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The Latest in Radiation Dose Reduction Techniques in CT

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DISCLOSURES

Research Support:

NIH: EB 079861
DK 083007
DK 059933
EB 04898
RR 018898

Siemens Healthcare

Off Label Usage

None

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CT Dose per exam

- ***The radiation dose required to produce images of <u>sufficient quality to answer the clinical question</u>***

- **CTDIvol for a routine abdomen exam**

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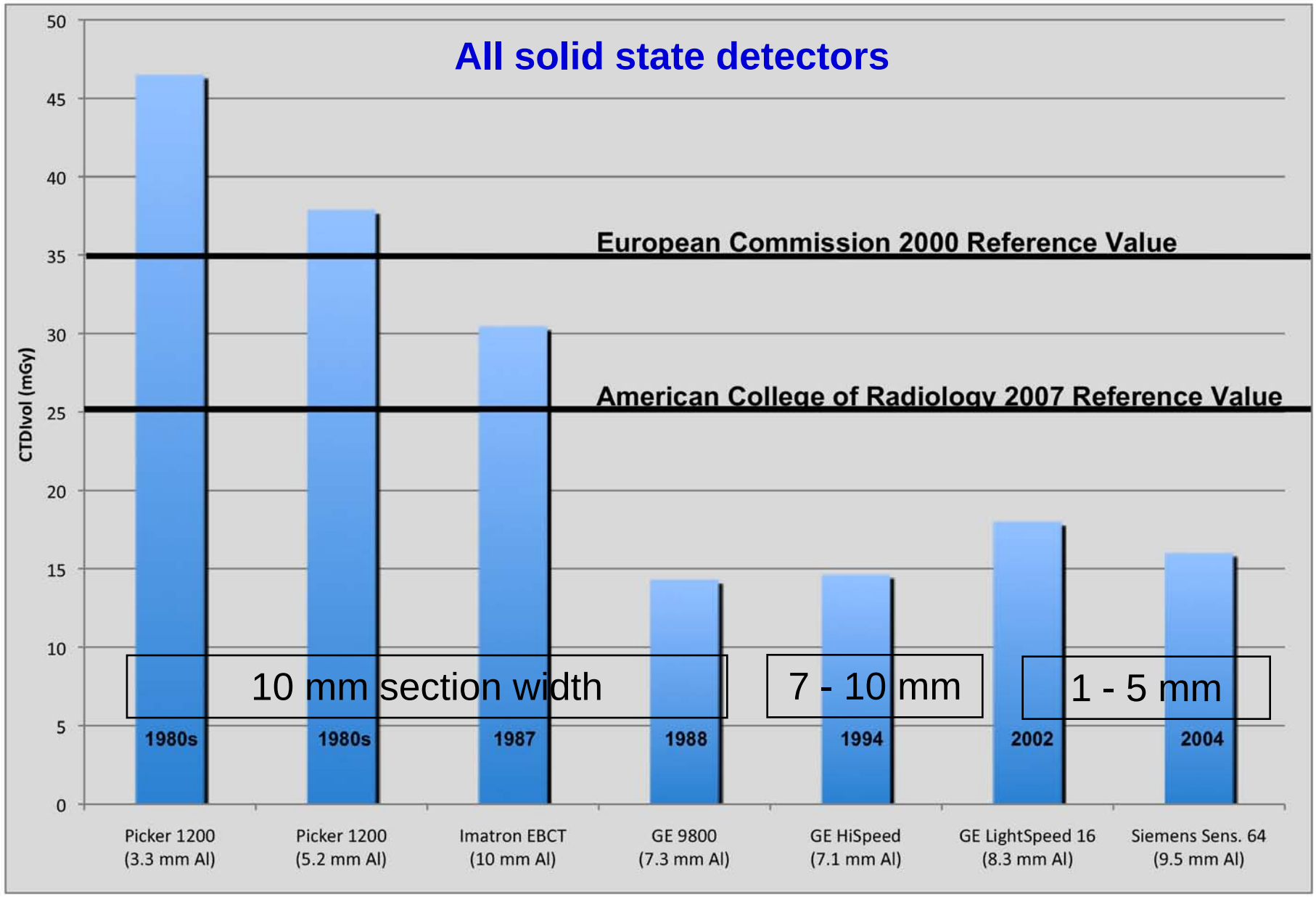
Routine Body CT Doses over 2 Decades



Clinical Impact

- Dose has decreased since 1980s by a factor of 2-3
- Expect another factor of 2 (at least)

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Dose Reduction Techniques

Technique	Cardiac CT	Non-Cardiac CT
Tube current (mA) modulation (i.e. Automatic Exposure Control)	ECG-based	Attenuation-based
Axial (non-spiral) cardiac modes	Yes	N/A
Increased spiral pitch	Yes	No
Organ-based tube current modulation	N/A	Yes
Active Z-axis collimation	Yes	Yes
Optimized tube potential (kV)	Yes	Yes
Noise reduction algorithms	Yes	Yes
- Projection space based (i.e. require raw data)	Yes	Yes
- Image based	Yes	Yes

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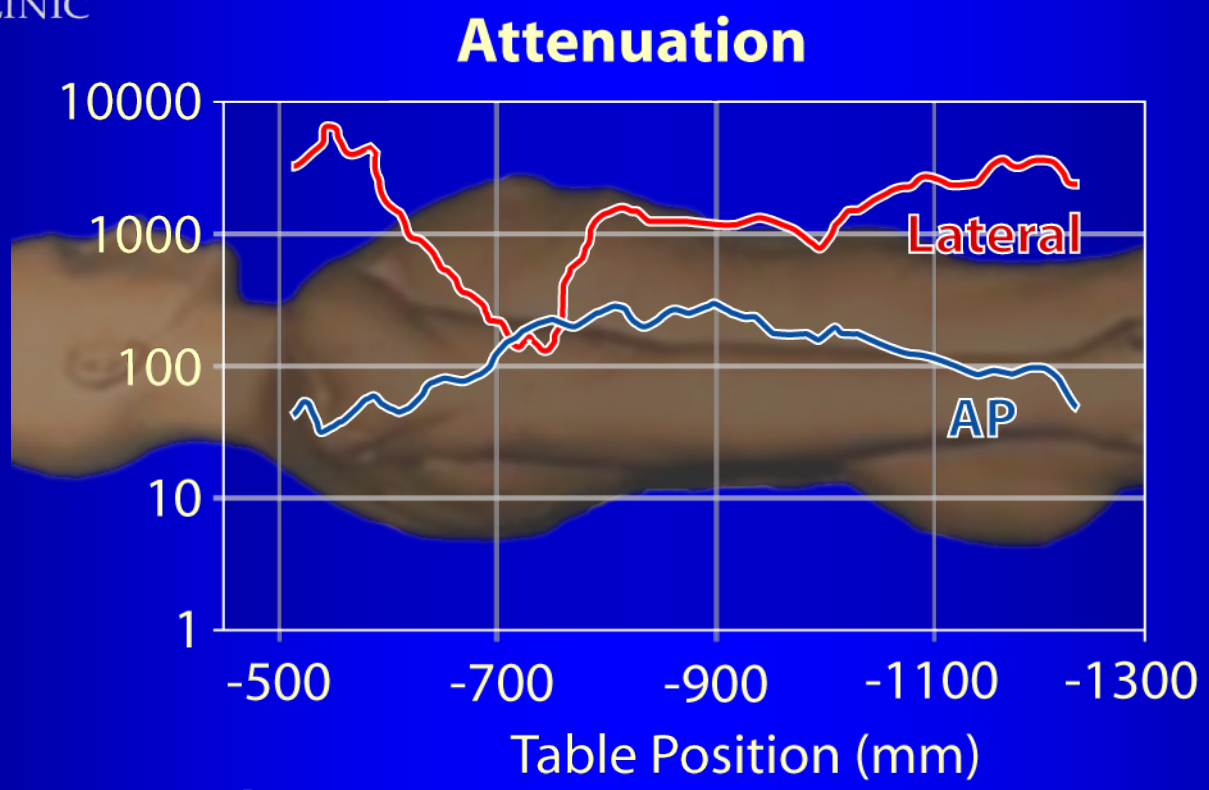
AEC:
Automatic Exposure Control



X-ray attenuation

- Varies over body region and with projection angle
- Noise in final image is primarily determined by the smallest number of detected photons.
- The larger number of detected photons along other directions is unnecessary radiation dose

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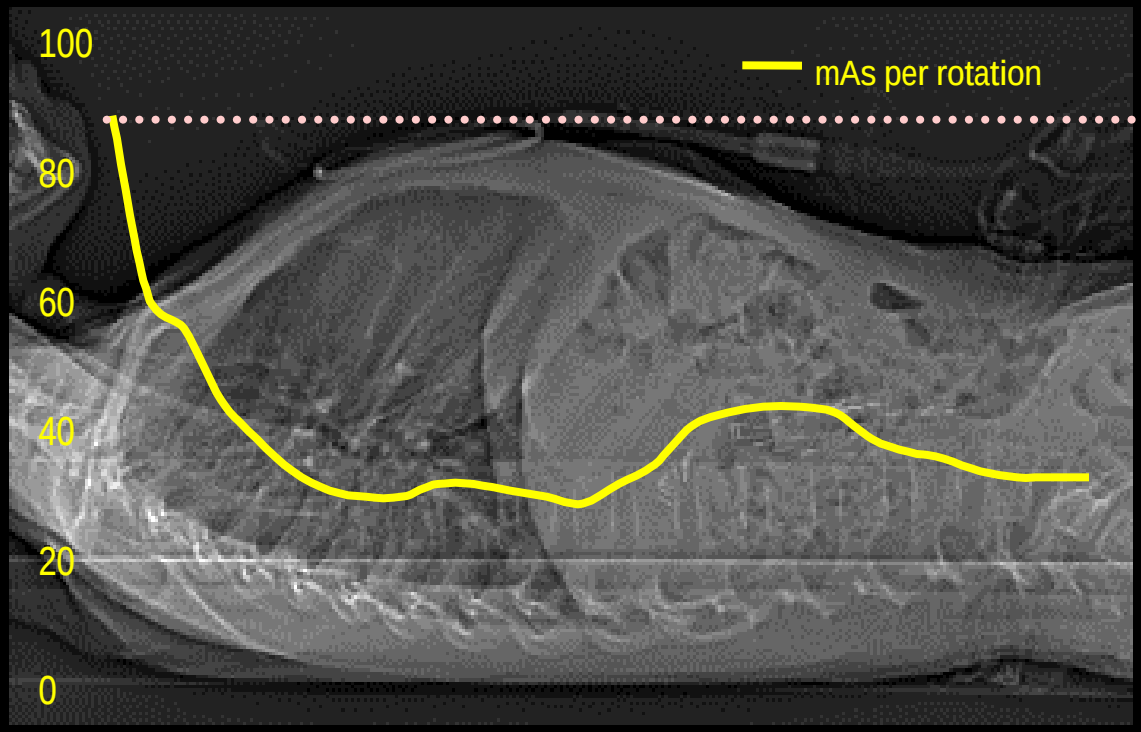
Three Levels of AEC

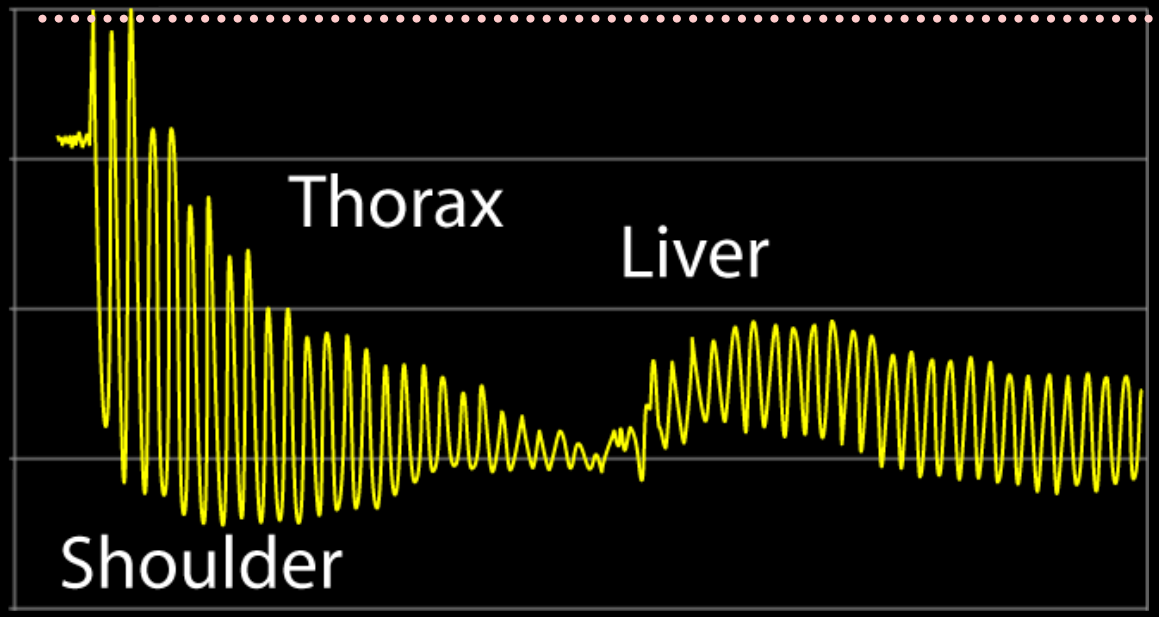
- For a single cross section, automatically adjust the mA along different directions
  - (x-y modulation)
- For a single patient, automatically adjust the mA for different body parts
  - (z modulation)
- For different patients, automatically adjust the mA based upon the patient size
  - "Right sizing" dose for each patient

Z modulation



Without modulation

Angular modulation



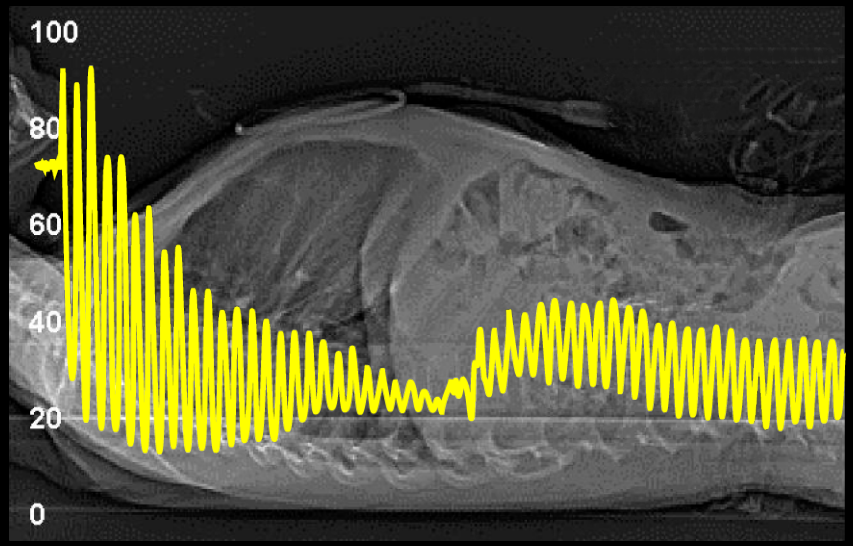
Without modulation

Example: 6 year old child

Scanned with adult protocol
(but using AEC dose reduction strategy)

Reference eff. mAs = 165

Mean eff. mAs = 38

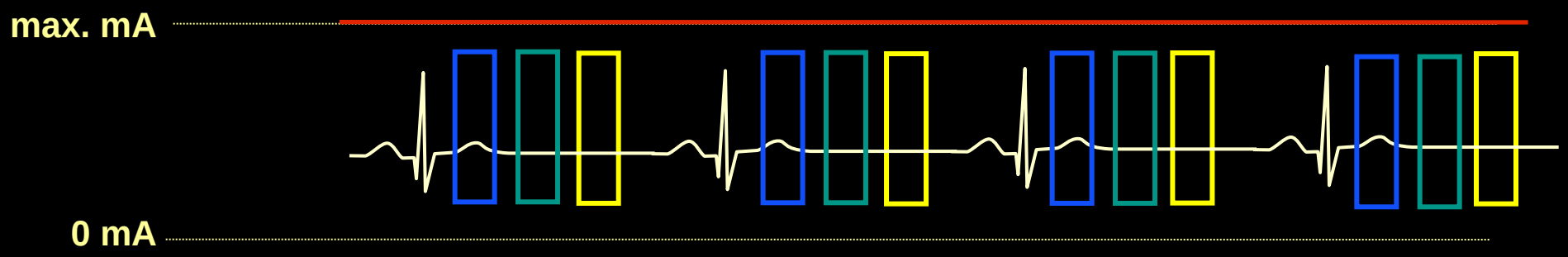


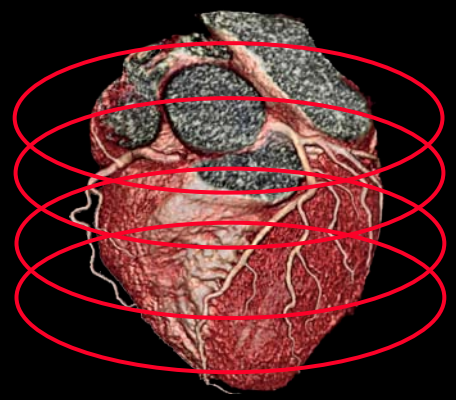
mA variation

Cardiac AEC

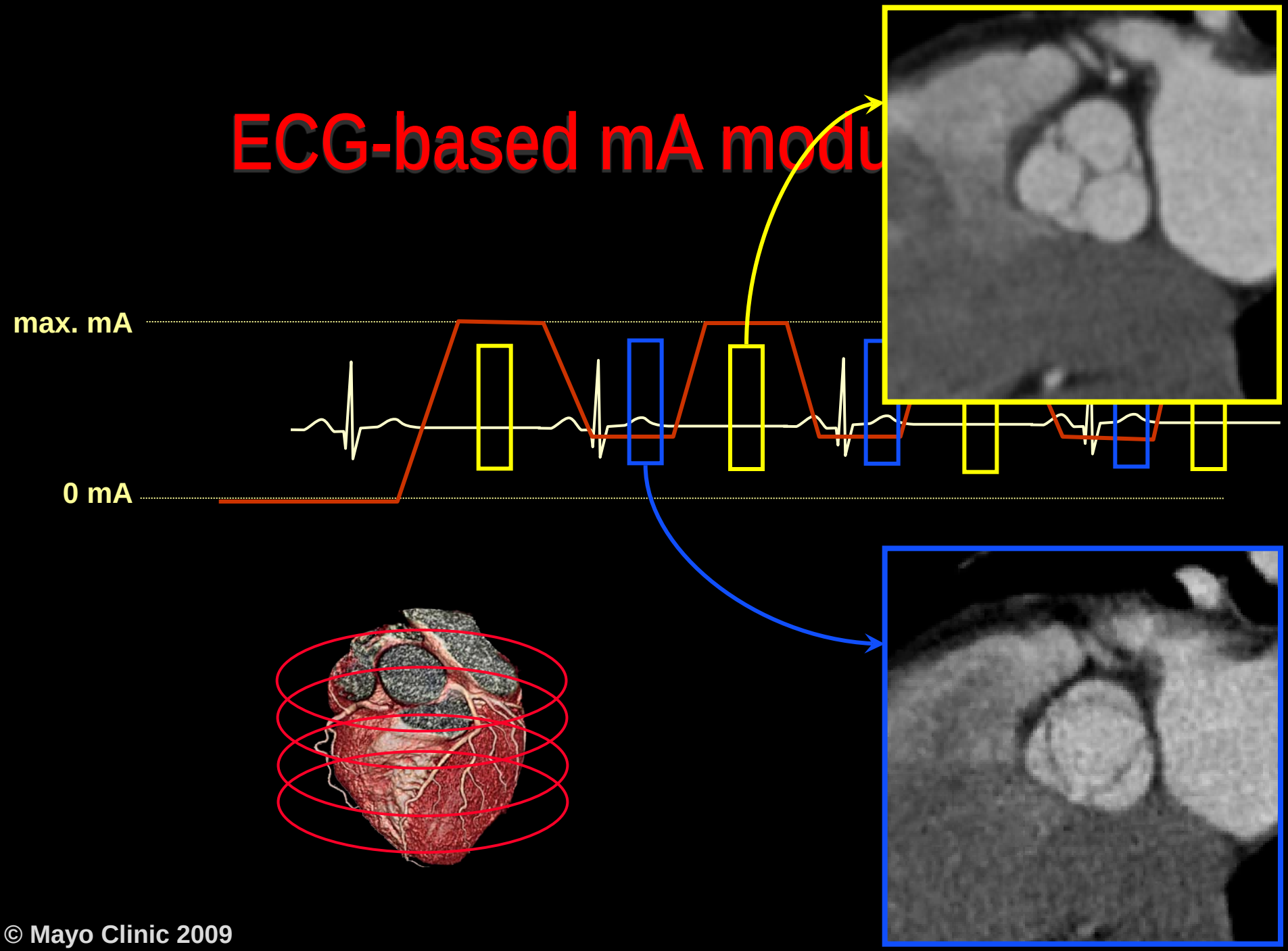
- Varying mA with angle or z position risks having low dose data at the needed angle/position
- Instead modulation based on phase within the cardiac cycle

