Adaptive Imaging: Review of techniques and update on state-of-the-art CT

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COI

TPS consultant GE Healthcare, supplies CT protocols under a licensing agreement to GE Healthcare, founder Protocolshare.org LLC, CAB and consultant to iMALOGIX, consultant Takeda Pharmaceuticals

Outline

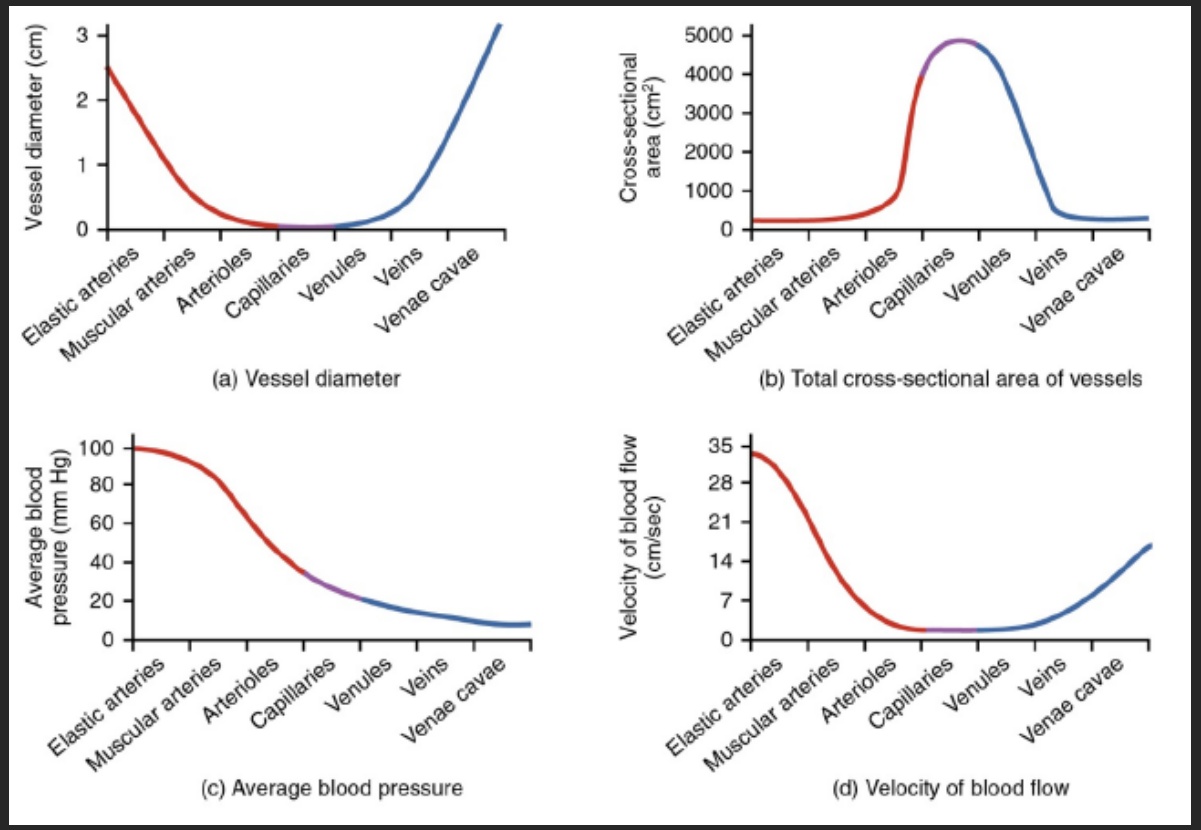
1. **Motivation for Patient Specific Imaging in CT: Cardiac**
2. **Heart Rate based Adaption**
3. **Motivation for Patient Specific Imaging in CT: Fluence modulation**
4. **Patient Specific Fluence Modulation**

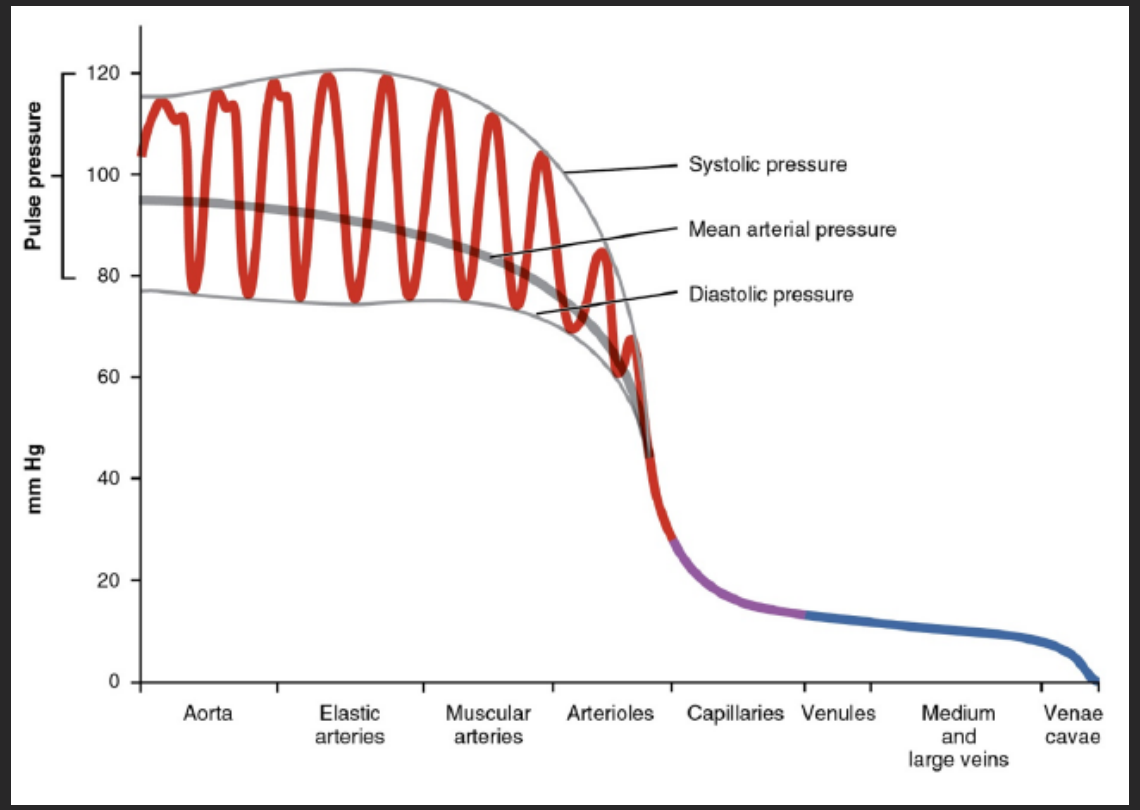
Motivation for patient specific imaging in CT

- Human body
  - It is not static
    - Blood is always moving through arteries/veins and perfusing through soft tissue
    - Heart is always moving
    - Lungs are always moving

Motivation for patient specific imaging in CT

- Human body
  - It is not static
    - Blood is always moving through arteries/veins and perfusing through soft tissue
      - Rate of blood movement is a function of cardiac output, local impedance (i.e. is there a plaque?)
      - Opacification level is a function of blood pool volume





Anatomy and Physiology 2016 Rice University

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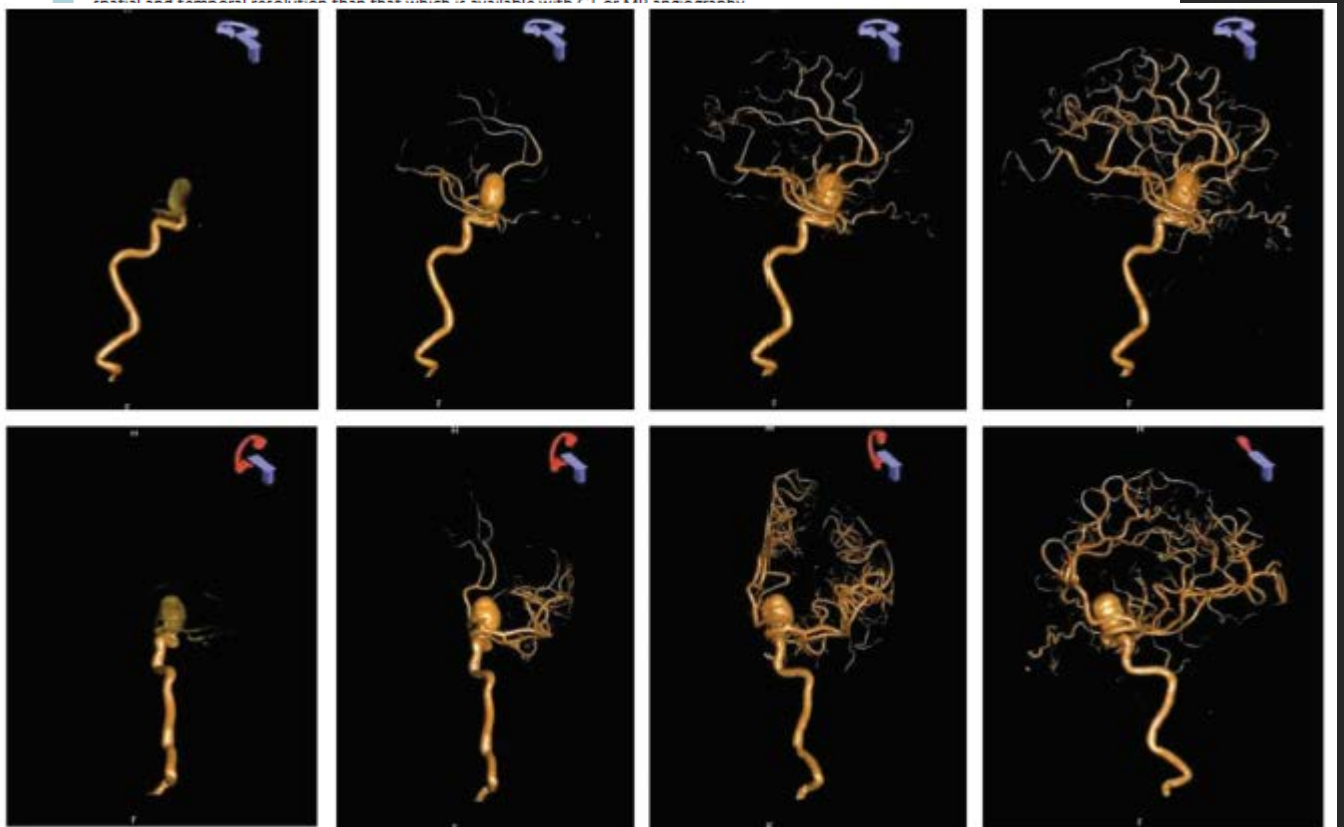
ORIGINAL RESEARCH
BRAIN

4D Digital Subtraction Angiography: Implementation and Demonstration of Feasibility

B. Davis, K. Royalty, M. Kowarschik, C. Rohkohl, E. Oberstar, B. Aagaard-Kienitz, D. Niemann, O. Ozkan, C. Strother, and C. Mistretta

ABSTRACT

BACKGROUND AND PURPOSE: Conventional 3D-DSA volumes are reconstructed from a series of projections containing temporal information. It was our purpose to develop a technique which would generate fully time-resolved 3D-DSA vascular volumes having better



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Deconvolution-Based CT and MR Brain Perfusion Measurement: Theoretical Model Revisited and Practical Implementation Details

Andreas Fieselmann, [1, 2, 3, *] Markus Kowarschik, [3] Arundhuti Ganguly, [4] Joachim Hornegger, [1, 2] and Rebecca Fahrig [4]

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Int J Biomed Imaging

Abstract

Deconvolution-based analy
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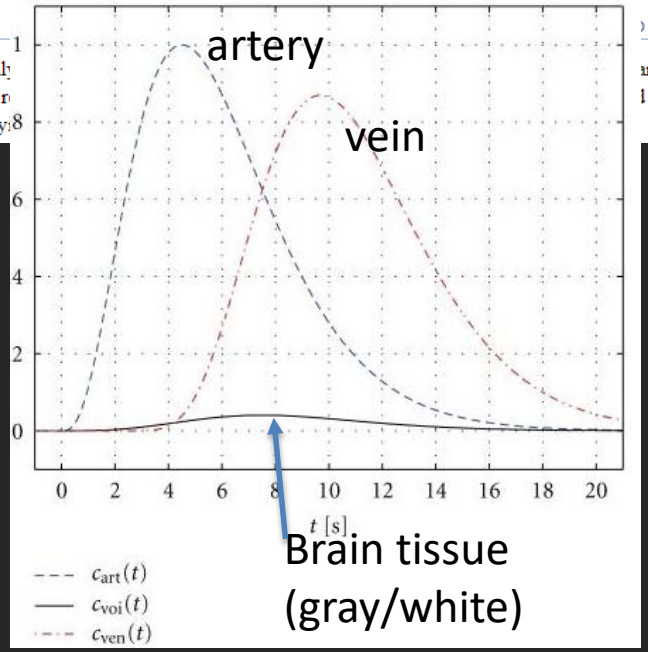


Enhancement seen inside vessels usually much higher than inside parenchyma

Brain tissue (gray/white)

Motivation for patient specific imaging in CT

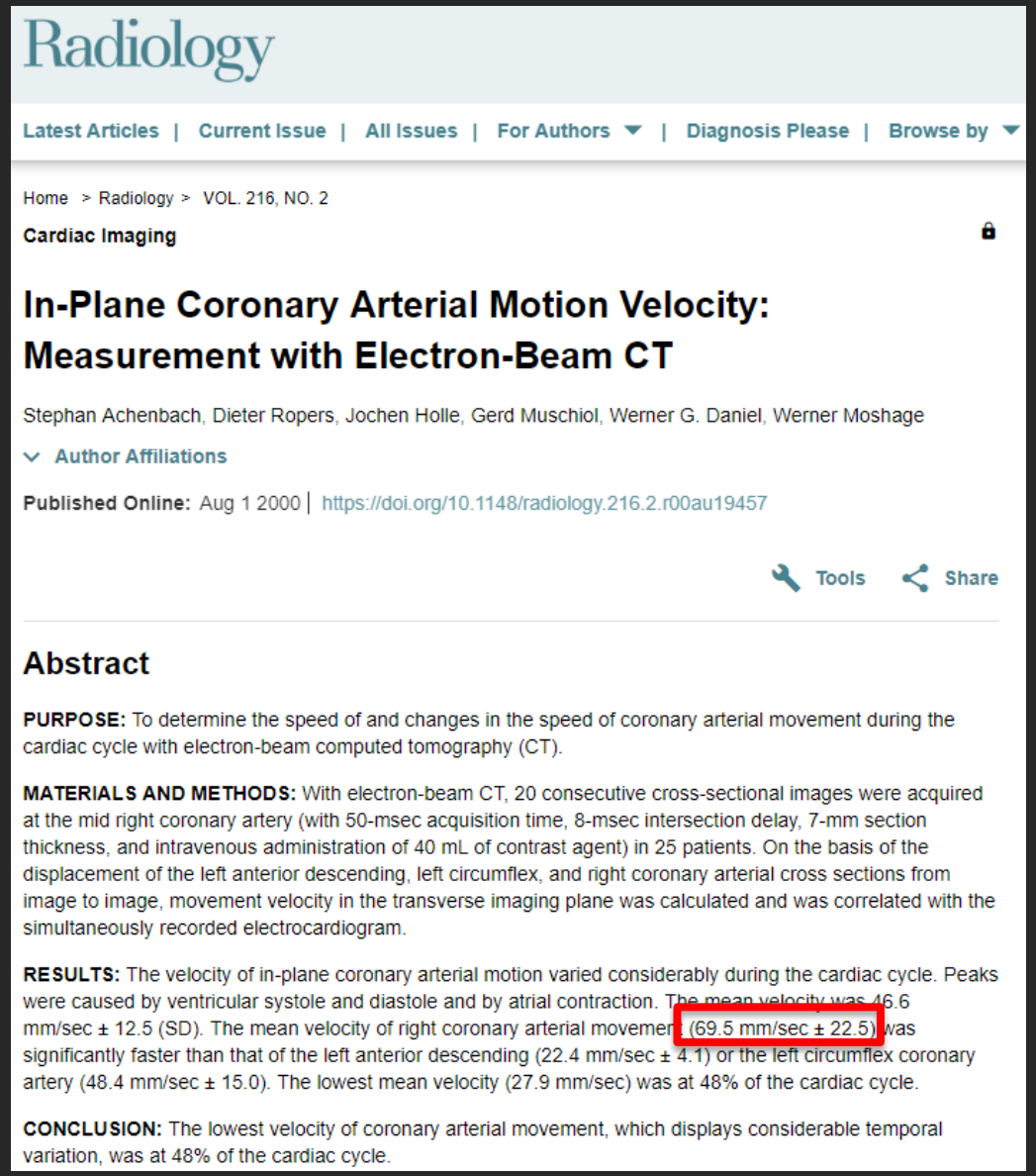
- Human body
  - It is not static
    - Heart is always moving

Speed

70	=	0.156586
Millimeter / Second		Miles per hour

Formula divide the speed value by 447.04

This may not seem fast, but consider we commonly use a RFOV of 25 cm and 512 voxels, that's a voxel size of 0.48 mm. In 1 second @ 70 mm/s…we will see blurring



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Cardiac Imaging

In-Plane Coronary Arterial Motion Velocity: Measurement with Electron-Beam CT

Stephan Achenbach, Dieter Ropers, Jochen Holle, Gerd Muschiol, Werner G. Daniel, Werner Moshage

Author Affiliations

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Tools Share

Abstract

PURPOSE: To determine the speed of and changes in the speed of coronary arterial movement during the cardiac cycle with electron-beam computed tomography (CT).

MATERIALS AND METHODS: With electron-beam CT, 20 consecutive cross-sectional images were acquired at the mid right coronary artery (with 50-msec acquisition time, 8-msec intersection delay, 7-mm section thickness, and intravenous administration of 40 mL of contrast agent) in 25 patients. On the basis of the displacement of the left anterior descending, left circumflex, and right coronary arterial cross sections from image to image, movement velocity in the transverse imaging plane was calculated and was correlated with the simultaneously recorded electrocardiogram.

RESULTS: The velocity of in-plane coronary arterial motion varied considerably during the cardiac cycle. Peaks were caused by ventricular systole and diastole and by atrial contraction. The mean velocity was 46.6 mm/sec ± 12.5 (SD). The mean velocity of right coronary arterial movement (69.5 mm/sec ± 22.5) was significantly faster than that of the left anterior descending (22.4 mm/sec ± 4.1) or the left circumflex coronary artery (48.4 mm/sec ± 15.0). The lowest mean velocity (27.9 mm/sec) was at 48% of the cardiac cycle.

CONCLUSION: The lowest velocity of coronary arterial movement, which displays considerable temporal variation, was at 48% of the cardiac cycle.

Motivation for patient specific imaging in CT

- Human body
  - It is not static
    - Heart is always moving

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Displacement and Velocity of the Coronary Arteries: Cardiac and Respiratory Motion

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USA.

Elliot R. McVeigh
The Laboratory of Cardiac
and Human Services (DHI

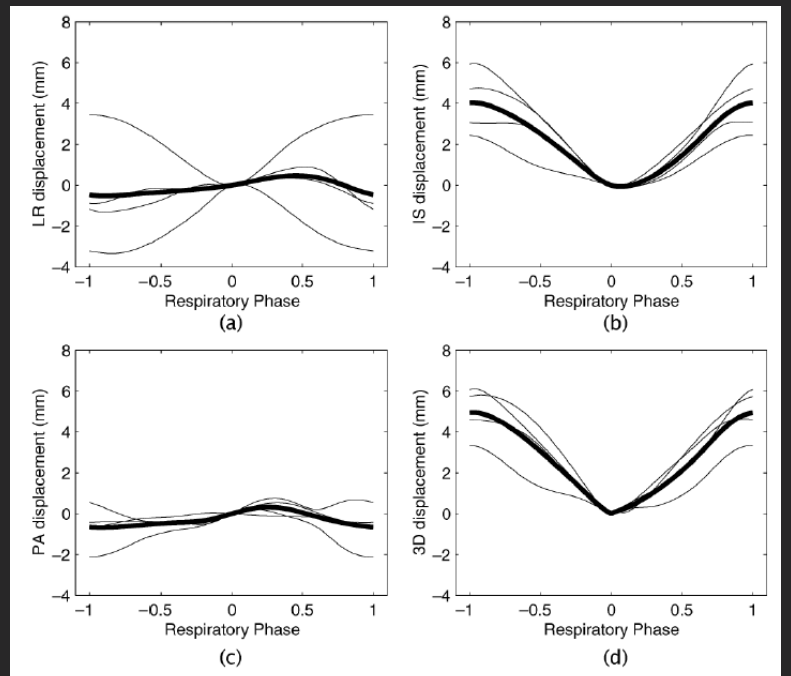


Fig. 2.
Displacement of the RCA origin during a tidal breathing cycle. The plots show individual results for four patients (thin lines) and the mean displacement (thick line). One-dimensional displacements are with respect to the patient's (a) left-right, (b) inferior-superior, and (c) posterior-anterior axes. Positive displacements are toward the left, inferior, and posterior, respectively. Since end-expiration was the reference state, the shape of the 3-D magnitude displacement curve (d) has a minimum at end-expiration ($\rho = 0$), and a maximum near end-inspiration ($\rho = \pm 1$).

