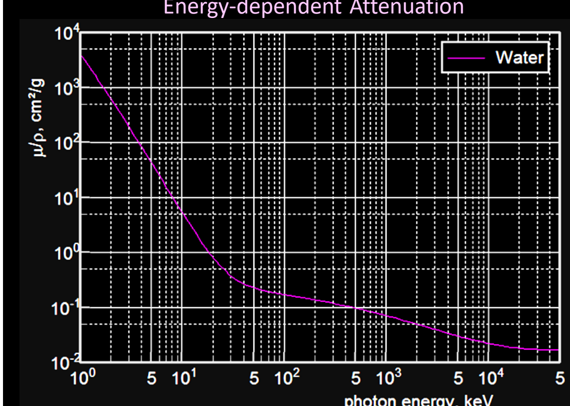
Tube Current Modulation – 166 mAs



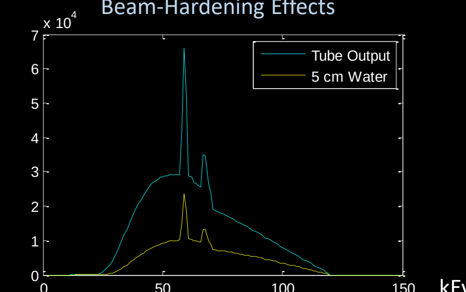
Fuchs T, Kachelrieß M and Kalender W A 2000 Technical advances in multi-slice spiral CT *Eur. J. Radiol.* **36** 69–73

What about Tube Voltage? - kVp

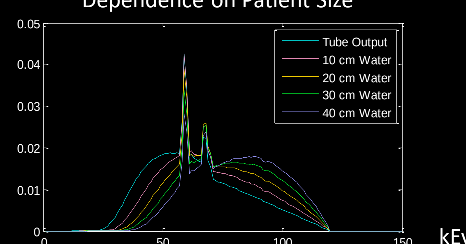
Energy-dependent Attenuation



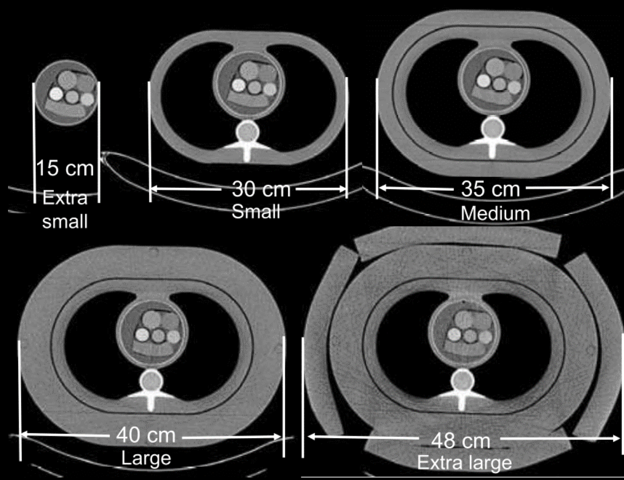
Beam-Hardening Effects

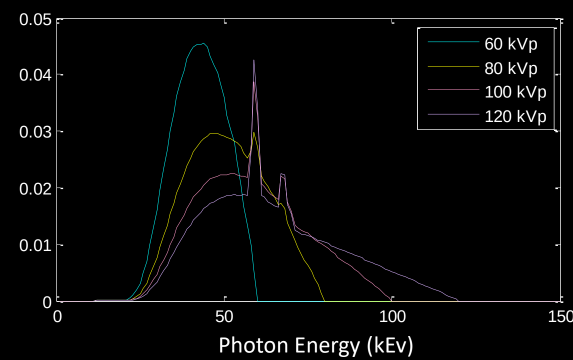


Dependence on Patient Size



Automatic kVp Selection

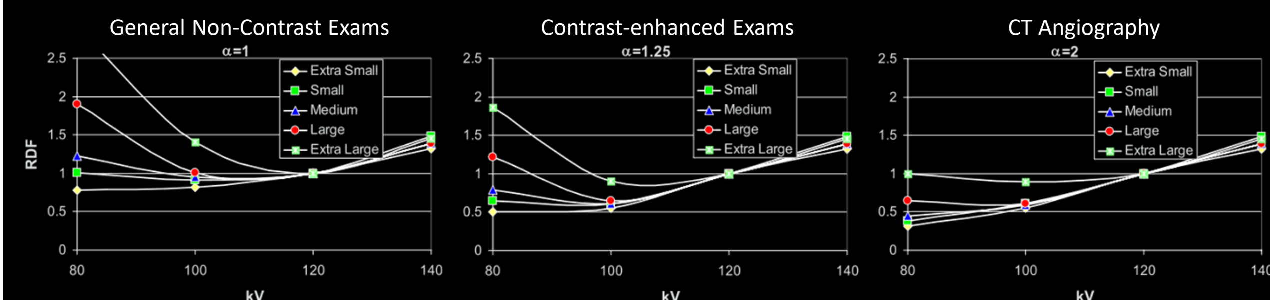




Yu L, Li H, Fletcher J G and McCollough C H 2009 Automatic selection of tube potential for radiation dose reduction in CT: A general strategy *Med. Phys.* **37** 234–43