Spiral Mode

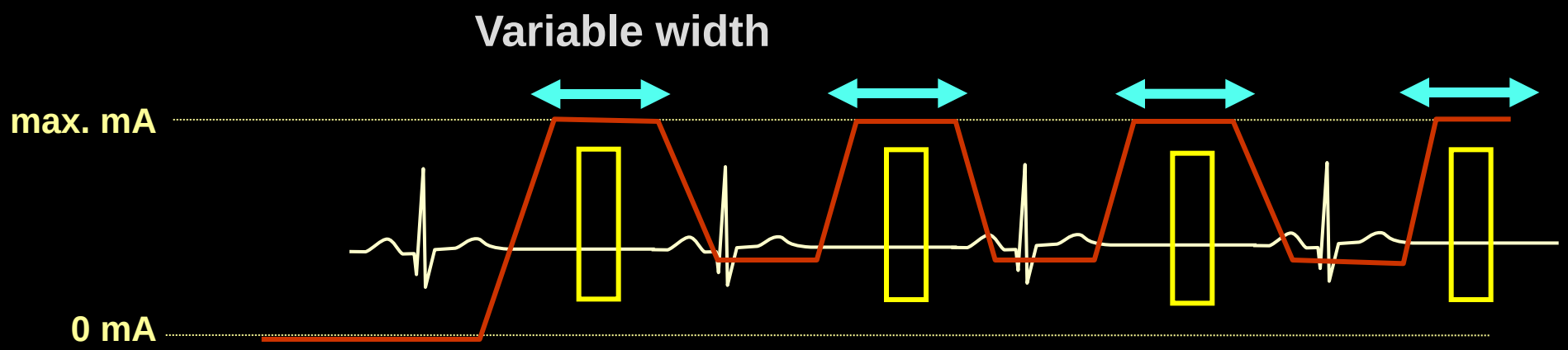


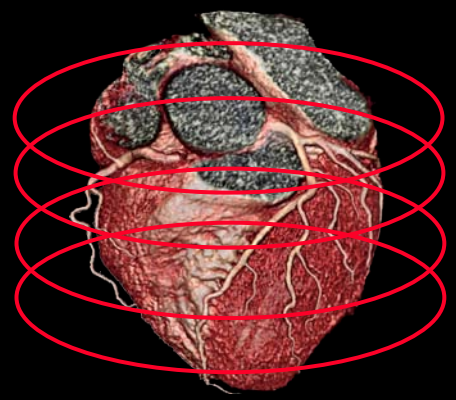


ECG-based mA modu

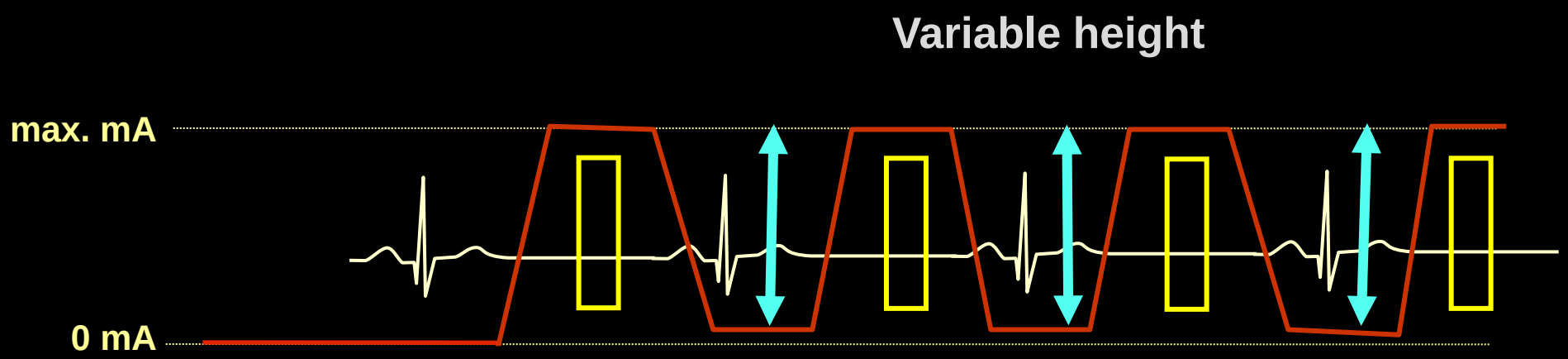


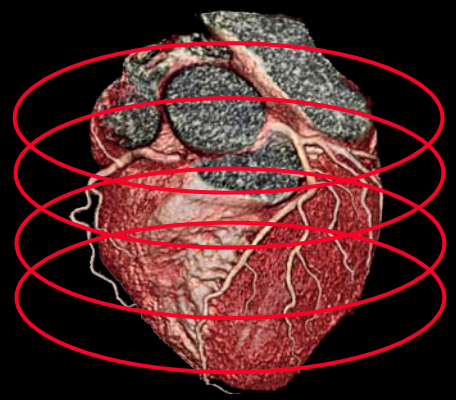
Adjustable Phase Width



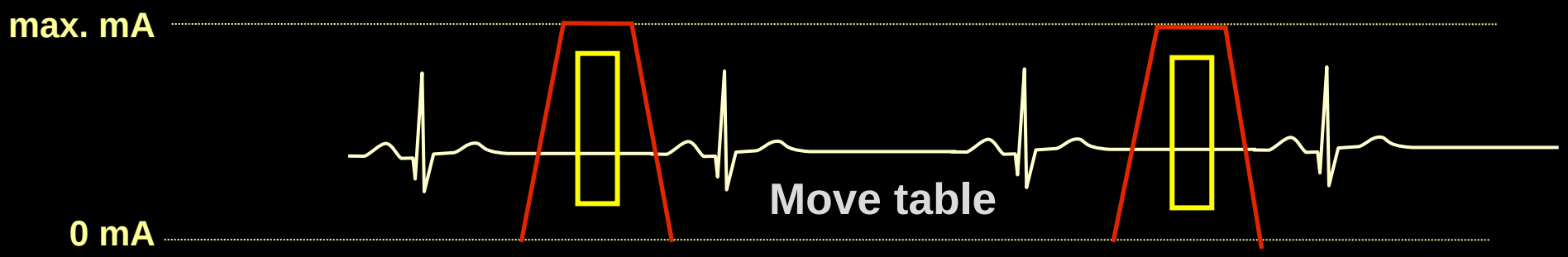


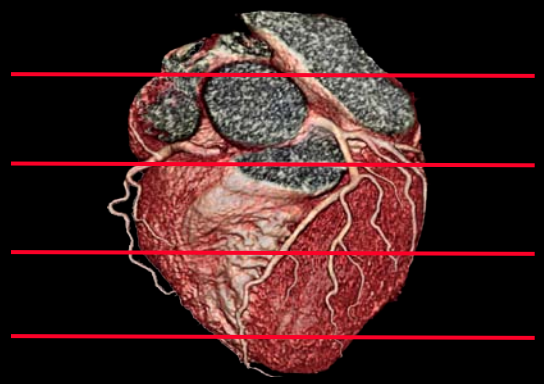
Adjustable minimum mA



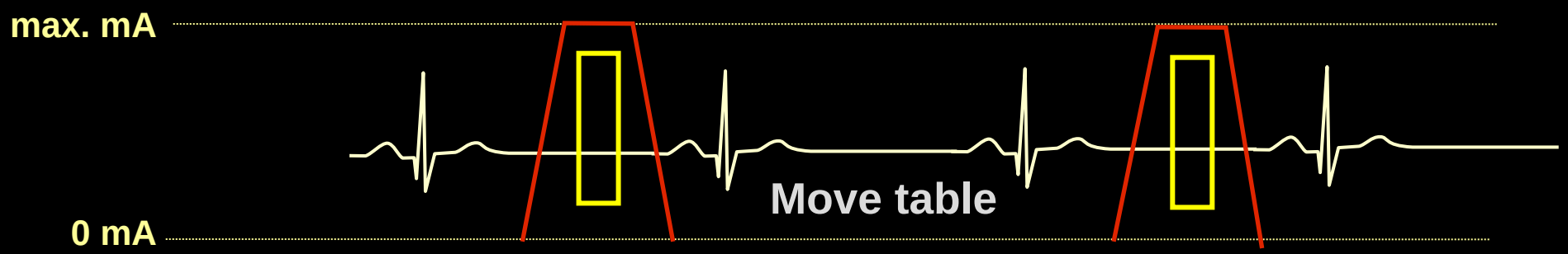


Sequential Mode



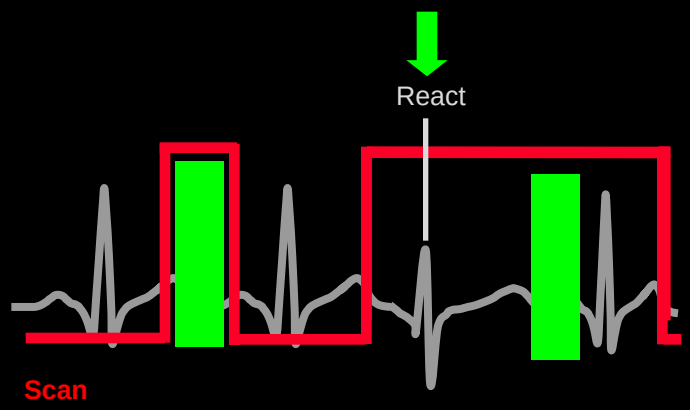


Sequential Mode

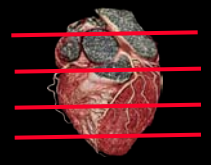


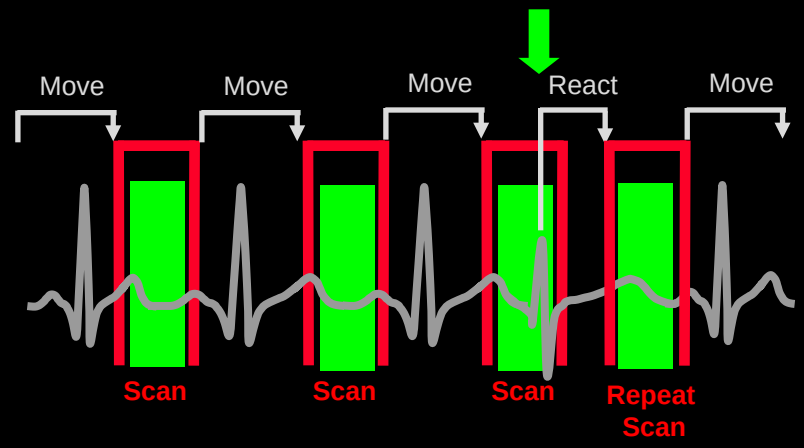
Arrhythmia Detection

Spiral

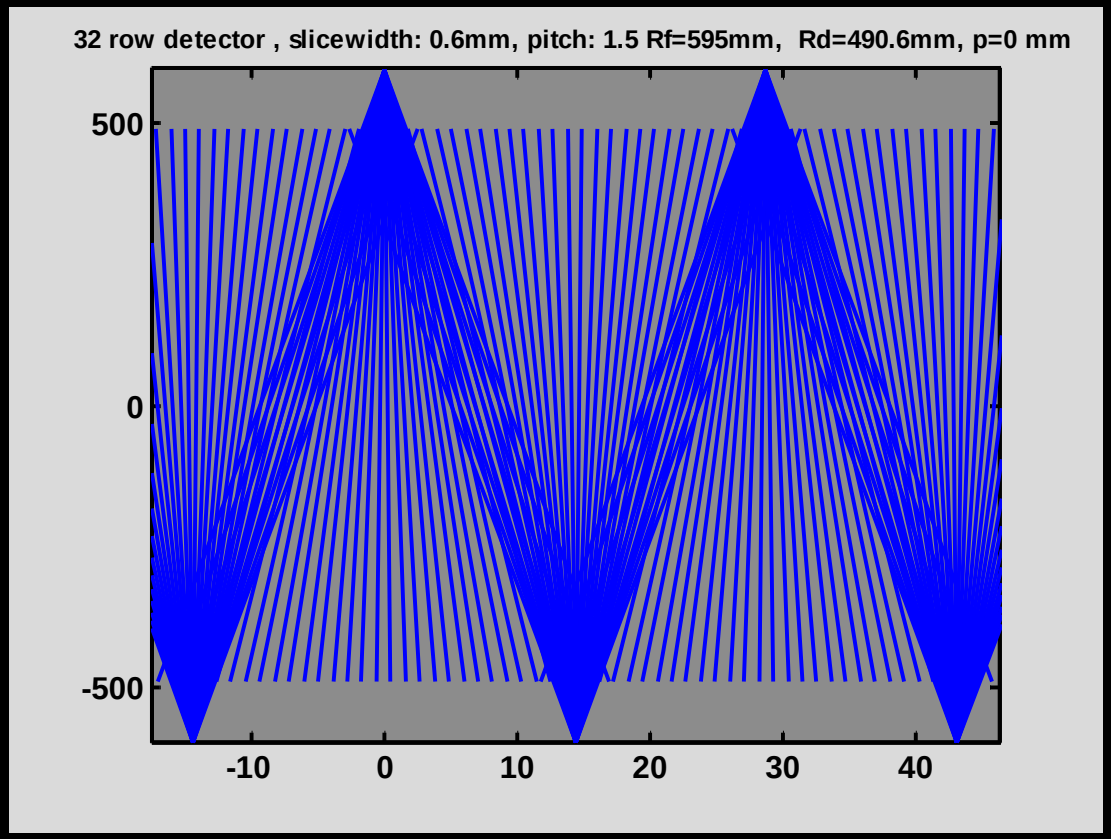


Axial



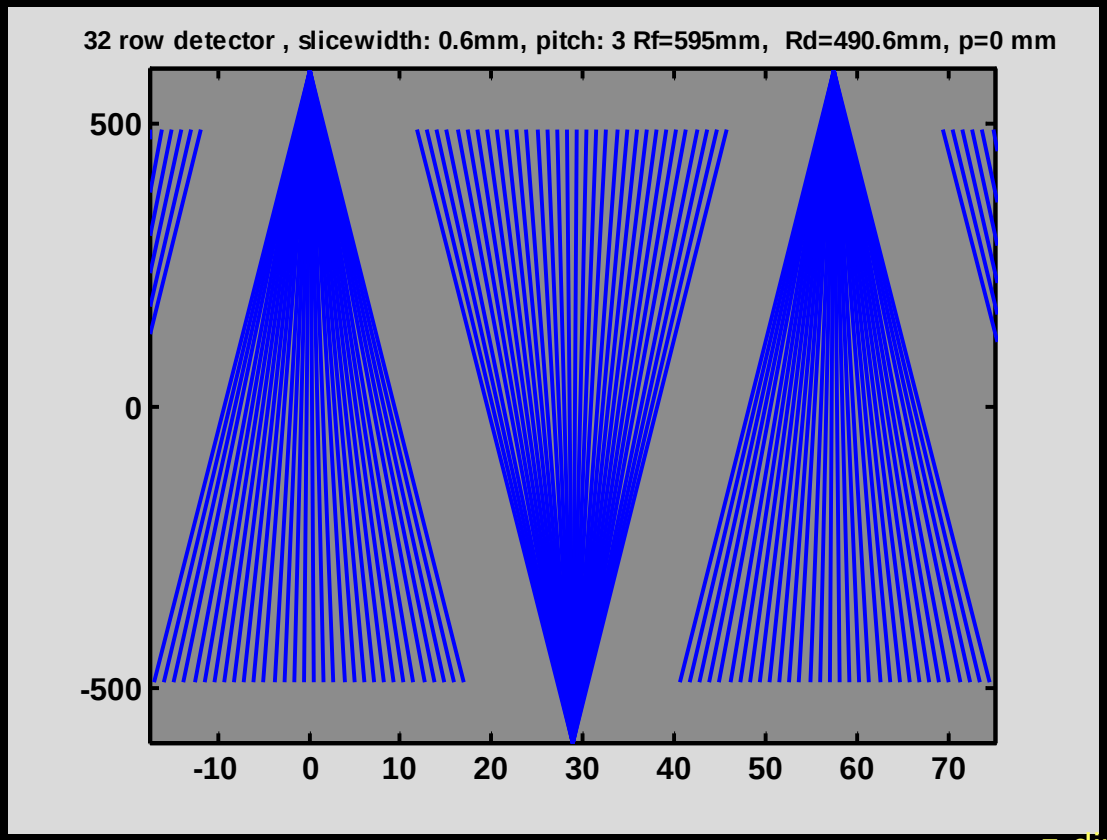


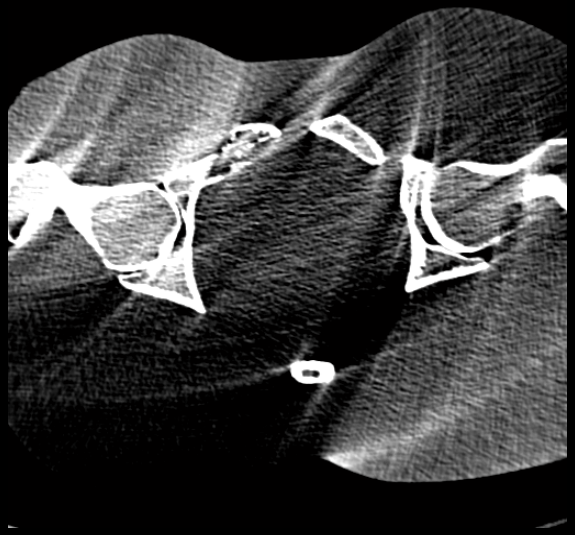
Single source CT: upper pitch limit 1.5 for gapless z-sampling



z-direction

Single source CT: upper pitch limit 1.5 for gapless z-sampling
Faster table feed: z-sampling gaps, degradation of image quality

