CT Simulation Optimization Strategies in Radiation Oncology

Timothy P. Szczykutowicz PhD, DABR

@Prof_TimStick

Associate Professor

University of Wisconsin Madison Departments of Radiology, Medical Physics and Biomedical Engineering

Caution, these slides may be edited before I give the talk, but in large part this content is what you will see me presenting at the meeting. Thanks!

@Prof_TimStick's Rad Onc Naughty list

- Using fixed mA because you are afraid of changing CT number
- Not using CT contrast agents
- If you are using contrast agents, using fixed time delays or fixed contrast bolus amounts
- Believing CT number can be trusted at fixed kV…

I want you to
get your SAM
question
correct

@Prof_TimStick says out of Reconstruction Kernel, Beam energy, Bowtie filter size and composition, and Patient positioning within the gantry, <u>beam energy</u> **will have the biggest affect on CT number**

Chapter 9 "Beam Energy, CT Number, and Dual Energy CT". The CT Handbook: Optimizing Protocols for Today's Feature-Rich Scanners. Medical Physics Publishing 2020.

I want you to get your SAM question correct

@Prof_TimStick says if you don't want to worry about beam energy being changed by your CT scanner, turn off your scanner's automatic beam energy selection AEC (CarekV, KVAssist, SurekV)

Chapter 7 Automatic Exposure Control. The CT Handbook: Optimizing Protocols for Today's Feature-Rich Scanners. Medical Physics Publishing 2020.

outline

- CT Number 101
- AEC in CT

What is CT number?

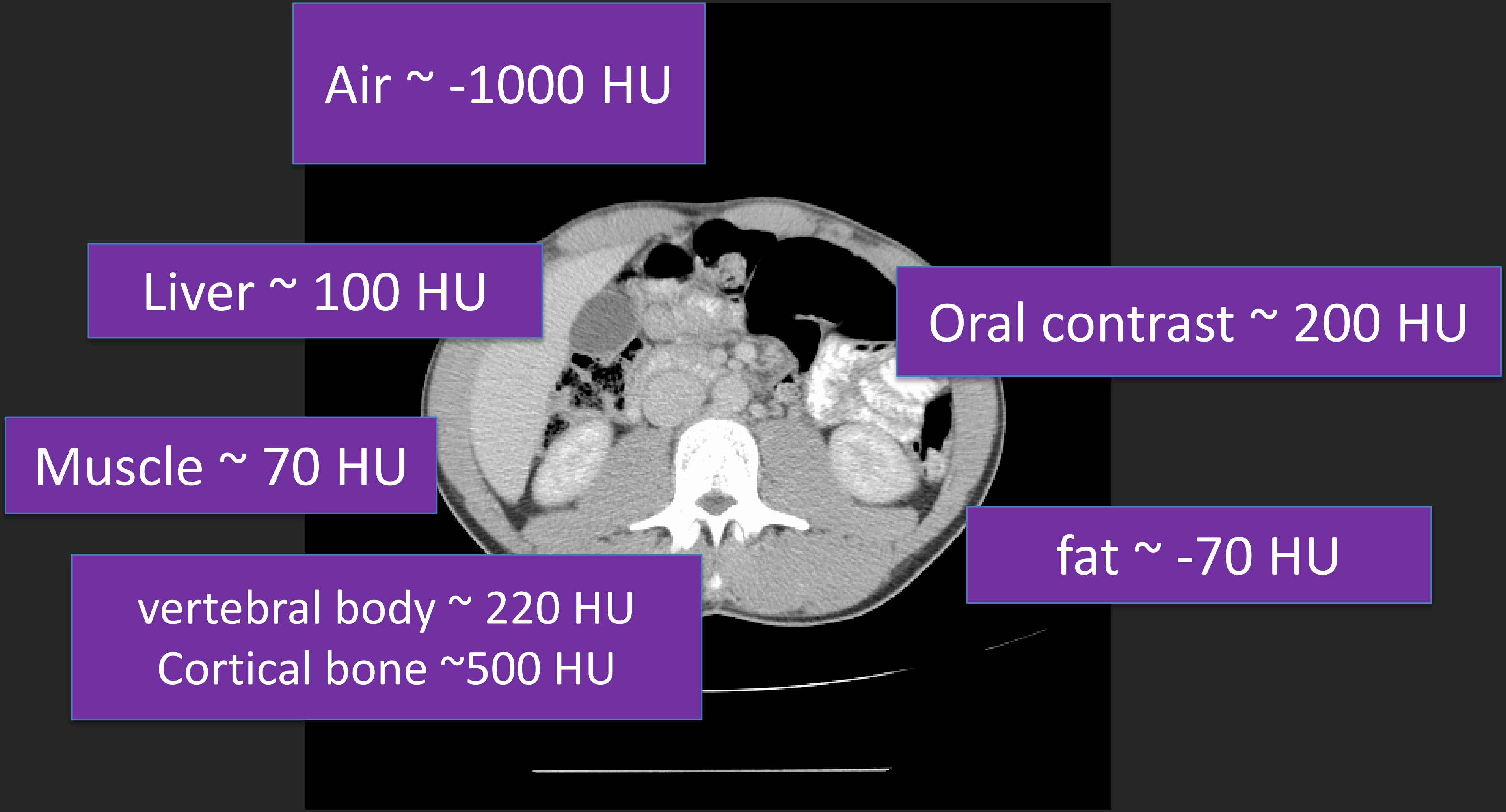
- Pixels represent attenuation
- Places with low attenuation are dark
- Places with high attenuation are bright

CT scan of an extremely fit 27 year old male, current Associate Professor of Radiology

Air is bad at stopping x-rays, so it gets a low attenuation value and a corresponding low HU number

Oral contrast is good at stopping x-rays, so it gets a high attenuation value and a corresponding high HU number

CT scan of an extremely fit 27 year old male, current Associate Professor of Radiology

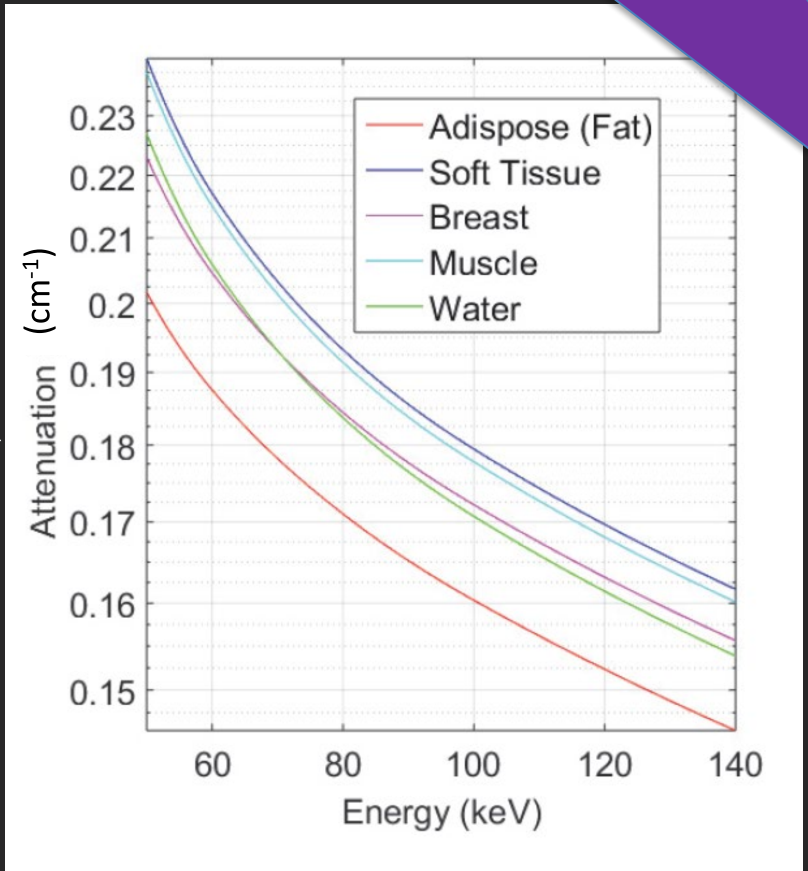


CT scan of an extremely fit 27 year old male, current Associate Professor of Radiology

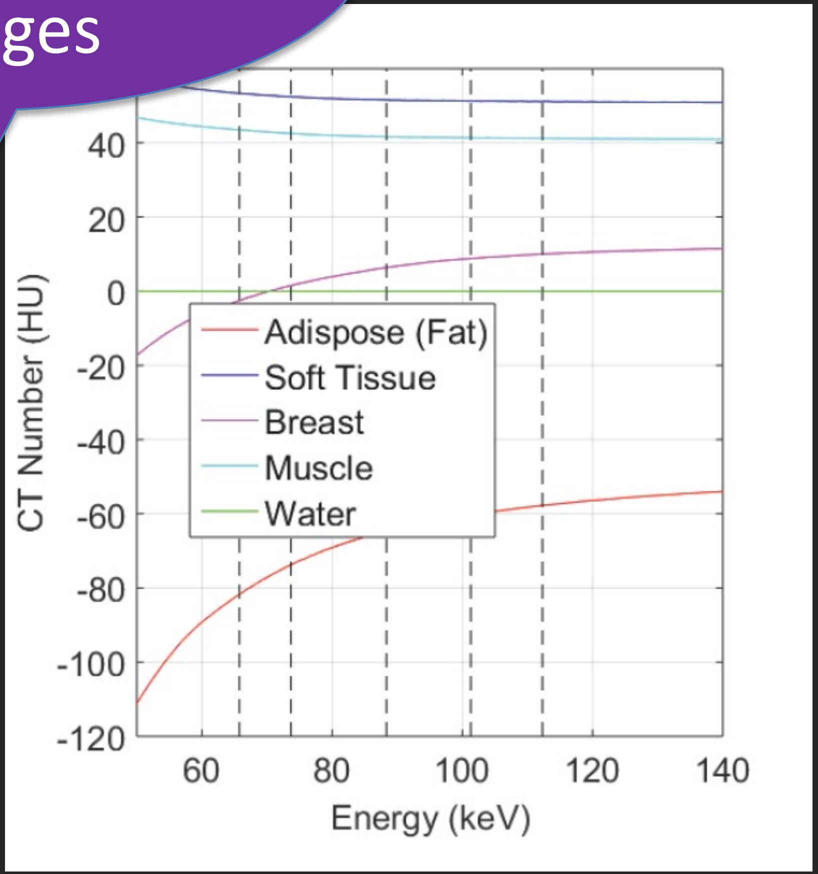
This makes HU tell us how attenuating something is relative to water