Optimal kVp Selection

Optimization of kVp can be a bit more complex (than mA modulation)
- Dependent on patient size
- Competing IQ metrics – contrast and noise
- Dependent on imaging task



Yu L, Li H, Fletcher J G and McCollough C H 2009 Automatic selection of tube potential for radiation dose reduction in CT: A general strategy *Med. Phys.* **37** 234–43

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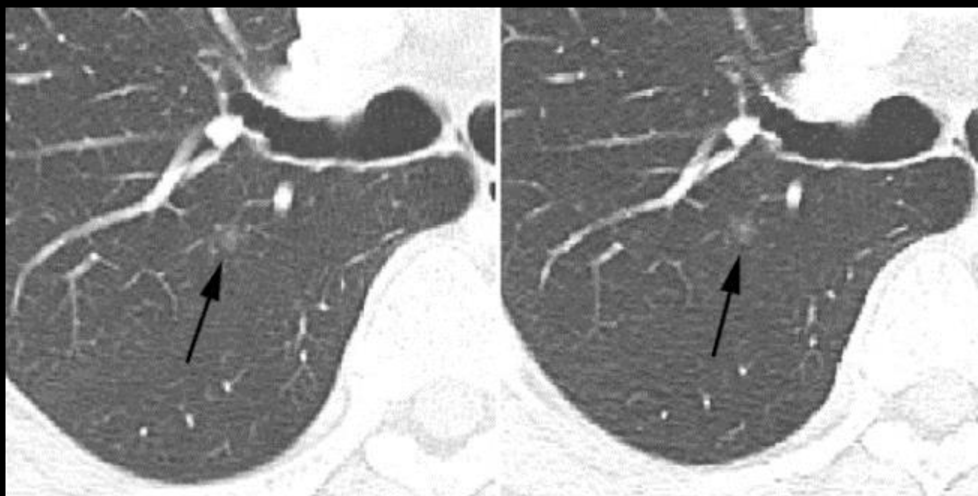
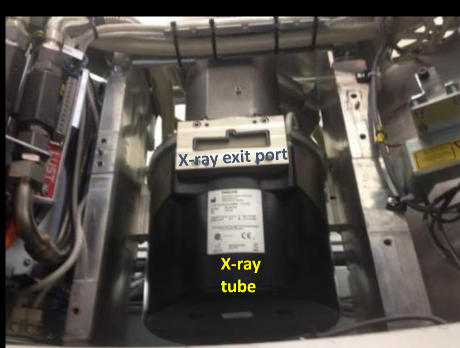
Tube Voltage Optimization in Patient Studies



120 kVp, 284 mGy/cm | 100 kVp, 165 mGy/cm

Chae I H, Kim Y, Lee S W, Park J E, Shim S S and Lee J H 2014 Standard chest CT using combined automated tube potential selection and iterative reconstruction: Image quality and radiation dose reduction *Clin. Imaging* **38** 641–7

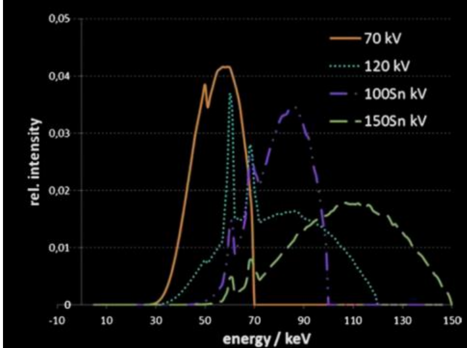
Filtration



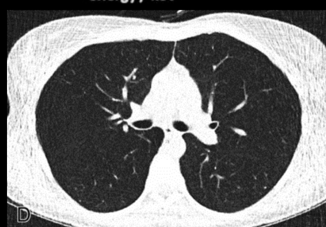
Generally there is room in front of the x-ray tube port for x-ray filters

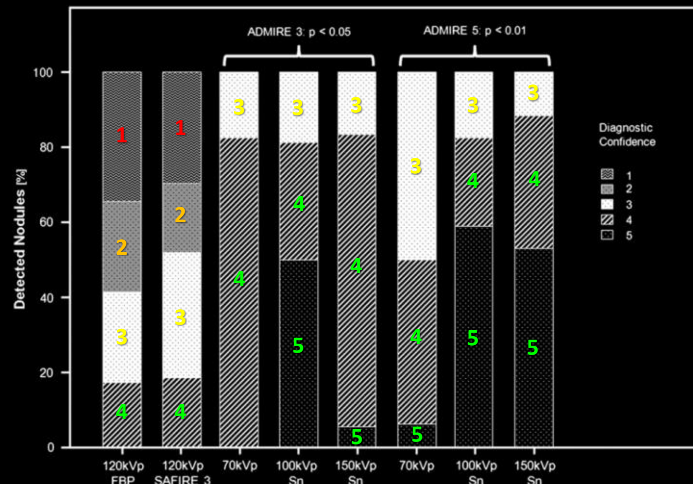
Change x-ray beam characteristics through selective attenuation of x-rays