Motion varies a lot w.r.t phase/cycle

Motion varies a lot by location within/on the heart

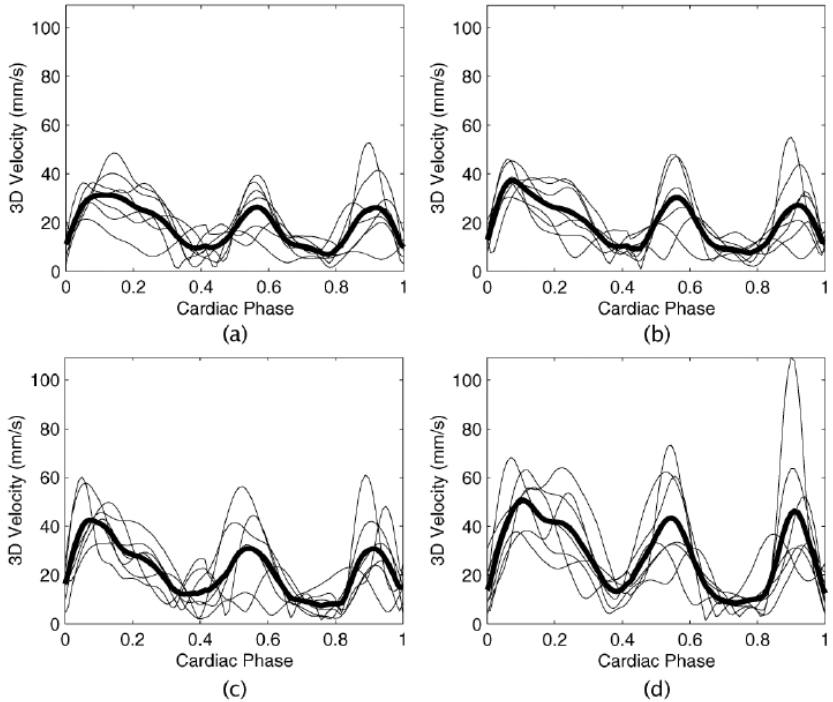


Fig. 3.
Velocity of the left coronary tree during the cardiac contraction. The plot shows individual results for seven patients (thin lines) and the mean velocity (thick line). Velocities are plotted at (a) the LM ostium, (b) the LM bifurcation, (c) a point on the LAD 5 cm from the LM ostium, and (d) a point on the LCx 5 cm from the LM ostium.

Motivation for patient specific imaging in CT

- Human body
  - It is not static
    - Lungs are always moving…even during breath holds!

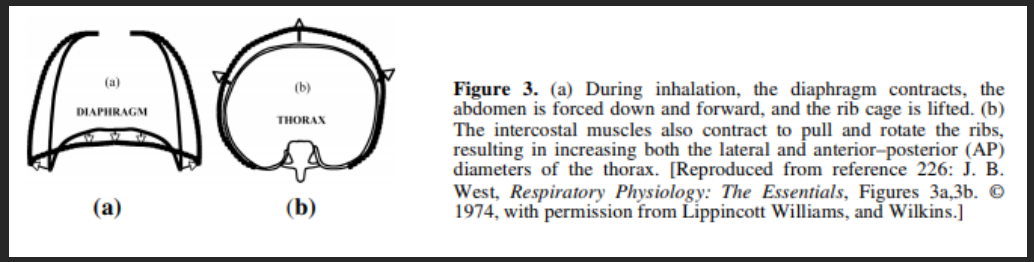


Figure 3. (a) During inhalation, the diaphragm contracts, the abdomen is forced down and forward, and the rib cage is lifted. (b) The intercostal muscles also contract to pull and rotate the ribs, resulting in increasing both the lateral and anterior–posterior (AP) diameters of the thorax. [Reproduced from reference 226: J. B. West, *Respiratory Physiology: The Essentials*, Figures 3a,3b. © 1974, with permission from Lippincott Williams, and Wilkins.]

AAPM Report 91 "The management of respiratory motion in Radiation Oncology"

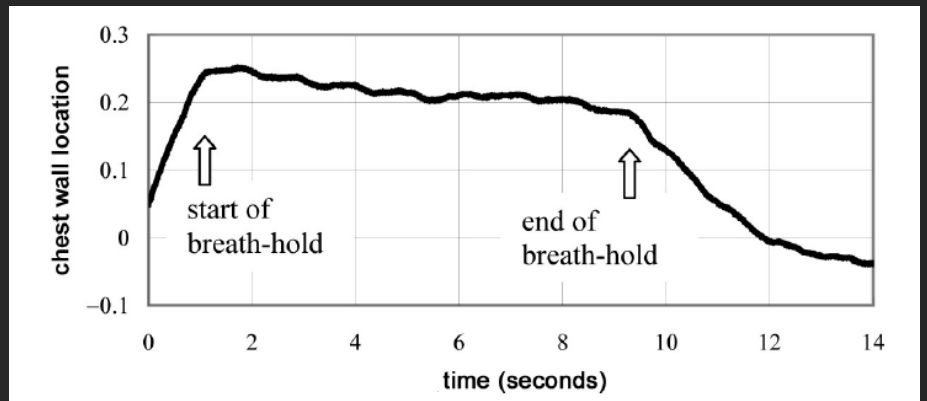


Figure 7.54 Example of a chest wall motion under "breath-hold" condition.

"Computed Tomography" by Hsieh

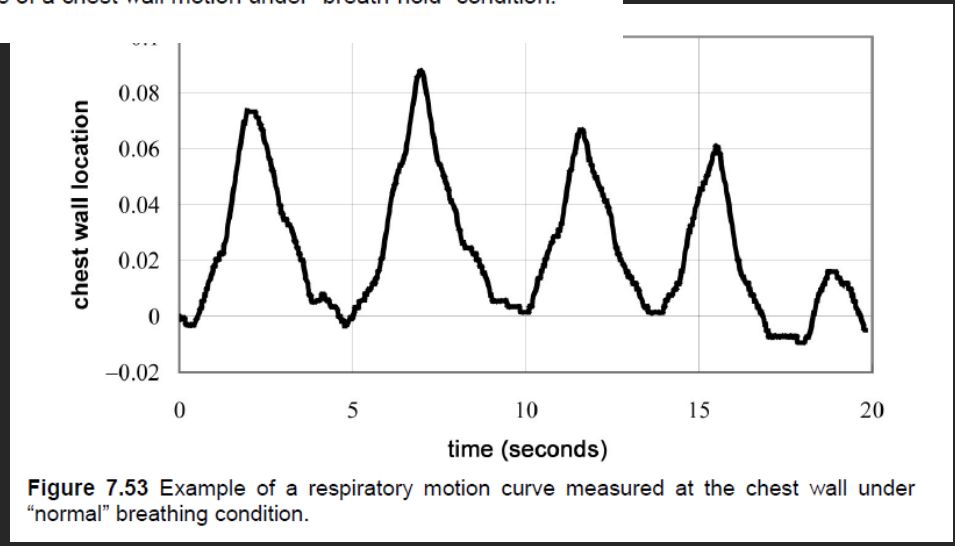


Figure 7.53 Example of a respiratory motion curve measured at the chest wall under "normal" breathing condition.

Table 2. Lung tumor–motion data. The mean range of motion and the (minimum–maximum) ranges in millimeters for each cohort of subjects. The motion is in three dimensions (SI, AP, LR).

Observer	Direction		
	SI	AP	LR
Barnes[85]: Lower lobe	18.5 (9–32)	--	--
Middle, upper lobe	7.5 (2–11)	--	--
Chen et al.[84]	(0–50)	--	--
Ekberg et al.[26]	3.9 (0–12)	2.4 (0–5)	2.4 (0–5)
Engelsman et al.[28]:			
Middle/upper lobe	(2–6)	--	--
Lower lobe	(2–9)	--	--
Erridge et al.[101]	12.5 (6–34)	9.4 (5–22)	7.3 (3–12)
Ross[76]: Upper lobe	--	1 (0–5)	1 (0–3)
Middle lobe	--	0	9 (0–16)
Lower lobe	--	1 (0–4)	10.5 (0–13)
Grills et al.[91]	(2–30)	(0–10)	(0–6)
Hanley et al.[77]	12 (1–20)	5 (0–13)	1 (0–1)
Murphy et al.[87]	7 (2–15)	--	--
Plathow[220]: Lower lobe	9.5 (4.5–16.4)	6.1 (2.5–9.8)	6.0 (2.9–9.8)
Middle lobe	7.2 (4.3–10.2)	4.3 (1.9–7.5)	4.3 (1.5–7.1)
Upper lobe	4.3 (2.6–7.1)	2.8 (1.2–5.1)	3.4 (1.3–5.3)
Seppenwoolde et al.[67]	5.8 (0–25)	2.5 (0–8)	1.5 (0–3)
Shimizu et al.[52]	--	6.4 (2–24)	--
Sixel et al.[92]	(0–13)	(0–5)	(0–4)
Stevens et al.[66]	4.5 (0–22)	--	--

AP: anterior–posterior; LR: left–right; SI: superior–inferior.

Table 3. Abdominal motion data. The mean range of motion and the (minimum–maximum) ranges in millimeters for each site and each cohort of subjects. The motion is in the superior–inferior (SI) direction.

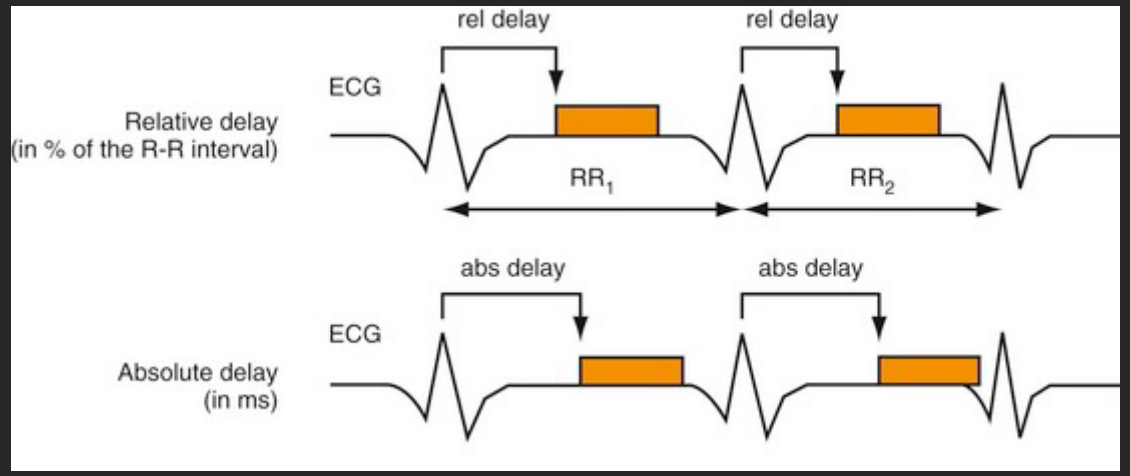
Site	Observer	Breathing mode	
		Shallow	Deep
Pancreas	Suramo et al.[74]	20 (10–30)	43 (20–80)
	Bryan et al.[75]	20 (0–35)	--
Liver	Weiss et al.[89]	13 +/– 5	--
	Harauz et al.[90]	14	--
	Suramo et al.[74]	25 (10–40)	55 (30–80)
	Davies et al.[68]	10 (5–17)	37 (21–57)
Kidney	Suramo et al.[74]	19 (10–40)	40 (20–70)
	Davies et al.[68]	11 (5–16)	--
Diaphragm	Wade[80]	17	101
	Korin et al.[79]	13	39
	Davies et al.[68]	12 (7–28)	43 (25–57)
	Weiss et al.[89]	13 +/– 5	--
	Giraud et al.[78]	--	35 (3–95)
	Ford et al.[86]	20 (13–31)	--

AAPM Report 91 “The management of respiratory motion in Radiation Oncology”

Outline

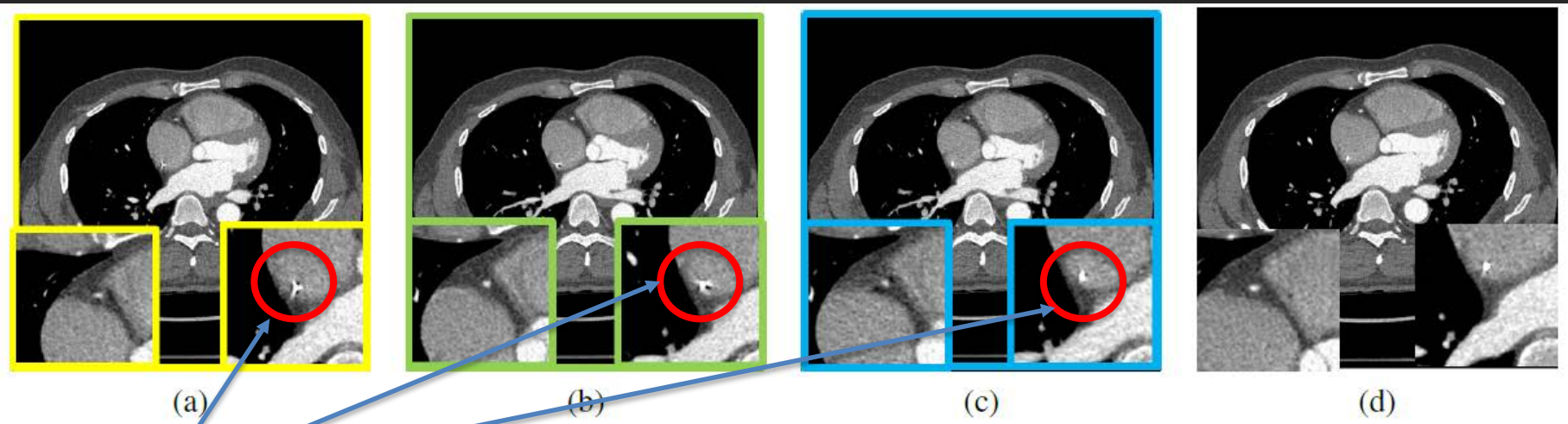
1. **Motivation for Patient Specific Imaging in CT: Cardiac**
2. **Heart Rate based Adaption**
3. **Motivation for Patient Specific Imaging in CT: Fluence modulation**
4. **Patient Specific Fluence Modulation**

- CCTA clinical reality
  - Patients will present with a wide range of heart rates
    - There exists and optimal time post contraction which varies as function of HR → we define image time using a relative time post R peak or an absolute time post R peak

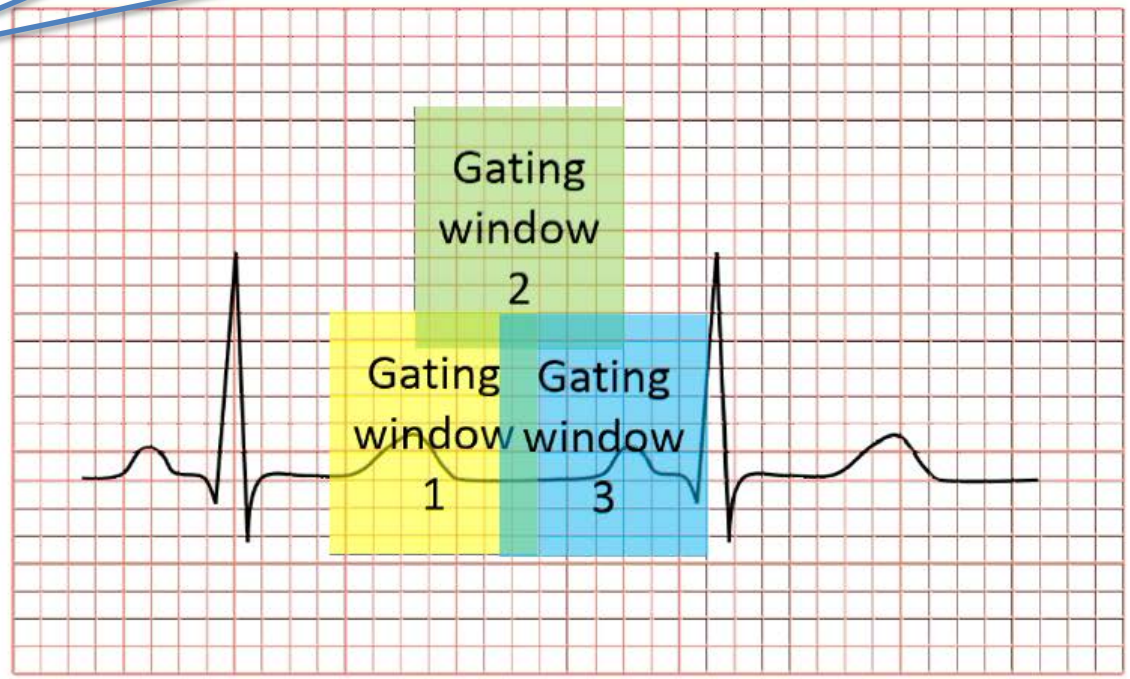


https://clinicalgate.com/physics-of-cardiac-computed-tomography/

Heart Rate based Adaption



Motion artifact is highly dependent on phase/cycle location



Heart Rate based Adaption

Springer Link

European Radiology

European Radiology
September 2006, Volume 16, Issue 9, pp 1964–1972 | Cite as

Optimal image reconstruction intervals for non-invasive coronary angiography with 64-slice CT

Authors | Authors and affiliations

Sebastian Leschka, Lars Husmann, Lotus M. Desbiolles, Oliver Gaemperli, Tiziano Schepis, Pascal Koepfli, Thomas Boehm, Borut Marincek, Philipp A. Kaufmann, Hatem Alkadhi