This makes little changes into big changes

μ

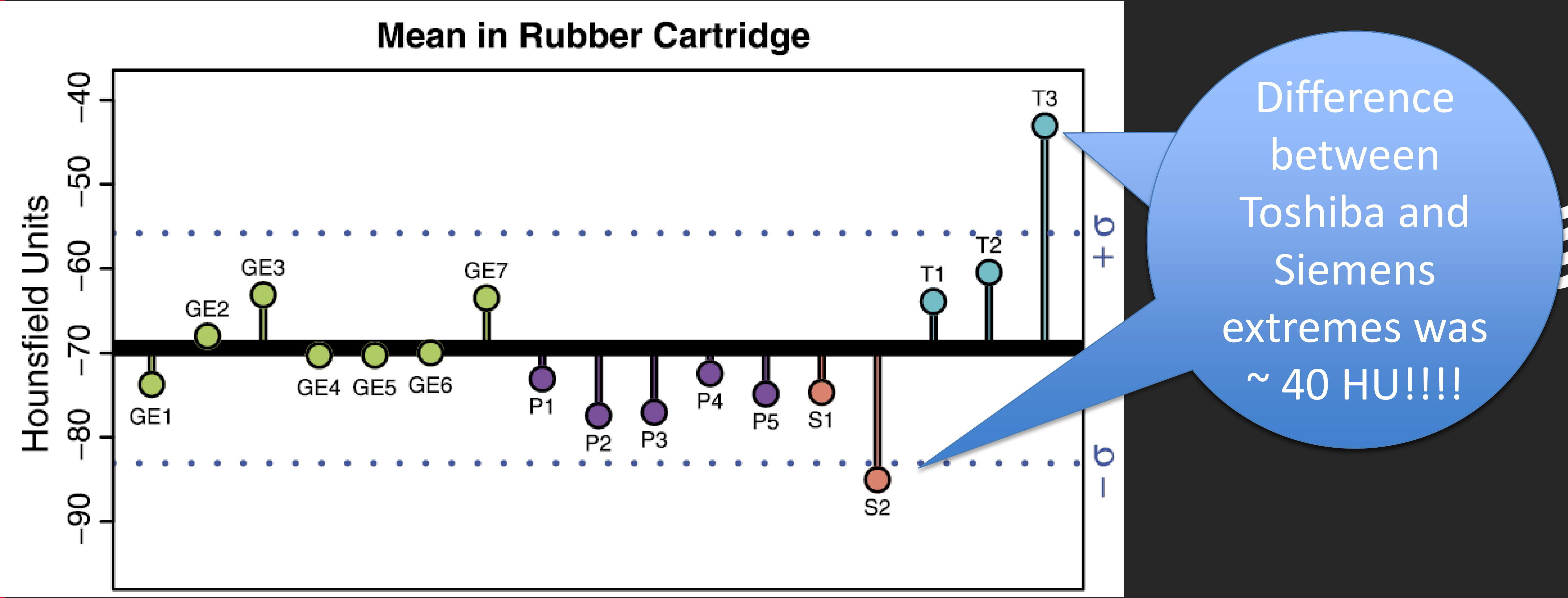


$$\text{HU} = \frac{\mu - \mu_{water}}{\mu_{water}} * 1000$$



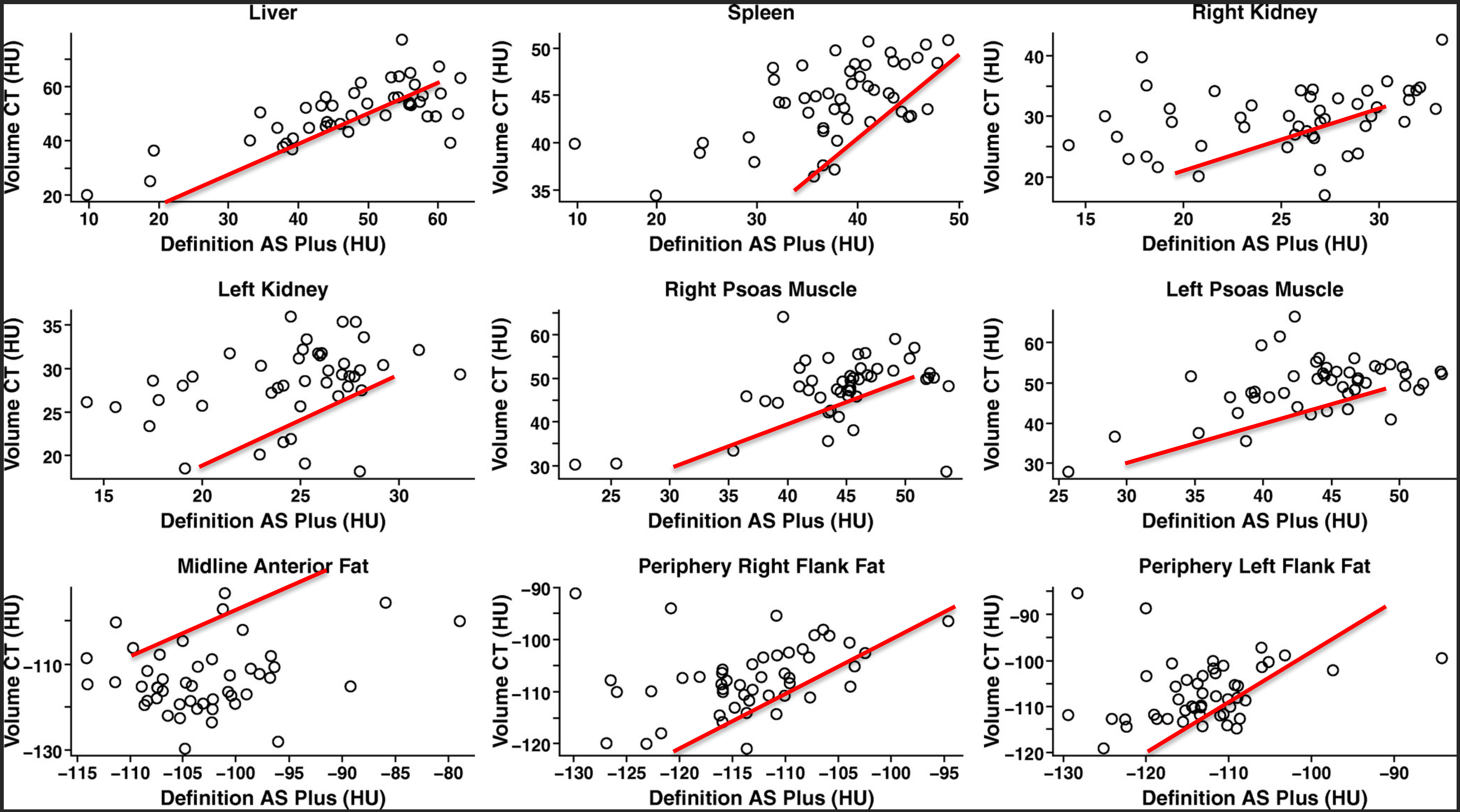
“The CT Handbook: Optimizing Protocols for Today’s feature-rich scanners” By Tim Szczykutowicz. Medical Physics Publishing 2020

CT number changes with vendor



Mackin, Dennis, et al. "Measuring CT scanner variability of radiomics features." *Investigative radiology* 50.11 (2015): 757.

GE



Siemens

Lamba, Ramit, et al. "CT Hounsfield numbers of soft tissues on unenhanced abdominal CT scans: variability between two different manufacturers' MDCT scanners." *American Journal of Roentgenology* 203.5 (2014): 1013-1020.

In conclusion, our study shows that Hounsfield unit measurements of unenhanced soft tissues in the abdomen vary between MDCT scanners of two different manufacturers. In view of our results and those of prior investigators, we think that established absolute Hounsfield unit thresholds that are currently used for CT characterization of renal lesions and adrenal nodules on unenhanced CT can result in mischaracterization of these lesions. We propose that, for tissue characterization on unenhanced CT that depends on absolute CT attenuation values, either the use of dedicated calibration phantoms or scanner- and convolution kernel–specific Hounsfield unit thresholds may need to be investigated for the modern MDCT scanners in clinical use. For renal and adrenal masses, the risk of misdiagnosis is greater for a malignant than for a benign lesion. Although Hounsfield characterization of tissues remains and will continue to be an important and effective decision-making tool in clinical CT, it is important for radiologists to be aware of these variations. Caution is thus advised when using absolute CT numbers to characterize masses on unenhanced CT and, if appropriate and warranted, further characterization using other methods should be considered. As with any other test result, CT Hounsfield unit value measurements should not be interpreted in a vacuum. Clinical data, together with other morphologic characteristics and the relative risk-benefit and cost of additional workup, must be considered in individual cases.

Lamba, Ramit, et al. "CT Hounsfield numbers of soft tissues on unenhanced abdominal CT scans: variability between two different manufacturers' MDCT scanners." *American Journal of Roentgenology* 203.5 (2014): 1013-1020.

CT number changes with kV

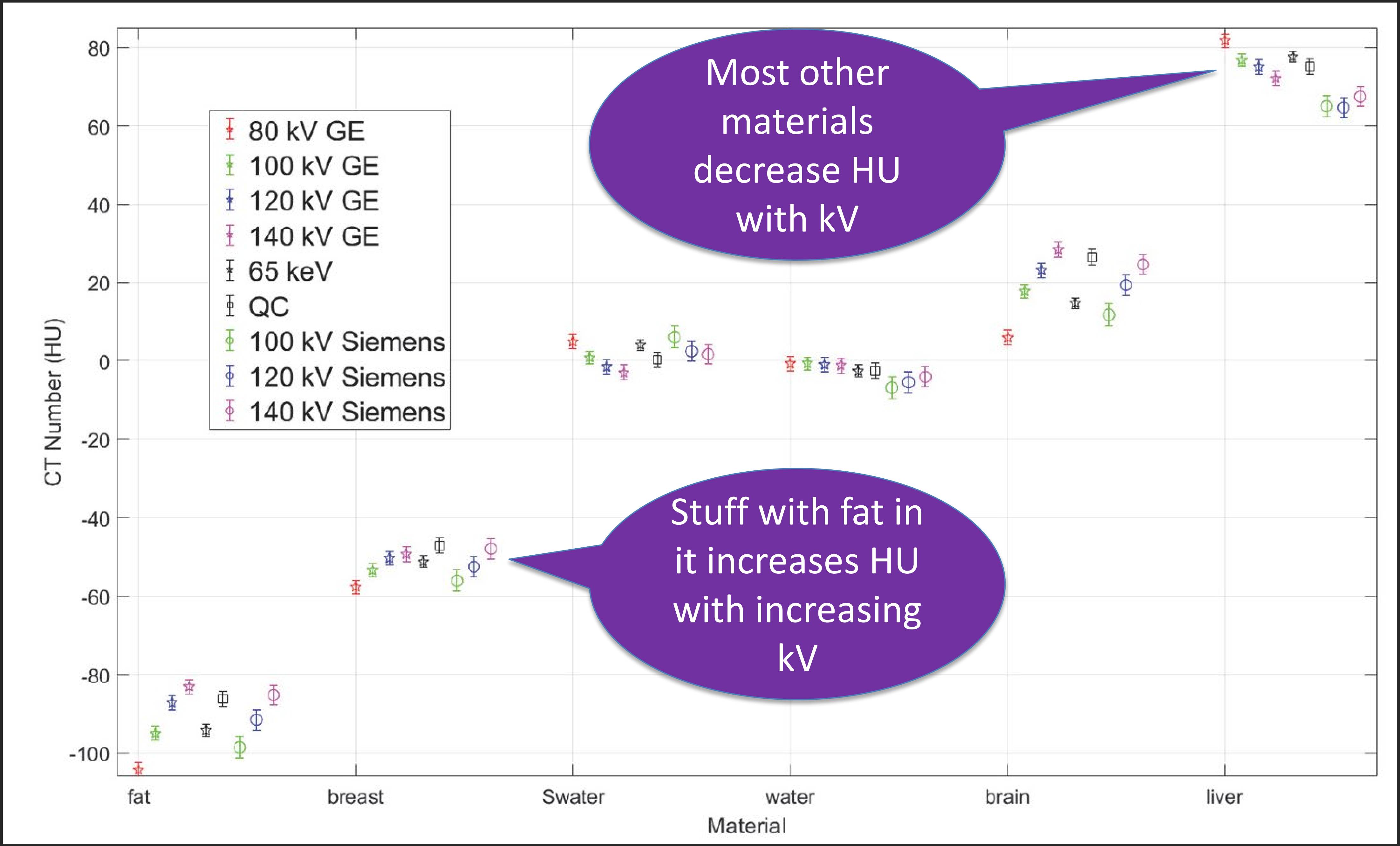
$$HU = \frac{\mu - \mu_{water}}{\mu_{water}} * 1000$$

- We normalize attenuation coefficient to that of water
- This does not take away energy dependence of CT number!