Spectral Filtration



(0.06 mSv)
100 kVp
+ Sn Filter

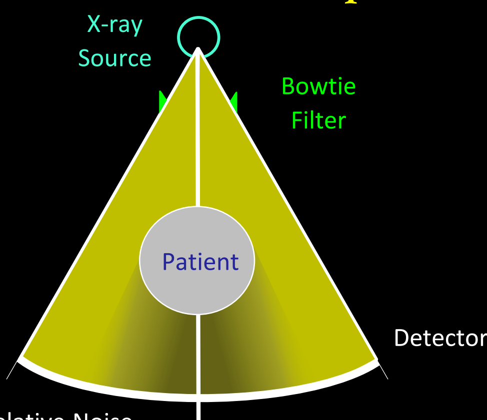




Gordic S, et al. 2014 Ultralow-dose chest computed tomography for pulmonary nodule detection: first performance evaluation of single energy scanning with spectral shaping. *Invest. Radiol.* **49** 465–73

(more on Sn filters) Messerli M, et al. S 2017 Ultralow dose CT for pulmonary nodule detection with chest x-ray equivalent dose – a prospective intra-individual comparative study *Eur. Radiol.* **27** 3290–9

Spatial Filtration



Relative Noise

(Optimal Bowtie Design) Harpen M D 1999 A simple theorem relating noise and patient dose in computed tomography *Med. Phys.* **26** 2231–4

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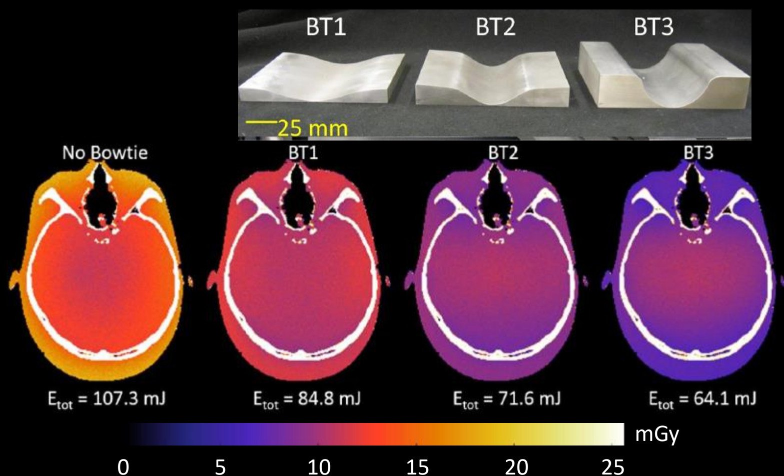
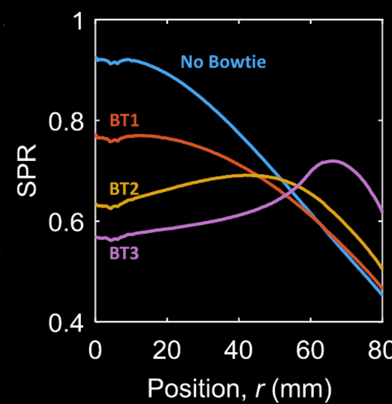
Bowtie Filters