Cardiac
First Online: 13 May 2006

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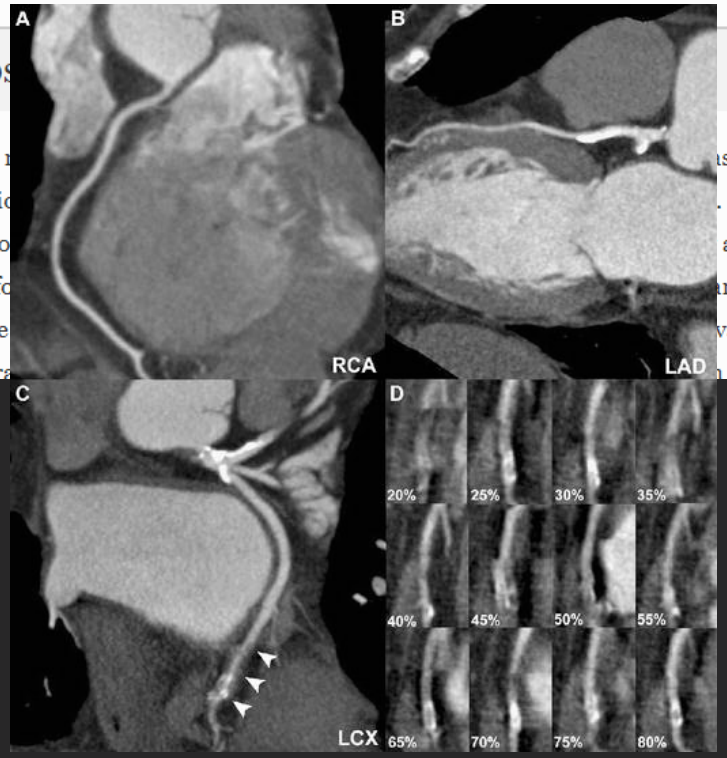
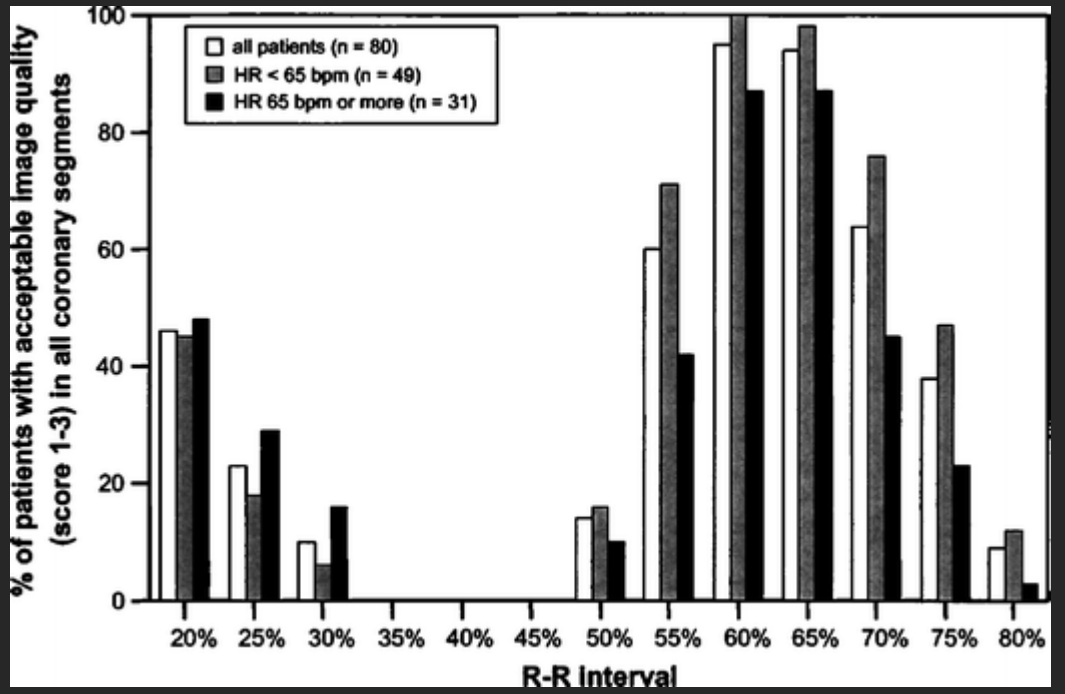
Abs

The r … asive coronary angi… . Contrast-enhanced, retro… angiography was perfo… rs). Thirteen data sets were… val. Depending on the avera… (*n*=49) and ≥65 bpm





Heart Rate based Adaption

BMC Med Imaging. 2013; 13: 5.
Published online 2013 Feb 1. doi: 10.1186/1471-2342-13-5
PMCID: PMC3570333
PMID: 23375107

Defining the mid-diastolic imaging period for cardiac CT – lessons from tissue Doppler echocardiography

James M Otton,[1,2] Justin Phan,[2] Michael Feneley,[1,2] Chung-yao Yu,[1] Neville Sammel,[1] and Jane McCrohon[1,2]

Abstract Go to:

Backgrou

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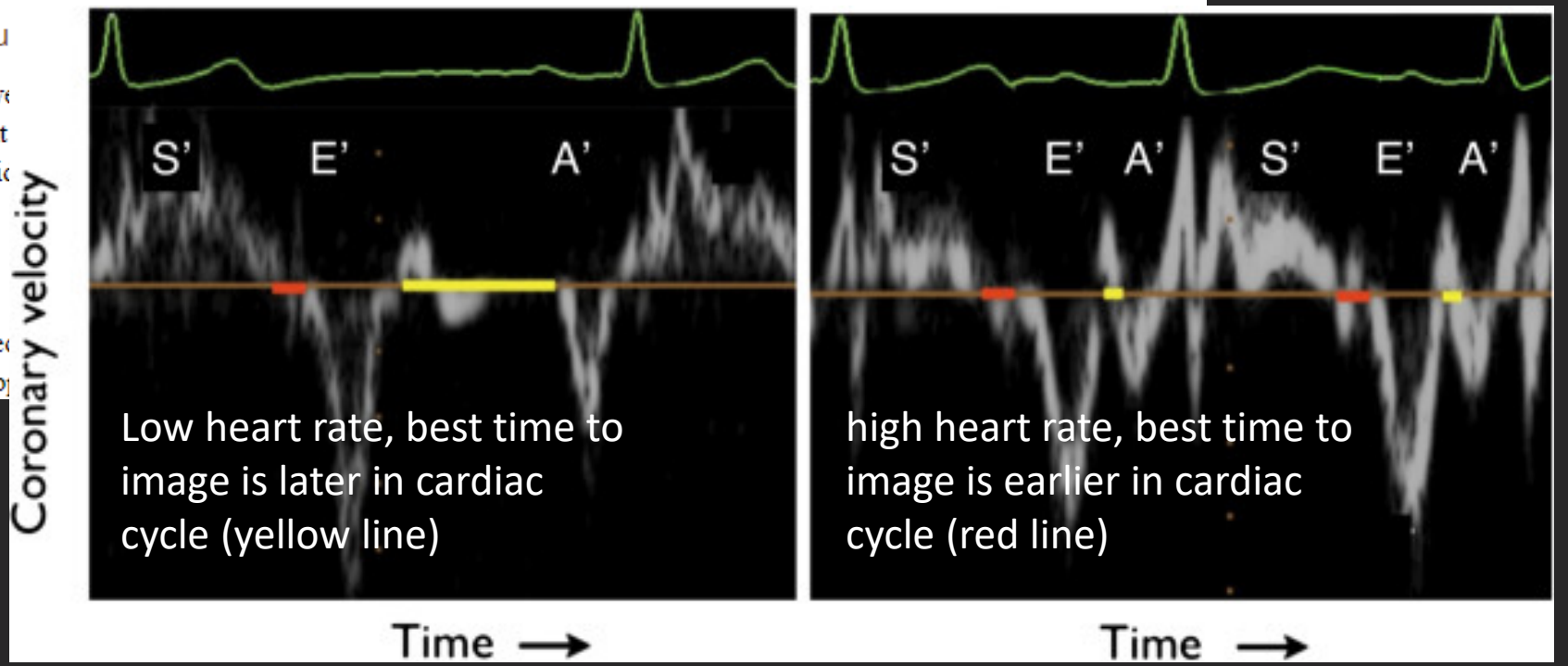
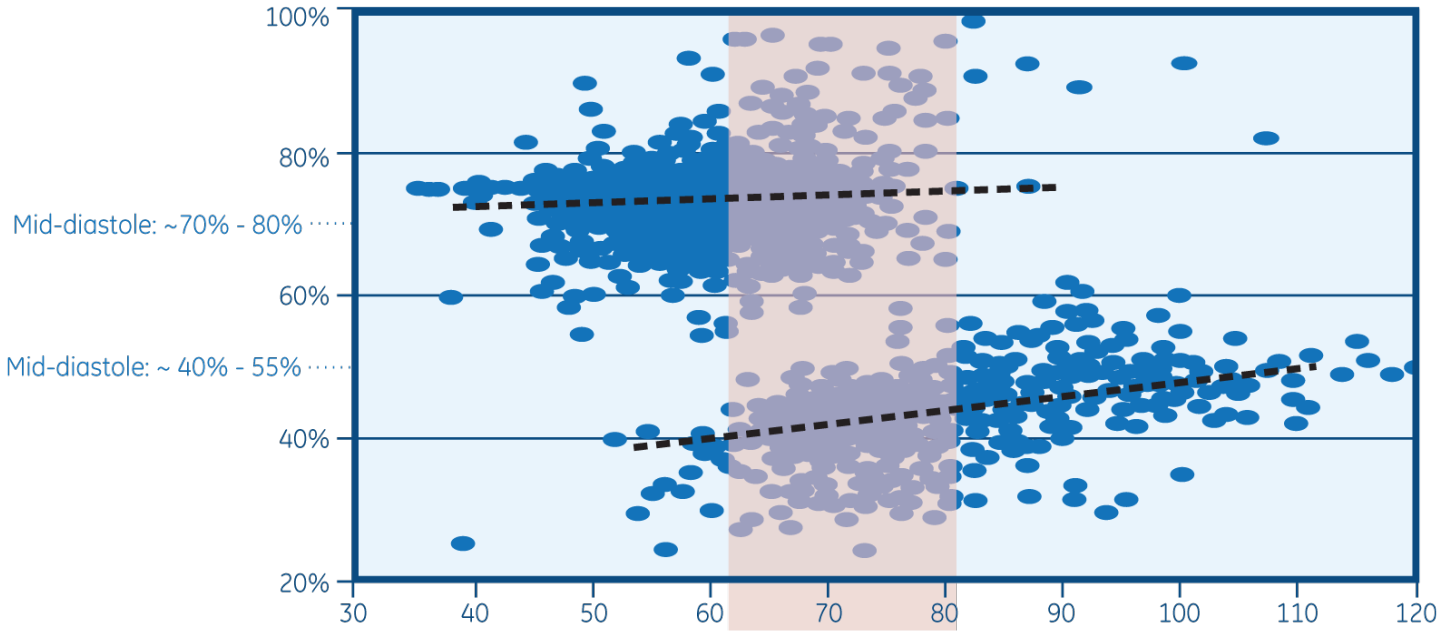
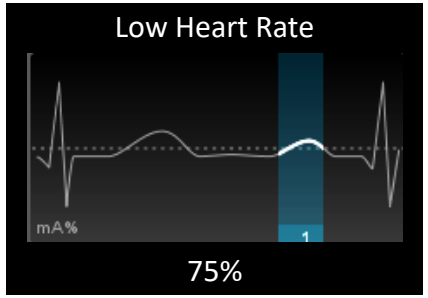
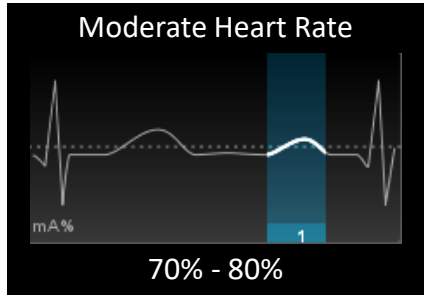


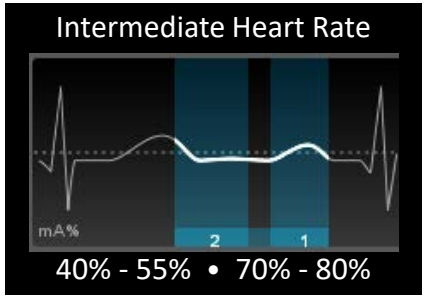
CME question answer ☺

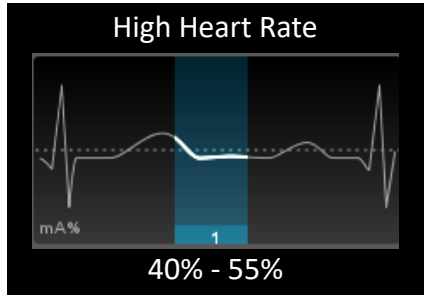
Heart Rate based Adaption



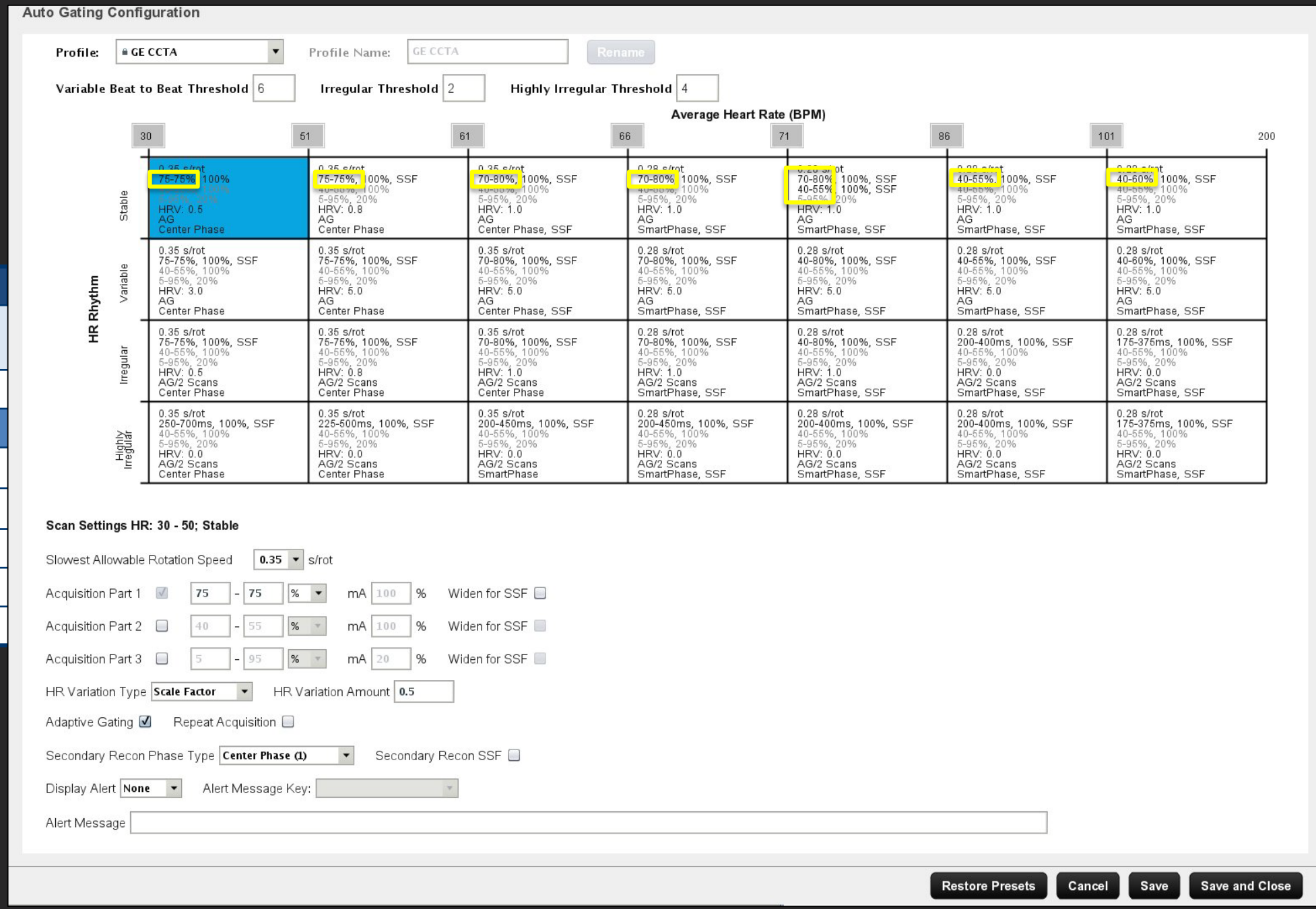








HR			
Lower Limit	Upper Limit	Peak 1	Peak 2
30	50	75	
51	60	75	
61	65	70 – 80	
66	70	70- 80	
71	85	70- 80	40 - 55
86	100	40 - 55	
101	200	40 - 60	



Heart Rate based Adaption

- CCTA clinical reality
  - Patients will present with heart rate variability
    - patients with irregular HRs (afib), or with PVCs

Now we need to talk about data collection.

Stable HR has HR variation ~ 5 bpm, variable >5 bpm

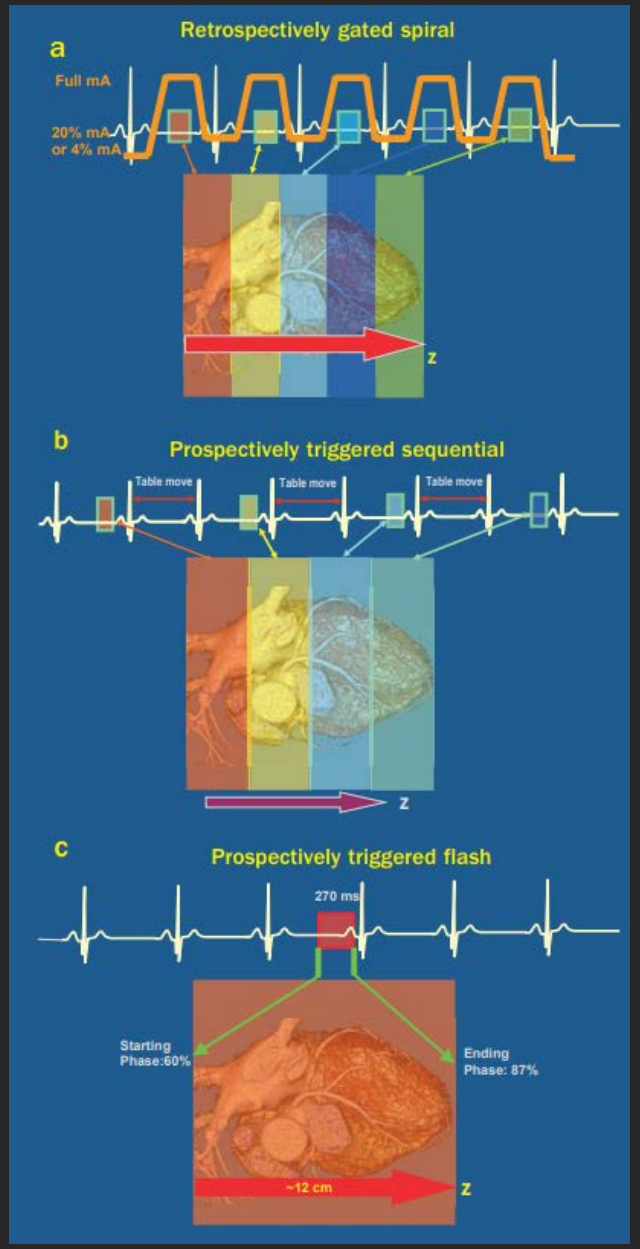


Image from 128-slice Dual Source CT: How Does it Work and What Can it Do? By Bruesewitz et al. Mayo Clinic 2010 RSNA

Heart Rate based Adaption

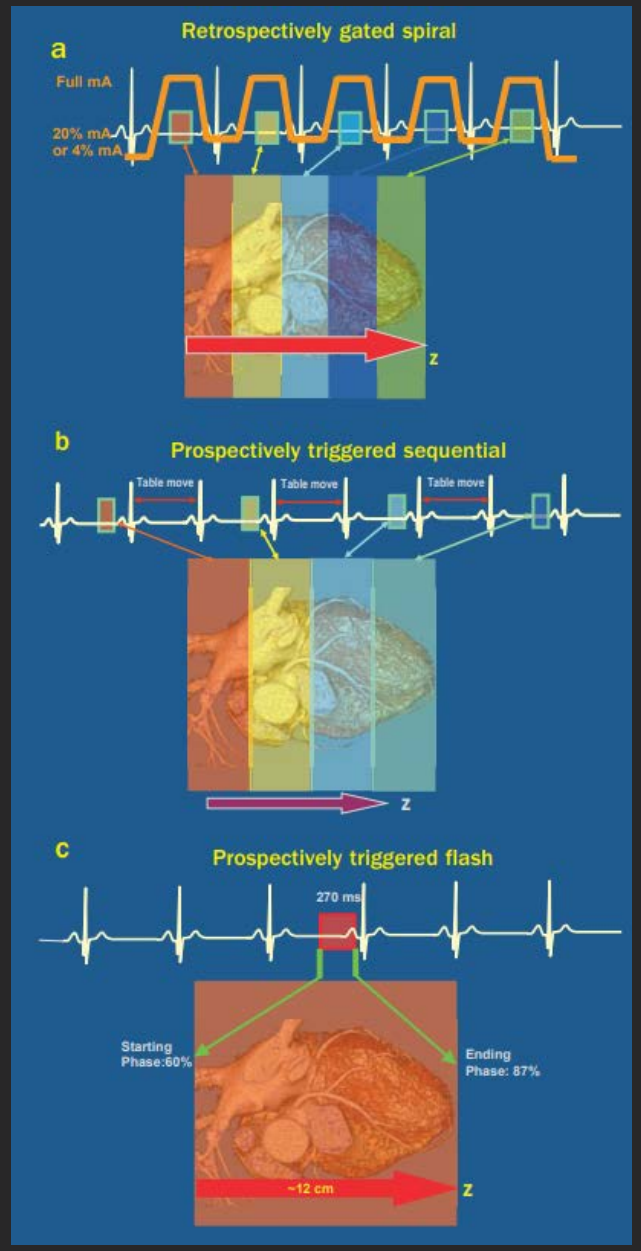


Image from 128-slice Dual Source CT: How Does it Work and What Can it Do? By Bruesewitz et al. Mayo Clinic 2010 RSNA