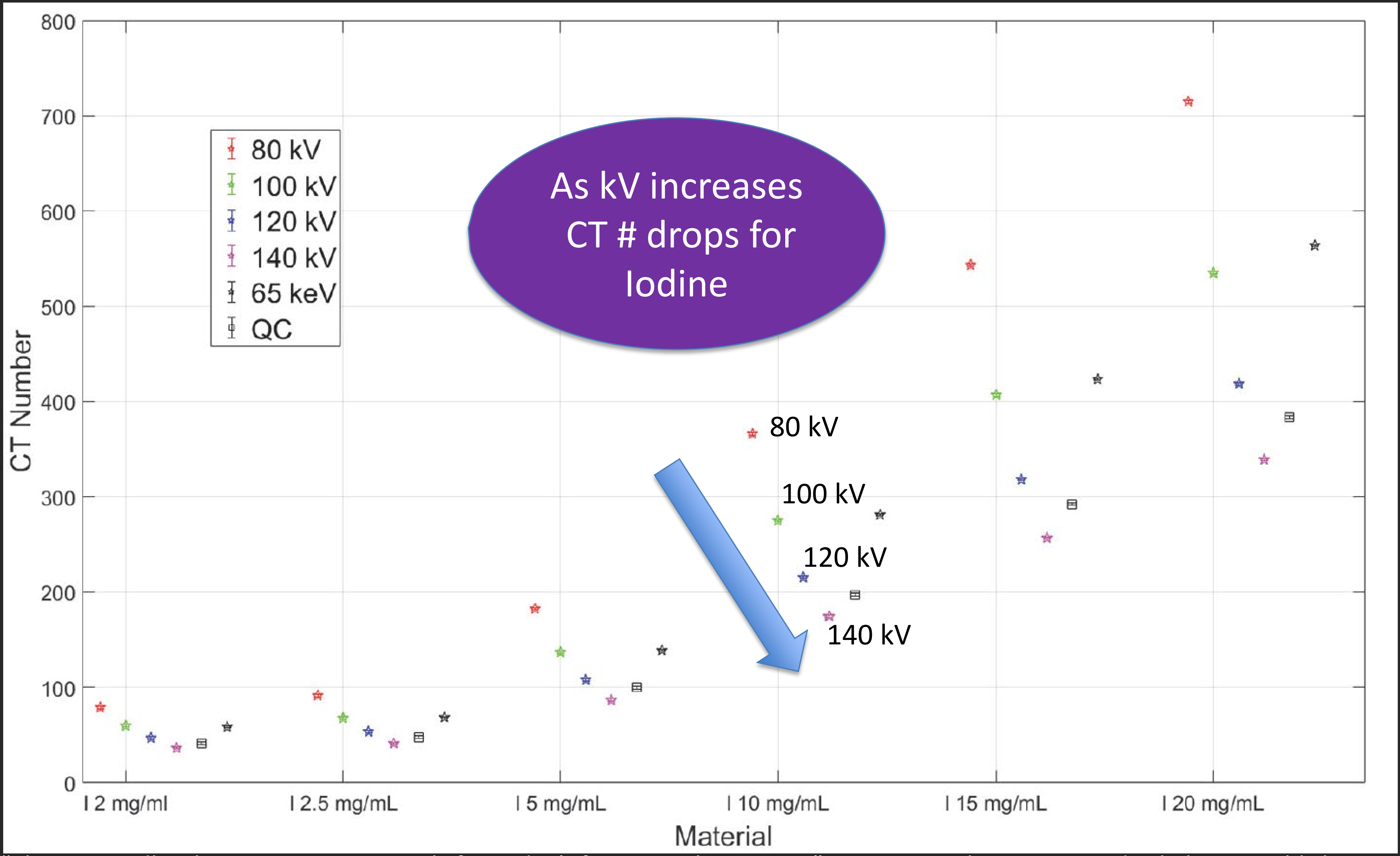
$$\mu(E) = k_1 * PE(E) + k_2 * CE(E)$$

Photoelectric effect depends on energy

Compton Effect depends on energy

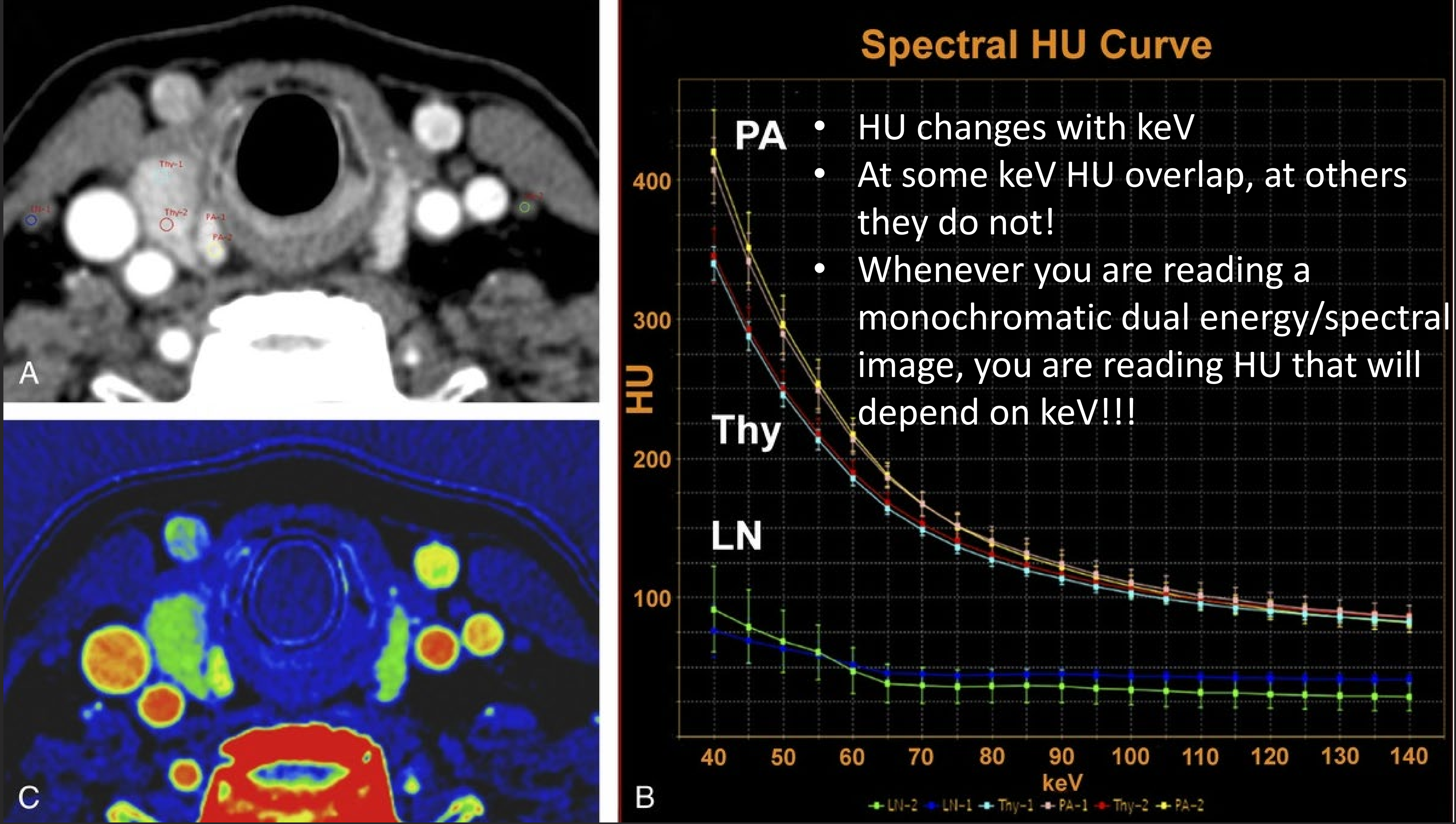


"The CT Handbook: Optimizing Protocols for Today's feature-rich scanners" By Tim Szczykutowicz. Medical Physics Publishing 2020



“The CT Handbook: Optimizing Protocols for Today’s feature-rich scanners” By Tim Szczykutowicz. Medical Physics Publishing 2020

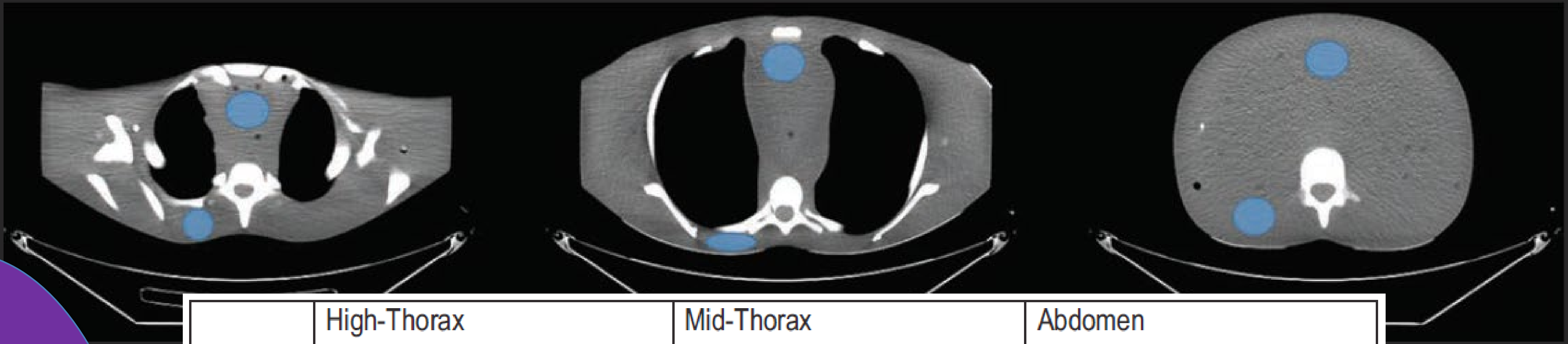
CT number changes with keV



- HU changes with keV
- At some keV HU overlap, at others they do not!
- Whenever you are reading a monochromatic dual energy/spectral image, you are reading HU that will depend on keV!!!

Forghani, Reza, et al. "Dual-energy CT characteristics of parathyroid adenomas on 25-and 55-second 4D-CT acquisitions: preliminary experience." *Journal of computer assisted tomography* 40.5 (2016): 806-814.

CT number changes with position



Even on the same scanner, just moving the patient up/down changes CT number!

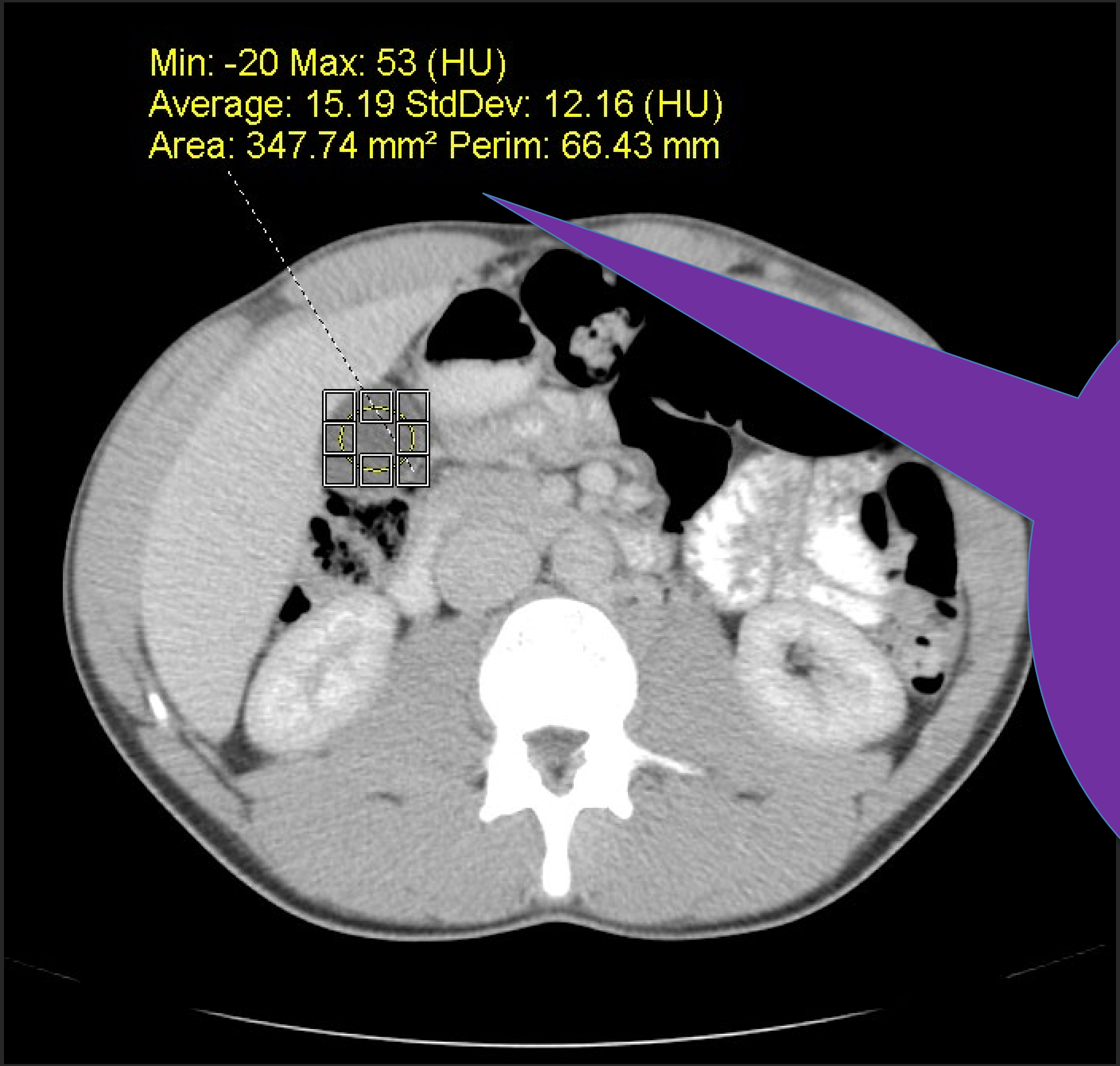
	High-Thorax				Mid-Thorax				Abdomen			
	Anterior		Posterior		Anterior		Posterior		Anterior		Posterior	
Position*	Mean	Noise	Mean	Noise	Mean	Noise	Mean	Noise	Mean	Noise	Mean	Noise
-10 cm	10±13	17±2	23±9	28±3	-2±1	9±1	0±9	25±2	-8±1	9±1	20±2	23±1
-6 cm	12±6	15±4	13±7	21±1	-2±2	8±1	-16±3	15±1	-6±1	9±1	5±3	16±1
-4 cm	0±12	13±3	6±4	15±1	-2±2	9±1	-8±5	14±2	-4±1	9±1	1±4	13±1
0 cm	8±9	13±3	-9±8	12±1	1±1	9±1	-10±6	12±2	-1±1	9±1	-3±2	12±1
4 cm	12±9	12±1	-7±3	12±2	1±2	11±1	-15±5	12±3	2±2	11±1	-8±2	11±1
6 cm	13±4	13±2	-13±3	12±2	2±2	12±1	-20±5	12±3	7±2	13±1	-9±4	11±1
10 cm	19±12	20±2	-15±6	11±1	5±1	15±1	-23±2	13±2	9±2	16±2	-10±4	12±1

Highlight key

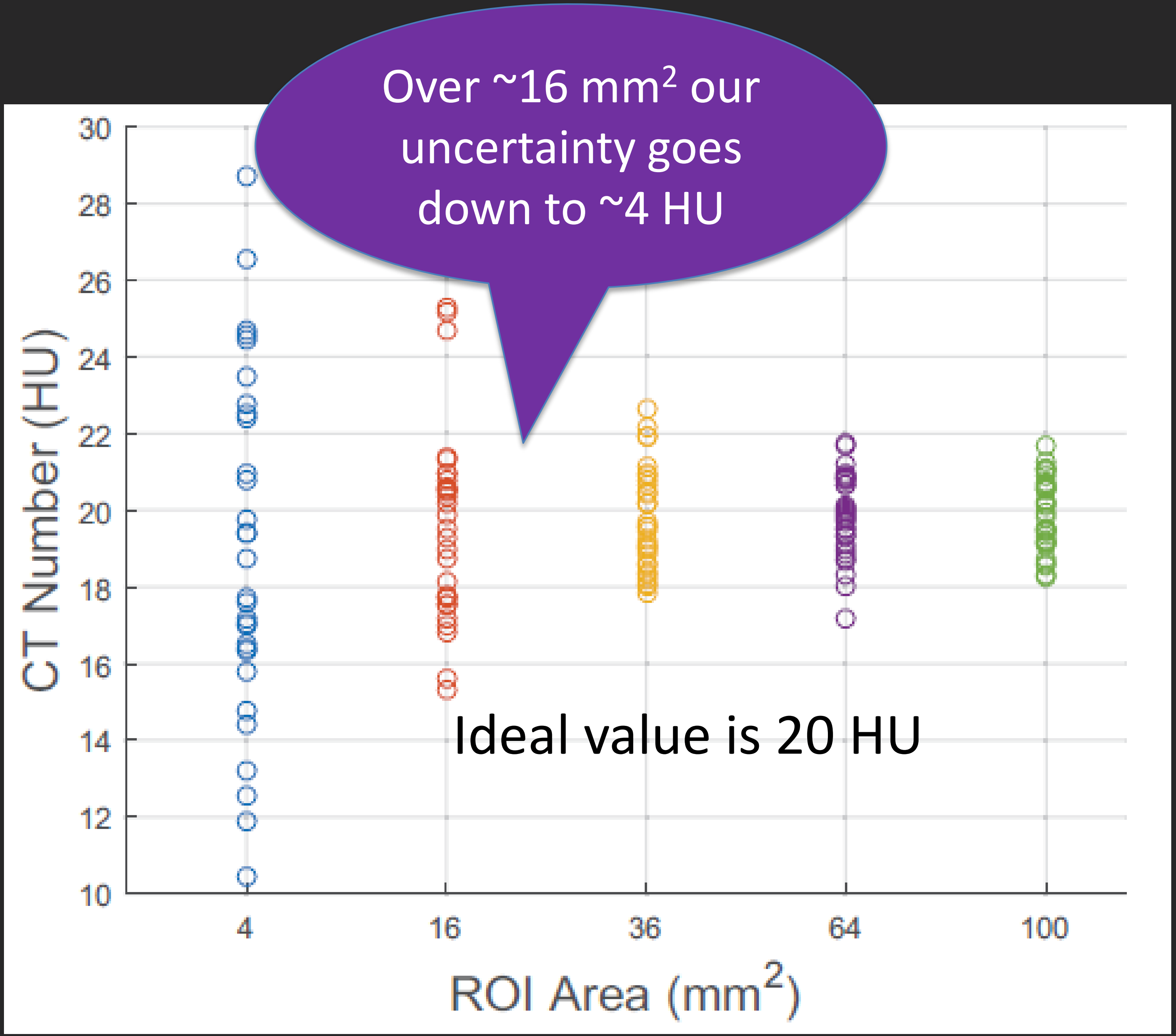
5-9 HU change
10-19 change
>=20 change

Szczykutowicz, Timothy P., Andrew DuPlissis, and Perry J. Pickhardt. "Variation in CT number and image noise uniformity according to patient positioning in MDCT." *American Journal of Roentgenology* 208.5 (2017): 1064-1072.

So my ROI has a high SD, can I trust it…?