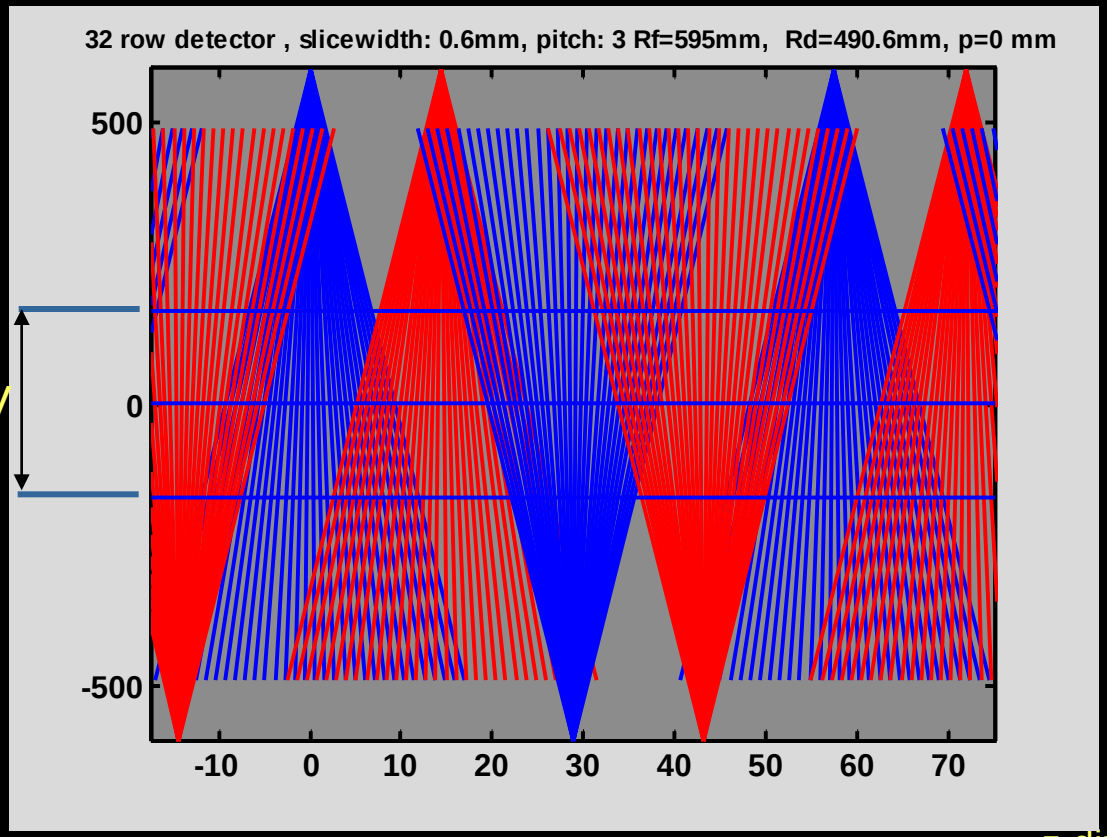




z-direction

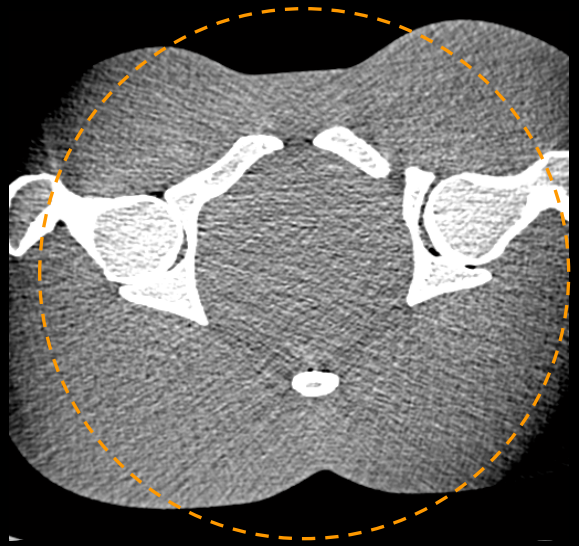
Single source CT: upper pitch limit 1.5 for gapless z-sampling

Dual source CT: up to pitch 3.4 possible, depending on SFOV

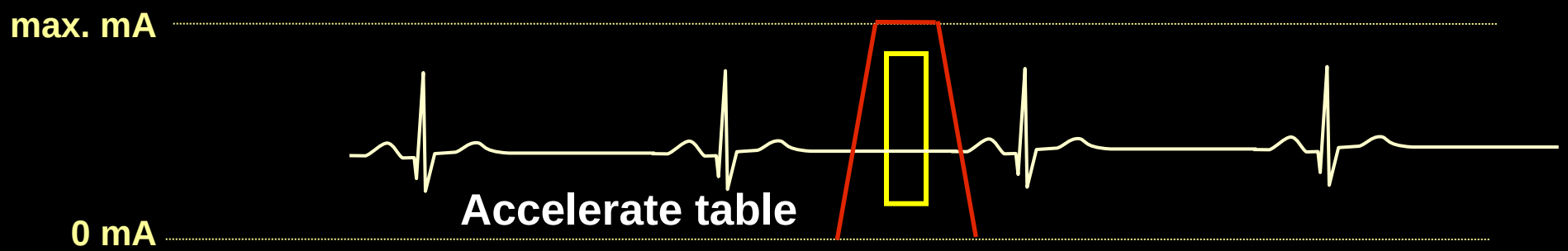


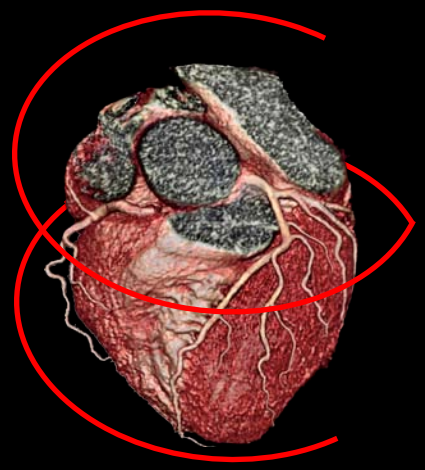
SFOV

z-direction

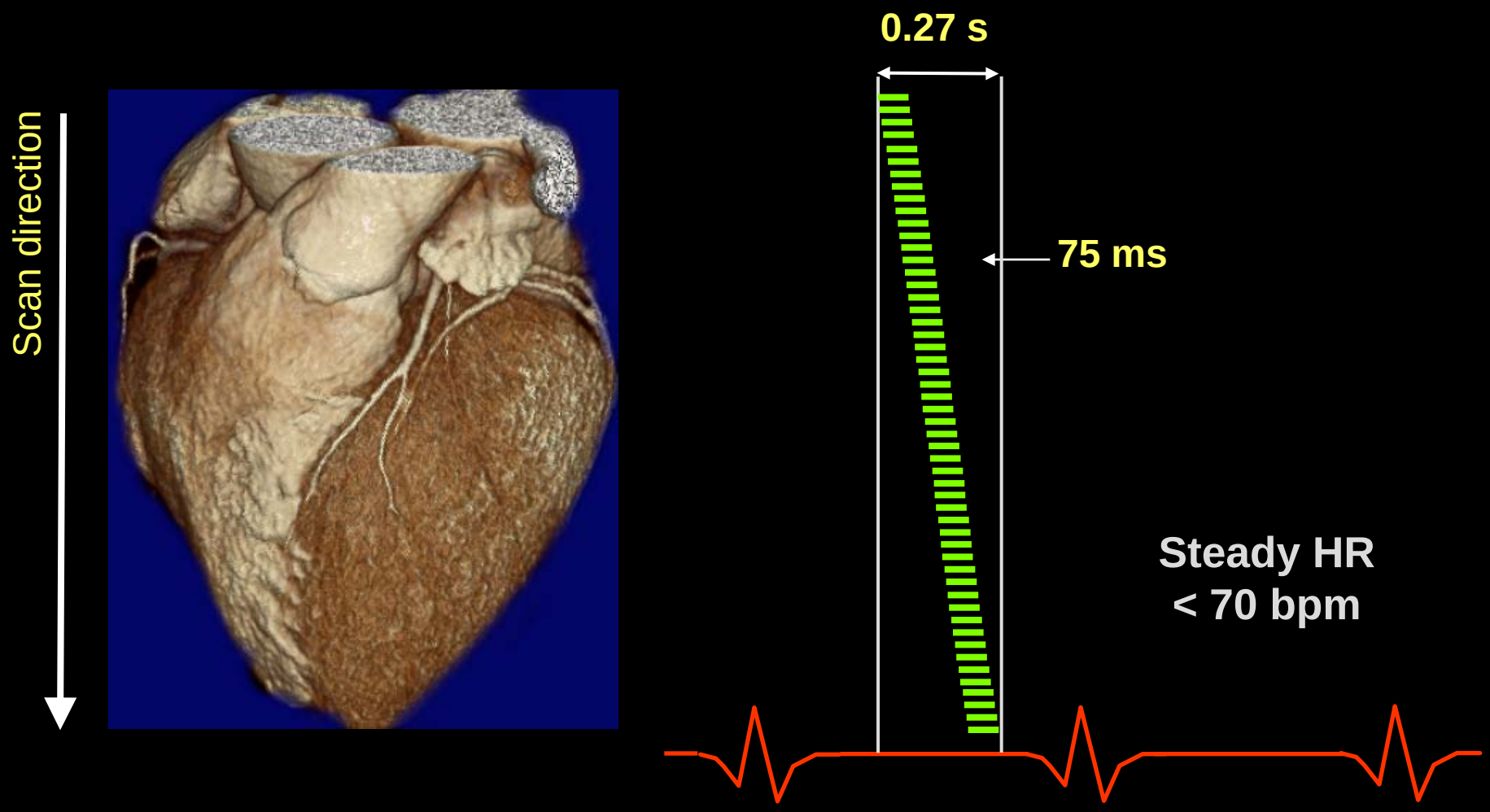


Spiral “Flash” Mode (dual-source CT only)



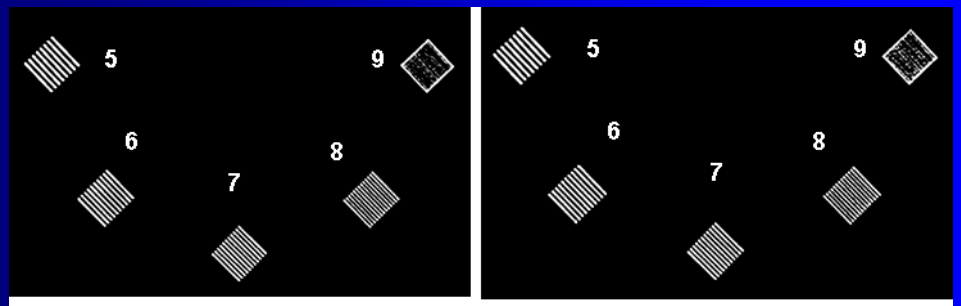


Spiral "Flash" Mode

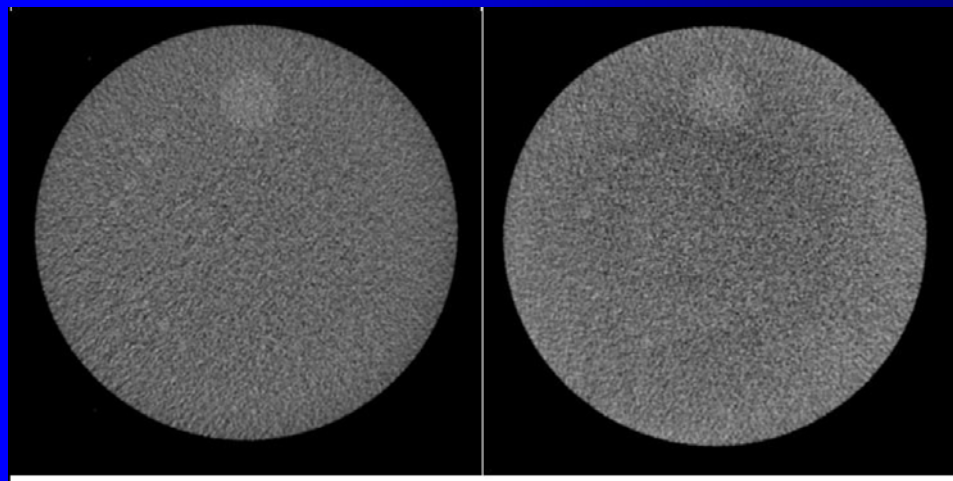


Flohr et al. "Dual-Source Spiral CT with Pitch up to 3.2 and 75 ms Temporal Resolution: Image Reconstruction and Assessment of Image Quality" Medical Physics, 36 (2009).

Image quality evaluation



SS Pitch 1.0 DS pitch 3.2



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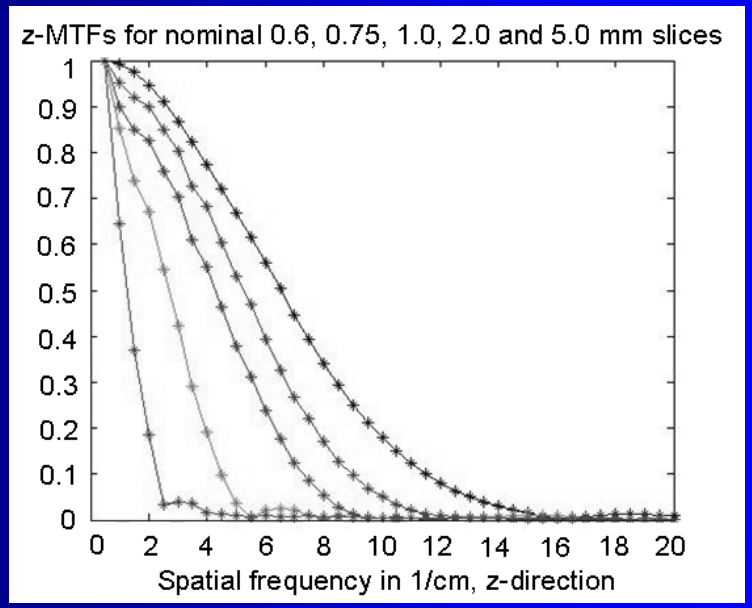
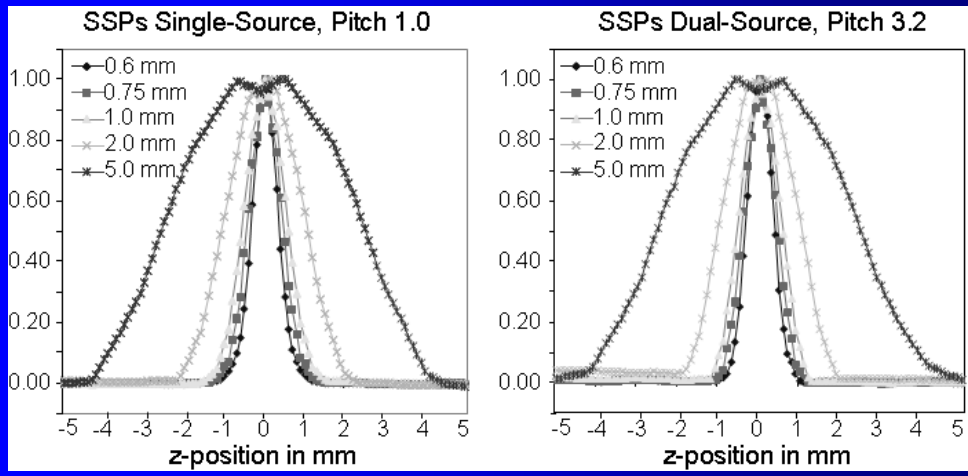
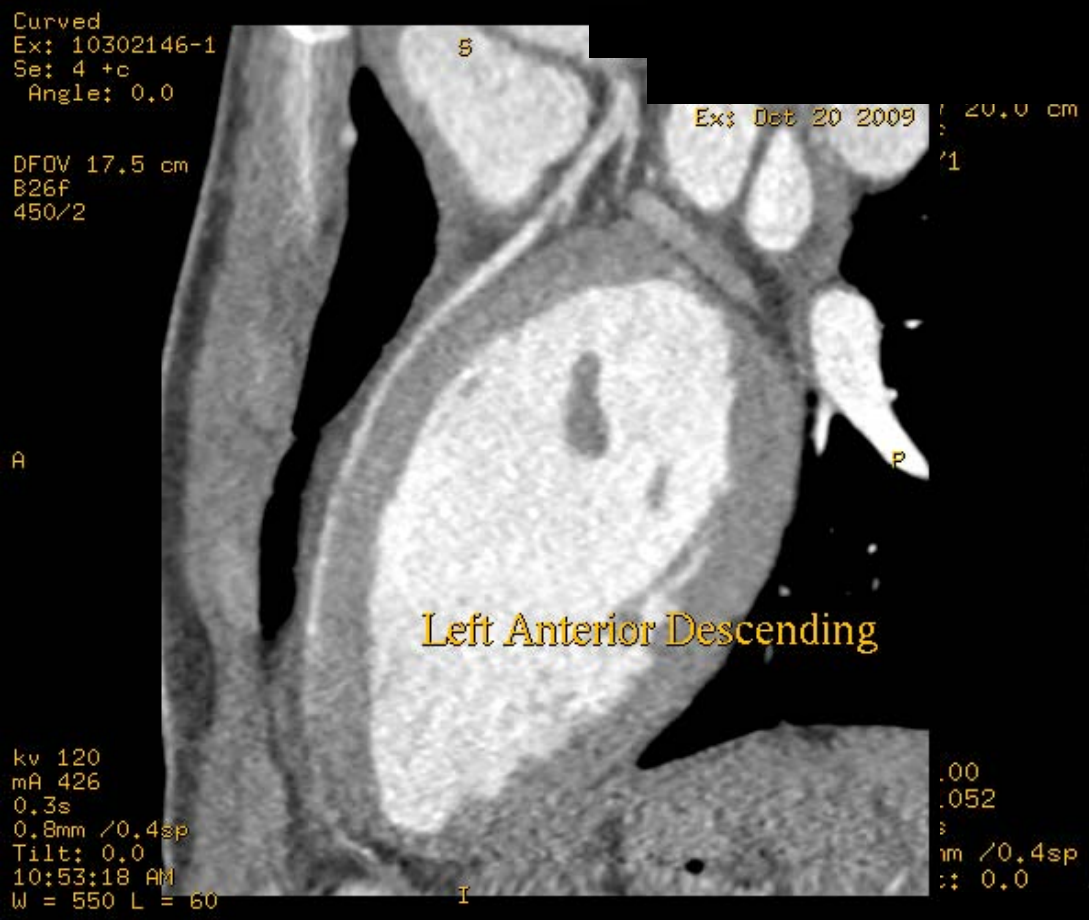




T. G. Flohr, S. Leng, L. Yu, T. Allmendinger, H. Bruder, M. Petersilka, C. D. Eusemann, K. Stierstorfer, B. Schmidt and C. H. McCollough, "Dual-source spiral CT with pitch up to 3.2 and 75 ms temporal resolution: Image reconstruction and assessment of image quality," Medical Physics. 36, 5641-5653 (2009).