Reduced Peripheral Dose

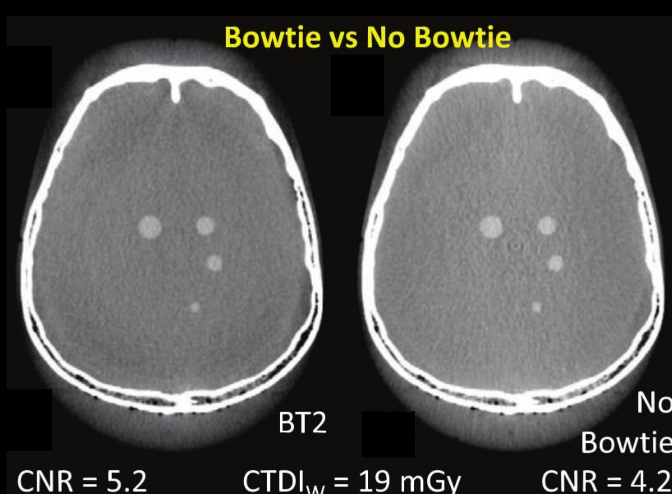


Reduced Scatter



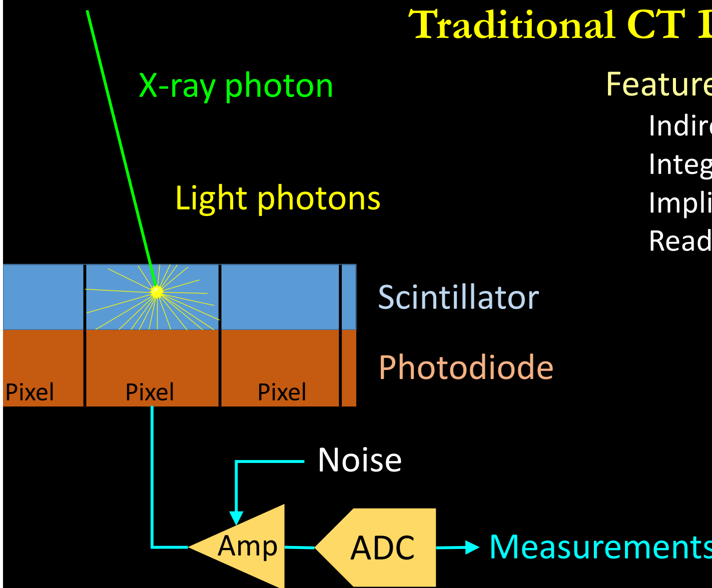
Xu J, Sisniega A, Zbijewski W, Dang H, Stayman J W, Wang X, Foos D H, Aygun N, Koliatsos V and Siewerdsen J H 2016 Evaluation of detector readout gain mode and bowtie filters for cone-beam CT imaging of the head. *Phys. Med. Biol.* **61** 5973–92
(centering) Toth T L, Ge Z and Daly M P 2007 The influence of patient centering on CT dose and image noise *Med. Phys.* **34** 3093

Example of Bowtie Use in Head Imaging



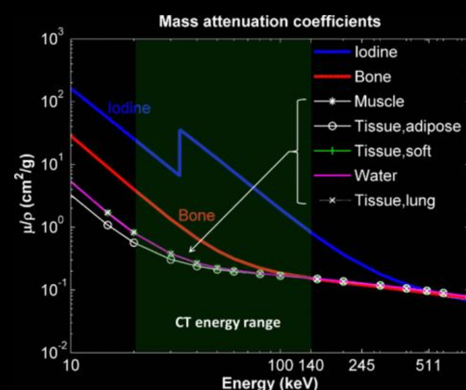
Xu J, Sisniega A, Zbijewski W, Dang H, Stayman J W, Wang X, Foos D H, Aygun N, Koliatsos V and Siewerdsen J H 2016 Evaluation of detector readout gain mode and bowtie filters for cone-beam CT imaging of the head. *Phys. Med. Biol.* **61** 5973–92

Traditional CT Detectors

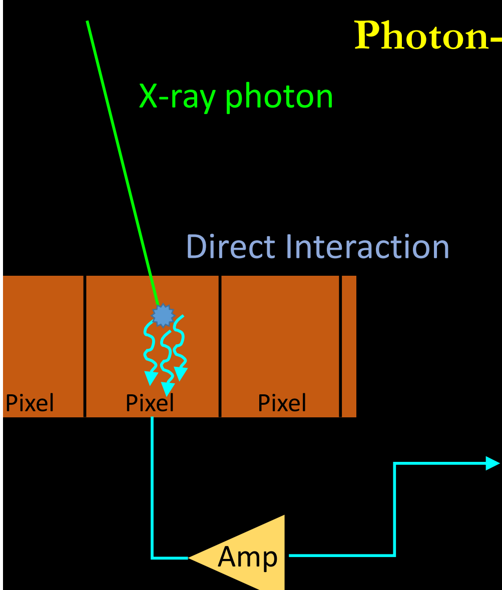


Features:

- Indirect detection (Scintillator)
- Integrating detector
- Implicit energy weighting (light ∝ kEv)
- Readout noise

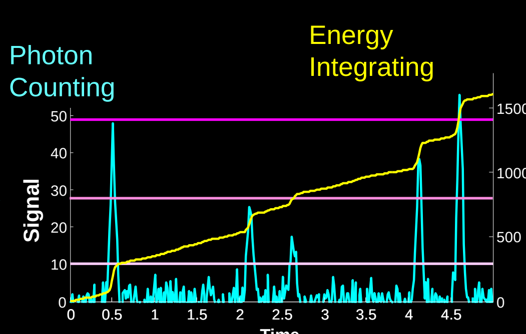


Photon-counting CT Detectors



Features:

- Direct detection (CdTe, CZT, Silicon)
- Possibly energy discriminating
- No implicit energy weighting
- No readout noise



(CZT Detector) Shikhaliev P M 2008 Computed tomography with energy-resolved detection: a feasibility study *Phys. Med. Biol.* 53 1475–95
(Silicon Detector) Bornefalk H and Danielsson M 2010 Photon-counting spectral computed tomography using silicon strip detectors: a feasibility study *Phys. Med. Biol.* 55 1999–2022

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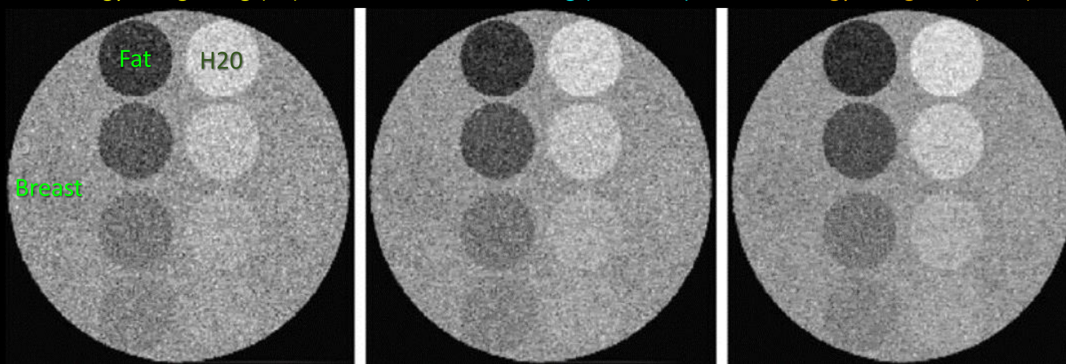
Comparison of Different Energy Weightings