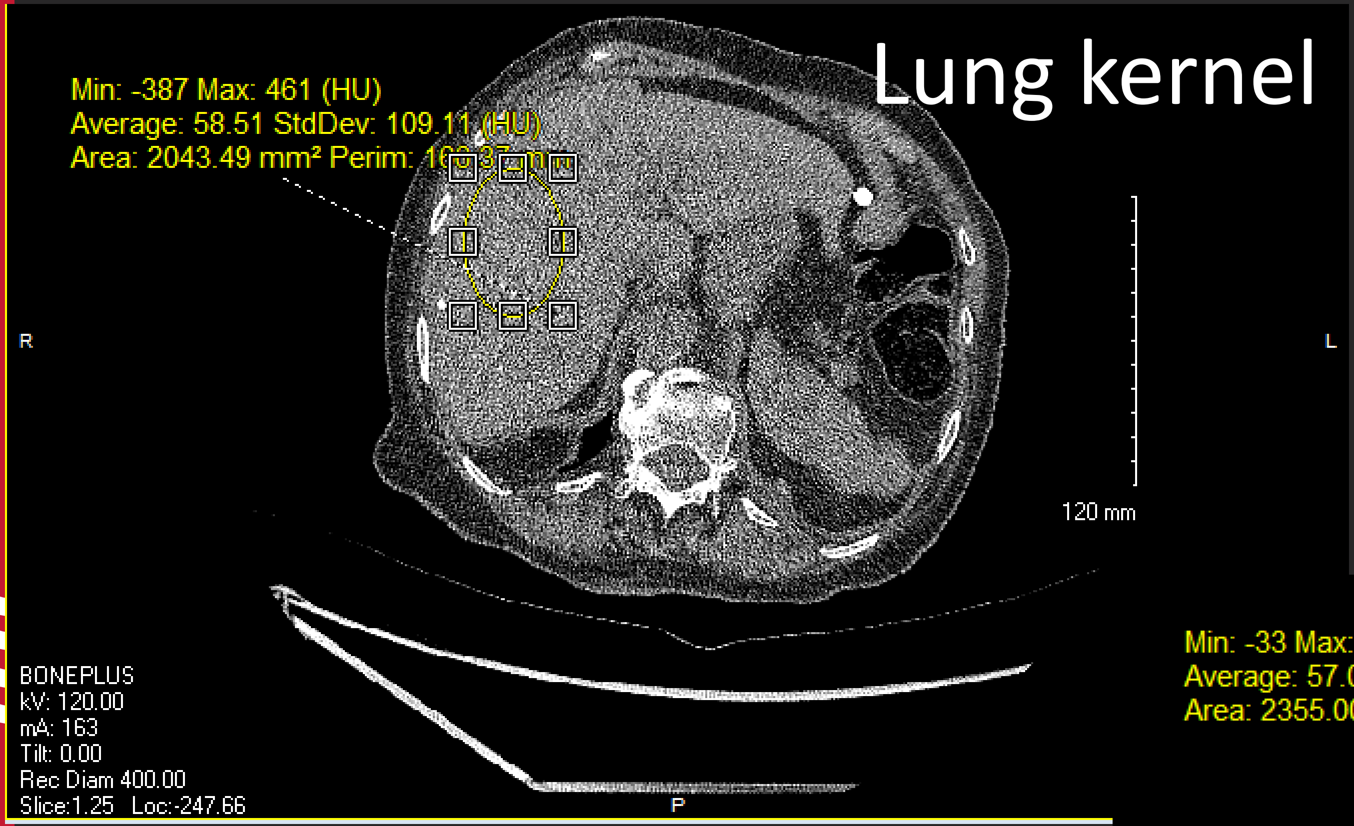


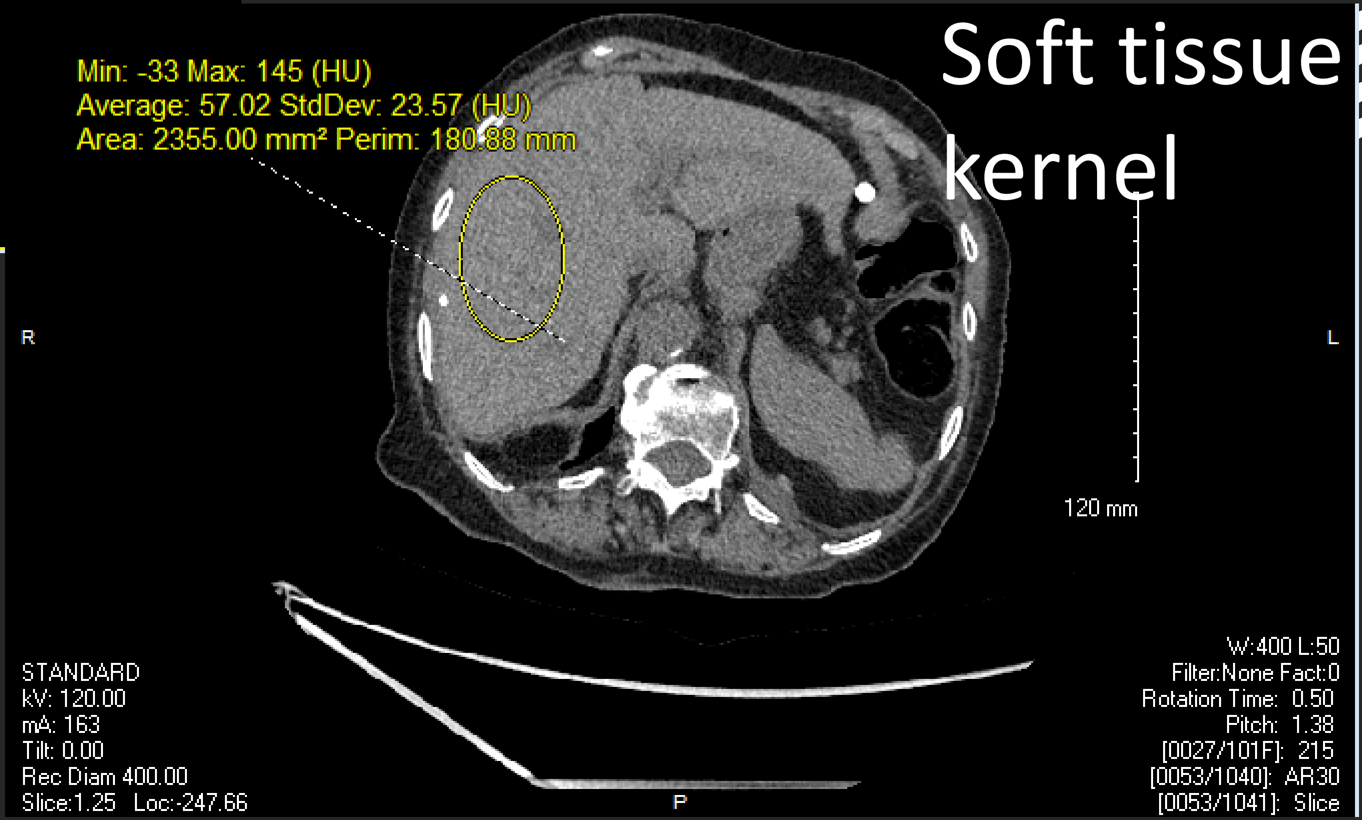
Can we trust a measurement where the noise is almost equal to the mean…?



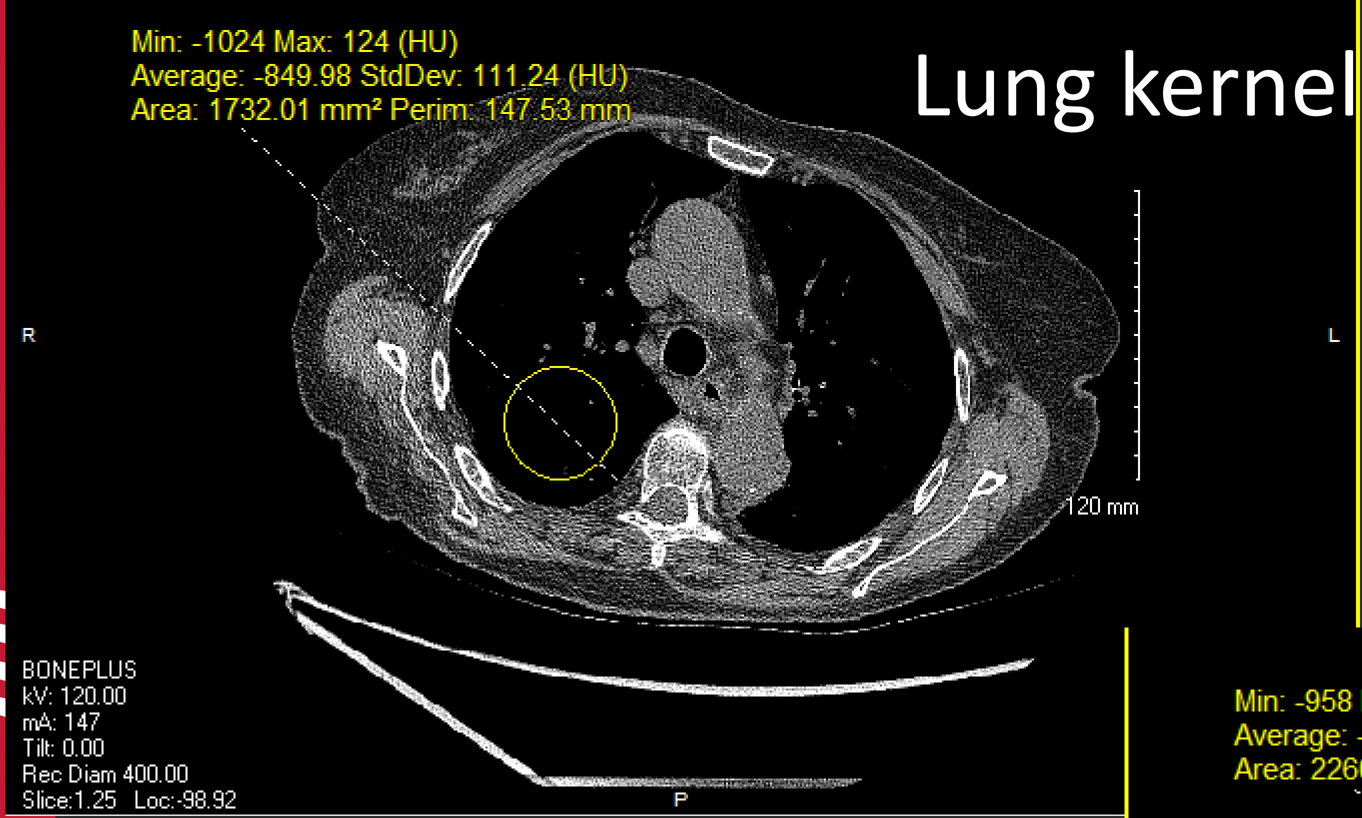
Don't get confused here by the difference between the standard error, which is a measure of the variation in sample mean, and the standard deviation, which when measured inside an ROI on a PACS system is reporting the pixel-to-pixel variation of measurements within an ROI.

I changed reconstruction filter/kernel…. Does that mean I can’t trust ROI measurements?

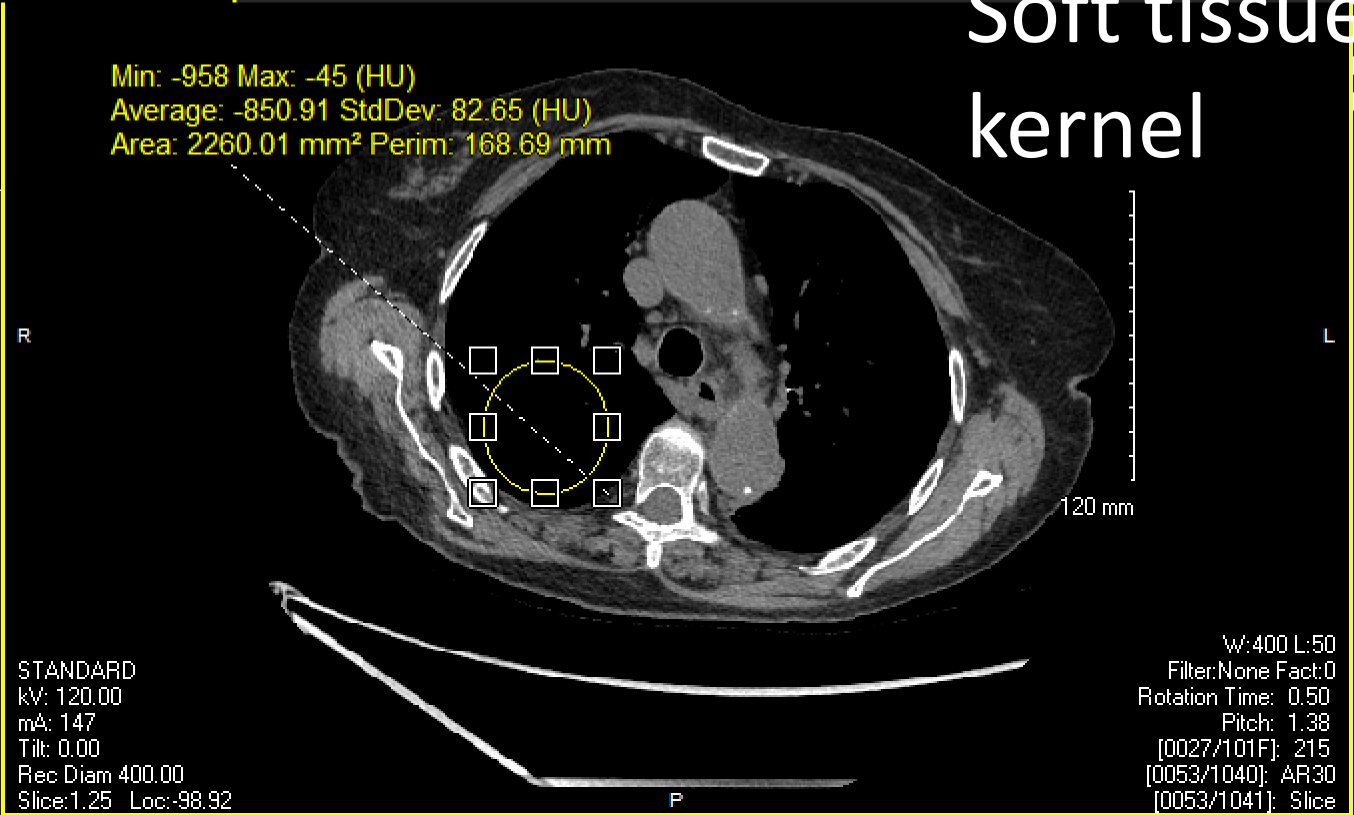

Lung kernel
Min: -387 Max: 461 (HU)
Average: 58.51 StdDev: 109.11 (HU)
Area: 2043.49 mm² Perim:
R
L
120 mm
BONEPLUS
kV: 120.00
mA: 163
Tilt: 0.00
Rec Diam 400.00
Slice:1.25 Loc:-247.66
P