Retrospectively gated spiral



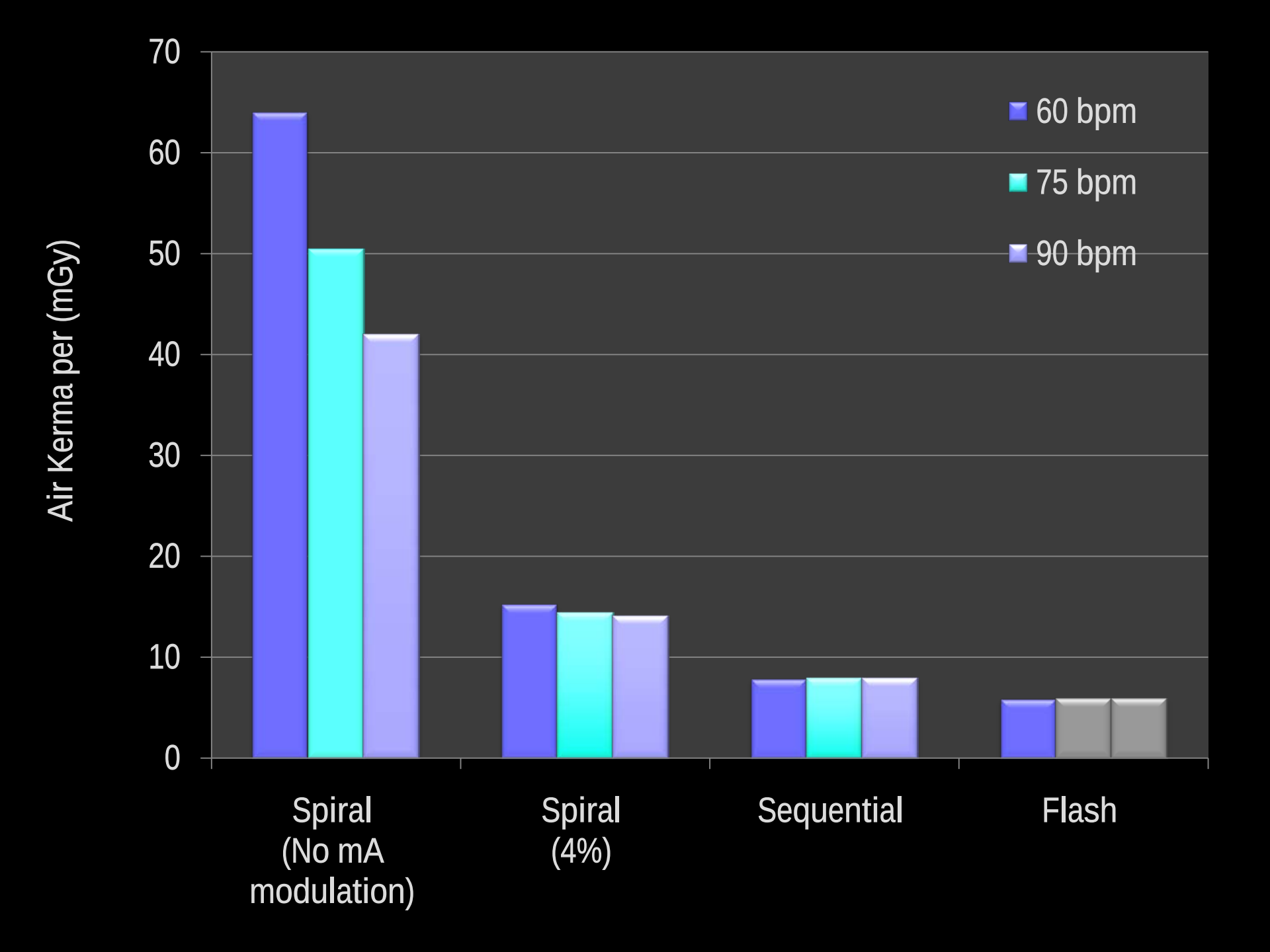
120 kV, 240 mAs/rot
pulsing 60-70%, 20% strength, ~60 bpm, pitch 0.23

CTDIvol 30.5 mGy, DLP 560 mGy-cm
Effective dose 7.8 mSv

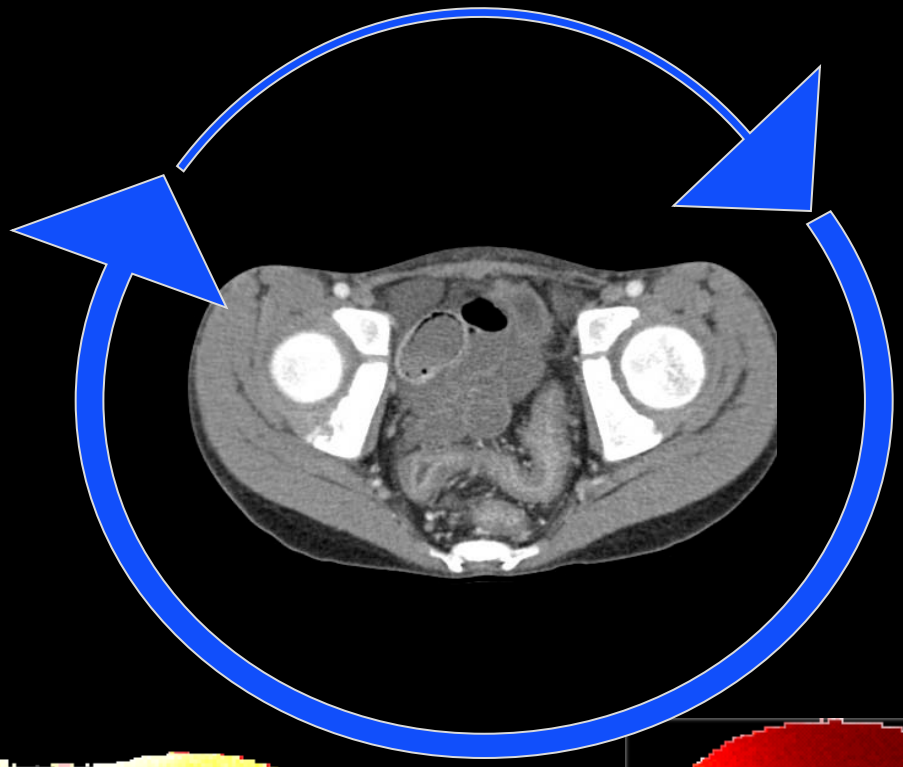
High Pitch Spiral

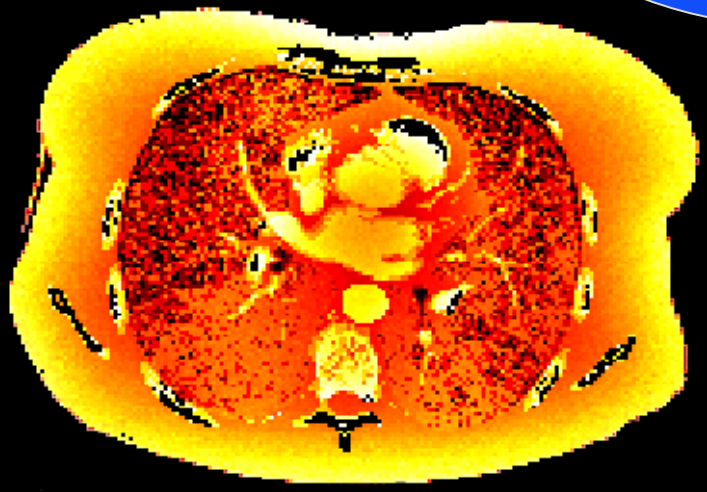
100 kV, 300 mAs/rot
~60 bpm, pitch 3.4

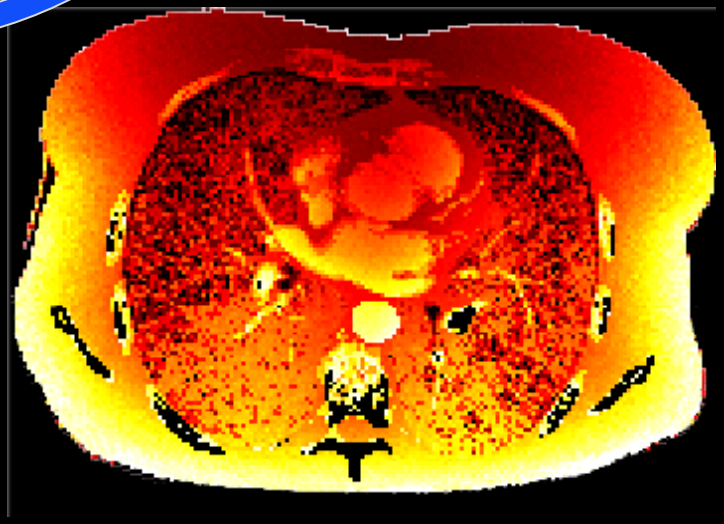
CTDIvol 2.9 mGy, DLP 60 mGy-cm
Effective dose 0.8 mSv

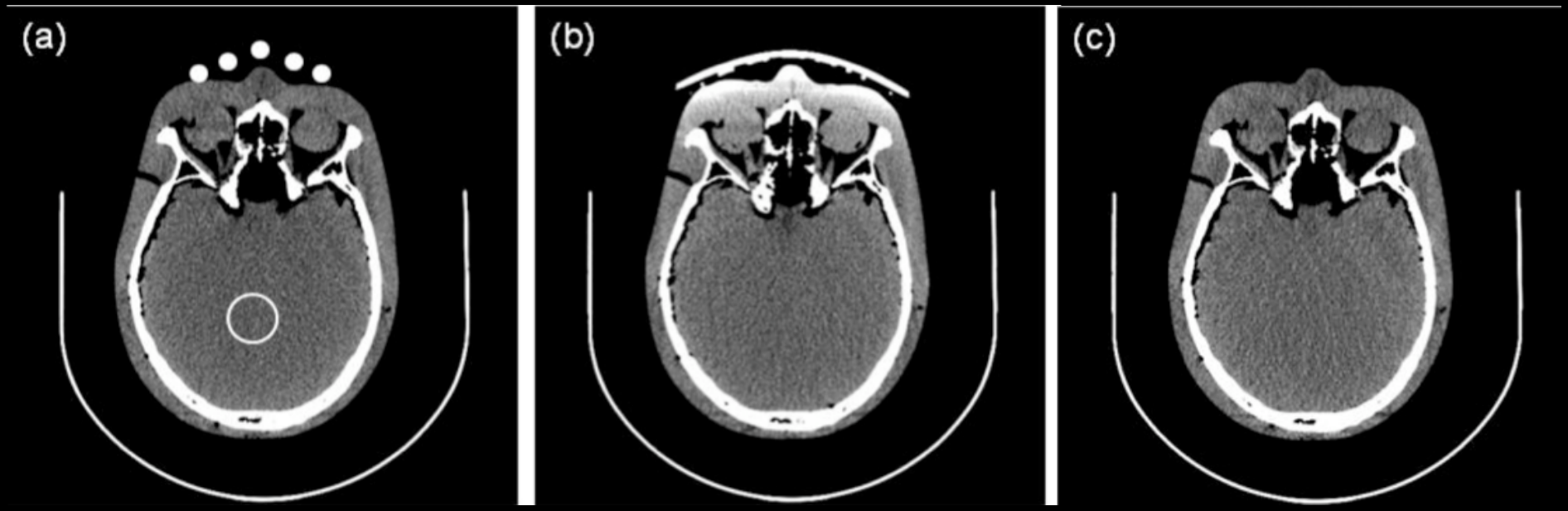

Air Kerma per (mGy)
70
60
50
40
30
20
10
0
60 bpm
75 bpm
90 bpm
Spiral (No mA modulation)
Spiral (4%)
Sequential
Flash

Organ-based tube current modulation

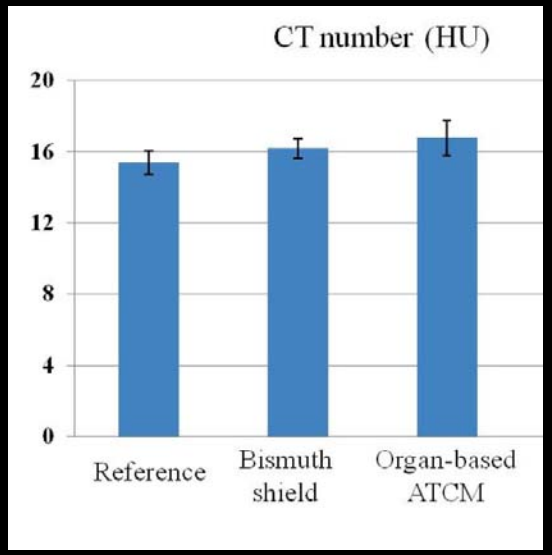


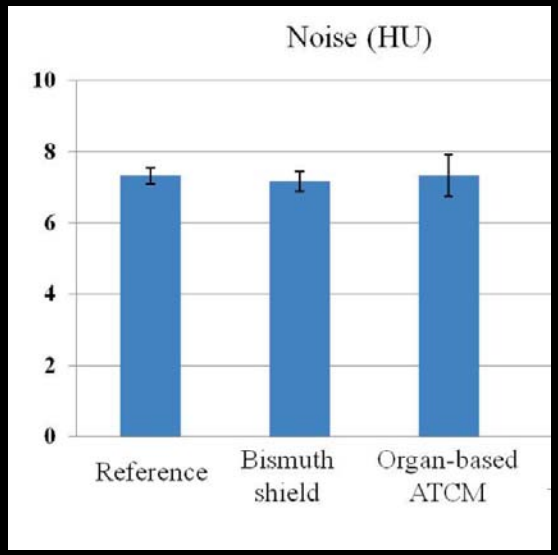






Reference **Bismuth (-41%)** **“X-Care” (-46%)**





Courtesy of Jia Wang, PhD

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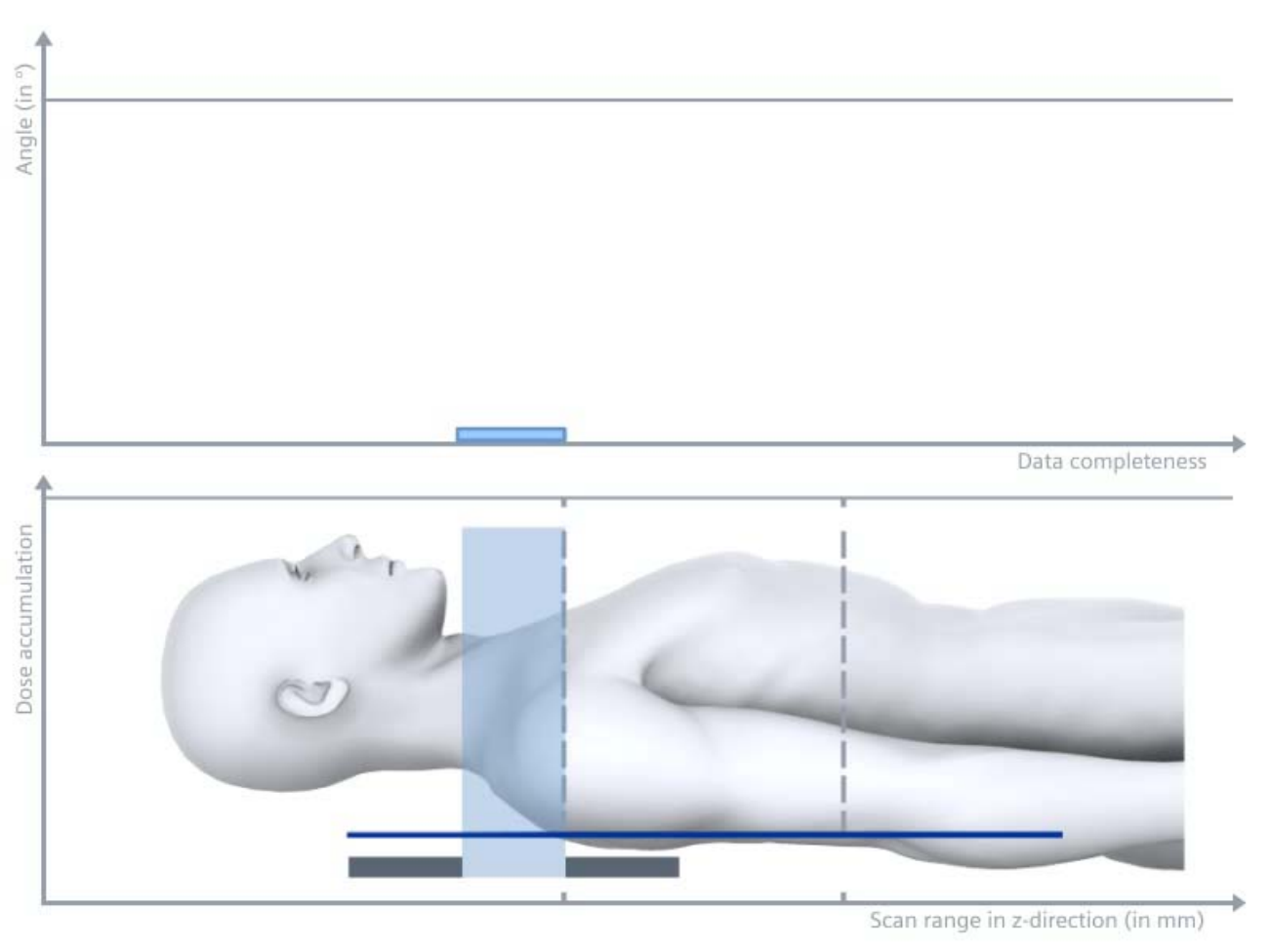
Active z-axis collimation to reduce over-scanning



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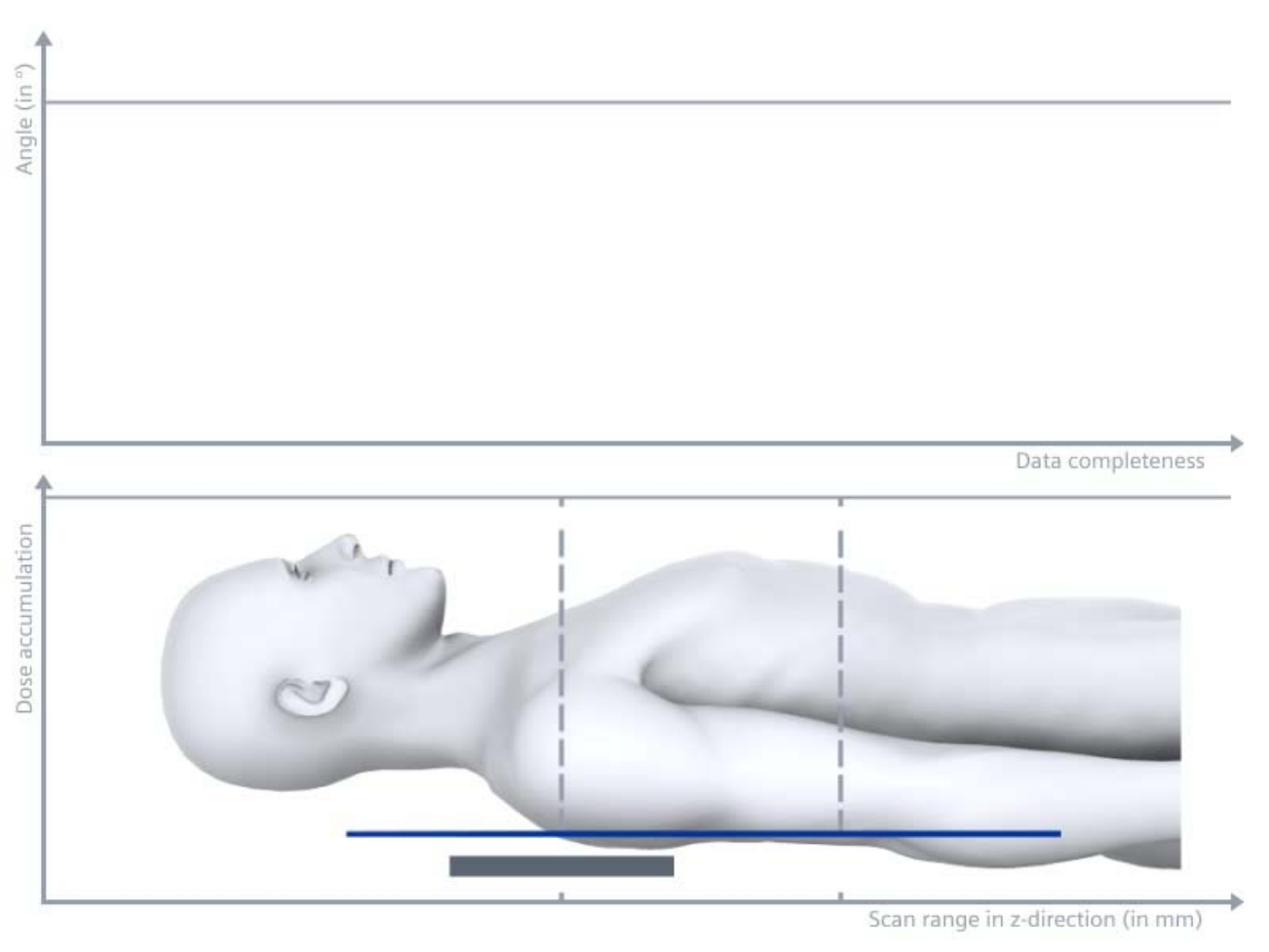
Active z-axis collimation to reduce over-scanning