Energy-Integrating (~E) | Photon-Counting (constant) | Energy-Weighted ($1/E^3$)

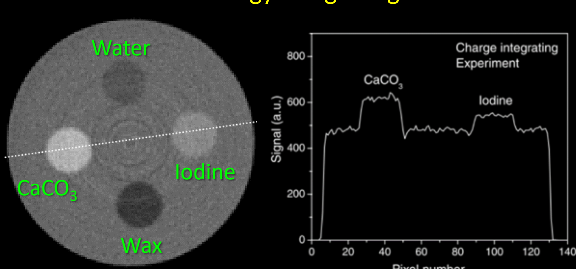


	Energy-Integrating (~E)	Photon-Counting (constant)	Energy-Weighted ($1/E^3$)
CNR Enhancement:	1.0 H20/Breast 1.0 Fat/Breast	1.2 H20/Breast 1.2 Fat/Breast	1.5 H20/Breast 1.4 Fat/Breast

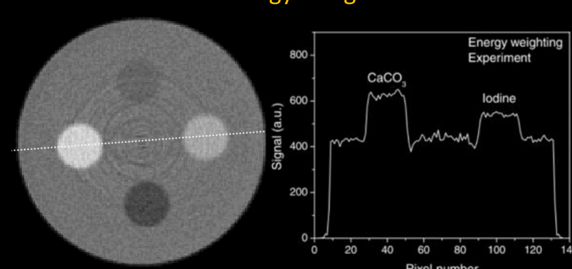
Giersch J, Niederlöhner D and Anton G 2004 The influence of energy weighting on X-ray imaging quality *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.* 531 68–74

Energy Weighting is Dependent on Task

Energy-Integrating



Energy-Weighted



Shikhaliev P M 2008b Energy-resolved computed tomography: first experimental results *Phys. Med. Biol.* **53** 5595–613
(more optimal weighting) Schmidt T G 2009 Optimal "image-based" weighting for energy-resolved CT *Med. Phys.* **36** 3018–27

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8/2/2017

Photon-Counting CT as an Emerging Technology

Many challenges with photon counting in physical CT systems

Taguchi K and Iwanczyk J S 2013 Vision 20/20: Single photon counting x-ray detectors in medical imaging *Med. Phys.* **40** 100901

Not yet wide-spread, starting to see (pre)clinical comparisons and evaluations

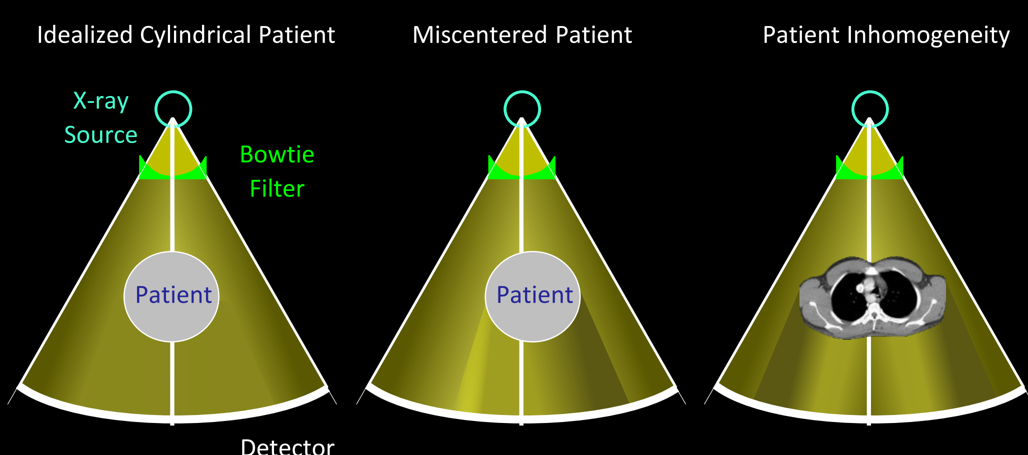
Yu Z, Leng S, Jorgensen S M, Li Z, Gutjahr R, Chen B, Halaweish A F, Kappler S, Yu L, Ritman E L and McCollough C H 2016 Evaluation of conventional imaging performance in a research whole-body CT system with a photon-counting detector array *Phys. Med. Biol.* **61** 1572–95