Soft tissue kernel
Min: -33 Max: 145 (HU)
Average: 57.02 StdDev: 23.57 (HU)
Area: 2355.00 mm² Perim: 180.88 mm
R
L
120 mm
STANDARD
kV: 120.00
mA: 163
Tilt: 0.00
Rec Diam 400.00
Slice:1.25 Loc:-247.66
P
W:400 L:50
Filter:None Fact:0
Rotation Time: 0.50
Pitch: 1.38
[0027/101F]: 215
[0053/1040]: AR30
[0053/1041]: Slice

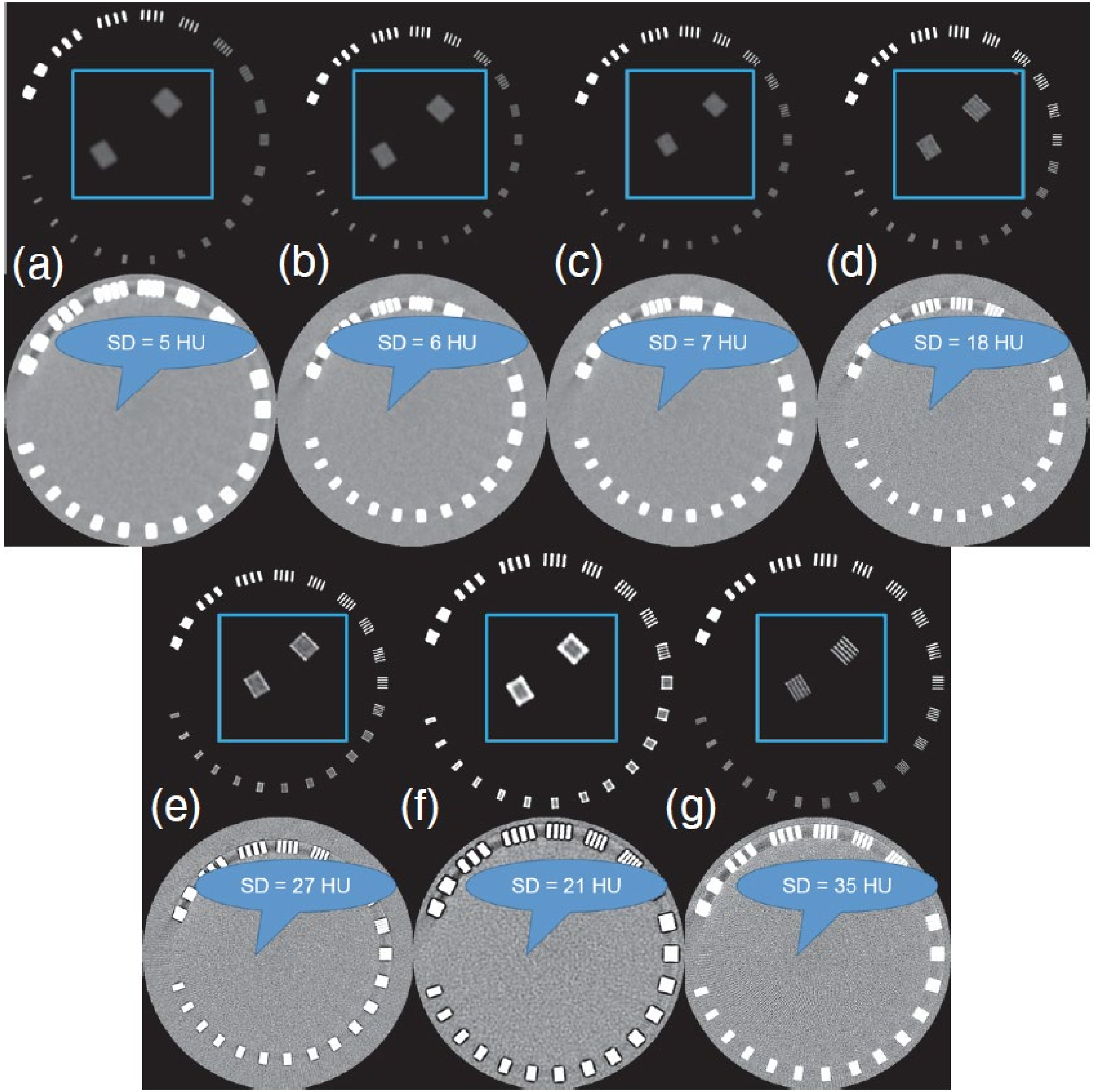
Lung kernel



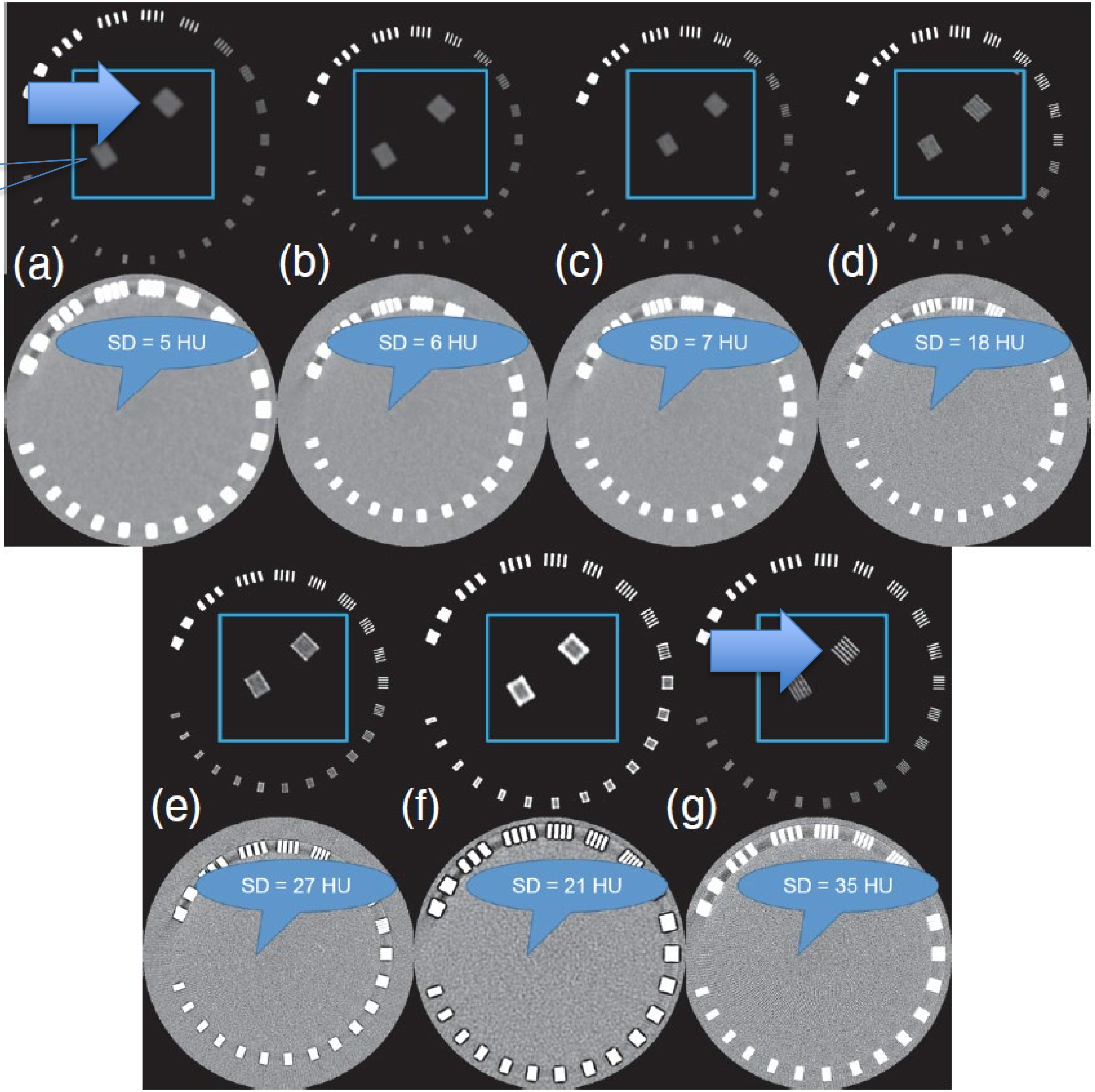
Soft tissue kernel

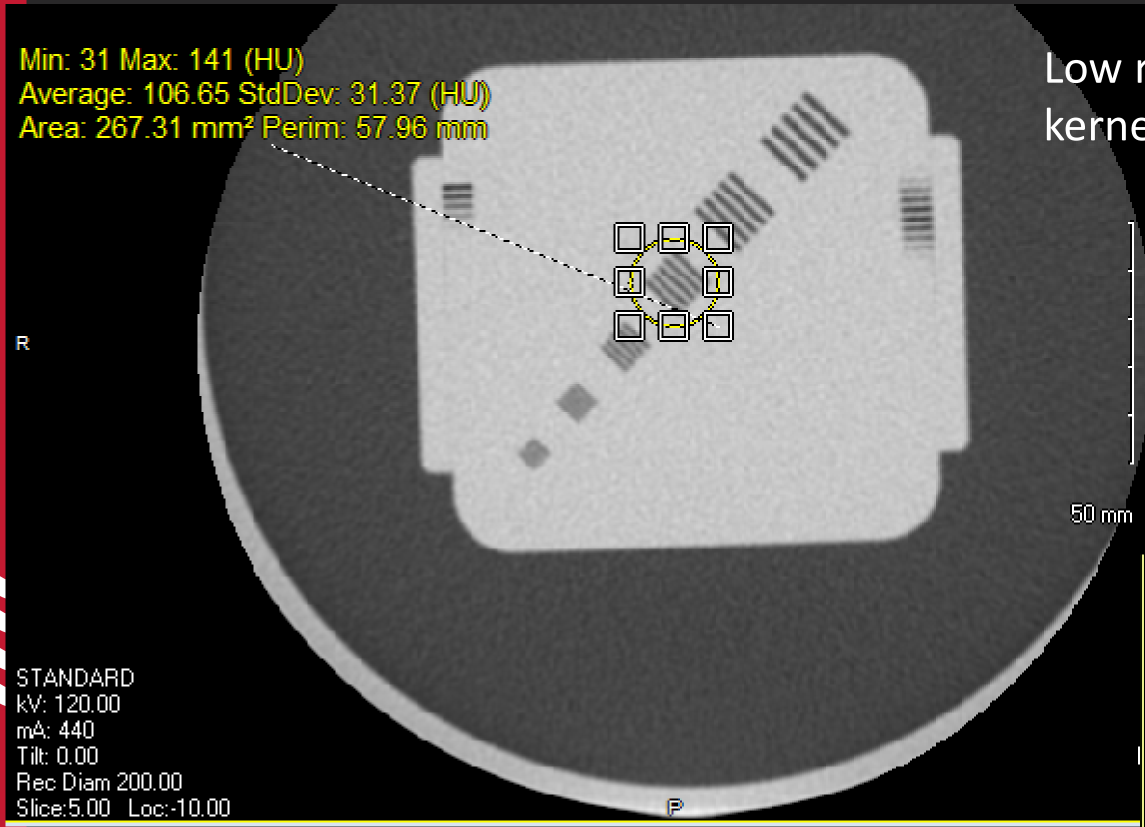


Changing kernel will change noise, spatial resolution, noise texture, and possible introduce edge enhancement



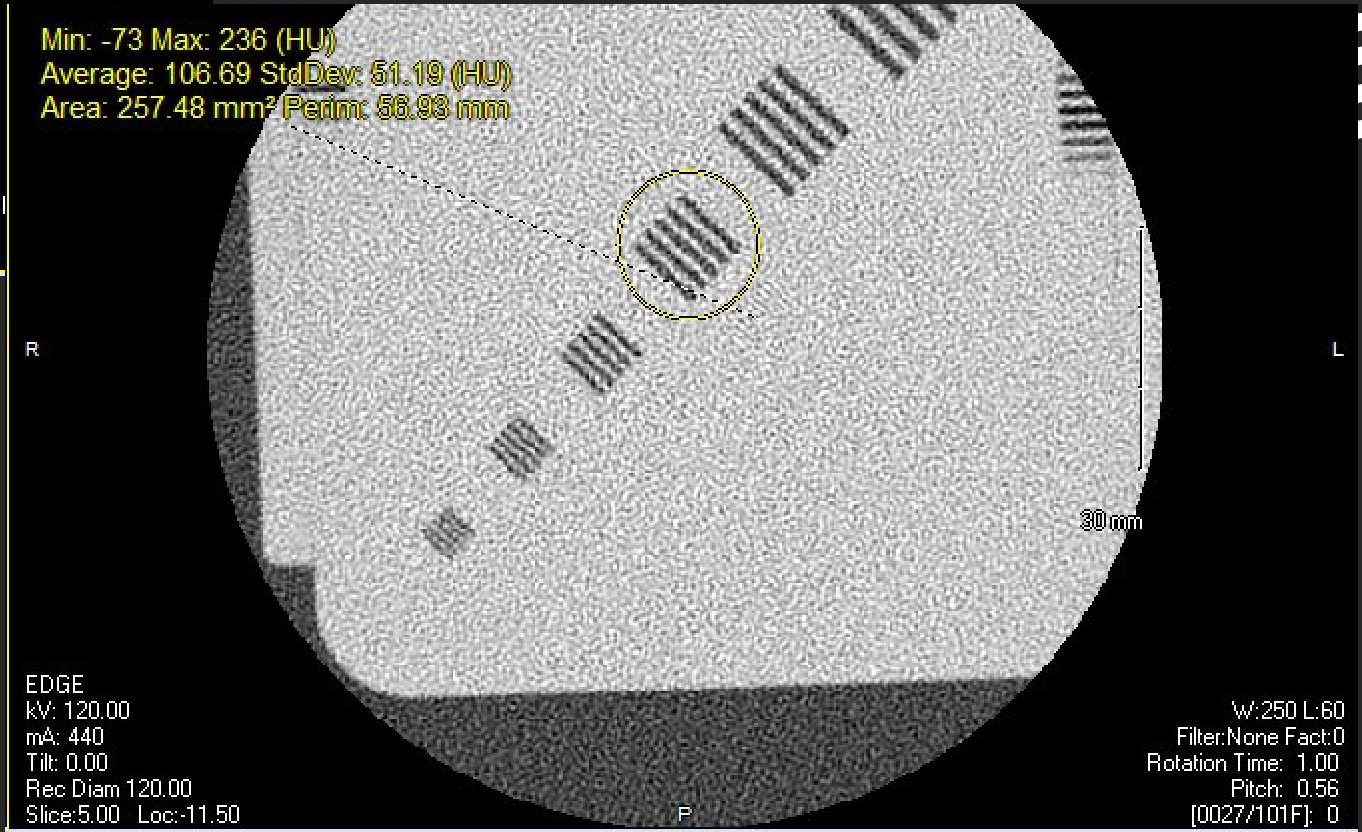
Changing kernel therefore only changes CT number for really small things…things that get blurred totally away in small ROI measurements.