<u>Slow pitch helical/spiral mode</u>

All vendors will just scan faster (i.e. higher pitch) when the heart rate is higher, if irregular beats are detected you would use a lower pitch

Heart rate range	Gantry speed	Pitch
30 to 42 BPM	0.4 sec	0.18
43 to 49 BPM	0.4 sec	0.20
50 to 59 BPM	0.4 sec	0.23
60 to 69 BPM	0.4 sec	0.26

Example table of scan pitches as a function of HR

<u>"Step and shoot" axial/sequential mode</u>

All vendors will just widen the time the x-rays are on for a given bed position or collect multiple spins one location if an irregular beat is detected

<u>High pitch method "Flash mode"</u>

Accelerate the table to a fast stopped and cover the entire heart in a single beat using a helical/spiral scan mode

<u>Wide axial/sequential mode</u>

Your detector can cover the entire heart, so you sit over the heart with ECG trace on scan when you predict your target phase will be

Scan for a longer time when the HR is high or you anticipate an irregular beat

Dual Source
cCTA Imaging Guidelines

SIEMENS Healthineers

	Flash / Turbo Flash Mode	Adaptive Cardio Sequence (Prospective Gating)	Retrospective ECG Gating
Heart Rate	Flash: <65bpm Force: <78bpm	Any Heart Rate	Any Heart Rate
HR Stability	Stable	At high HR's need to be stable	Any Wave Form
Contrast Amount	Physicians discretion	Scan time X injection rate plus 10 cc's	Scan time x injection rate plus 10 cc's
Injection Rate	5 to 6 ml/s (faster is better)	5 to 6 ml/s (faster is better)	5 to 6 ml/s (faster is better)
Rotation Time	Flash/Drive: 0.28, Force: 0.25	Flash/Drive: 0.28, Force: 0.25	Flash/Drive: 0.28, Force: 0.25
CARE kV	ON	ON	ON
Quality ref mAs	Use Default	Use Default	Use Default
CARE Dose 4D	ON	ON	ON
Iterative Reconstruction	ON	ON	ON
Patient Dose	Less than 1 mSv (100kV)	Depends on ECG pulsing range	Depends on ECG pulsing range, (4% min dose available)
When to use	Rule out CAD	Routine with HR variability	Atrial Fibrilation, very difficult cases, ECG editing capability
Cardiac Function	N/A	Yes	Yes
Beta Blockers	Physicians discretion	Physicians discretion	Physicians discretion

- Limitations of the gated Flash mode:
  - The heart rate must be regular. To scan using a high pitch, the table requires about 1 sec to be accelerated. The scanner must accurately predict the timing of future R-waves in order to synchronize the x-ray-on time with the diastolic phase.
- Limitations with wide axial scanners and prospective scanning
  - Dose reduction potential is reduced
    - Need to widen gating window
    - Need to “double scan” if a messed up beat is detected

- So in summary
  - There exist multiple modes for cardiac scanning
  - There are optimal modes for different heart rates
  - There are optimal modes for different degrees of HR irregularities
  - There are different target gating windows for different heart rates
  - There are different strategies for dealing with HR irregularities
- Current state of the art in cardiac scanning will have the scanner picking the mode and target window for the operator
- Honestly, the peer reviewed literature is not the place to understand state of the art in cardiac scanning, get your apps person to send your vendors whitepapers and user manuals for cardiac mode.

Outline

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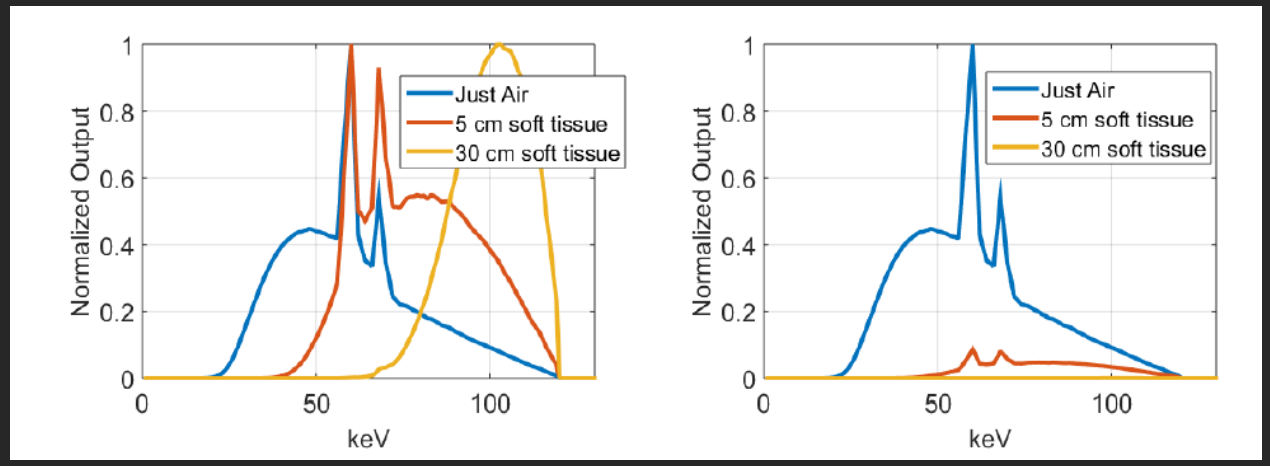
4. **Patient Specific Fluence Modulation**

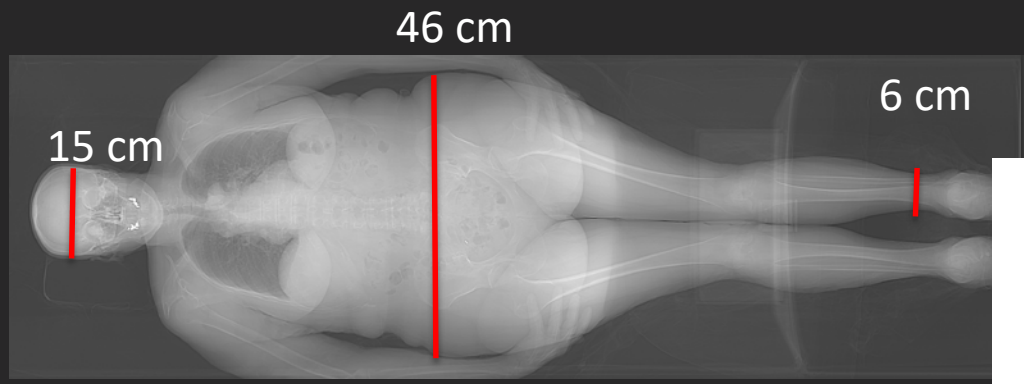
Motivation for patient specific imaging in CT

- Human body
  - It varies in size
    - Region to region
    - Angularly
    - Patient to patient
    - As a function of position

Motivation for patient specific imaging in CT

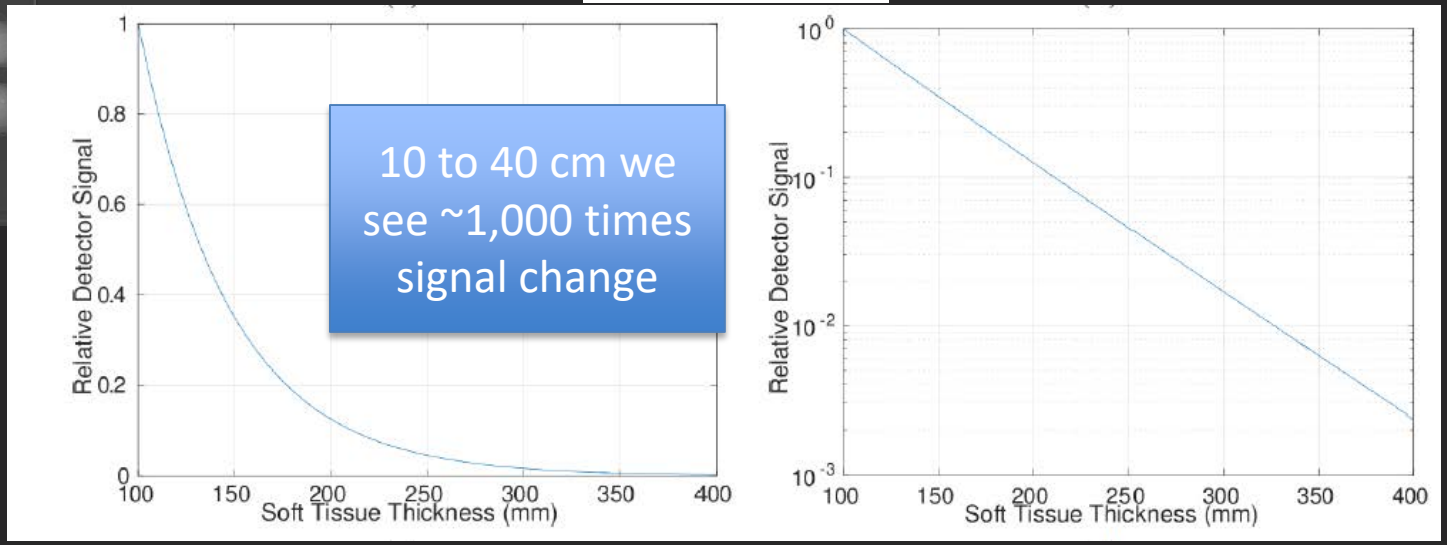
- Human body
  - It varies in size
    - Region to region
      - head vs. pelvis





Multiple orders of magnitude changes will occur in detector signal due to body region size changes!

Left is non log, right is log plot of detector signal as a function of soft tissue thickness



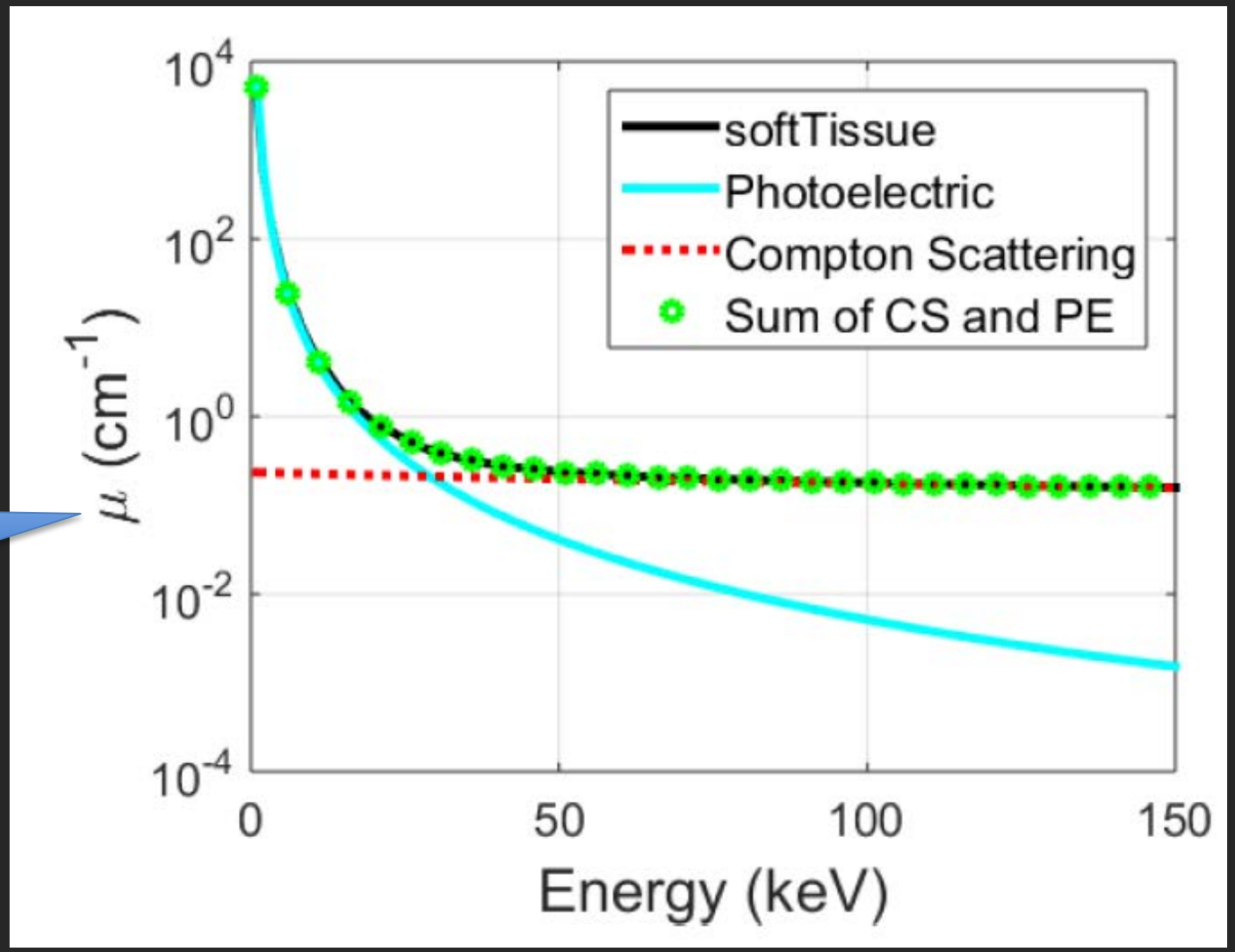
Motivation for patient specific imaging in CT

What we send in

$$I = I_0 \exp(-\mu x)$$

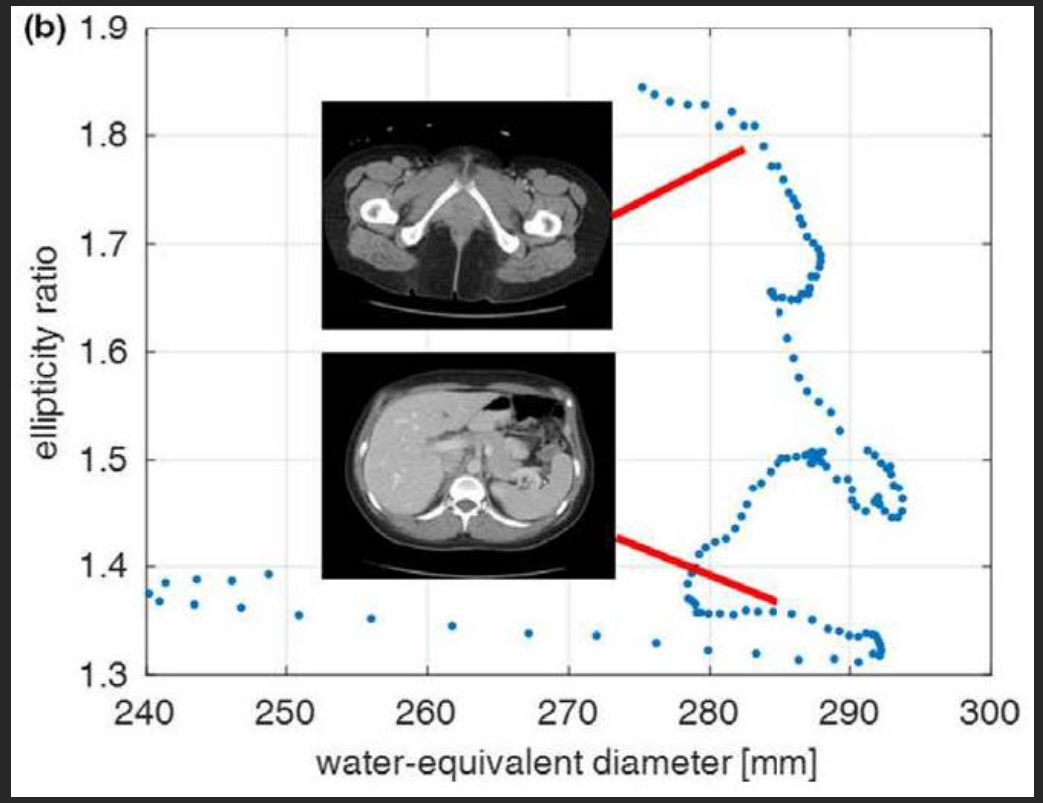
What we get out

Material property



Motivation for patient specific imaging in CT

- Human body
  - It varies in size
    - Angularly
      - projection through lateral direction longer than AP/PA for all regions except the head



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DOI: 10.1002/acm2.12223

IMAGING PHYSICS

WILEY

Evaluation of AAPM Reports 204 and 220: Estimation of effective diameter, water-equivalent diameter, and ellipticity ratios for chest, abdomen, pelvis, and head CT scans

Christiane S. Burton[1] | Timothy P. Szczykutowicz[2]

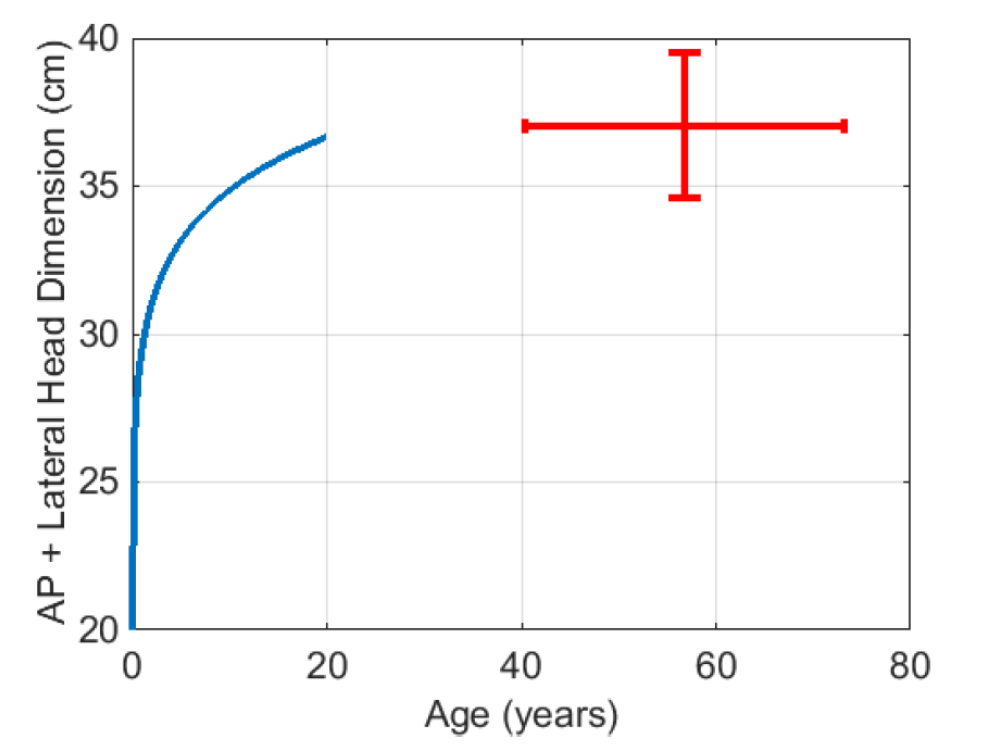
TABLE 2 Elliptical ratio (LAT/AP) calculation for patients of routine adult (abdomen and pelvis), adult chest (†subset of adult chest), and pediatric cases.