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Active z-axis collimation to reduce over-scanning

0.5 – 1.5 mSv reduction in effective dose for common scan types*

*Christner et al. Dose reduction in helical CT: Dynamically adjustable z-axis beam collimation AJR Jan. 2010

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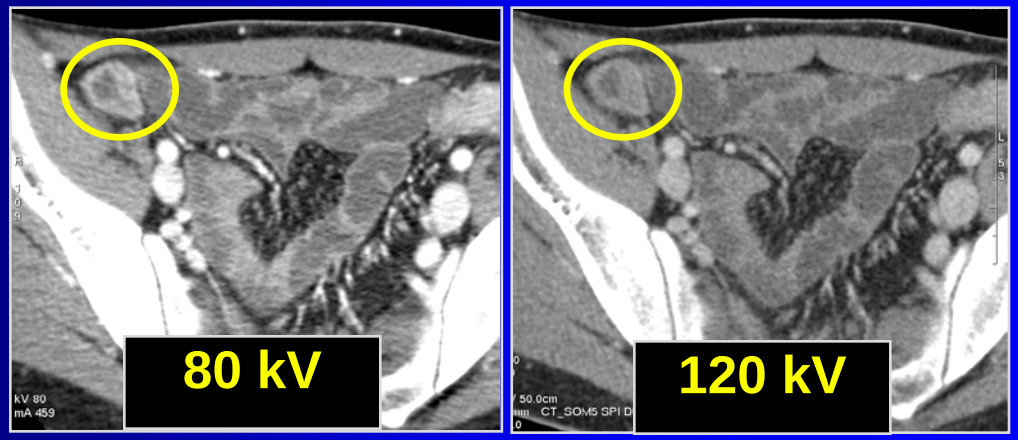
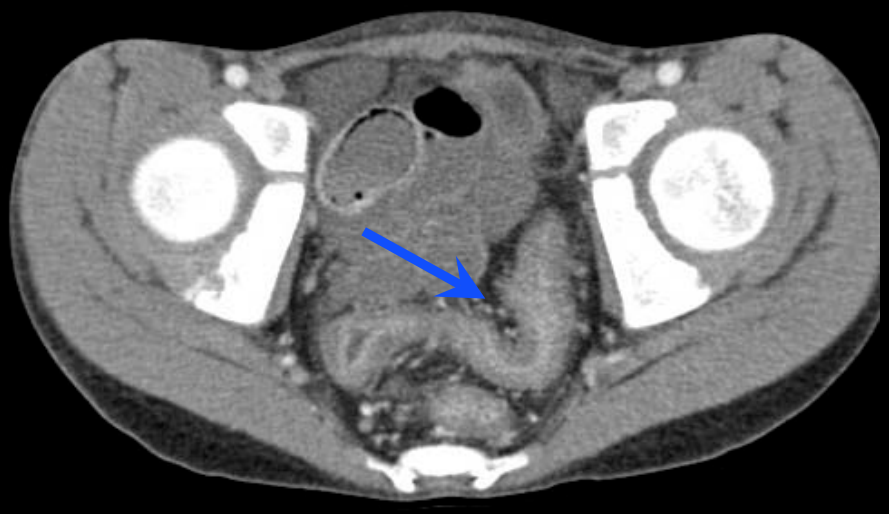
Background

- Majority of abdominal CT scans: 120 kV
- It is possible to reduce to 80-90 kV*
- Benefits of low-kV CT:
  - Radiation dose reduction**
  - Increased contrast provides increased conspicuity to enhancing lesions and structures ***

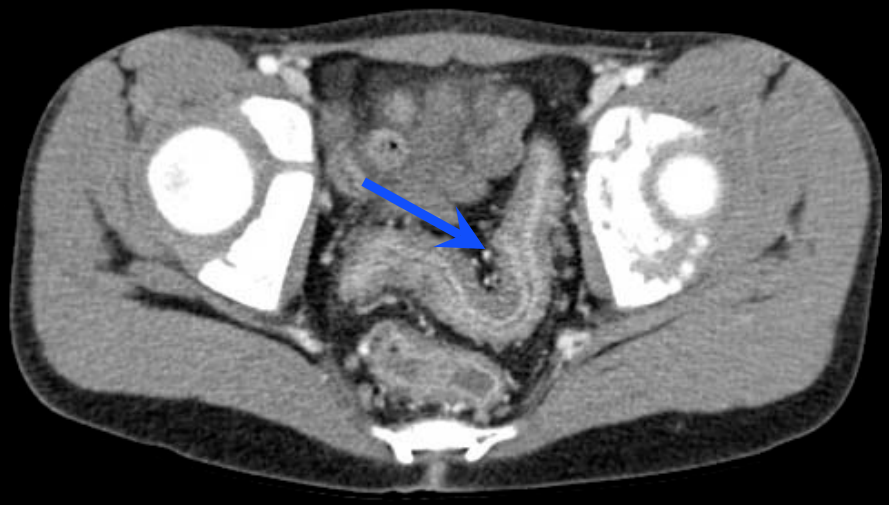


*Funama, et al., Radiology 2005
*Nakayama, et al., Radiology 2005
**Ende, et al., Invest Radiol 1999
**Huda, et al., Med Phys 2004
***Nakayama, et al. AJR 2006

Courtesy of J.G. Fletcher, MD



120 kV, $CTDI_{vol}$=5.18 mGy



100 kV, $CTDI_{vol}$=3.98 mGy

Lower-kV Benefits – Increased Iodine Contrast

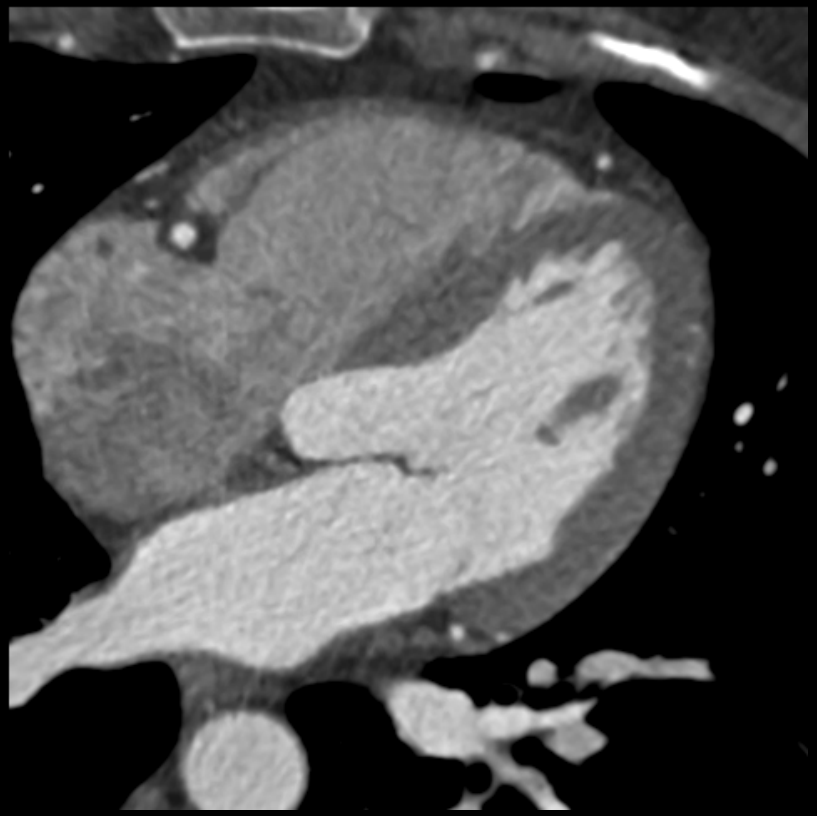
Courtesy of J.G. Fletcher, MD

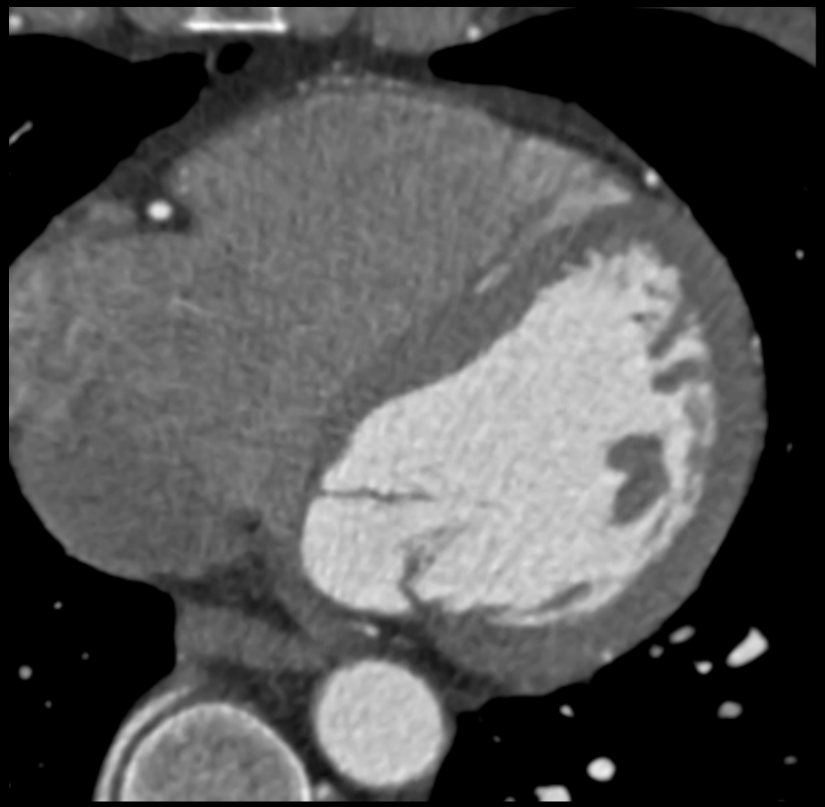
140kV **80kV**

Lower-kV Risks – Increased Noise or Artifacts

100 kV vs. 120 kV

100 kV, 330 mAs **(< 85 kg body weight)** **120 kV, 330 mAs**





Images courtesy of Ropers et al, Univ of Erlangen

Dose Predictor	Effect on Dose (%)	
Electrocardiographically controlled tube current modulation	–25 (–23 to –28)	<.001
Tube voltage, 100 kV vs ≥120 kV	–46 (–42 to –51)	<.001
Sequential vs spiral scanning	–78 (–77 to –79)	<.001

Hausleiter et al. “Estimated Radiation Dose Associated with Cardiac CT Angiography,” JAMA 2009

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The appropriateness of using lower-kV is highly dependent on *patient size* and *diagnostic task*

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General Strategy for Automatic kV selection

- Incorporate both the patient size and diagnostic task into kV selection process
- Iodine CNR is a not a sufficient image quality index
- Must also constrain image noise

$$\mathbf{CNR} \geq \mathbf{CNR_{ref}}, \quad \mathbf{and} \quad \boldsymbol{\sigma} \leq \boldsymbol{\alpha} \bullet \boldsymbol{\sigma_{ref}}$$

- Relative dose factor (RD)
  - Determine relative dose at each tube potential needed to achieve the same CNR as at the reference kV
  - A function of patient size, diagnostic task, and noise constraint α

L. Yu, H. Li, J. Fletcher, C. McCollough, Medical Physics, 37(1), 2010.

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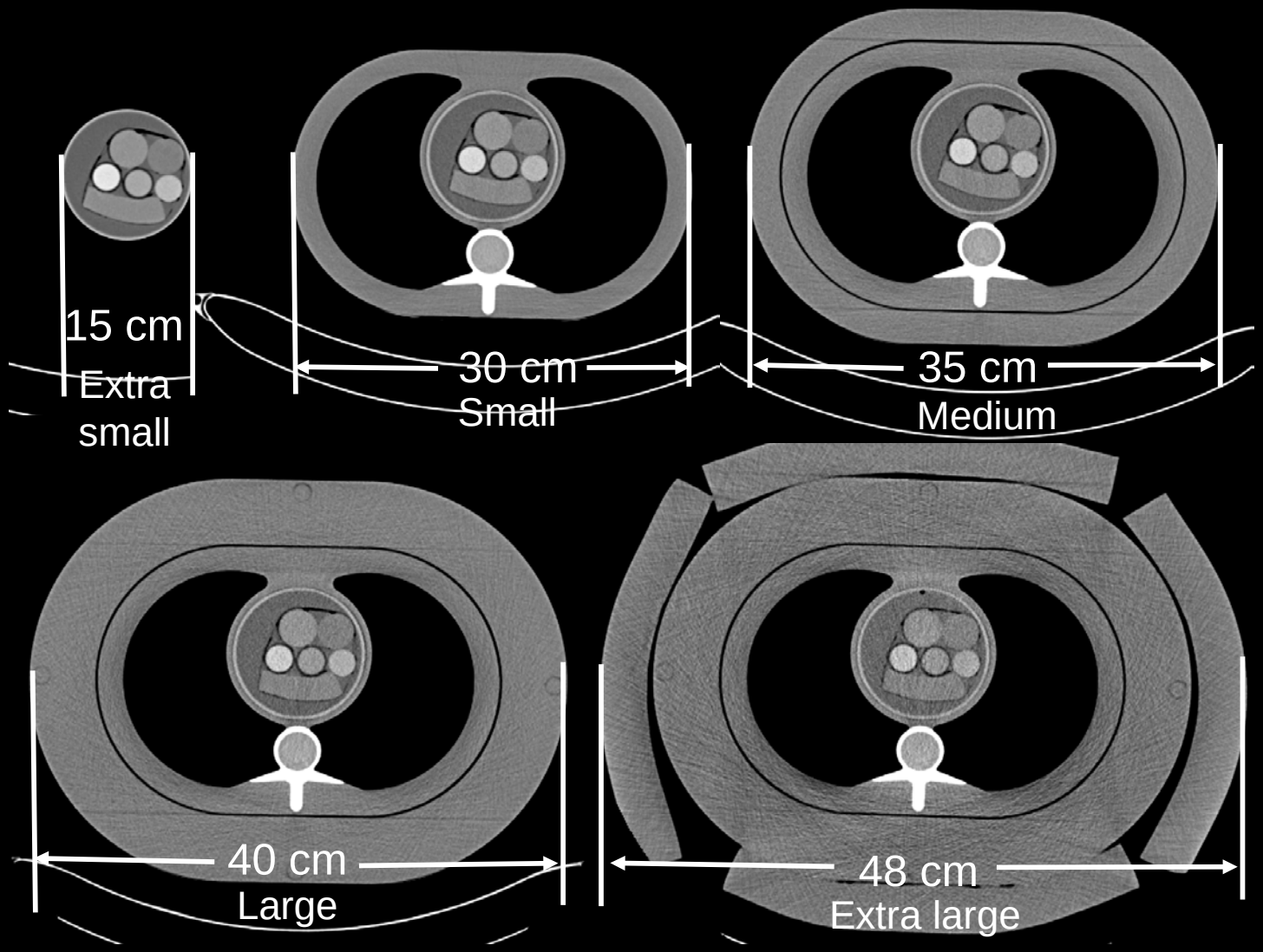
Workflow for Automatic kV Selection

- Acquire a CT radiograph (e.g., topogram, scout)
- Select a scanning technique (mAs, pitch) at a reference kV
- Select the noise constraint parameter
  - CT angiogram: minimal noise constraint (α = 1.5-2.0)
  - Routine contrast enhanced chest: moderate noise constraint (α = 1.1-1.25)
  - Routine non-contrast enhanced chest: maximum noise constraint (α = 1.0)
- Calculate the relative dose (RD)
- Choose the most dose-efficient kV (*with the smallest RD*), and adjust the mAs, rotation time, and/or pitch

Courtesy of Lifeng Yu, PhD



A semi-anthropomorphic thoracic phantom and three additional layers of attenuation were used to represent XS to XL adults

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patient lateral width

RD at each kV

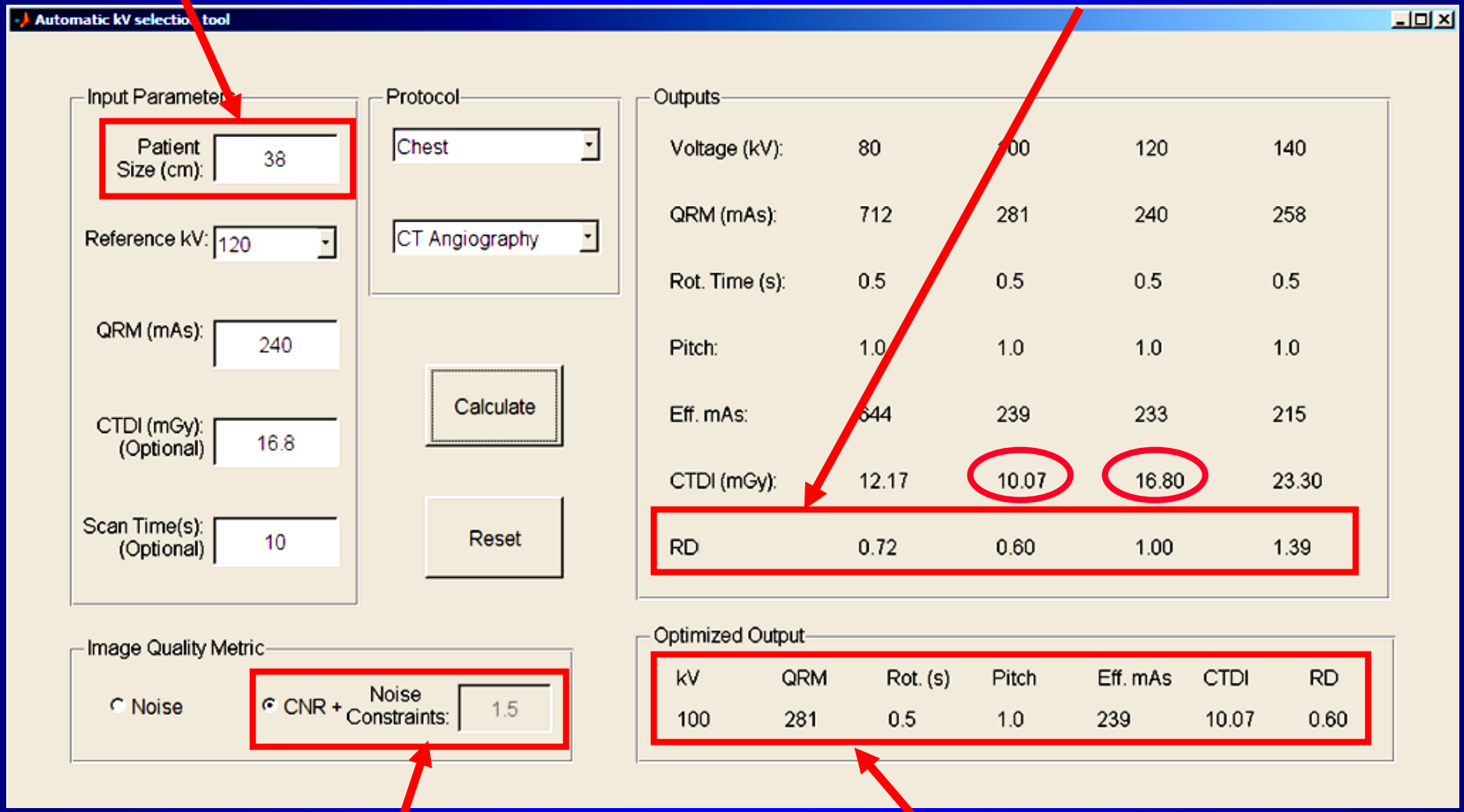

Image quality index

Final output

Courtesy of Hua Li, PhD

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Optimal kV Settings

Optimal kV based on RD for different phantom sizes with different noise constraints