Low resolution kernel

high resolution kernel



So even thought lower resolution kernel blurs edges, mean CT number over region not changed!

Protocol Optimization Considerations for Implementing Deep Learning CT Reconstruction

Timothy P. Szczykutowicz, PhD[1,2,3], Brian Nett, PhD[4], Lusik Cherkezyan, PhD[4], Myron Pozniak, MD[1], Jie Tang, PhD[4], Meghan G. Lubner, MD[1], Jiang Hsieh, PhD[4]

Multispecialty Articles · Original Research

Keywords
deep learning, image quality, protocol optimization, reconstruction

OBJECTIVE. Previous advances over filtered back projection (FBP) have incorporated model-based iterative reconstruction. The purpose of this study was to characterize the latest advance in image reconstruction, that is, deep learning. The focus was on ap-

In grouping B, in which only combinations at equal doses were considered, slice thickness or reconstruction algorithm changes were not found to produce statistically significant differences in mean CT numbers.

TABLE 5: CT Number Results: Grouping B

Material	CT Number Over All Combinations (HU)[a]			*p*		
	4 mGy	8 mGy	16 mGy	4 mGy	8 mGy	16 mGy
Polyethylene	−94.57 (−94.69, −94.02)	−94.89 (−94.98, −94.62)	−95.06 (−95.28, −95.00)	.18	> .99	.46
Water	3.76 (3.65, 3.81)	2.59 (2.43, 2.76)	2.54 (2.44, 2.55)	> .99	.97	> .99
Acrylic	123.06 (122.62, 123.45)	122.81 (122.69, 122.99)	123.49 (123.41, 123.75)	.33	> .99	> .99
Air	−990.73 (−991.23, −990.37)	−991.27 (−991.54, −991.12)	−991.71 (−991.96, −991.61)	.91	> .99	> .99
Bone	903.74 (903.53, 903.86)	905.95 (905.74, 906.12)	904.55 (904.35, 904.74)	.98	.10	> .99

Note—Grouping B contained three groups of 30 combinations each because dose was used to separate combinations. All measurements were acquired at 120 kV. In grouping B, results are sorted by dose level to show there are no statistically significant differences between reconstruction algorithms for our sample size. For each dose level, all combinations of the following reconstruction algorithms and slice thicknesses were tested: filtered back projection; 20% and 50% adaptive statistical iterative reconstruction; low-, medium-, and high-level deep learning image reconstruction; and 0.625-, 1.25-, 2.5-, 3.75-, and 5-mm slice thicknesses.
[a]Values are median with 25th and 75th percentiles in parentheses for all dose levels.

@Prof_TimStick's Actionable information

- Don't trust CT number when scanners change
- Don't trust CT number when kV changes
- Don't trust CT number when position changes
- ROI noise equal to the mean…don't worry, you can usually trust the measurement
- Changing reconstruction kernel/filter doesn't change CT number

outline

- CT Number 101
- AEC in CT

I don’t need AEC, all my images look fine. Maybe a few bariatrics are noisy.

I don’t need AEC, all my images look fine. Maybe a few bariatrics are noisy.

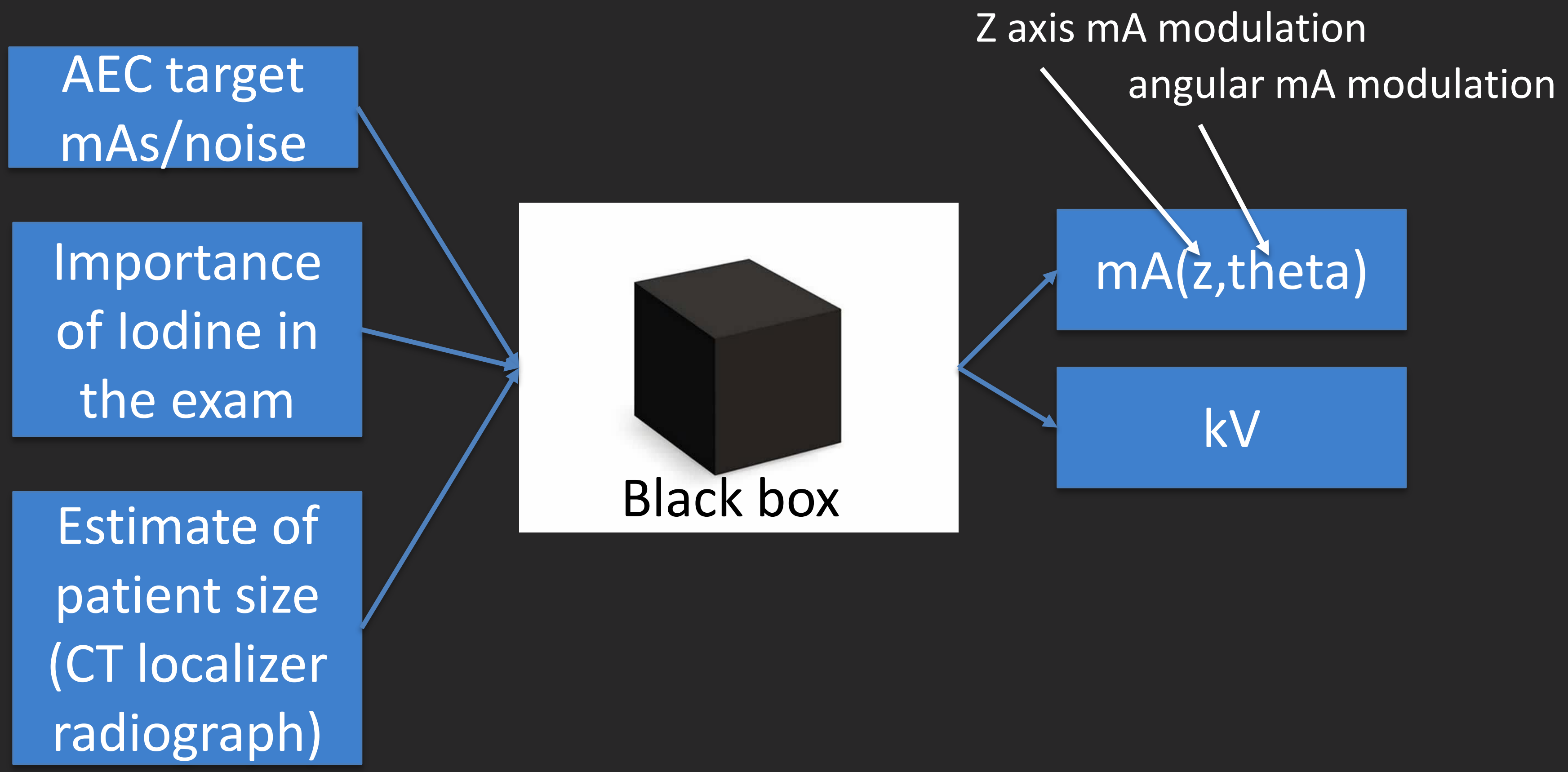
Well, noise will double in your patients with every 8 cm they grow in diameter, or over a single scan if you use constant mA!

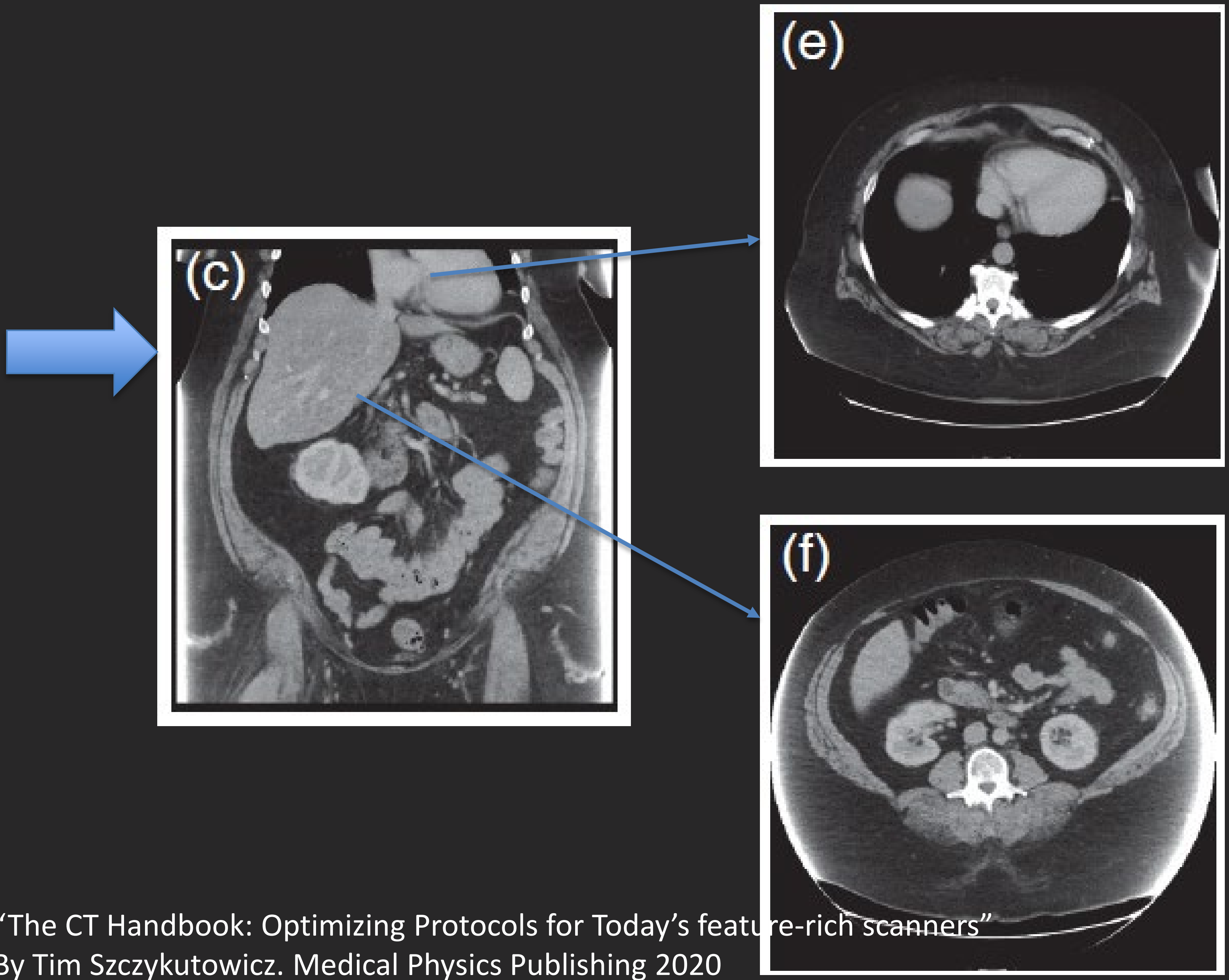
I don’t need AEC, all my images look fine. Maybe a few bariatrics are noisy.

So if you are “getting away” with a single mA, then 100% guaranteed you are making pretty pictures for smaller patients in excess of what you need

Well, noise will double in your patients with every 8 cm they grow in diameter, or over a single scan if you use constant mA!

- All Vendor’s AEC systems operate like this



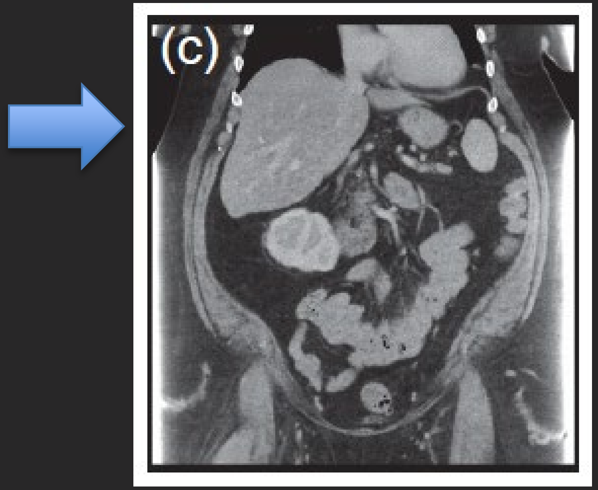


At this level we are just about to hit our mA max, noise still reasonable

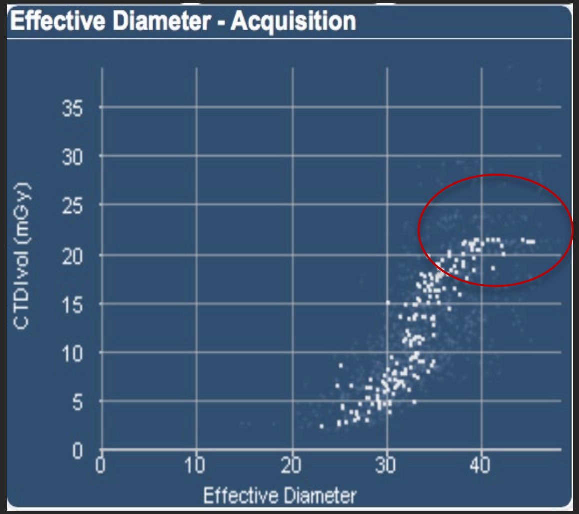
At this level we have hit our mA max, noise increases a lot!