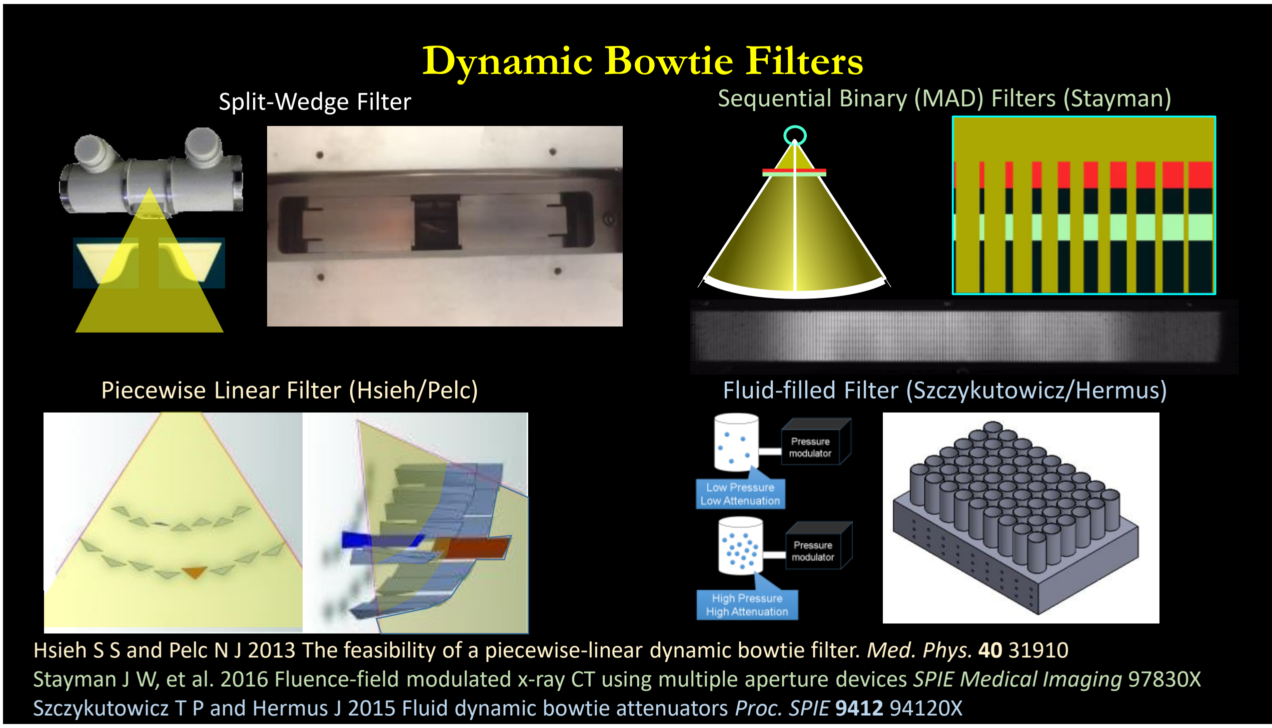
Pourmorteza A, Symons R, Sandfort V, Mallek M, Fuld M K, Henderson G, Jones E C, Malayeri A A, Folio L R and Bluemke D A 2016 Abdominal Imaging with Contrast-enhanced Photon-counting CT: First Human Experience *Radiology* **279** 239–45

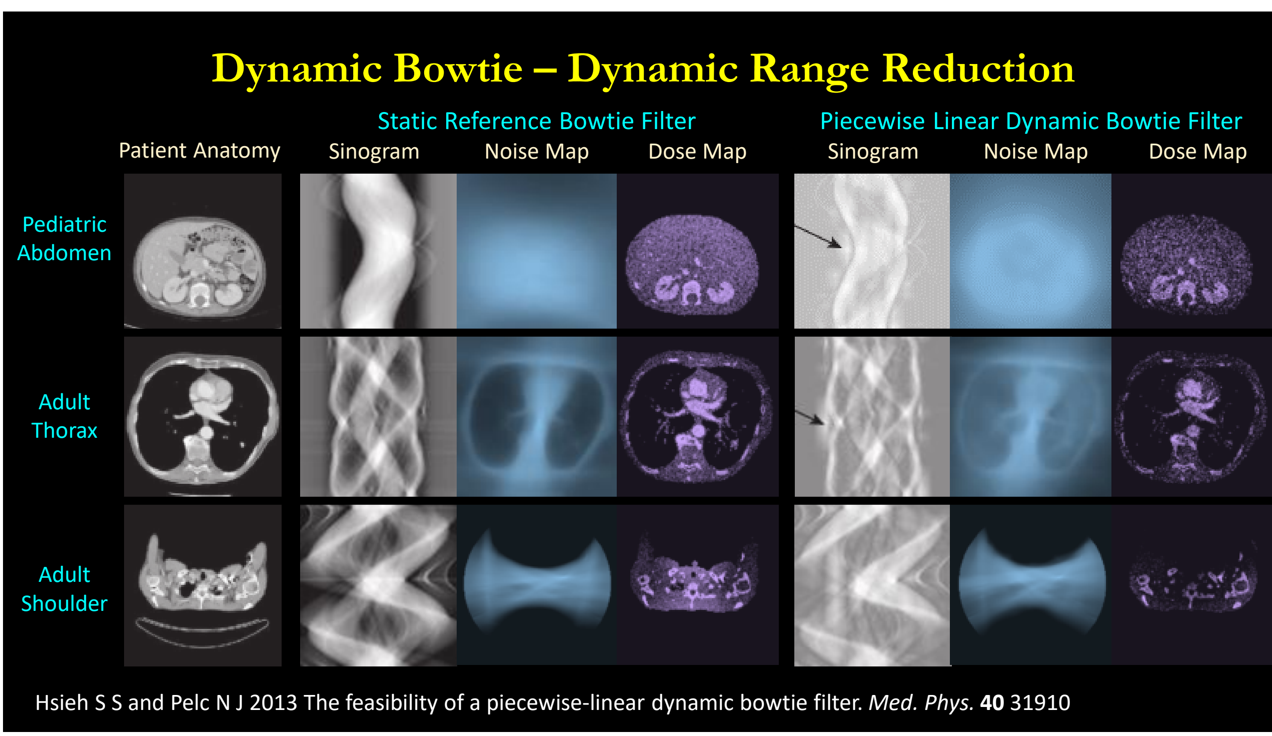
More potential for dose reduction in specific applications (contrast-enhanced imaging)