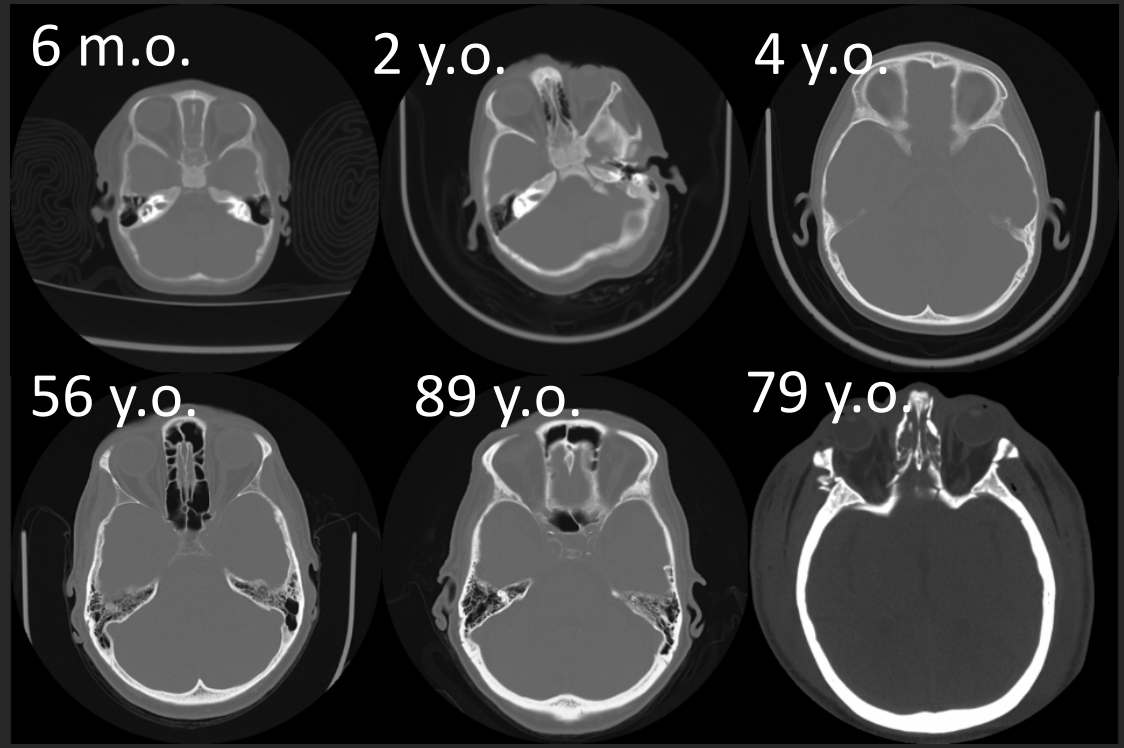
Data set	Mean ellipticity ratio (LAT/AP)	Std. Dev.	Min–Max
Adult abdomen pelvis	1.48	0.22	1.20–1.94
Adult chest	1.60	0.23	1.21–2.07
Adult shoulder†	2.28	0.22	1.08–3.34
Adult thorax†	1.51	0.21	1.09–1.98
Adult abdomen only†	1.38	0.20	1.16–1.73
Pediatric abdomen pelvis	1.53	0.30	1.07–1.75
Adult head	0.85	0.08	0.83–0.87

vide data for the future
e-scale confirmation of the
ith size surrogate data for
orts, and additionally pro-
erent body regions.
our analysis including data
l pediatrics. We calculated
ed in AAPM Reports 204/

Motivation for patient specific imaging in CT

- Human body
  - It varies in size
    - Patient to patient
      - newborn to bariatric adult





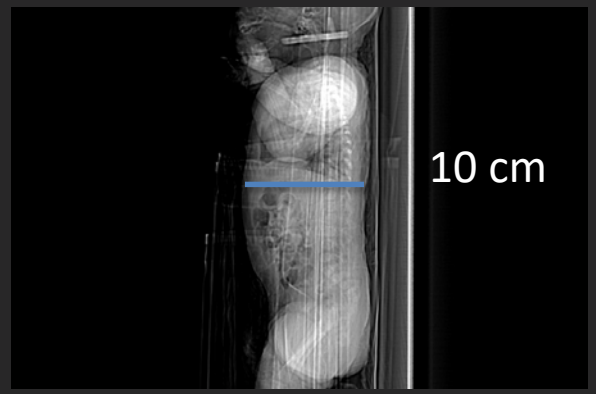
Kids have big heads… that is why they are cute and why we treat them as adults after they turn 7

Motivation for patient specific imaging in CT

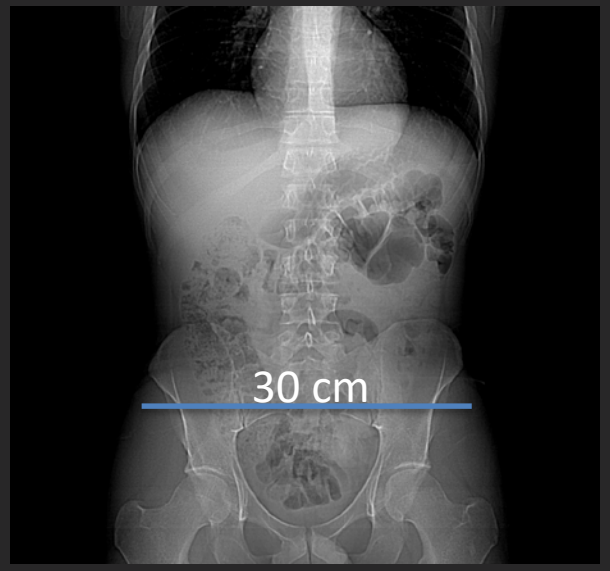
- Human body
  - It varies in size
    - Patient to patient
      - newborn to bariatric adult

Imaging bariatric patients is difficult. Rule of thumb in CT is we need 2x dose for every 4 cm of tissue to maintain image noise. So if we like the scan of a 30 cm person, to get to 50 cm we need 5x dose doublings. If we were using 300 mA for the 30 cm scan, then we need 1,500 mA for the bariatric person!

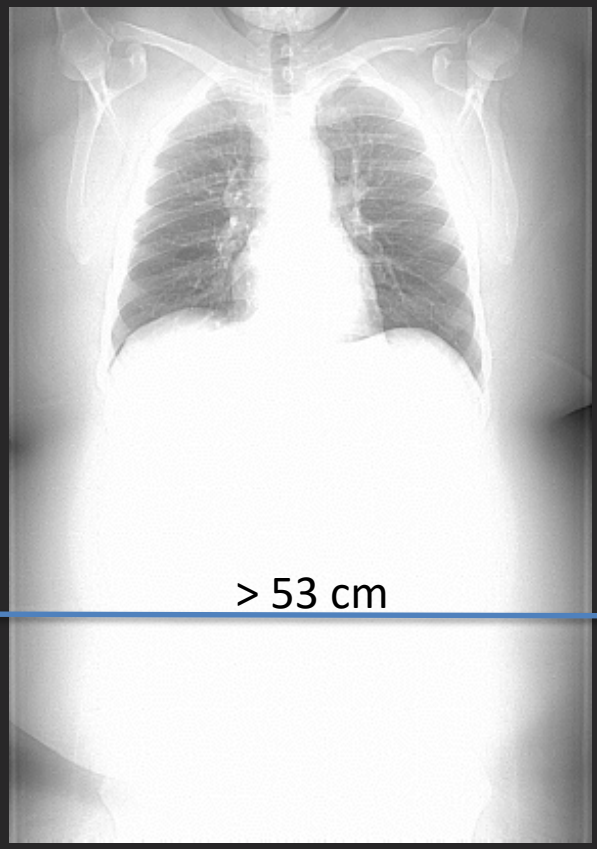
2 months old



Extremely fit 27 year old*



"white out" bariatric patient

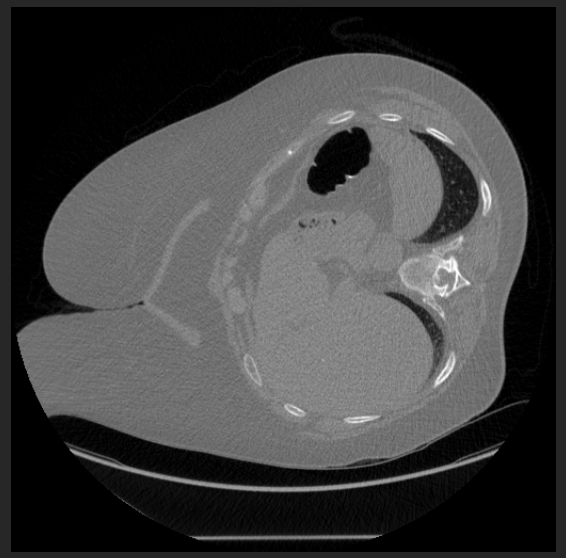


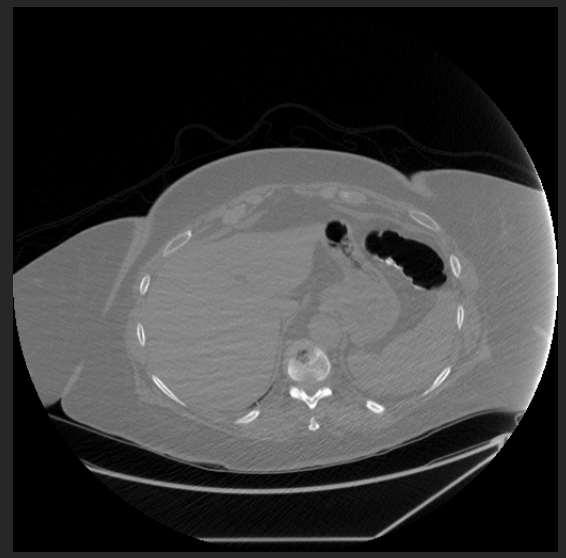
*its younger me ☺

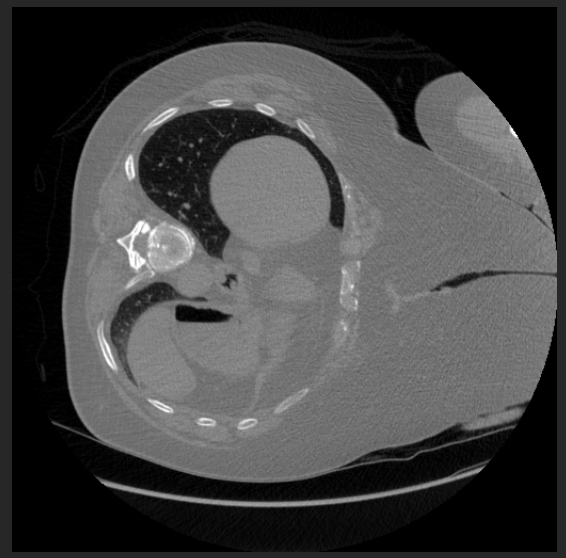
Motivation for patient specific imaging in CT

- Human body
  - It varies in size
    - As a function of position
      - prone versus supine, with respiratory state diaphragm/liver move multiple cm which changes attenuation

Same patient, three different positionings and three different attenuation distributions







Outline

1. **Motivation for Patient Specific Imaging in CT: Cardiac**
2. **Heart Rate based Adaption**
3. **Motivation for Patient Specific Imaging in CT: Fluence modulation**
4. **Patient Specific Fluence Modulation**

Patient Specific Fluence Modulation

- State of the art mA modulation
  - Adjustment of tube output as a function of z axis position, or both as a function of z position and gantry angle
  - Can reduce dose up to 60% in some cases[1]

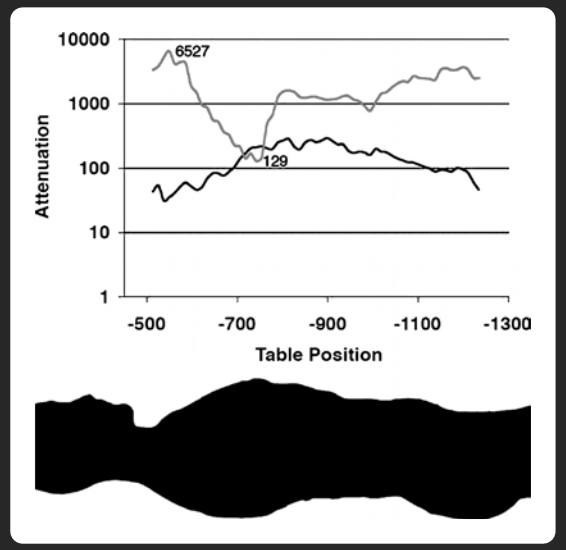


Image from: McCullough, C.H. *et al. "CT Dose Reduction and Dose Management Tools: Overview of Available Options" Radiographics* ***26*** *2006*

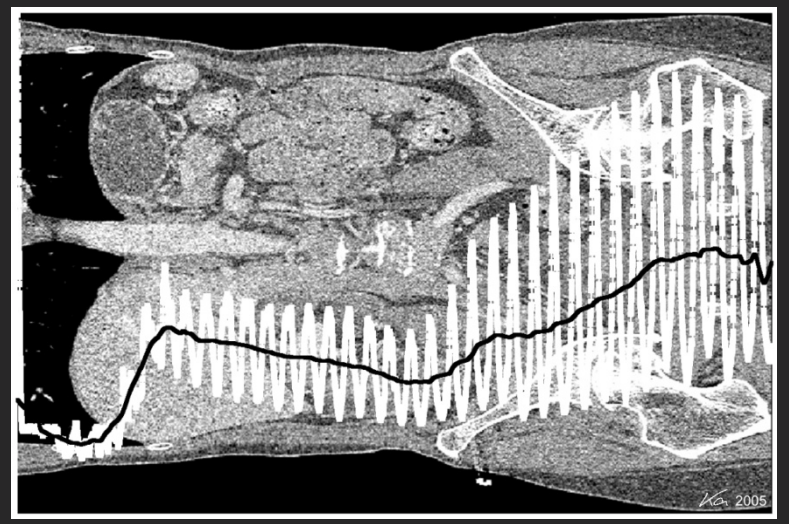
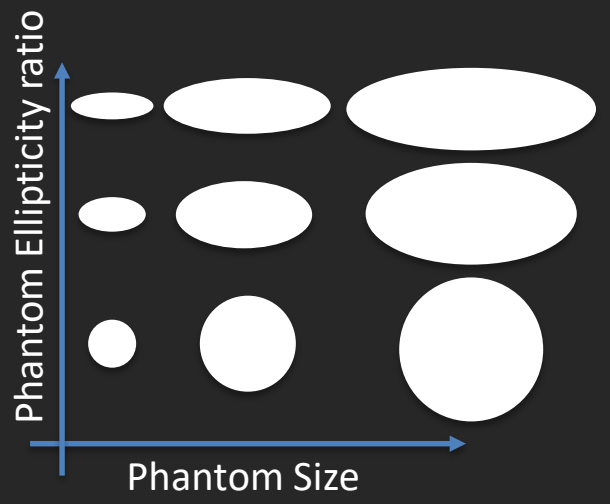


Image from *Computed Tomography* by Willi A. Kalender 2005



mA modulation can handle size and ellipticity changes

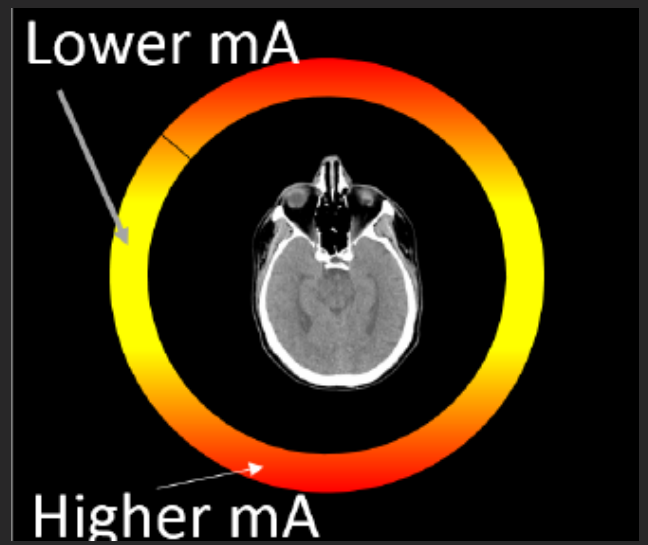
[1]Kalender *et al.* "Dose reduction in CT by anatomically adapted tube current modulation II: Phantom experiments" Med. Phys. **26** 1999

Patient Specific Fluence Modulation

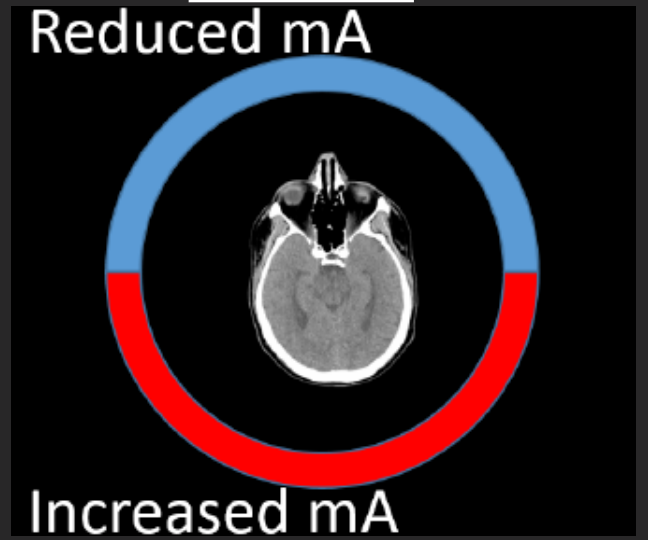
- Current state of the art in mA modulation is organ dose modulation
  - Reduces mA when the tube is directly irradiating a radio-sensitive organ
  - Typically, ~30% dose reduction possible

Old school, no mA modulation

Previous state of the art, angular mA modulation



Current state of the art, organ sparing plus angular and z mA modulation



- Patient Specific Fluence ModulationDixon, M. T., Loader, R. J., Stevens, G. C., & Rowles, N. P. (2016). An evaluation of organ dose modulation on a GE optima CT660-computed tomography scanner. Journal of applied clinical medical physics, 17(3), 380-391.
- Gandhi, D., Crotty, D. J., Stevens, G. M., & Schmidt, T. G. (2015). Phantom study to evaluate the dose and image quality effects of a computed tomography organ-based tube current modulation technique. *Medical physics*, *42*(11), 6572-6578.
- Lambert, J. W., & Gould, R. G. (2016). Evaluation of a net dose-reducing organ-based tube current modulation technique: comparison with standard dose and bismuth-shielded acquisitions. *American Journal of Roentgenology*, *206*(6), 1233-1240.
- Fu, W., Sturgeon, G. M., Agasthya, G., Segars, W. P., Kapadia, A. J., & Samei, E. (2017, March). Estimation of breast dose reduction potential for organ-based tube current modulated CT with wide dose reduction arc. In *Medical Imaging 2017: Physics of Medical Imaging* (Vol. 10132, p. 1013246). International Society for Optics and Photonics.

- That was mA modulation, what about kV?