Noise Constraint α	Extra Small	Small	Medium	Large	Extra Large
1.00	80	100	100	120	120
1.25	80	100	100	100	100
1.50	80	80	80	100	100
2.00	80	80	80	100	100

α = 1.0: Routine non-contrast exams

α = 1.25: Routine contrast-enhanced exams

α = 1.5: CTA with minimal noise constraint

α = 2.0: CT exams no noise constraint

Courtesy of Hua Li, PhD

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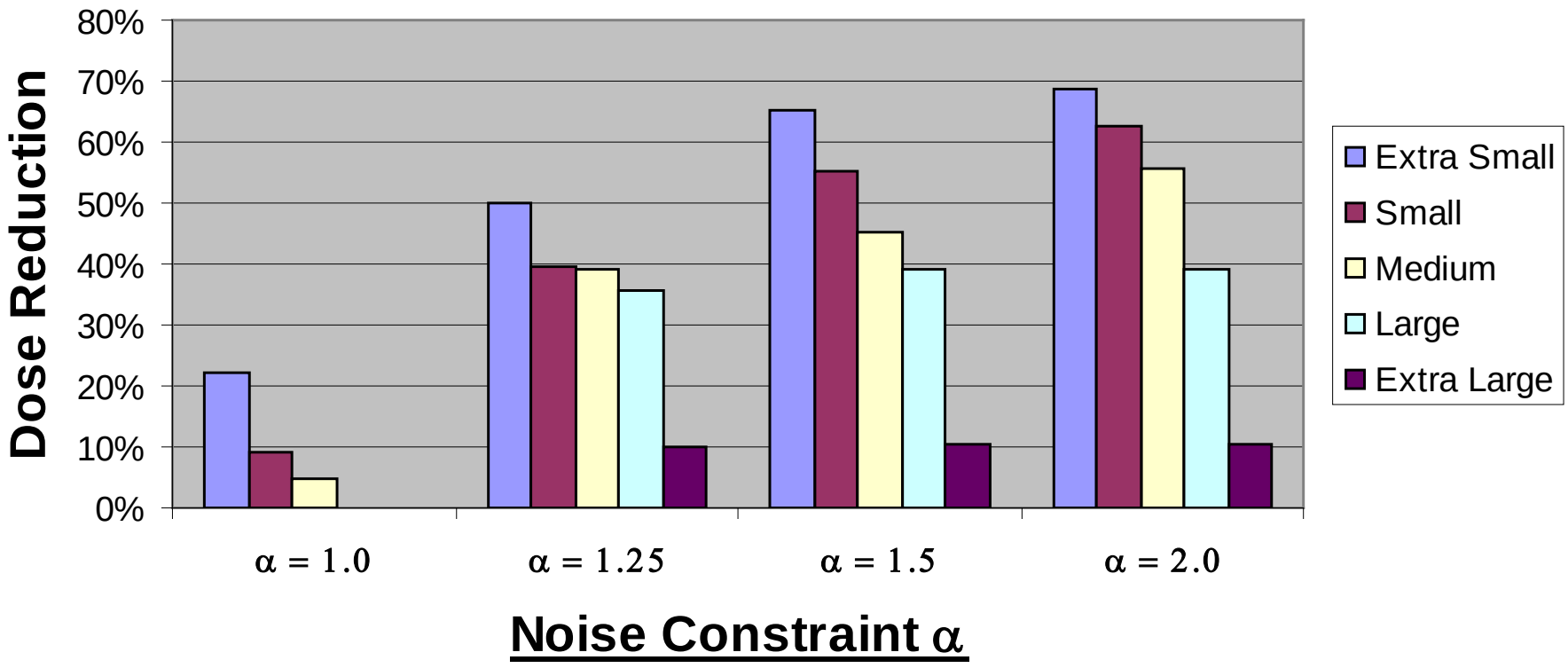
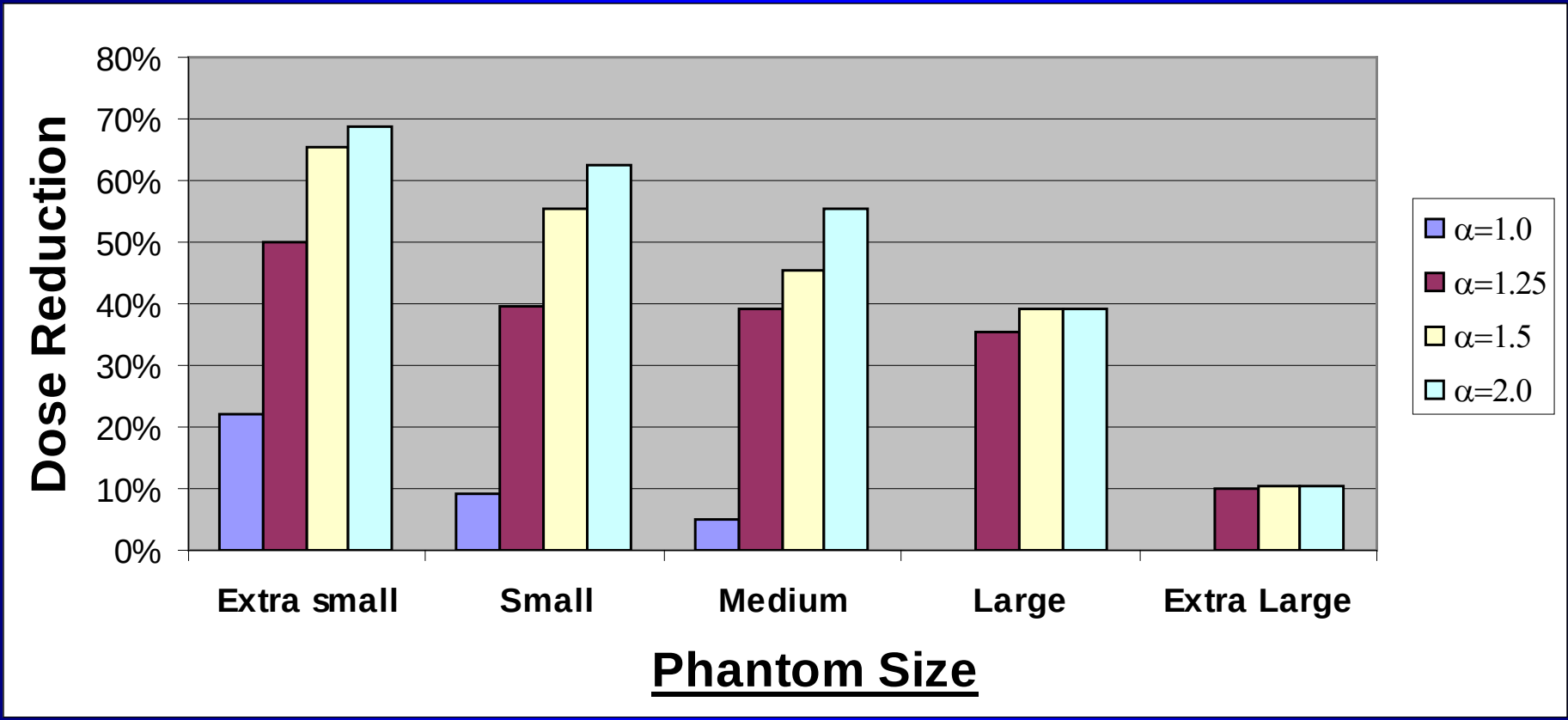
Dose Reduction vs Noise Level



Courtesy of Hua Li, PhD

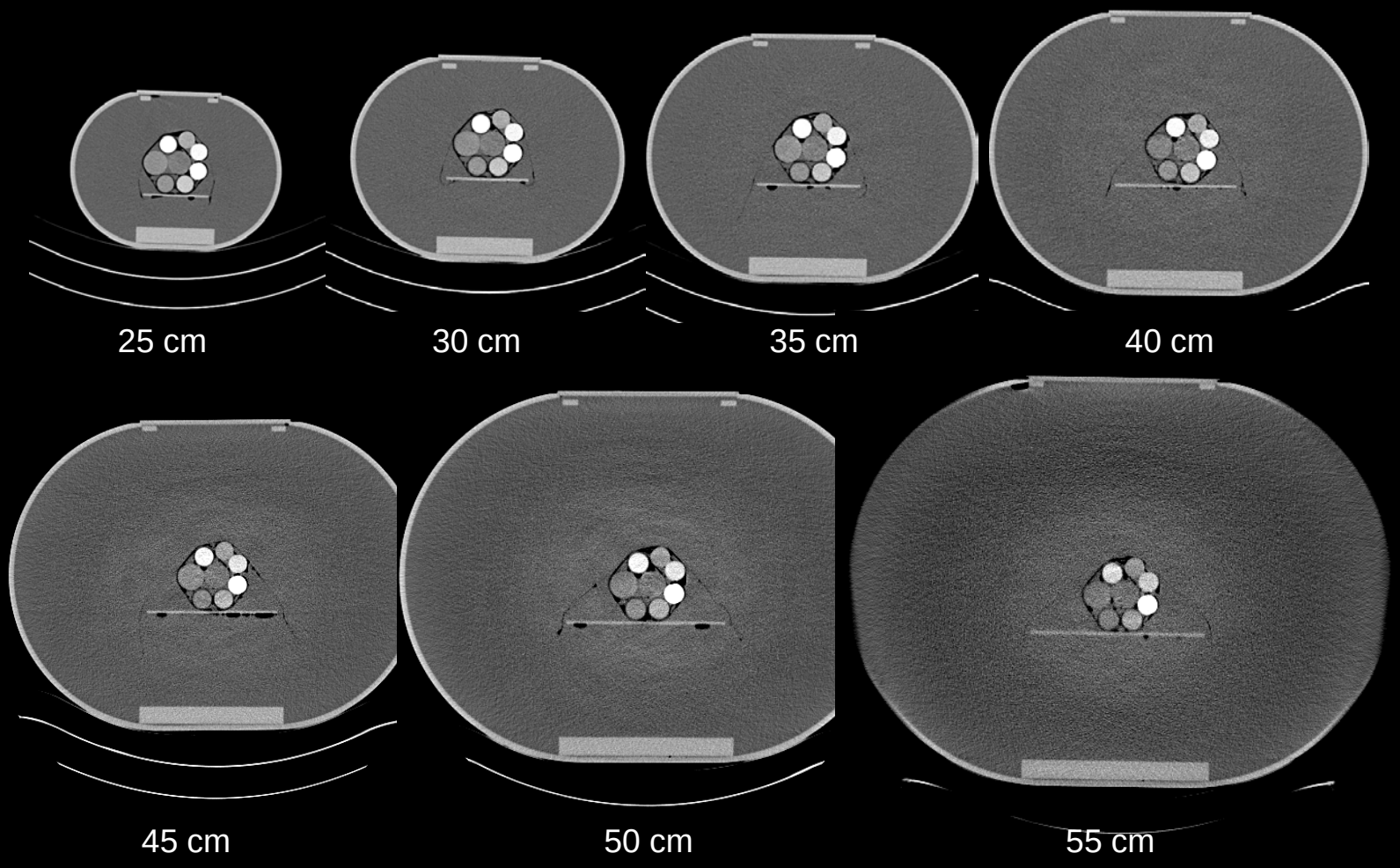
MAYO CLINIC

Dose Reduction vs Phantom Size



Courtesy of Hua Li, PhD

Abdominal Phantoms



Courtesy of Lifeng Yu, PhD

Optimal kV – Abdominal CT

Optimal kV based on RDF for different phantom sizes with different noise constraint parameters

Noise Constraint α	25 cm	30 cm	35 cm	40 cm	45 cm	50 cm	55 cm
1.00	120	120	120	120	120	120	140
1.25	100	100	100	100	120	120	140
1.50	80	80	100	100	100	120	140
2.00	80	80	80	100	100	120	140

- α = 1.0: Routine non-contrast exams
- α = 1.25: Routine contrast-enhanced exams
- α = 1.5: CTA with noise constraint
- α = 2.0: CTA without noise constraint

Courtesy of Lifeng Yu, PhD

Dose Reduction – Abdominal CT

Dose reduction at the optimal kV relative to 120 kV for different phantom sizes with different noise constraint parameters

Noise Constraint α	25 cm	30 cm	35 cm	40 cm	45 cm	50 cm	55 cm
1.00	0	0	0	0	0	0	13%
1.25	36%	27%	25%	11%	0	0	13%
1.50	42%	34%	26%	18%	9%	0	13%
2.00	53%	49%	42%	18%	9%	0	13%

- α = 1.0: Routine non-contrast exams
- α = 1.25: Routine contrast-enhanced exams
- α = 1.5: CTA with noise constraint
- α = 2.0: CTA without noise constraint

Courtesy of Lifeng Yu, PhD

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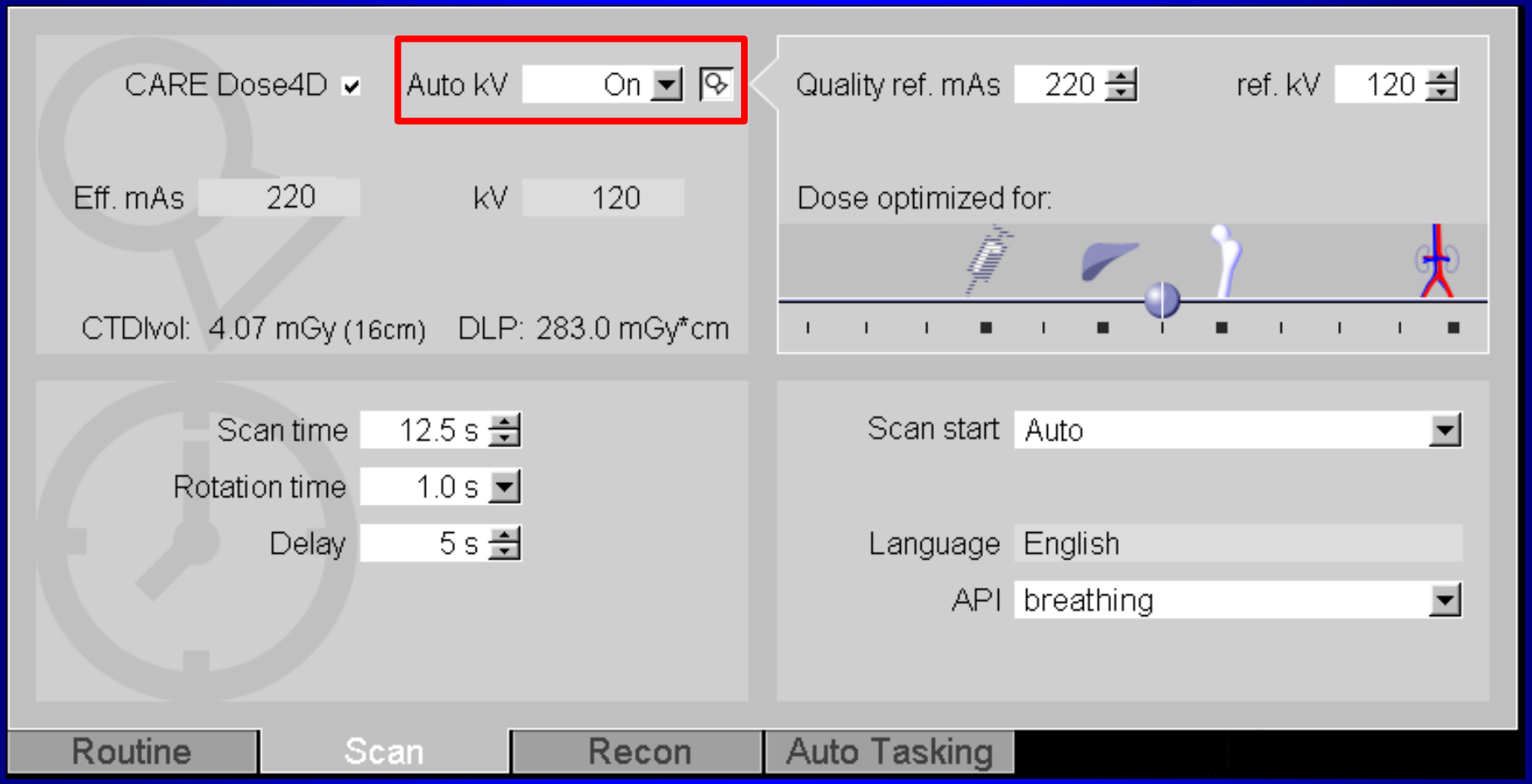

Courtesy of Bernhard Schmidt, PhD

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Projection-Based Noise Reduction Algorithms