Schlomka J P, Roessl E, Dorscheid R, Dill S, Martens G, Istel T, Bäumer C, Herrmann C, Steadman R, Zeitler G, Livne A and Proksa R 2008 Experimental feasibility of multi-energy photon-counting K-edge imaging in pre-clinical computed tomography *Phys. Med. Biol.* **53** 4031–47

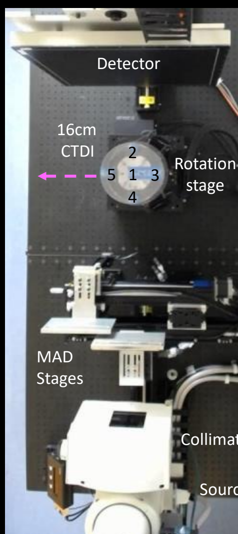
Spatial Filtering Revisited

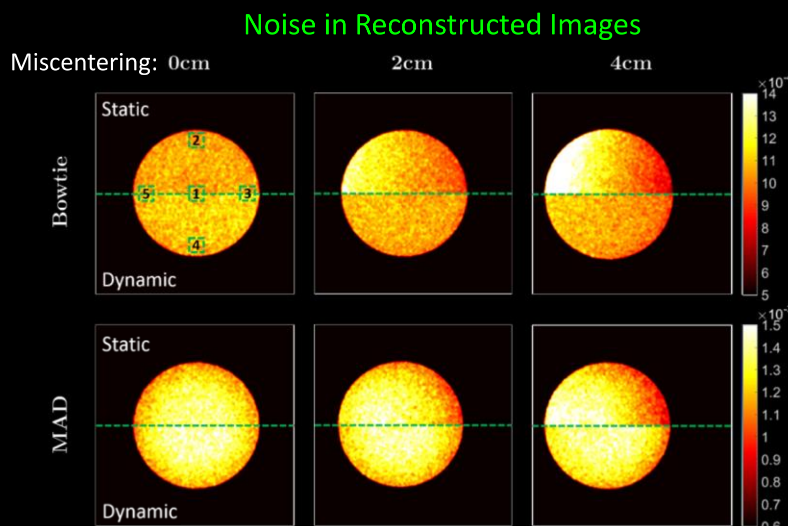



Dynamic Bowtie Filters
Split-Wedge Filter
Sequential Binary (MAD) Filters (Stayman)
Piecewise Linear Filter (Hsieh/Pelc)
Fluid-filled Filter (Szczykutowicz/Hermus)
Pressure modulator
Low Pressure
Low Attenuation
Pressure modulator
High Pressure
High Attenuation
Hsieh S S and Pelc N J 2013 The feasibility of a piecewise-linear dynamic bowtie filter. Med. Phys. 40 31910
Stayman J W, et al. 2016 Fluence-field modulated x-ray CT using multiple aperture devices SPIE Medical Imaging 97830X
Szczykutowicz T P and Hermus J 2015 Fluid dynamic bowtie attenuators Proc. SPIE 9412 94120X


Dynamic Bowtie – Dynamic Range Reduction
Static Reference Bowtie Filter
Piecewise Linear Dynamic Bowtie Filter
Patient Anatomy
Sinogram
Noise Map
Dose Map
Sinogram
Noise Map
Dose Map
Pediatric Abdomen
Adult Thorax
Adult Shoulder
Hsieh S S and Pelc N J 2013 The feasibility of a piecewise-linear dynamic bowtie filter. Med. Phys. 40 31910

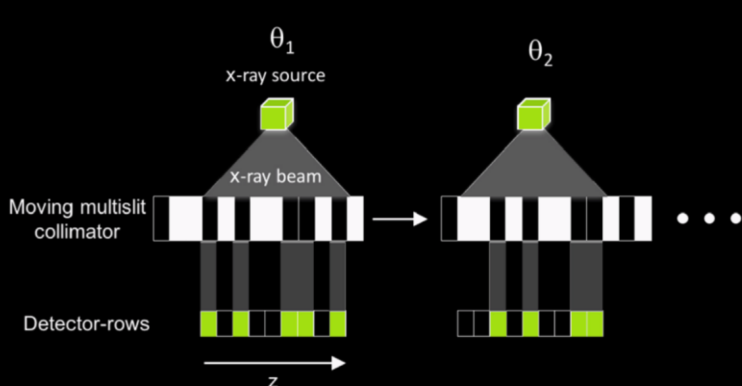
Adapting to Miscentered Patients with Dynamic Bowties





Mao A, Shyr W, Gang G, Stayman J W, 2018 Dynamic beam filtering for miscentered patients *SPIE Medical Imaging*, in prep.