- Key references for understanding the optimal beam energy in CT

Application- and patient size-dependent optimization of x-ray spectra for CT

Willi A. Kalender,[a),b)] Paul Deak,[a)] Markus Kellermeier,[a)] Marcel van Straten,[a),c)] and Sabrina V. Vollmar[a)]
Institute of Medical Physics, University Erlangen-Nürnberg, Henkestr. 91 91052 Erlangen, Germany

(Received 21 August 2008; revised 20 November 2008; accepted for publication 6 January 2009; published 25 February 2009)

Although x-ray computed tomography (CT) has been in clinical use for over 3 decades, spectral optimization has not been a topic of great concern; high voltages around 120 kV have been in use since the beginning of CT. It is the purpose of this study to analyze, in a rigorous manner, the energies at which the patient dose necessary to provide a given contrast-to-noise ratio (CNR) for various diagnostic tasks can be minimized. The authors used cylindrical water phantoms and quasianthropomorphic phantoms of the thorax and the abdomen with inserts of 13 mm diameter

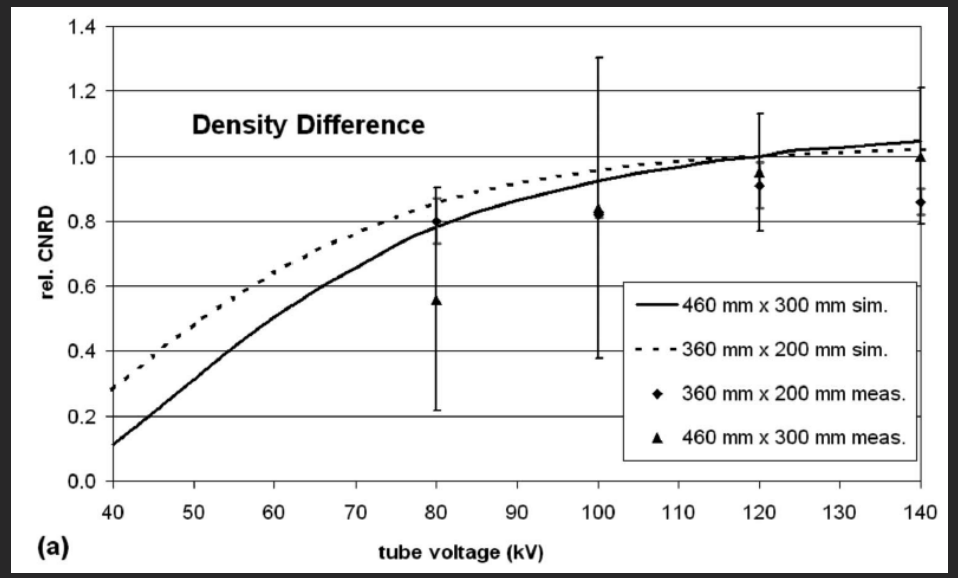
Automatic selection of tube potential for radiation dose reduction in CT: A general strategy

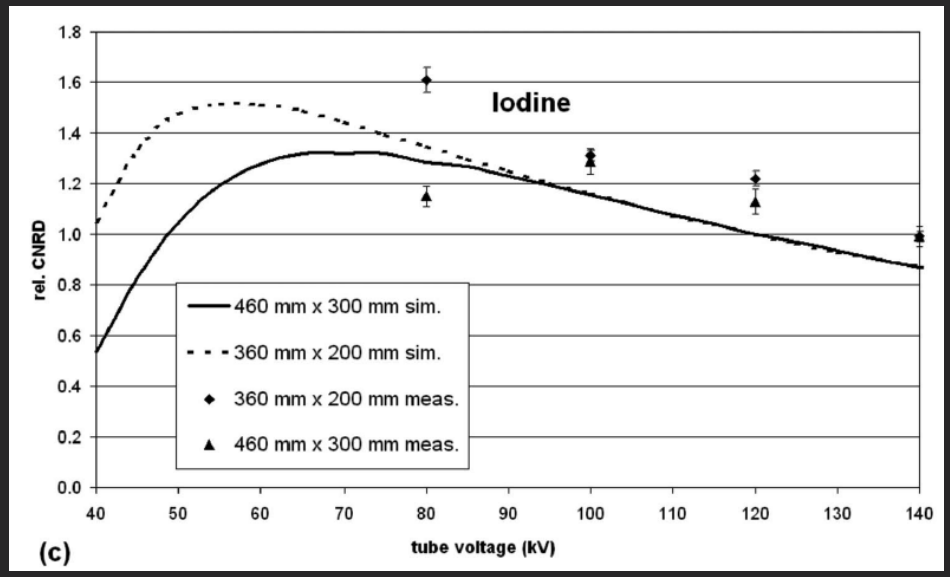
Lifeng Yu,[a)] Hua Li, Joel G. Fletcher, and Cynthia H. McCollough
Department of Radiology, Mayo Clinic, Rochester, Minnesota 55905

(Received 13 July 2009; revised 23 October 2009; accepted for publication 27 October 2009; published 10 December 2009)

Purpose: To optimize radiation dose efficiency in CT while maintaining image quality, it is important to select the optimal tube potential. The selection of optimal tube potential, however, is highly dependent on patient size and diagnostic task. The purpose of this work was to develop a general strategy that allows for automatic tube potential selection for each individual patient and each diagnostic task.
Methods: The authors propose a general strategy that allows automatic adaptation of the tube potential as a function of patient size and diagnostic task, using a novel index of image quality, "iodine contrast to noise ratio with a noise constraint (iCNR_NC)," to characterize the different

Optimal Beam Energy Selection in CT





Density difference was difference between 10 HU of soft tissue like material

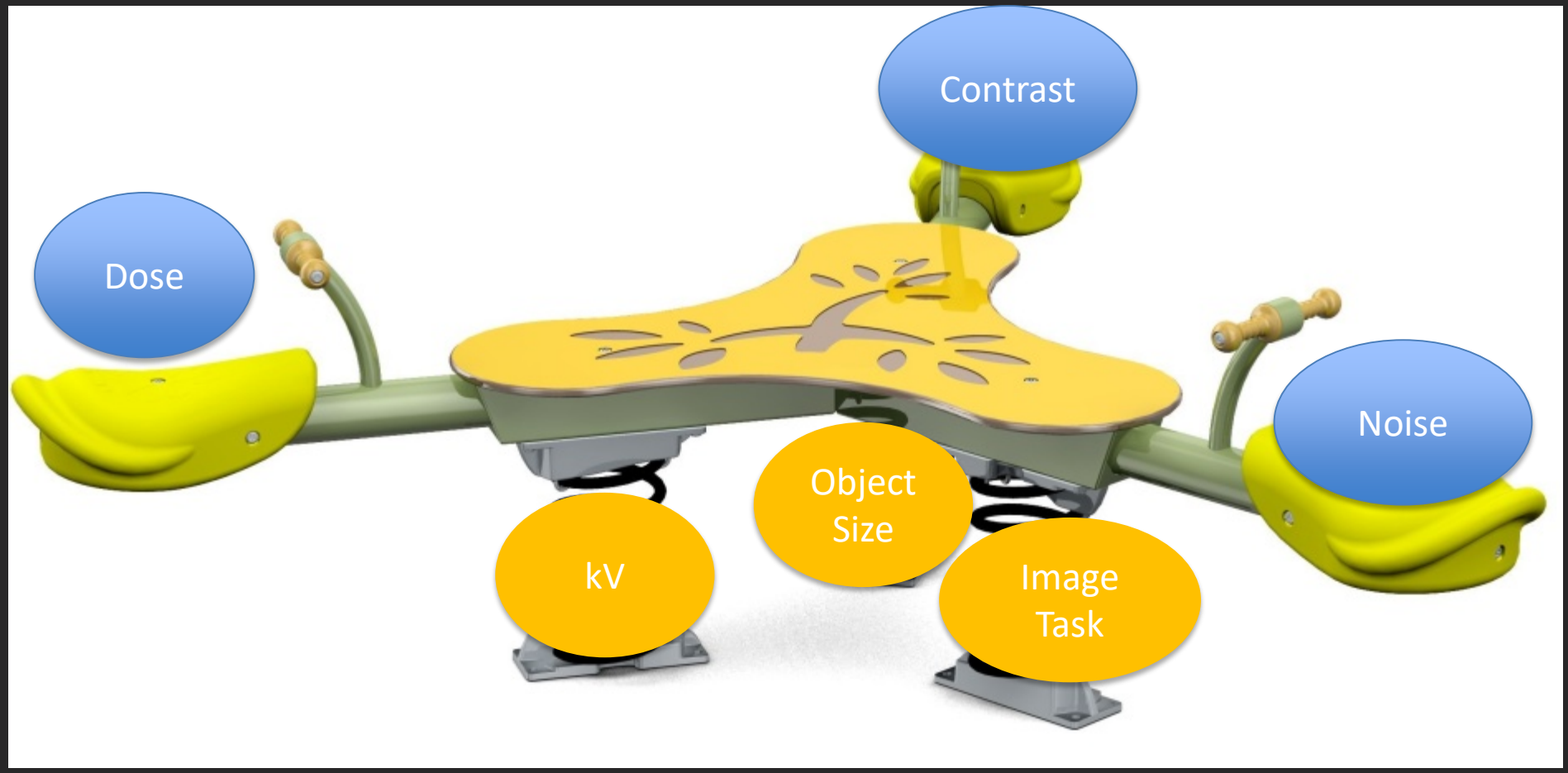
Raising kV means lower noise for the same dose

Lower kV means better image contrast

Iodine difference was difference between Iodine rod and background

Medical Physics, Vol. 36, No. 3, March 2009

Optimal Beam Energy Selection in CT



https://www.edu-quip.co.uk/prod/27573/matrix-springer-3-way-see-saw

	Canon	GE	Philips	Siemens
mA AEC	SUREExposure 3D	smartmA	DoseRight	CAREDose 4D
kV AEC	SURE kV	kV Assist	{}**	CARE kV
Organ sparing	OEM*	ODM	{}	X-CARE
Quality target	SD	NI	DRI	Quality ref.mAs
Quality target to dose	$SD \propto \frac{1}{\sqrt{CTDI_{vol}}}$	$NI \propto \frac{1}{\sqrt{CTDI_{vol}}}$	$CTDI_{vol} \propto (1.12)^{DRI-24}$*** $CTDI_{vol} \propto (0.88)^{24-DRI}$****	Quality ref.mAs ∝ CTDIvol
Quality target to noise	$SD \approx Image\ Noise$	$NI \approx Image\ Noise$	$DRI \propto 24 - \frac{\ln(image\ noise)}{2\ln(1.12)}$*** $DRI \propto 24 + \frac{\ln(image\ noise)}{2\ln 0.88}$****	Quality ref.mAs ∝ $\frac{1}{\sqrt{Image\ Noise}}$
Quality Target with patient size	Non linear, not adjustable	constant	Non linear, not adjustable	Non linear, adjustable (strength setting)
Organ Region boost	Allows you to set different SD for different scan regions	{}	Liver Brain DoseRight	{}

*In CT fluoroscopy mode only

**Philips recommends performing a dual energy scan

*** For dose increase above reference patient DRI

**** For dose decrease below reference patient DRI

Patient Specific Fluence Modulation

Table 1.1: A summary of x-ray fluence modulating methods. Values in parenthesis represent ideal parameter values assuming the system could be optimized beyond the prototype stage according to the authors of the respective works.

Method	Separable Modulation Function	Used Clinically	Temporal Modulation	Spatial Modulation[a]	Applicability to FFMCT[b]
bowtie filtering[13]	no	yes	none	infinite	low
piston driven mask equalization[17–21]	yes	no	3 min (<5 sec)	0.159 cm	low
DBA (older version)[22–31]	yes	no	120 min (1 min)[22] 3.5 min.[23]	0.3 mm[22]	low
rotating aperture[32,33]	no	no	2.5 ms	none	possible
ROI filter[34,35]	no	no	none	fixed ROI	possible
z-axis collimation[13]	no	yes	none	variable	possible
wedges[36]	no	yes	none	infinite	possible
slot scanning[37–40]	yes	yes	9 sec.[38]	3.5 cm[38]	possible[c]
Volume of Interest[41,42]	yes	no	≈150 ms[41]	?	low-high[d]
mA modulation[8]	no	yes	90% in 1 sec[8]	none	possible
SBDX[43,44]	yes	no	21-62 ms[43]	16 mm[e 43]	**high**
electronic bowtie[45]	yes	no	?	?	**high**
TomoTherapy™[f 46]	yes	not for FFMCT	≈30-70 msec[47]	6.25 mm[g]	**high**
DBA-FFMCT[48]	yes	no	?	?	**high**

[a]Dimension of modulation at the modulator plane, not at the object or image plane unless otherwise noted.
[b]Application to non-separable FFMCT, in the opinion of the author.
[c]Slot scanning can be thought of as a combination of mA modulation and x/z axis collimation in CT.
[d]Low applicability to FFMCT when the goal is uniform detector fluence, high applicability when the goal is VOI.
[e]Dimension of modulation at the image plane.
[f]Use of this method for FFMCT has not been studied, but in the opinion of the author it is possible.
[g]Leaf size projected to isocenter.

Circa ~2012, the concept of fluence modulated imaging in x-ray imaging was not new. Many approaches had been studied and were in clinical use.

Patient Specific Fluence Modulation

Bowtie filter, kV

Changing mAs

In the clinic today, we can write the modulation of the x-ray beam in MDCT as M(d,n) = F(d)*D(n) where d is the detector element index and n is the view angle. **THIS IS A SEPERABLE FUNCTION**

The rest of this talk will be about approaches that modulate the fluence profile in real time.

Bowtie filters have a fixed fluence pattern w.r.t. fan angle

CME question answer ☺

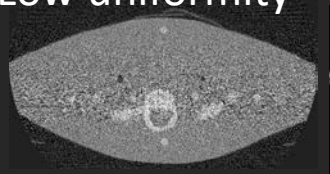
Patient Specific Fluence Modulation

- References for this new type of CT beam fluence modulation
- Stanford group
  - Working prototype
    - Hsieh, S. S., Peng, M. V., May, C. A., Shunhavanich, P., Fleischmann, D., & Pelc, N. J. (2016). A prototype piecewise-linear dynamic attenuator. *Physics in Medicine & Biology*, *61*(13), 4974.
  - Fluence control models
    - Hsieh, S. S., & Pelc, N. J. (2014, March). Algorithms for optimizing CT fluence control. In *Medical Imaging 2014: Physics of Medical Imaging* (Vol. 9033, p. 90330M). International Society for Optics and Photonics.
- Hokpins group
  - Mathews, A. J., Gang, G., Levinson, R., Zbijewski, W., Kawamoto, S., Siewerdsen, J. H., & Stayman, J. W. (2017, March). Experimental evaluation of dual multiple aperture devices for fluence field modulated x-ray computed tomography. In *Medical Imaging 2017: Physics of Medical Imaging* (Vol. 10132, p. 101322O). International Society for Optics and Photonics.
- UW-Madison group
  - Implemented on a clinical MVCT scanner
    - Szczykutowicz, T. P., Hermus, J., Geurts, M., & Smilowitz, J. (2015). Realization of fluence field modulated CT on a clinical TomoTherapy megavoltage CT system. *Physics in Medicine & Biology*, *60*(18), 7245.
  - Prototype
    - Szczykutowicz, T. P., & Mistretta, C. A. (2014). Experimental realization of fluence field modulated CT using digital beam attenuation. *Physics in Medicine & Biology*, *59*(5), 1305.
- Toronto group
  - Bartolac, S., & Jaffray, D. (2013). Compensator models for fluence field modulated computed tomography. *Medical physics*, *40*(12), 121909.

Patient Specific Fluence Modulation

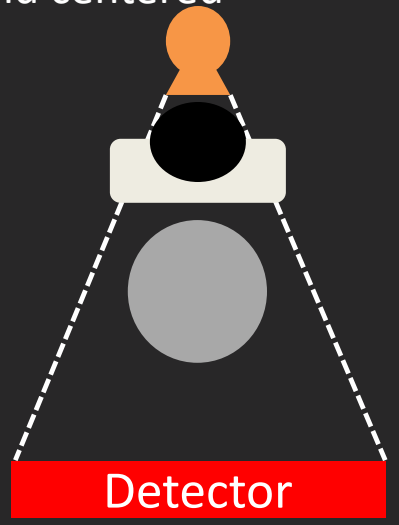
- Bowtie filter works perfectly when
  - Patient object is homogeneous and cylindrical
  - Patient is perfectly centered on isocenter
- Advantages
  - Decrease dose and scatter by ~50%[1]
  - Increase noise uniformity[2]

Low uniformity

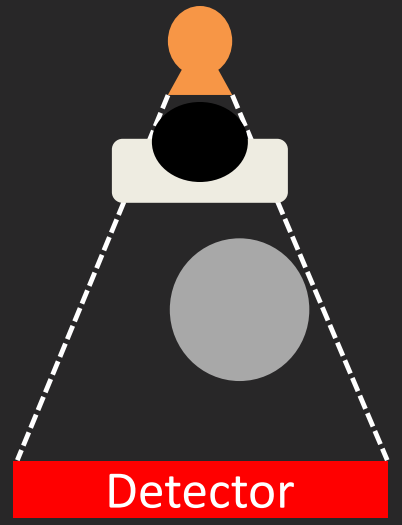


High uniformity

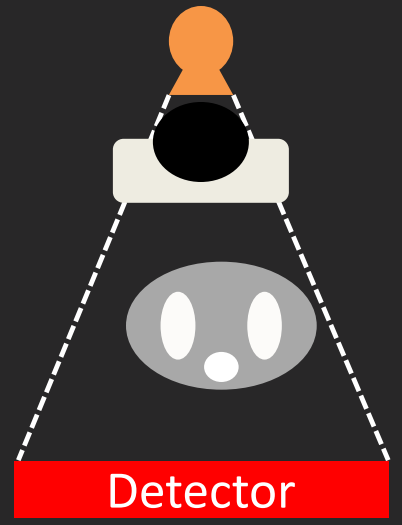
Homogeneous and centered



Homogeneous, not centered



Not homogeneous, not centered

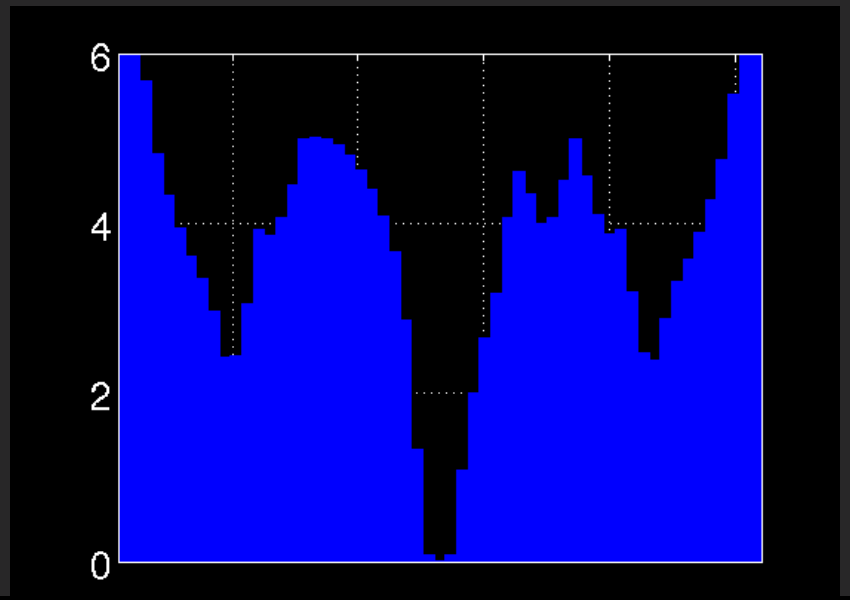


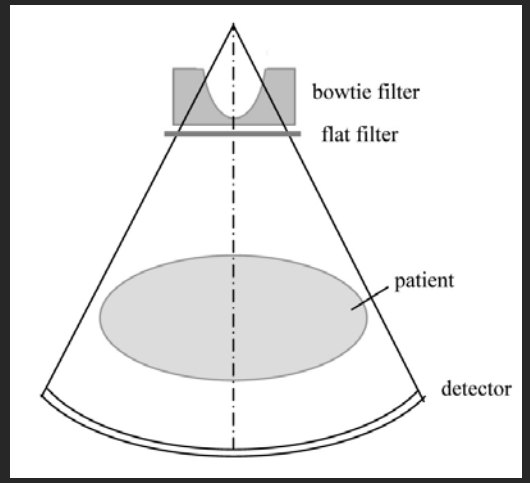
Can double surface dose! Can increase $CTDI_w$ by ~20%[2]

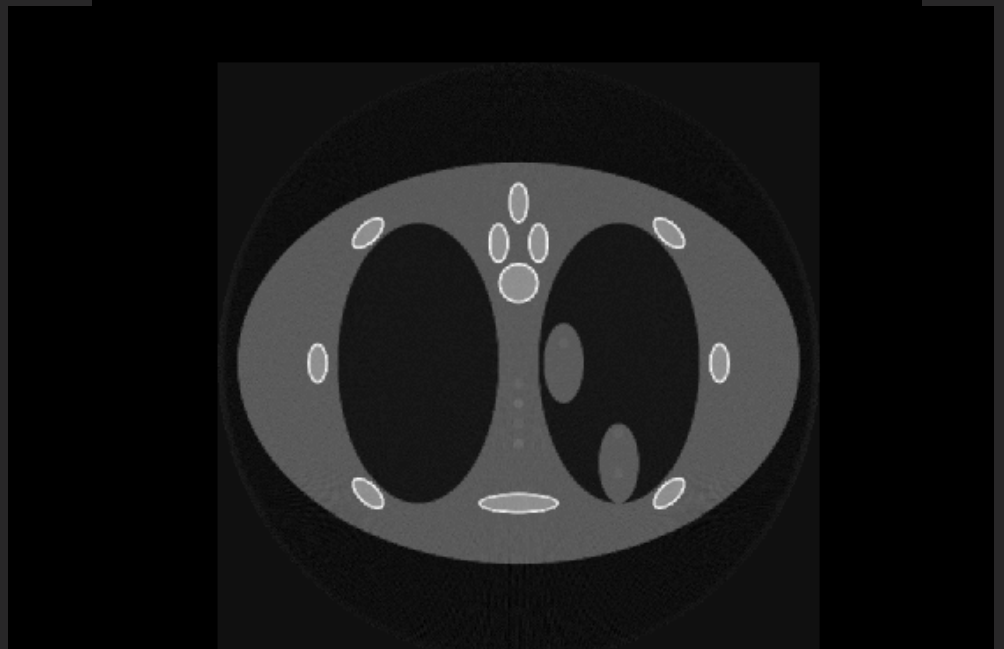
[1]Graham *et al.* "Compensators for dose and scatter management in CBCT" Med. Phys. **34** 2007