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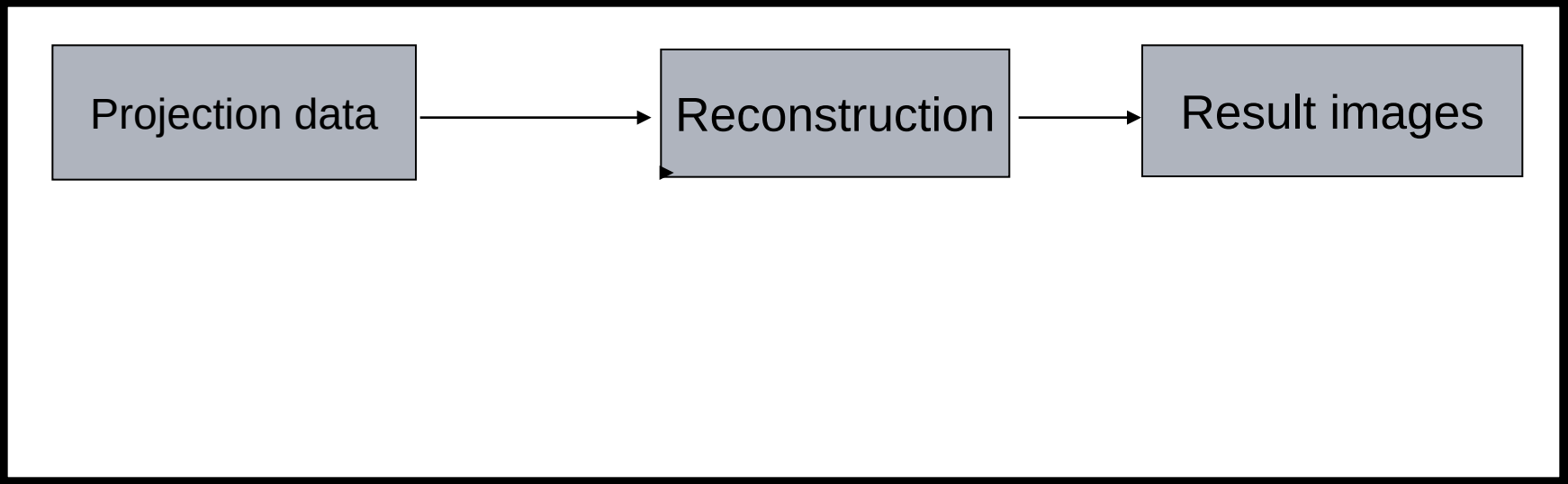
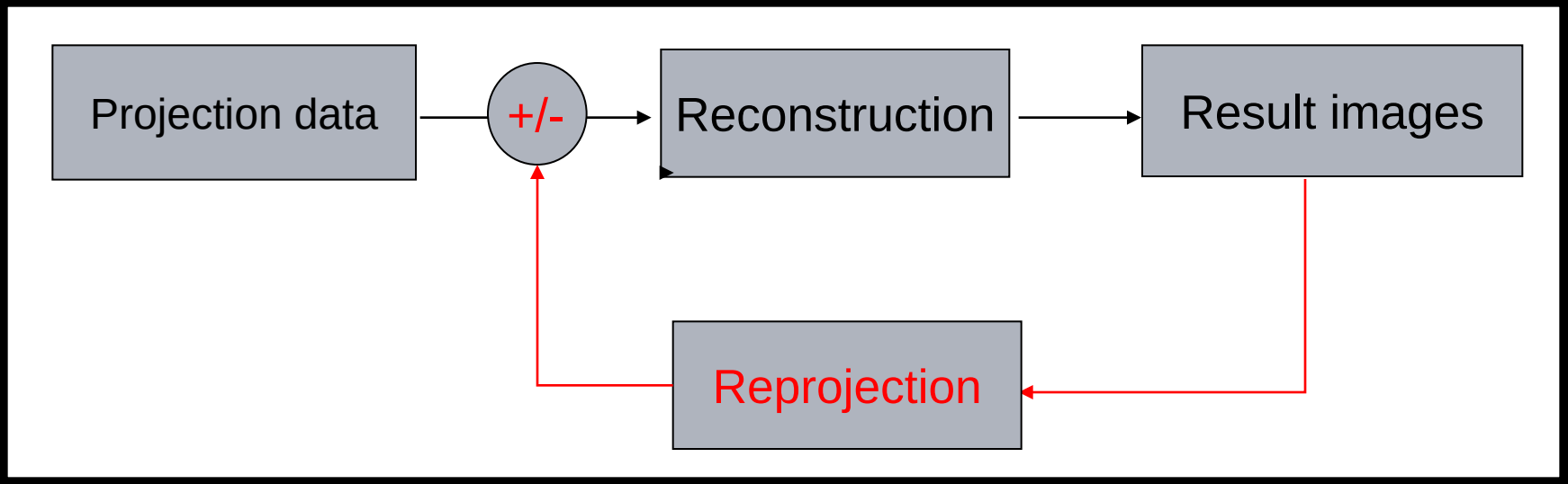
IR:
Iterative Reconstruction

Noise reduction enables dose reduction

Standard reconstruction



Iterative reconstruction



Many Different Approaches

- Algebraic reconstruction technique
  - ART
- Statistical iterative reconstruction
- Compressed sensing based methods
  - Convex and non-convex
- …

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			2		5			1
		2			9	8		
	3		8			2	4	5
	1	4	7	5		9		
	8						3	
		6			3			
	4				2		5	
		9	5			7		
8			1		6			

Like solving a big sudoku puzzle

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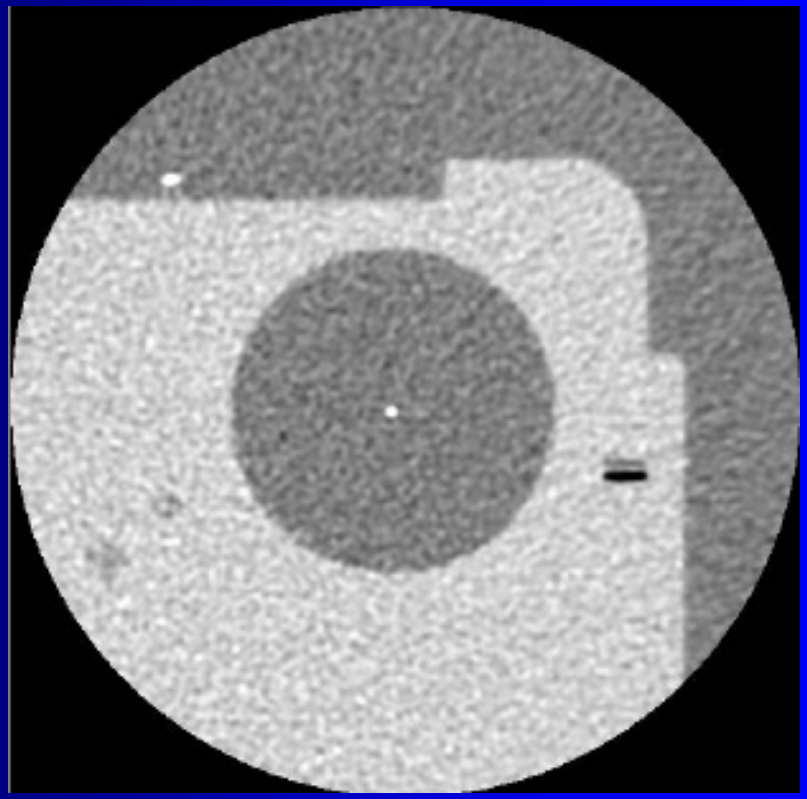
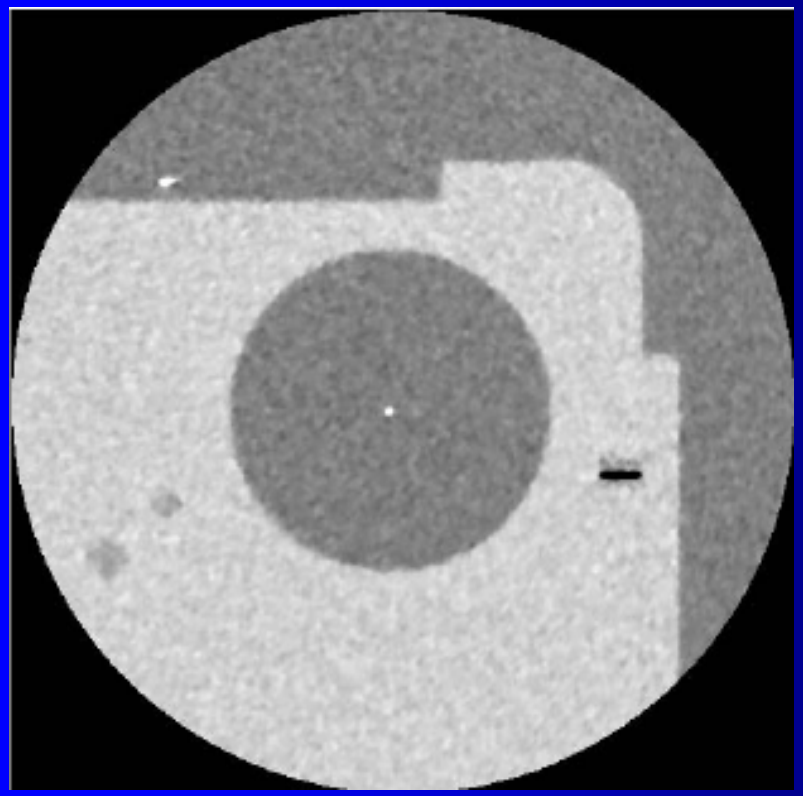
Iterative Reconstruction



Standard recon



Iterative recon

Thibault et al, Med. Phys. 2007

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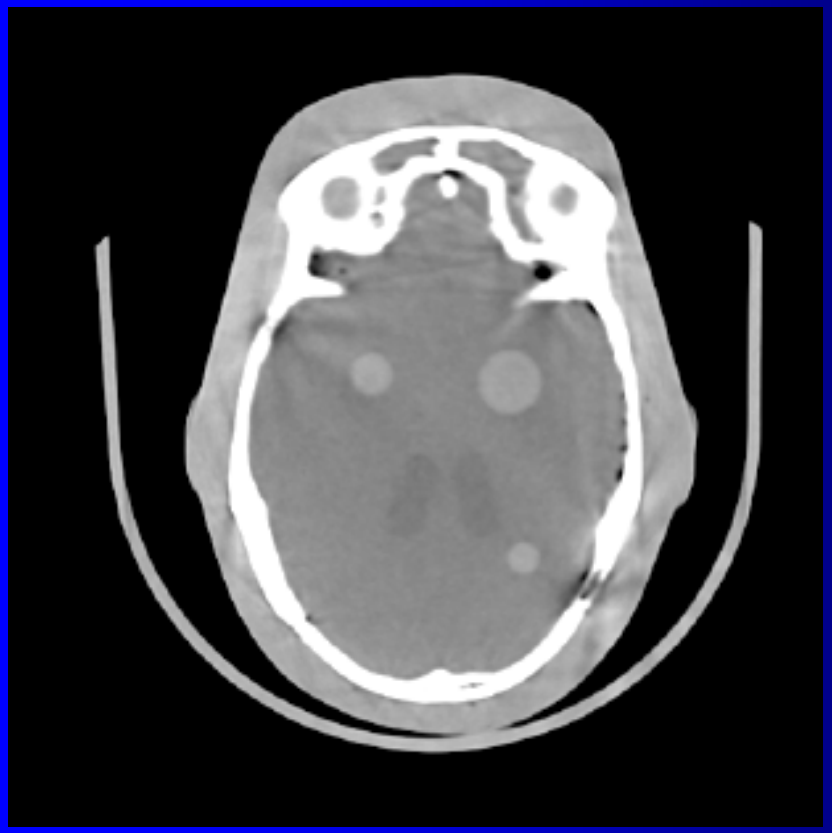
Iterative Reconstruction

Standard recon



Iterative recon

Thibault et al, Med. Phys. 2007

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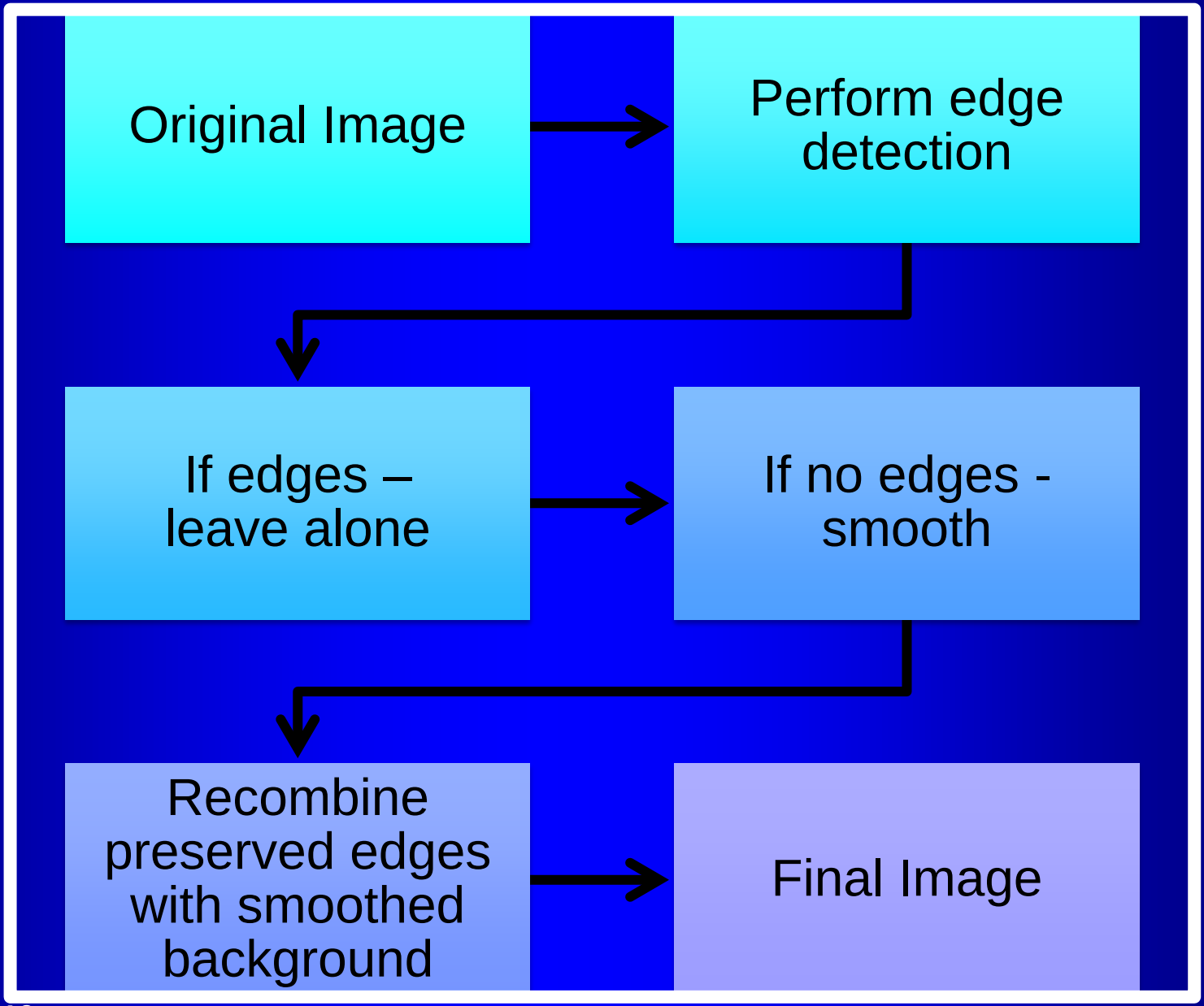
Image-Based Noise Reduction Algorithms

Adaptive Filtering (2D or 3D)



Original

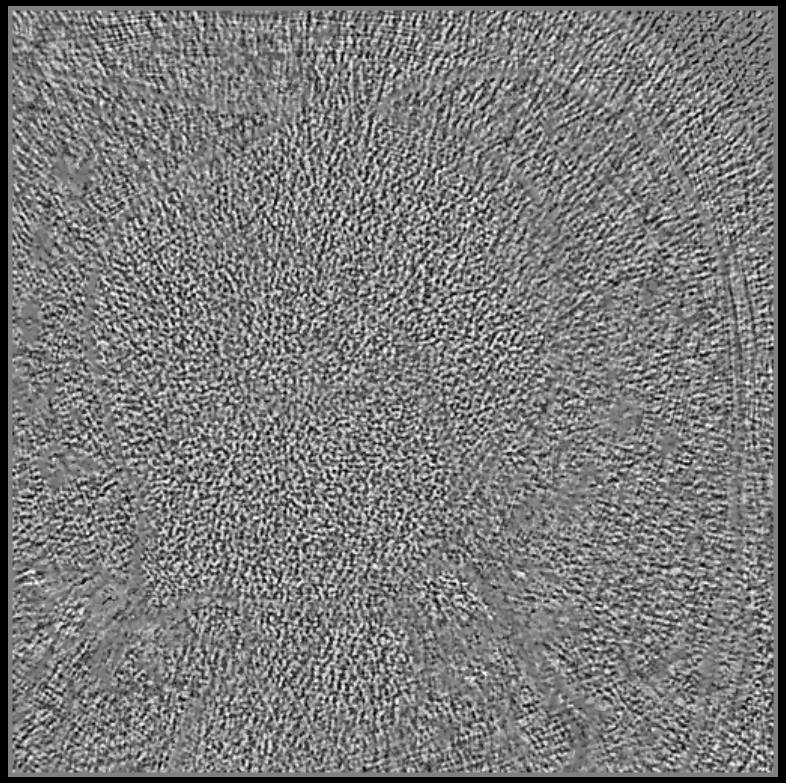
3D Edge Preserving Noise Reduction

61.5 HU → 36.3 HU

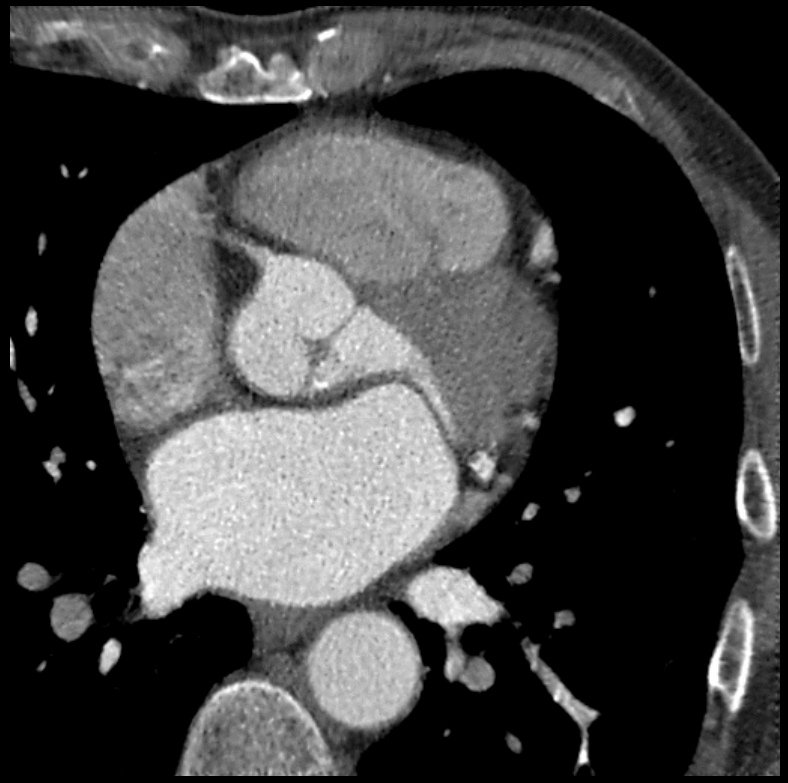
- 41%

Courtesy of R. Raupach

NR minus Original



3D Edge Preserving Noise Reduction (NR)



- **No smoothing of contours**
- **Difference essentially shows noise**

Courtesy of R. Raupach

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HYPR-LR

HighlY constrained back PRojection Local Reconstruction

Noise reduction for time-resolved CT (e.g. perfusion CT)

Mistretta CA, et al. Magnetic Resonance in Medicine 2006; 55:30-40.
Johnson KM, et al. Magnetic Resonance in Medicine 2008; 59:456-462.
Liu X, et al. Radiology, 2009; 253:98-105.