“The CT Handbook: Optimizing Protocols for Today’s feature-rich scanners”
By Tim Szczykutowicz. Medical Physics Publishing 2020

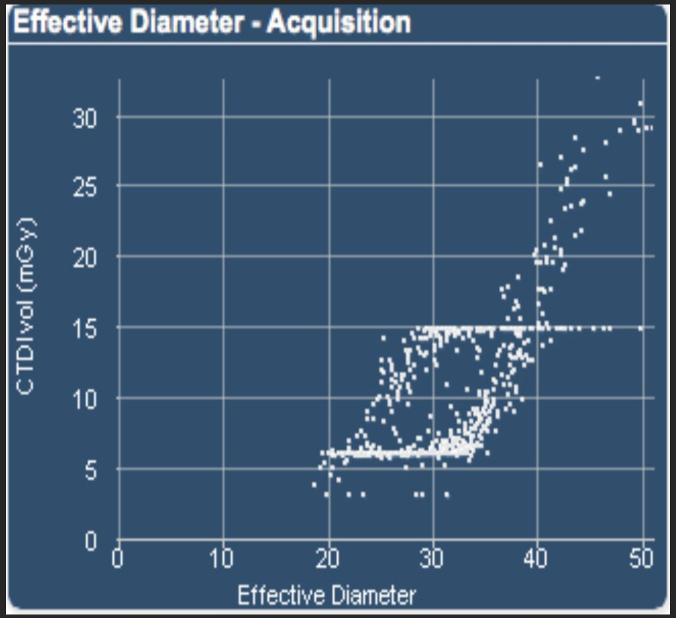
- You will find that mA limits are reached
  - Within a single patient exam



  - Over a certain patient size



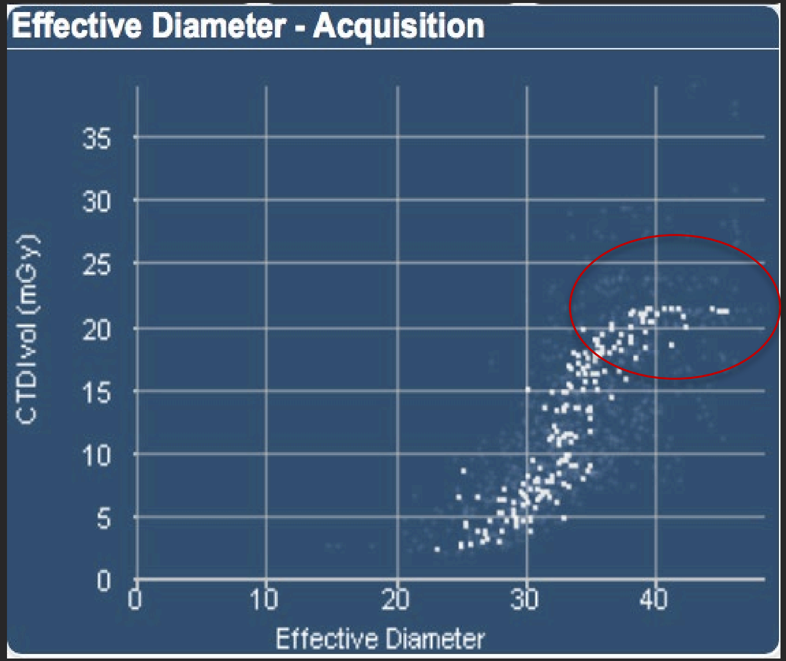
Two scanners shown here, one is having issues maxing out, one is minning out



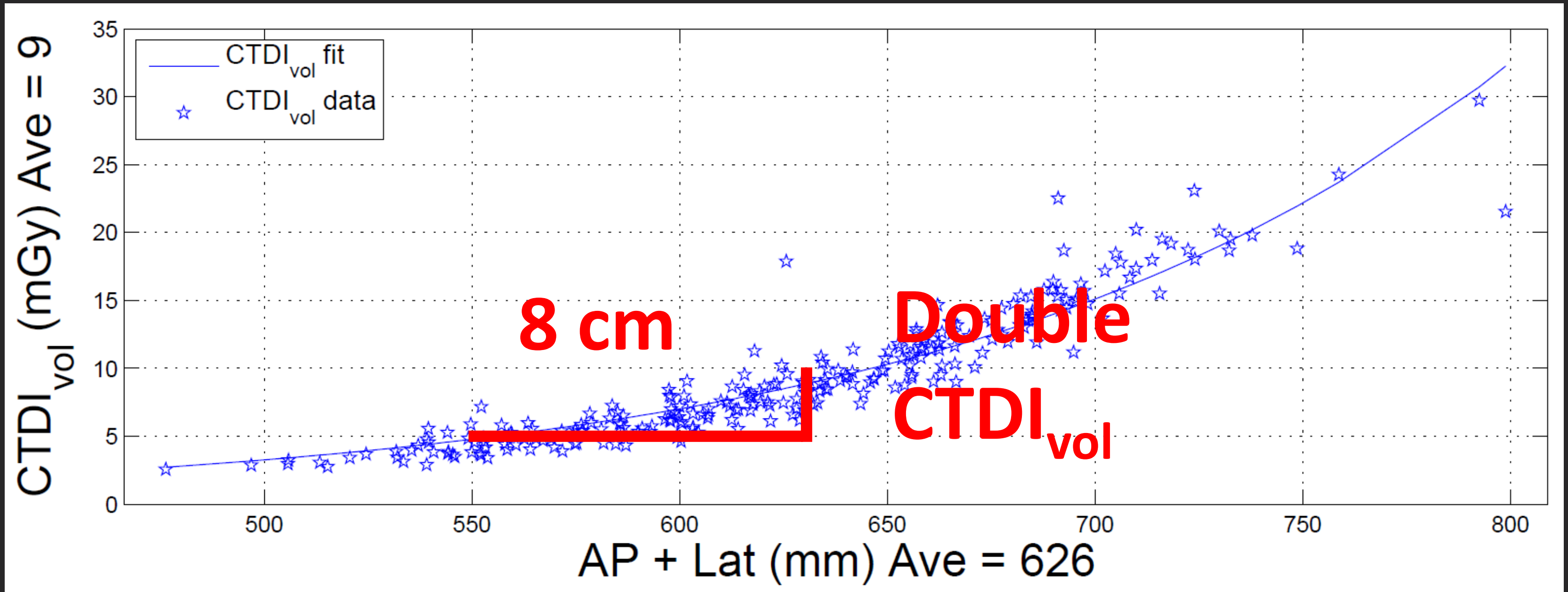
Maxxing out

Minning out

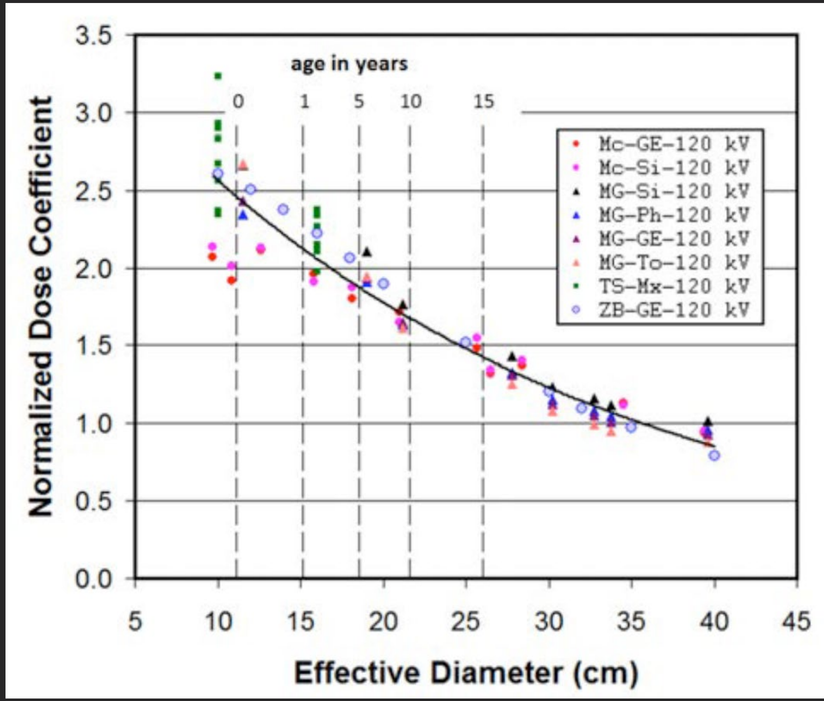
- For what patient sizes will your protocol hit an mA limit?
  - We can answer by looking over CTDIvol data as a function of patient size and looking for "flat spots"
    - But this is using a trial and error approach, can we do this prospectively?



- Providing constant image noise/quality means you have to off-set the Beer-Lambert law of exponential x-ray attenuation as a function of patient size.
  - GE AEC operates like this (rule of thumb, every 4 cm of soft tissue increase → dose doubling)



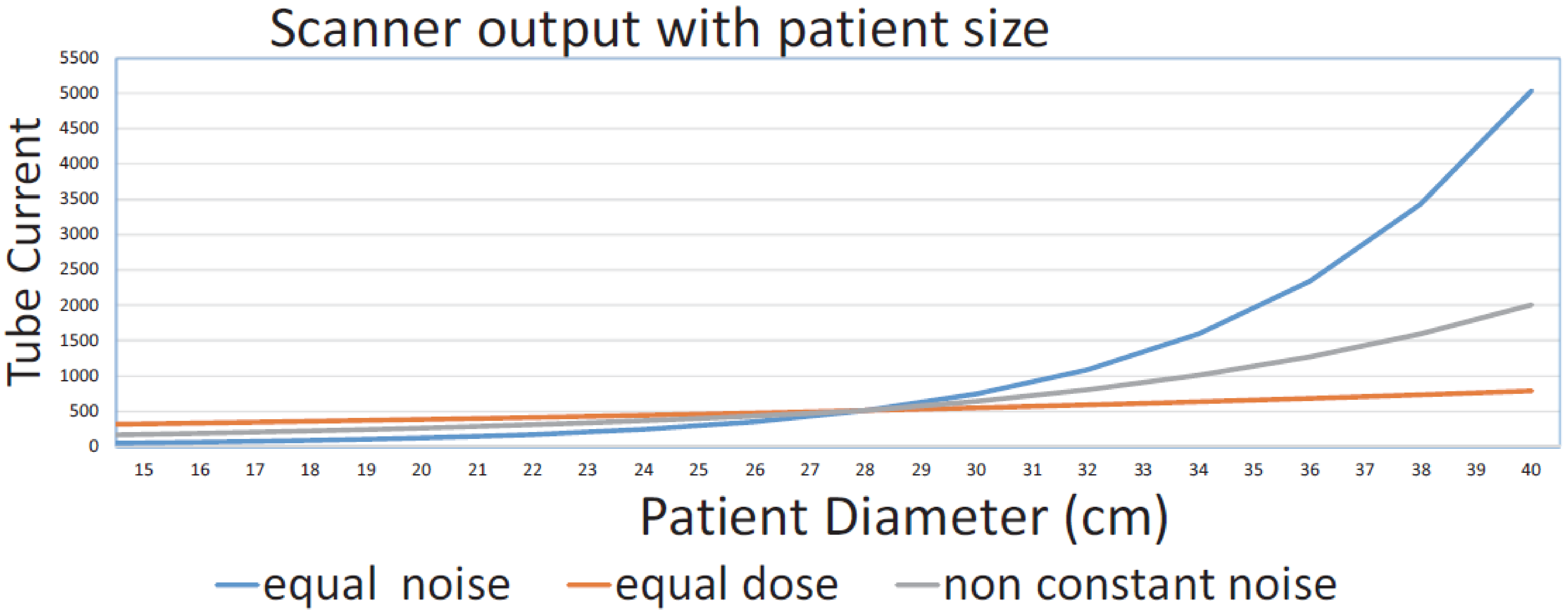
- Providing constant dose means you have to scale scanner output to give a patient a constant ratio of energy/mass (i.e. dose).
  - I don't think any vendor does this
  - This would be like setting your AEC according to the normalized dose curve shown in AAPM Reports 204/220



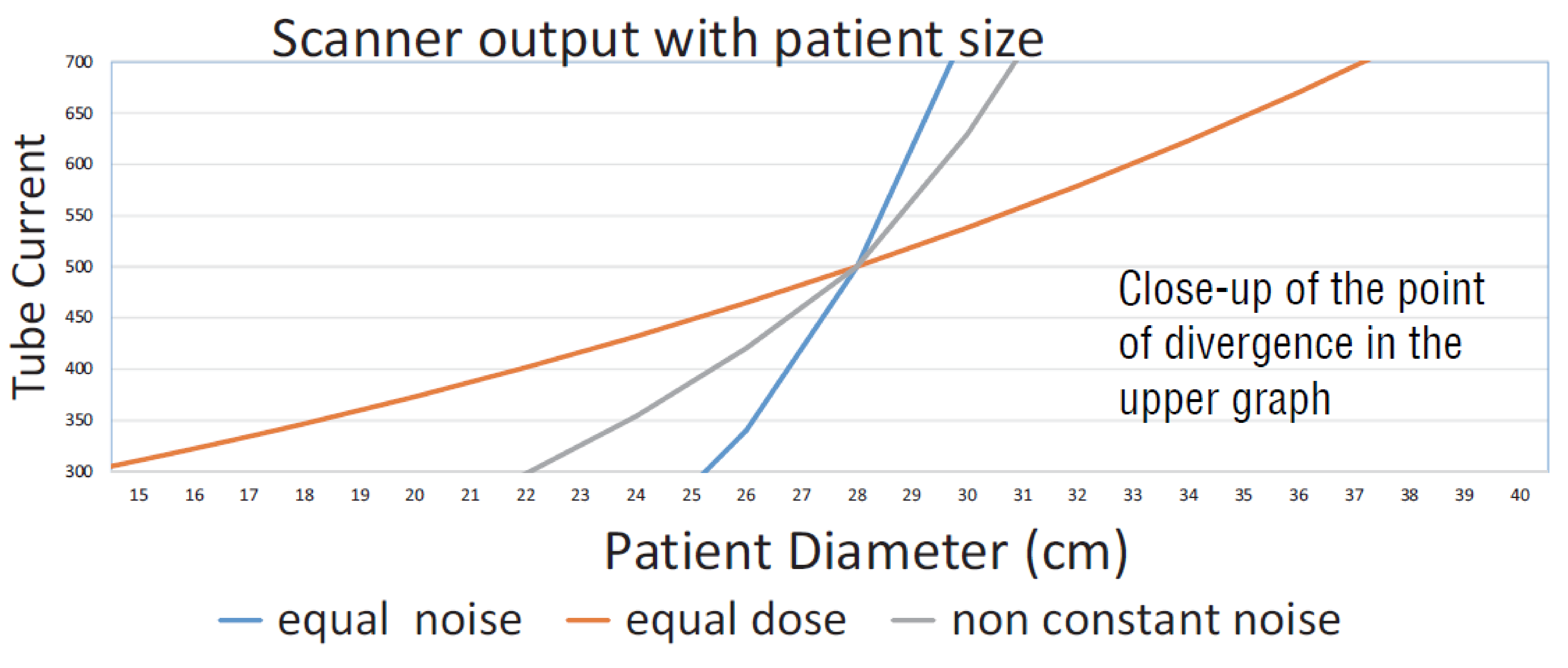
$$\mathrm{NDC} = 3.7 * e^{-0.0367x}$$

HVL of ~18 cm

Interesting side note, if we changed dose by NDC prescription, images would get noisy faster as a function of patient size w.r.t. vendor AEC systems