[2]Toth, T *et* al. "*The influence of patient centering on CT dose and image noise*" Med. Phy. **37(7)** 2007

Patient Specific Fluence Modulation

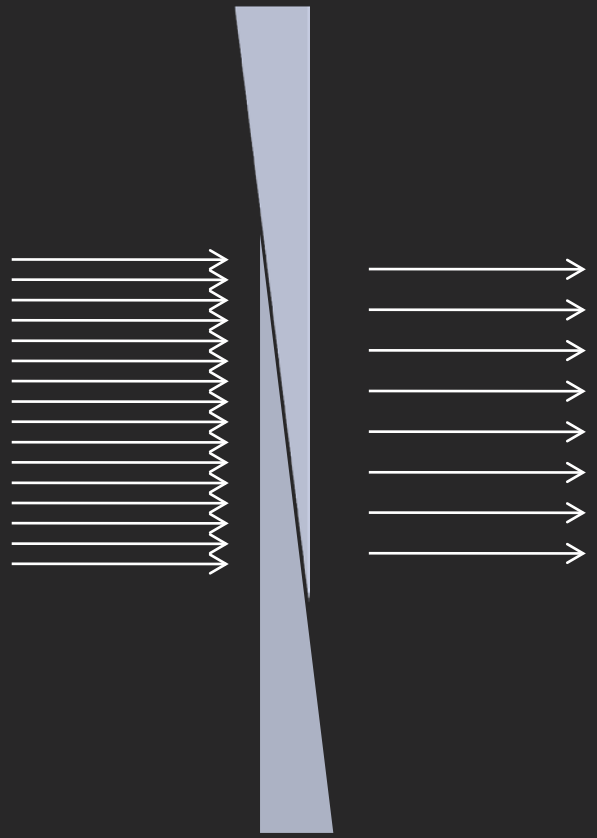




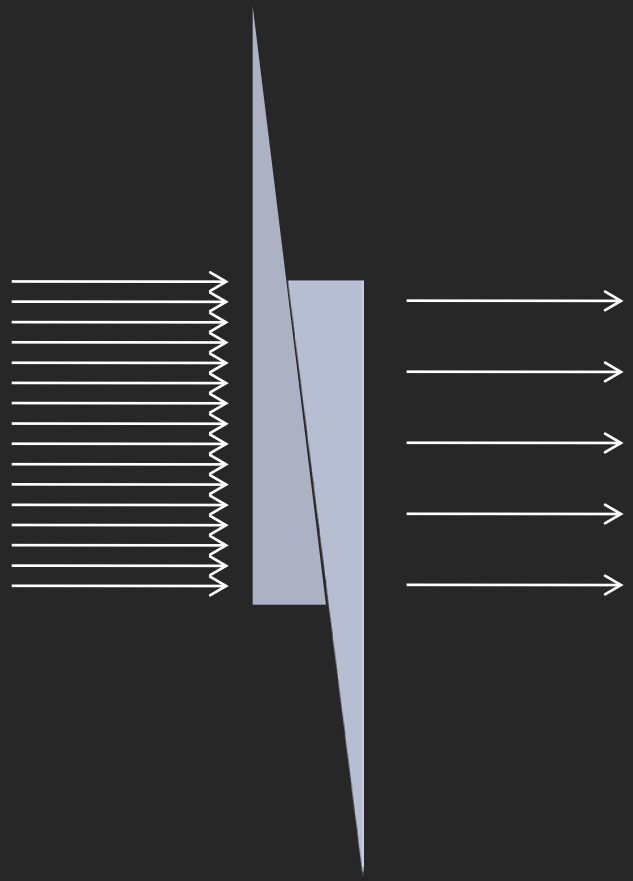


"Computed Tomography Principles, Design, Artifacts, and Recent Advances" by Jiang Hsieh

Patient Specific Fluence Modulation

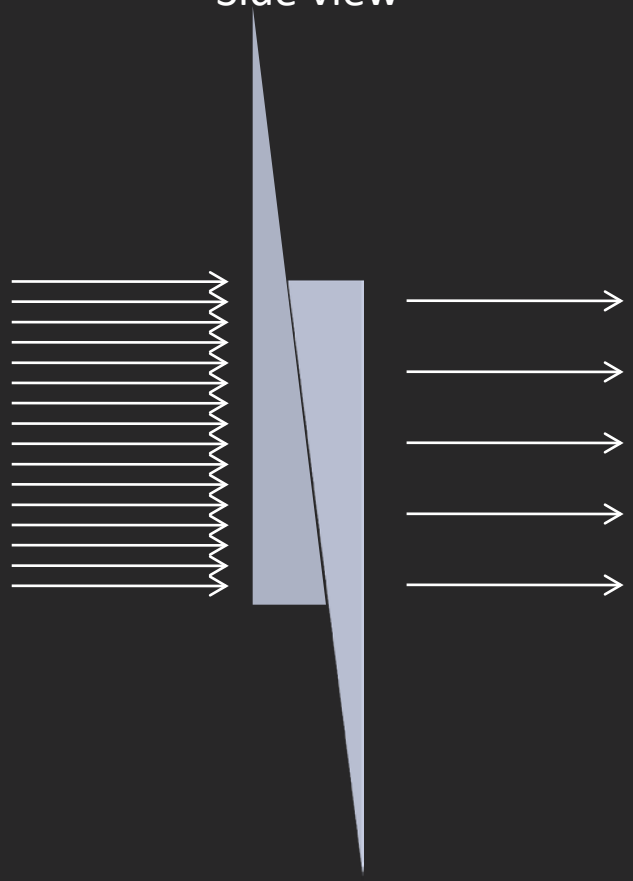


Patient Specific Fluence Modulation

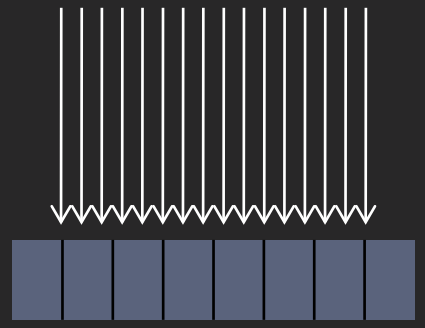


Patient Specific Fluence Modulation

Side view



View along fan beam



Putting a bunch of wedges together

Patient Specific Fluence Modulation

Physics in Medicine & Biology

PAPER

Experimental realization of fluence field modulated CT using digital beam attenuation

T P Szczykutowicz[1] and C A Mistretta[1,2,3]

Published 20 February 2014 • 2014 Institute of Physics and Engineering in Medicine
Physics in Medicine & Biology, Volume 59, Number 5

Article PDF

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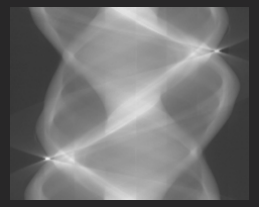
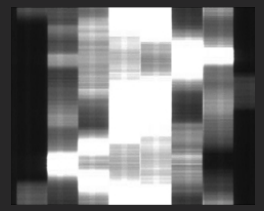
Abstract

Tailoring CT scan acquisition parameters to individual patients is a topic of much research in the CT imaging community. It is now common place to find automatically adjusted tube current options for modern CT scanners. In addition, the use of beam shaping filters, commonly called bowtie filters, is





Physics in Medicine & Biology

PAPER

A prototype piecewise-linear dynamic attenuator

Scott S Hsieh[1,2,4], Mark V Peng[3], Christopher A May[3], Picha Shunhavanich[3], Dominik Fleischmann[1] and Norbert J Pelc[1,3]

Published 10 June 2016 • © 2016 Institute of Physics and Engineering in Medicine
Physics in Medicine & Biology, Volume 61, Number 13

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Abstract

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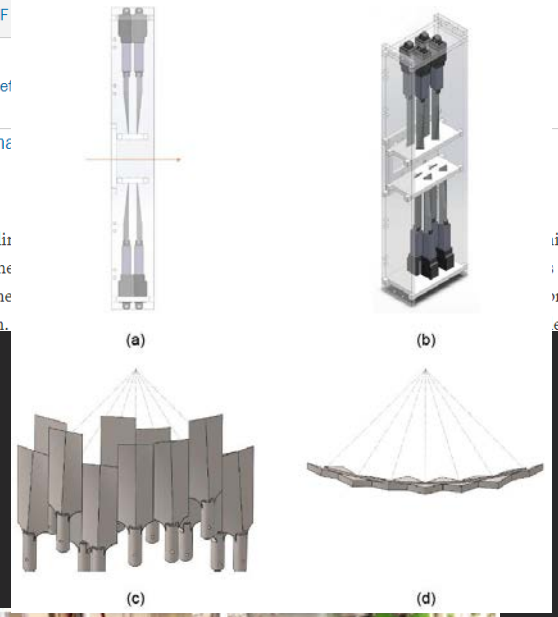

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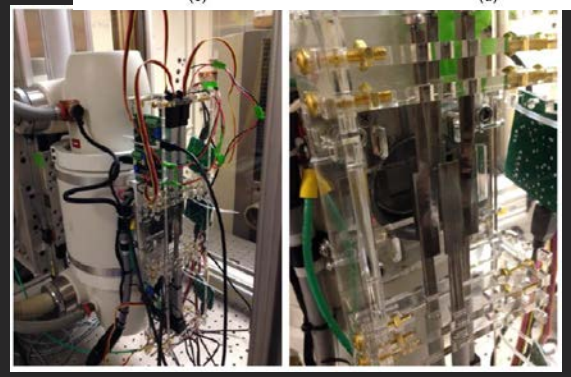

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22 March 2016

Fluence-field modulated x-ray CT using multiple aperture devices

J. Webster Stayman; Aswin Mathews; Wojciech Zbijewski; Grace Gang; Jeffrey Siewerdsen; Satomi Kawamoto; Ira Blevis; Reuven Levinson

Author Affiliations +

Proceedings Volume 9783, Medical Imaging 2016: Physics of Medical Imaging; 97830X (2016)
https://doi.org/10.1117/12.2214358
Event: SPIE Medical Imaging, 2016, San Diego, California, United States

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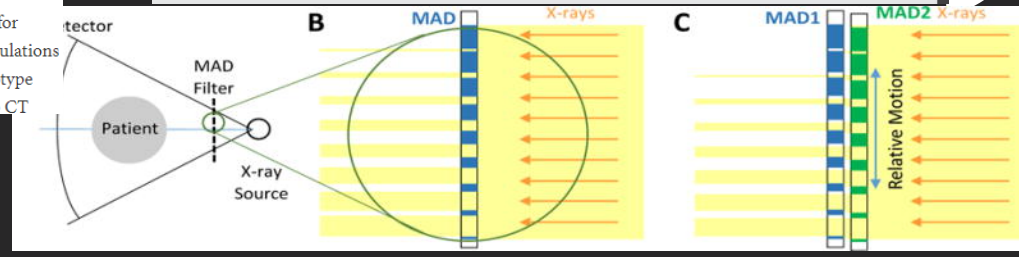
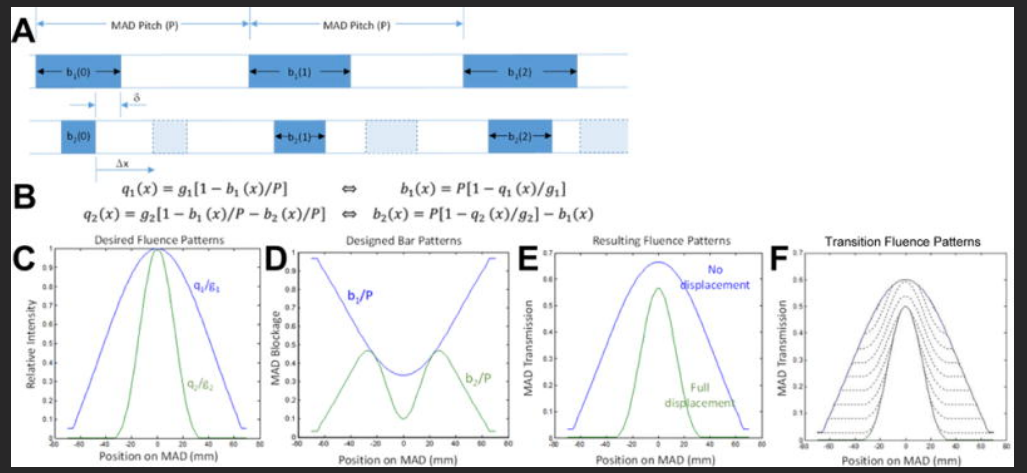
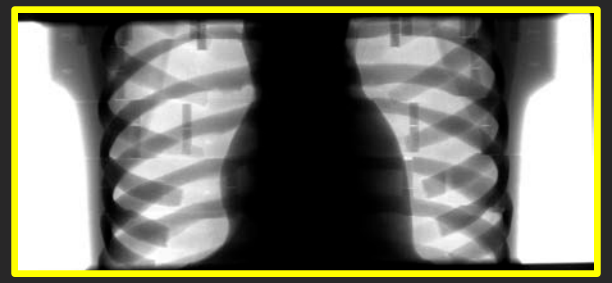


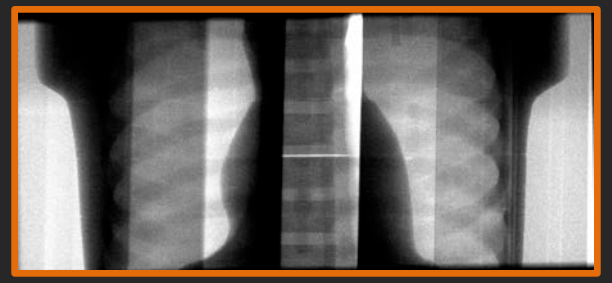


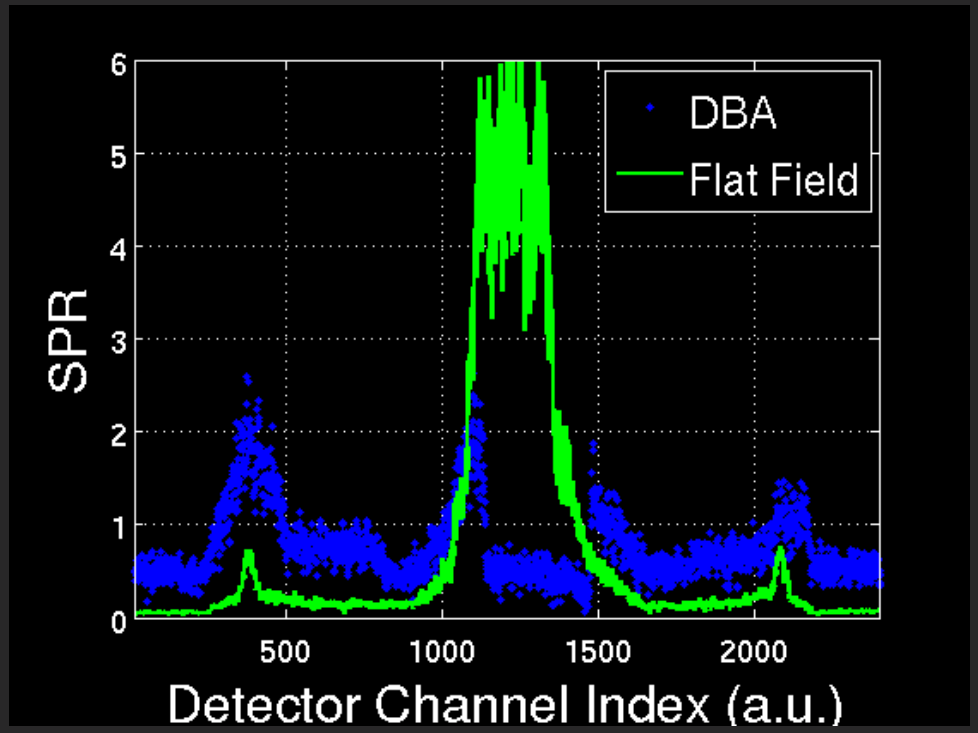
Patient Specific Fluence Modulation

No DBA

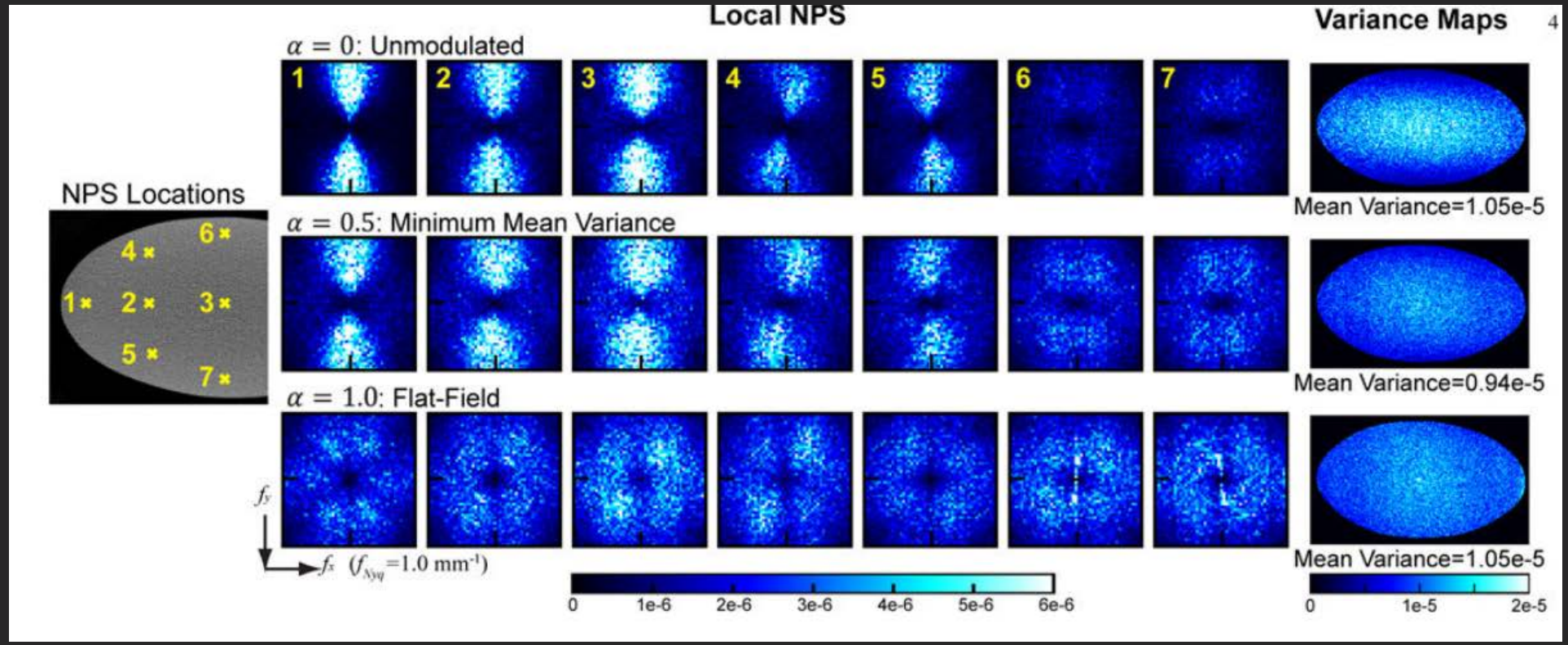


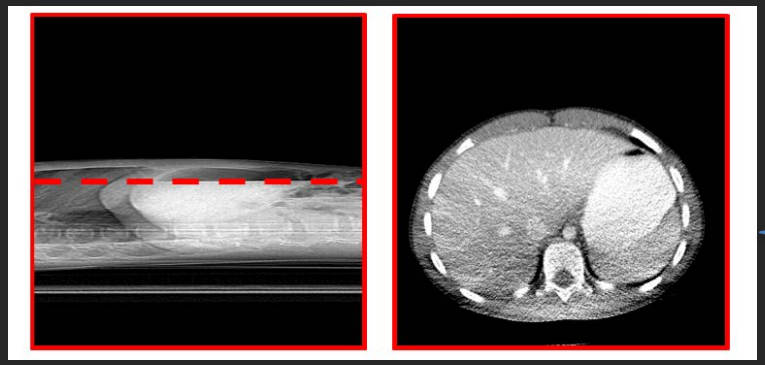
DBA





- Hopkins group- noise uniformity better with FFMCT relative to static bowtie

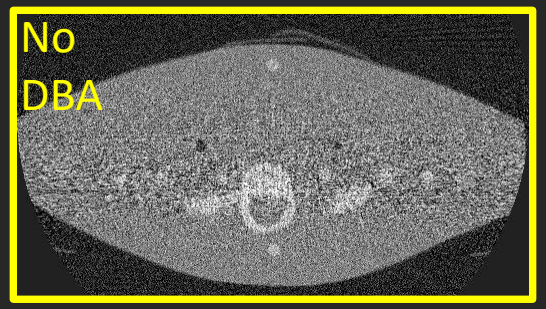




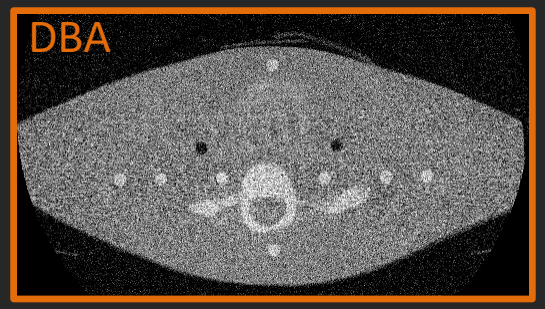
Can help us avoid situations like this, bad positioning caused large noise non uniformity