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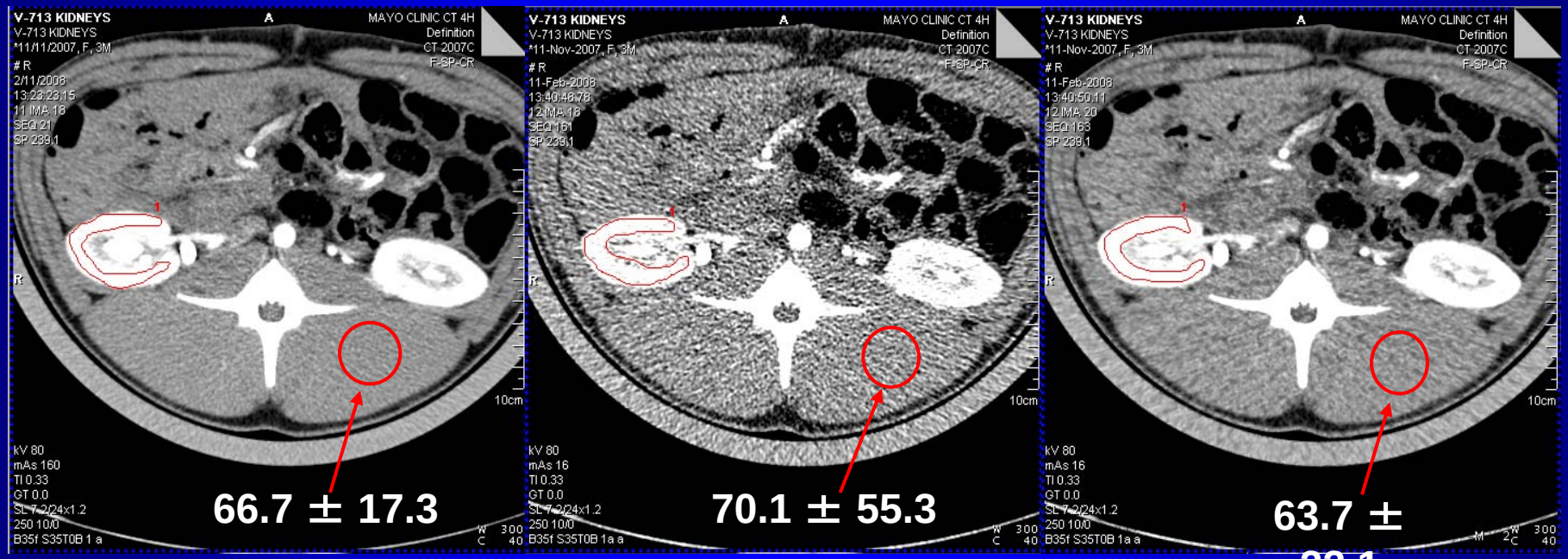
Image Quality Comparison



Full dose

SNR = 4.18

1/10th dose

SNR = 1.29

1/10th dose HYPR-LR processed

SNR = 2.96

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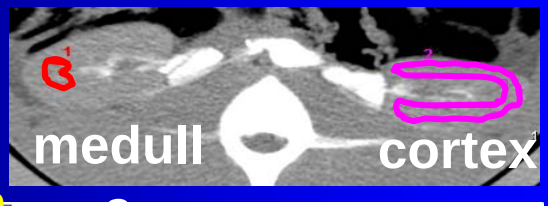
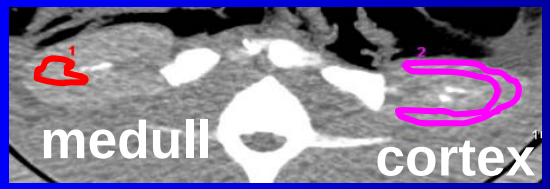
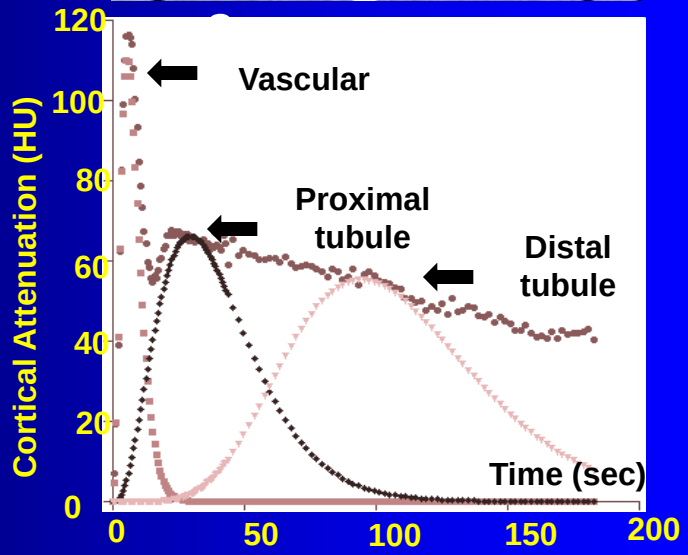
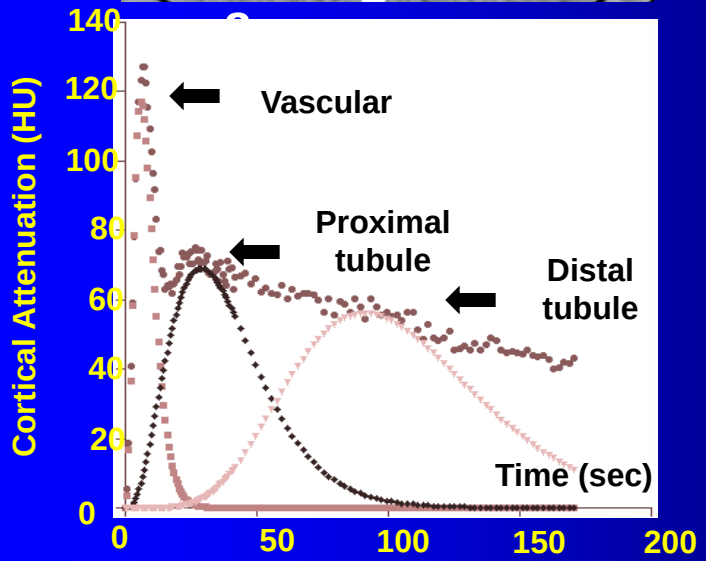
Full dose

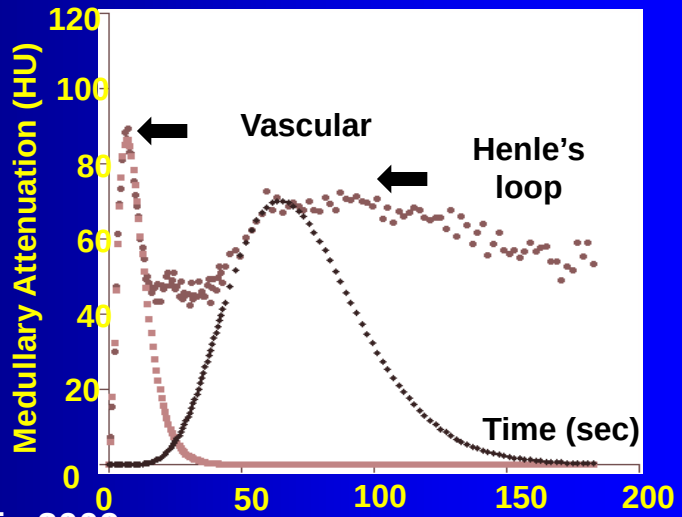
1/10th dose, HYPR-LR processed

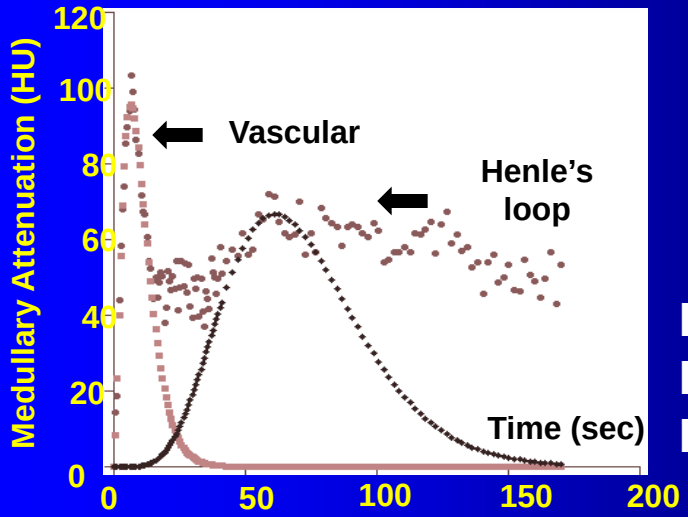












Liu et al
Radiology
In Press

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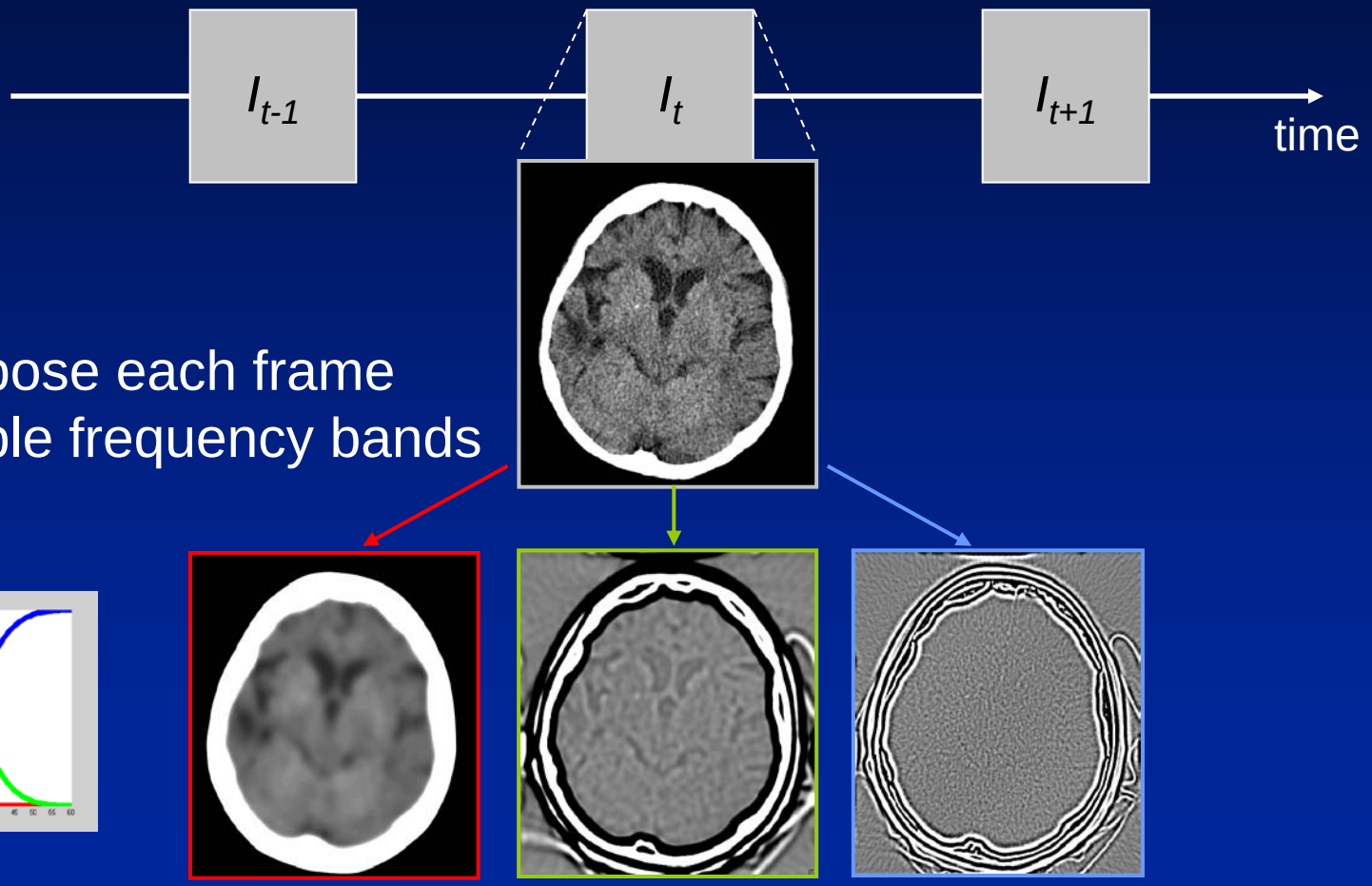
MBF:
Multiple band filtration

TSFF:
Targeted Spatial Frequency Filtration

Noise reduction for
perfusion CT
brain CT
(and more)

Multi-Band Filter (MBF): Step 1

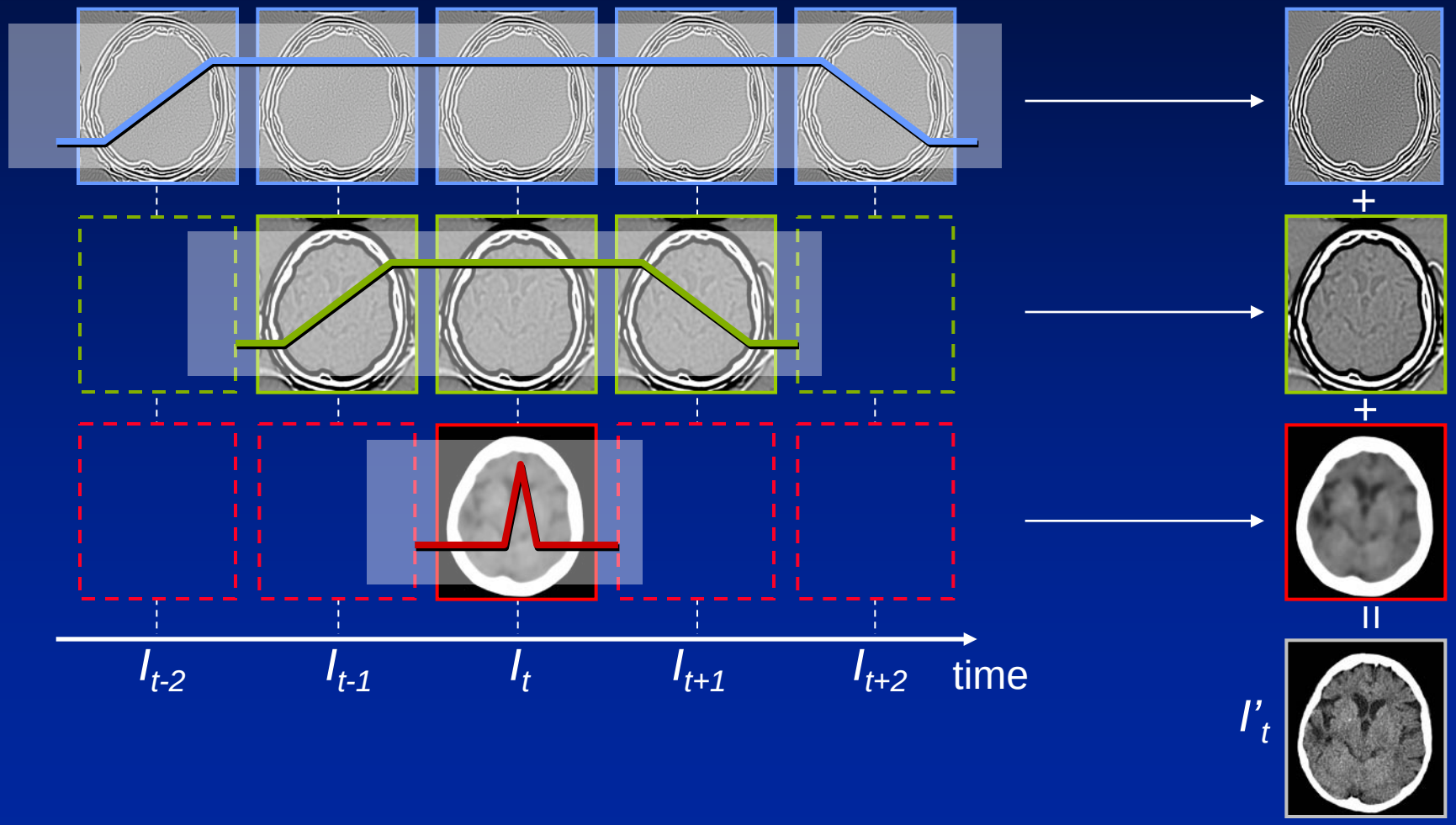
- Time series of image data



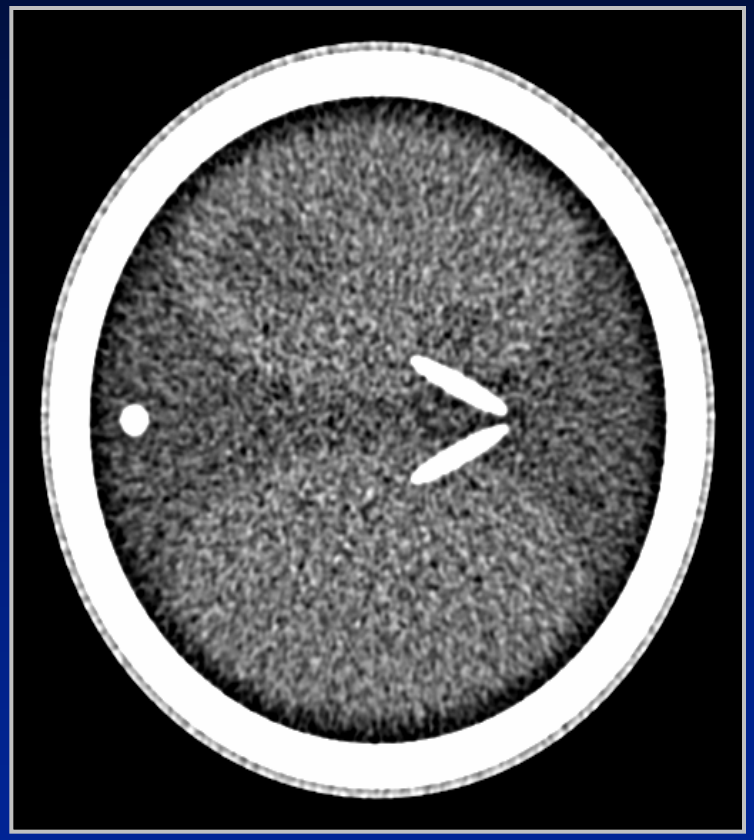
- Decompose each frame into multiple frequency bands

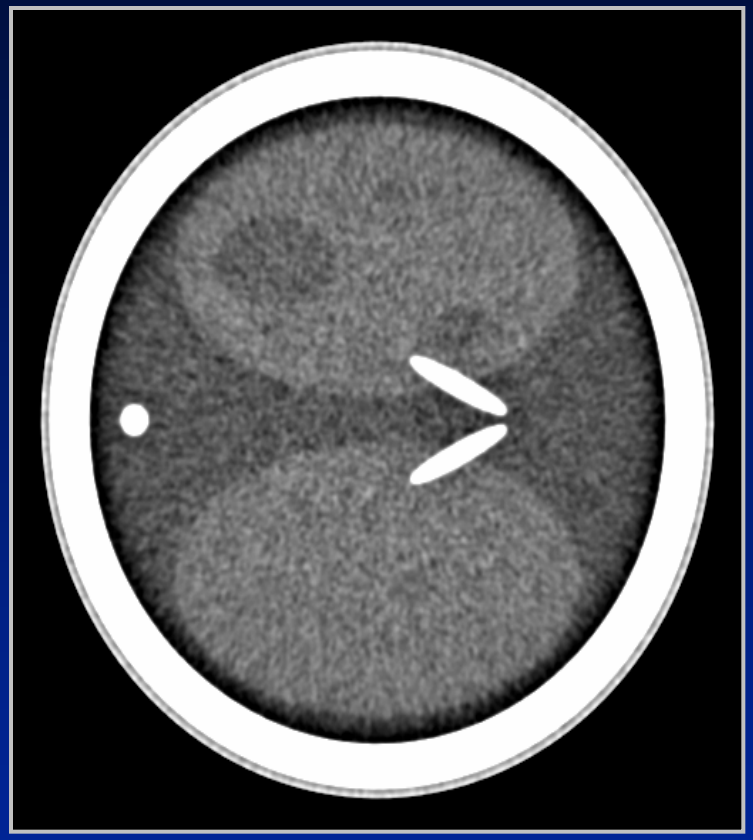
Multi-Band Filter (MBF): Step 2

- Temporal filtering



Effect of MBF





original → MBF

- noise reduction by a factor 2.5
- time-density information preserved

Measured Brain Perfusion Data

original → MBF

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Thank you

Mayo CT Clinic Innovation Center and Dept. of Radiology

Lifeng Yu, Shuai Leng, Jim Kofler

http://mayoresearch.mayo.edu/CTCIC