Sparse CT Data Acquisitions



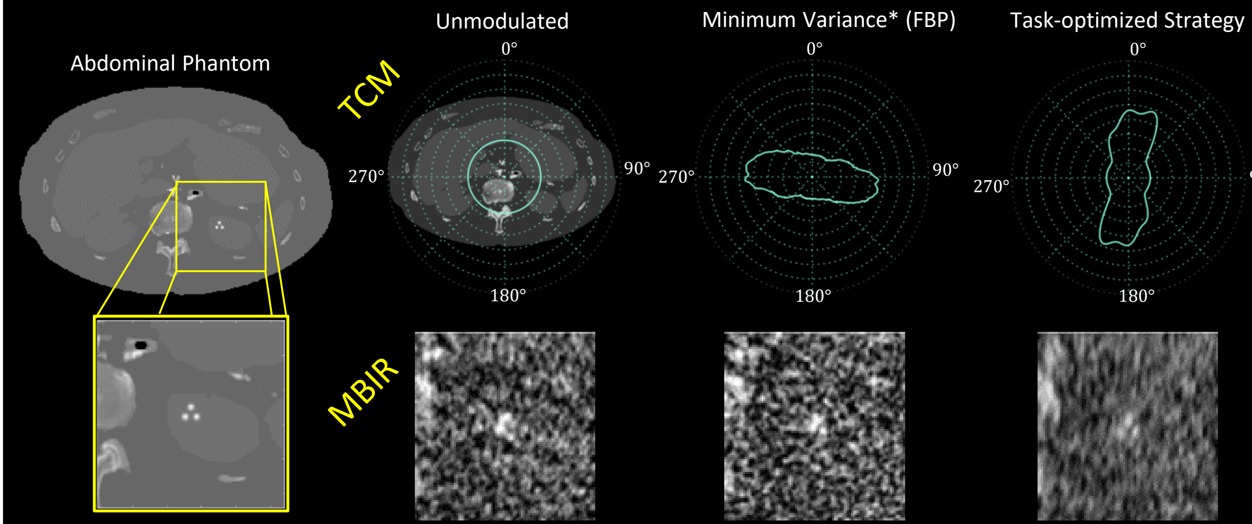
Siemens ADMIRE
120 kVp 210 mAs
100% data

Siemens ADMIRE
120 kVp 21 mAs
100% data

SparseCT
120 kVp 210 mAs
10.4% data

Koesters T, Knoll F, Sodickson A, Sodickson D K and Otazo R 2017 SparseCT: interrupted-beam acquisition and sparse reconstruction for radiation dose reduction *SPIE Medical Imaging* p 101320Q

Tube Current Revisited (with new reconstruction algorithms)



Gang G J, Siewerdsen J H and Webster Stayman J 2017 Task-driven optimization of CT tube current modulation and regularization in model-based iterative reconstruction *Phys. Med. Biol.* **62** 4777–97

Discussion

Presented traditional and emerging hardware modifications to CT

- Tube current modulation, tube voltage optimization
- Spatial and spectral filtration
- Photon counting and energy-discriminating detectors

General trend of increasing adaptation to the patient – “Personalized Imaging”

- Collect the data you need for the given task
- Allow lower fidelity data when possible and avoid exposing beyond what is needed

Increasing coupling between data acquisition and reconstruction

- Energy-weighting
- Sparse data / compressed sensing
- New reconstruction algorithms may change optimality for traditional adaptations

Thank You / References

Automatic Exposure Control / Tube Current Modulation
(Namasivayam *et al* 2006)
(Angel *et al* 2009)
(Gies *et al* 1999)
(Fuchs *et al* 2000)

Automatic Tube Voltage Selection
(Yu *et al* 2009)
(Chae *et al* 2014)

Spectral Filters
(Gordic *et al* 2014)
(Messerli *et al* 2017)

Bowtie Filters
(Harpen 1999)
(Xu *et al* 2016)
(Toth *et al* 2007)

Photon-Counting Detectors
(Shikhaliev 2008a)
(Bornefalk and Danielsson 2010)
(Giersch *et al* 2004)
(Shikhaliev 2008b)
(Schmidt 2009)
(Taguchi and Iwanczyk 2013)
(Yu et al 2016)
(Pourmorteza *et al* 2016)
(Schlomka *et al* 2008)

Dynamic Bowtie Filters
(Hsieh and Pelc 2013)
(Szczykutowicz and Hermus 2015)
(Stayman *et al* 2016)
(Mao *et al* 2018)

Joint Hardware/Software Solutions
(Koesters *et al* 2017)
(Gang *et al* 2017)