Patient Specific Fluence Modulation

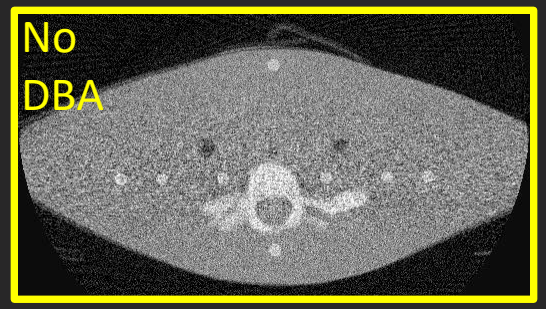
"full" dose



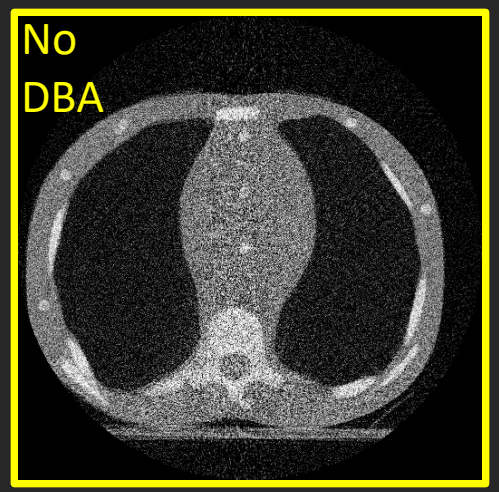
"full" dose



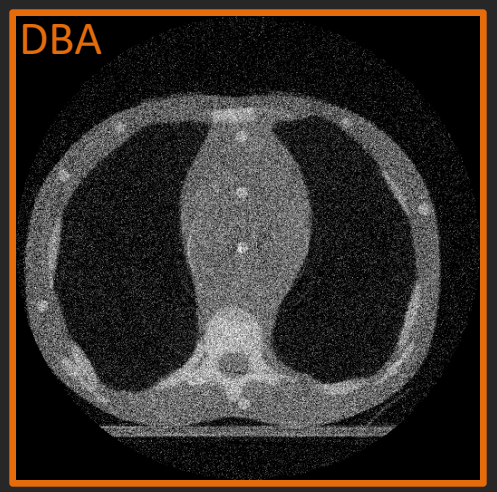
2 times higher dose



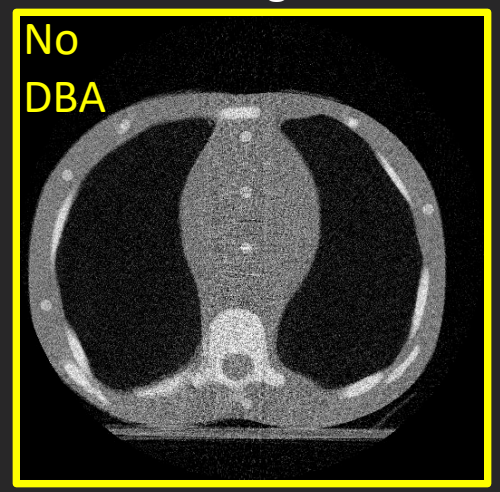
"full" dose



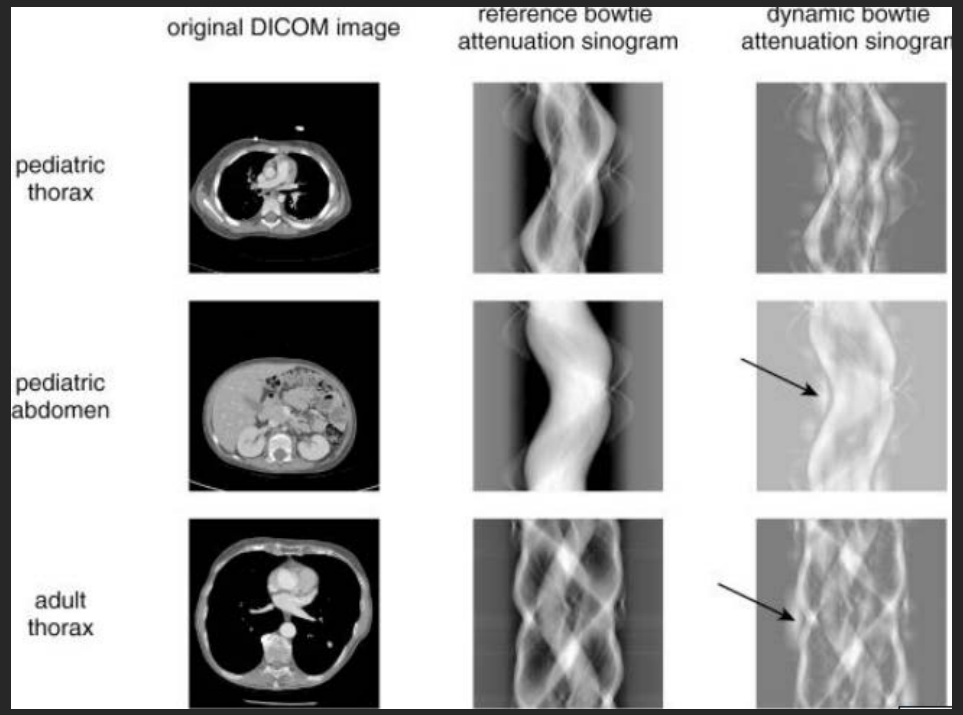
"full" dose

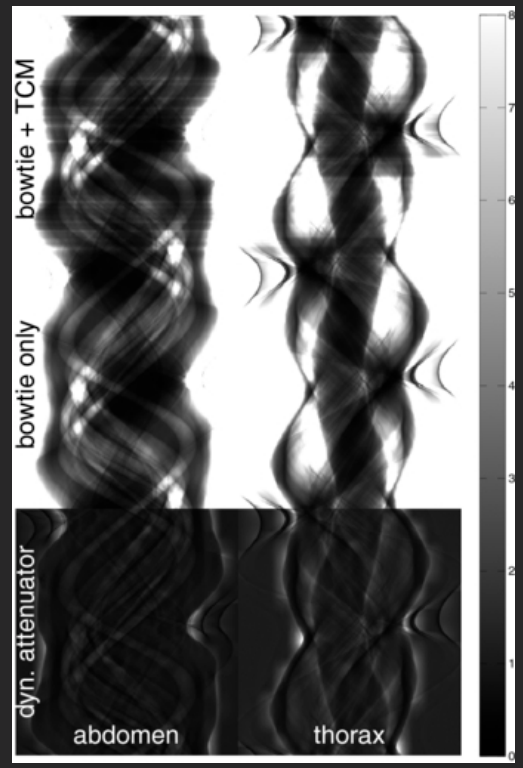


3.6 times higher dose



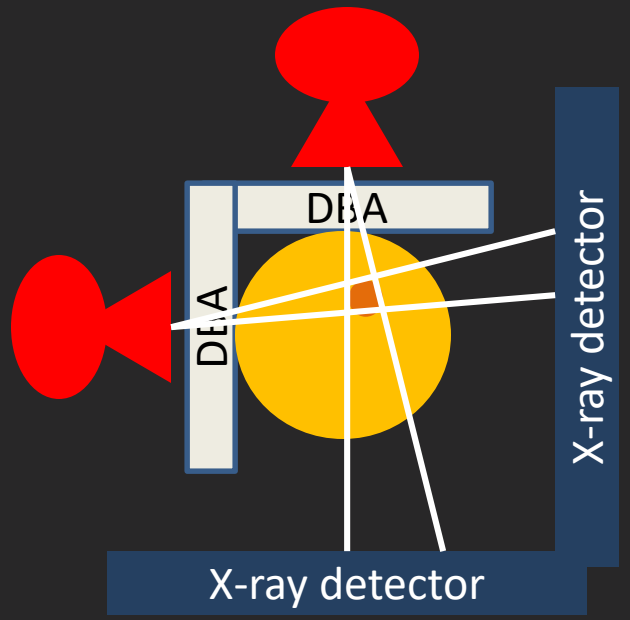
- Stanford group (Hsieh and Pelc) have looked at how FFMCT can help with photon counting CT via reducing dynamic range needs of detector

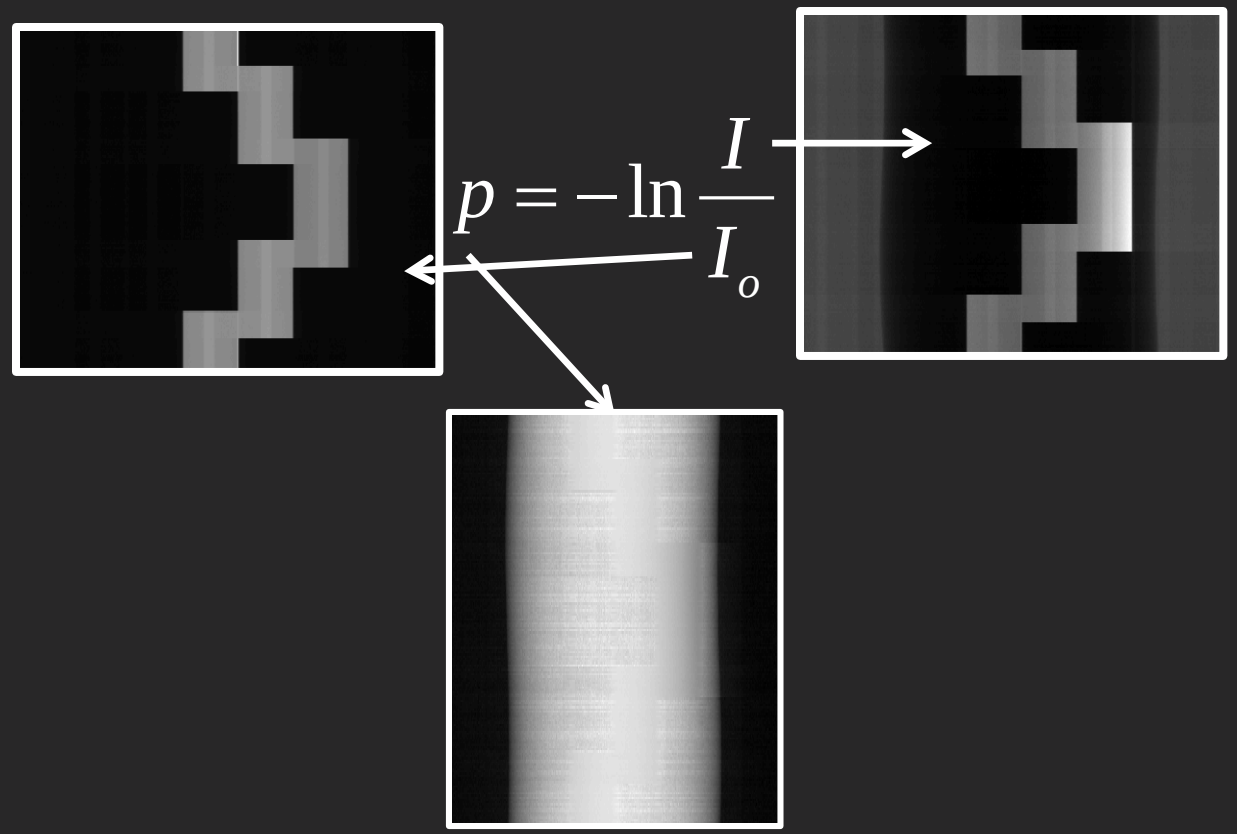




Patient Specific Fluence Modulation

- What about for VOI imaging?
  - Need to predefine a SNR “prescription” for the image
  - Then the required wedge positions must be calculated
- Our first implementation
  - Max signal (minimum wedge thickness) to where ROI intersects wedgelet, minimum signal (maximum wedge thickness) otherwise

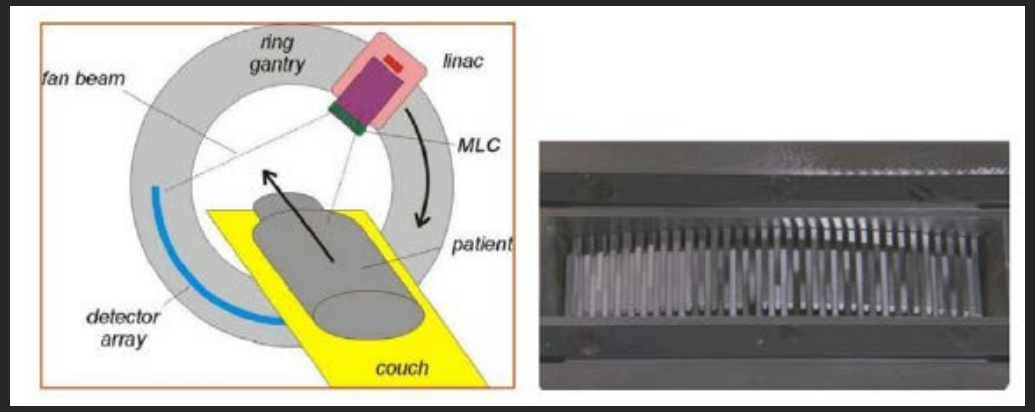




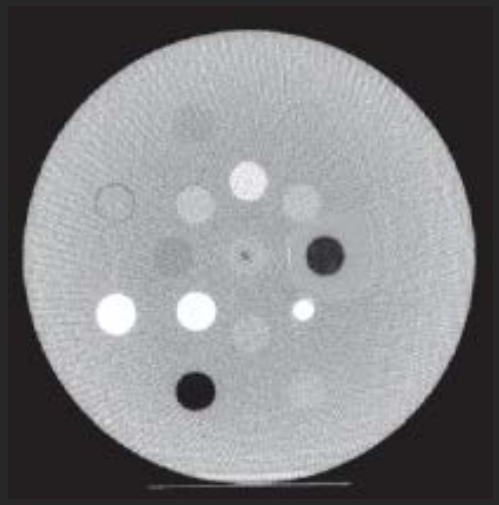
Patient Specific Fluence Modulation

- Clinicians often do not need good image quality everywhere!
- Use FFMCT to provide region specific SNR enhancement/suppression

FFMCT implemented on a clinical MVCT scanner



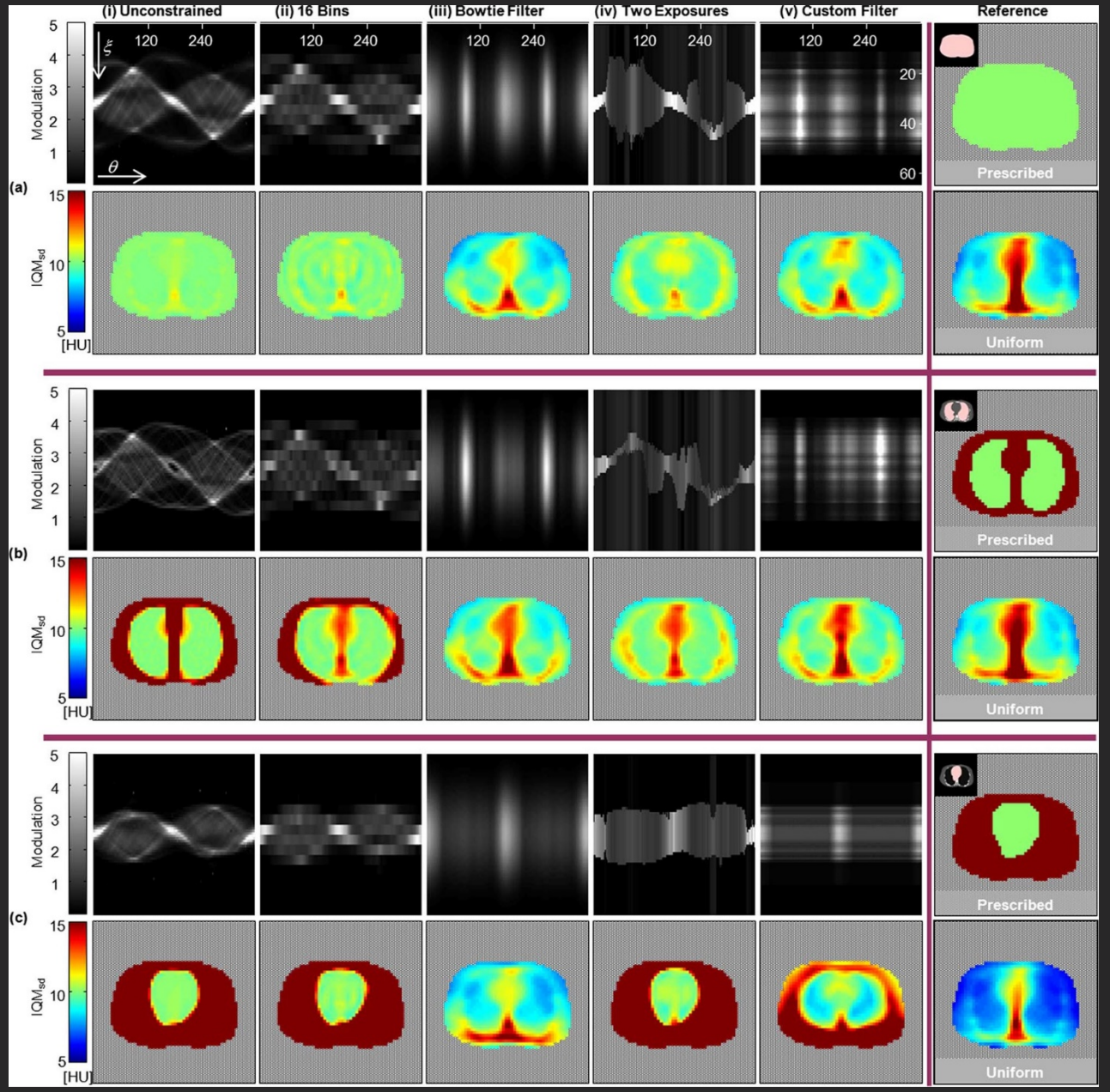
Tomotherapy scanners already have a set of beam modulators, so we used them to do FFMCT!



Scan focused on “VOI 4” is shown here

Patient Specific Fluence Modulation

- Toronto group looked at VOI imaging using different types of fluence modulation devices



MEDICAL PHYSICS

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Steven Bartolac, David Jaffray

First published: 18 November 2013 | https://doi.org/10.1118/1.4829513 | Cited by: 7

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- FFMCT can be thought of as a way to actually weight data during the collection process, in stead of post acquisition during reconstruction like one can do with noise weighting schemes in an iterative/non-linear reconstruction algorithm (D term below weights data based on its signal strength)
  - FFMCT would allow one to increase signal levels for highly attenuating rays OR
  - FFMCT would allow one to give up on highly attenuating rays and give them little to no dose

$$\hat{\mu} = \arg\min_{\mu} \left\{ \frac{1}{2} (p - A\mu)^T D (p - A\mu) + G(\mu) \right\}$$

Thanks!

Feel free to contact me at tszczykutowicz@uwhealth.org

Patient Specific Fluence Modulation

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