“The CT Handbook: Optimizing Protocols for Today’s feature-rich scanners”
By Tim Szczykutowicz. Medical Physics Publishing 2020



“The CT Handbook: Optimizing Protocols for Today’s feature-rich scanners”
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@Prof_TimStick's Actionable information

- Not all CT makes and models have the same AEC behavior, characterize your specific scanner
  - Use historical patient data (plots of CTDIvol versus pt size)
  - Use various sized phantoms
- mA plateaus are bad
  - Over entire patient size ranges
  - Within a single patient's scan

Okay okay okay, I'll use AEC. What about when I use IV contrast?

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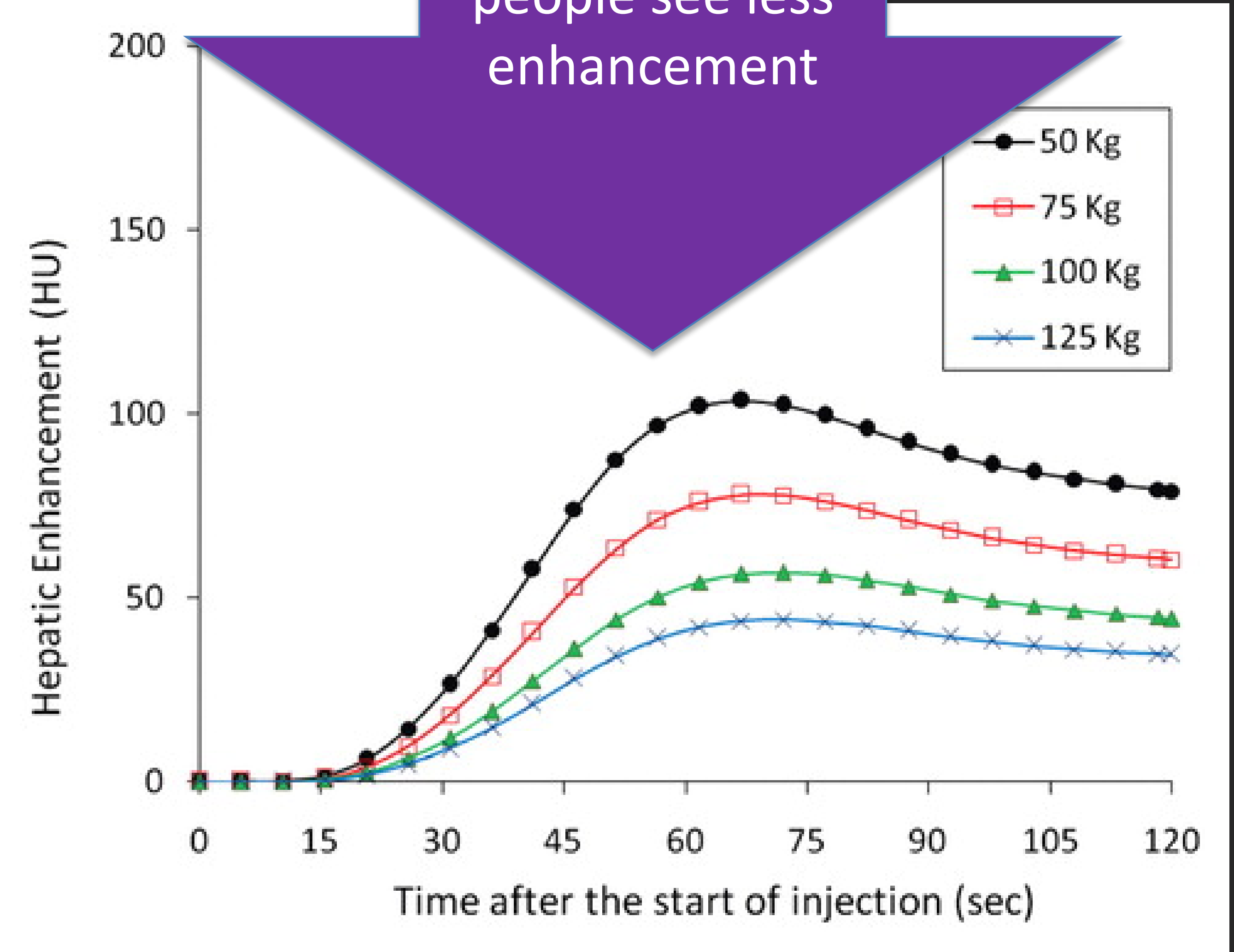
Kyongtae T. Bae

Author Affiliations

If every ones gets 125 mls…big people see less enhancement



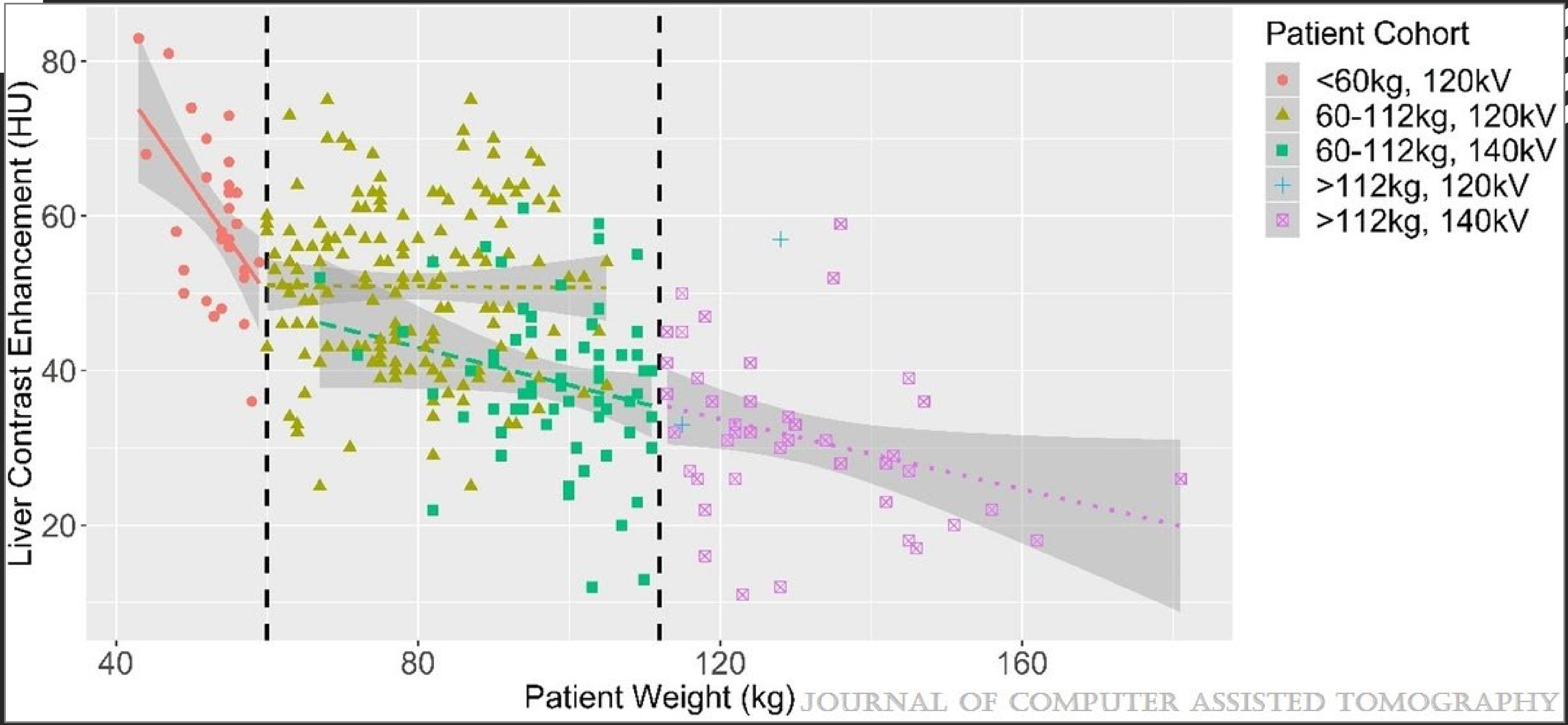
JCAT Journal of Computer Assisted Tomography
Covering the Spectrum of Advanced Radiologic Imaging

CT: TECHNOLOGY AND PHYSICS

A Metric for Quantification of Iodine Contrast Enhancement (Q-ICE) in Computed Tomography

Szczykutowicz, Timothy P. PhD[*,†,‡]; Viggiano, Ben BS[*,‡]; Rose, Sean PhD[*]; Pickhardt, Perry J. MD[*]; Lubner, Meghan G. MD[*]
Author Information

Journal of Computer Assisted Tomography: 11/12 2021 - Volume 45 - Issue 6 - p 870-876
doi: 10.1097/RCT.0000000000001215



- Typical IV contrast prescription. Most sites around the world will have increases in I contrast with weight.

Example CTPA (PE) contrast prescription

IV Contrast Parameters

Patient weight < 140 kilos.(Less than 300 lbs.)

- 100 mL Iohexol (Omnipaque) 300 MG/ML @ 5 mL/sec
- 10 mL Sodium Chloride 0.9% @ 5 mL/sec

Patient weight 140-160 kilos.(300-350 lbs.)

- 100 mL Iopamidol (Isovue 370) 370 mgI/ml @ 5 mL/sec
- 10 mL Sodium Chloride 0.9% @ 5 mL/sec

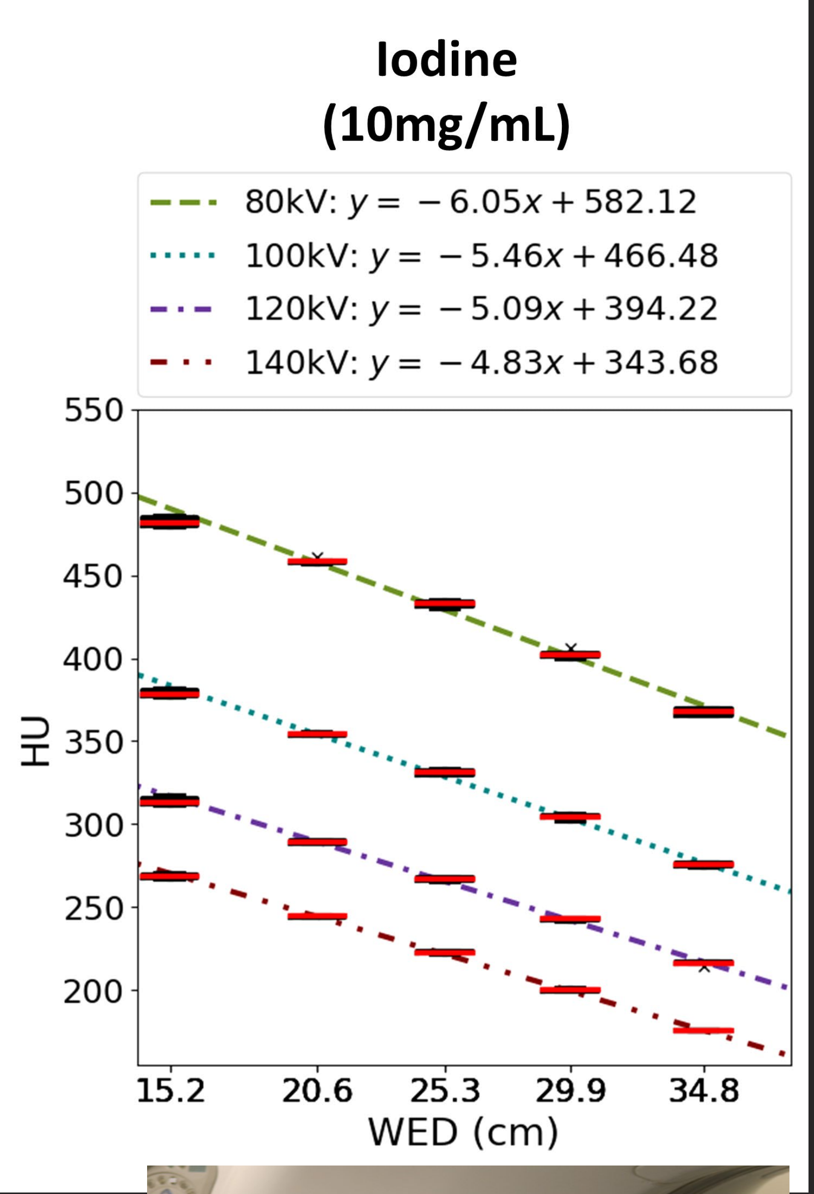
Patient weight > 160 kilos.(More than 350 lbs.)

- 150 mL Iopamidol (Isovue 370) 370 mgI/ml @ 5 mL/sec
- 10 mL Sodium Chloride 0.9% @ 5 mL/sec

Example routine parenchymal phase torso contrast prescription

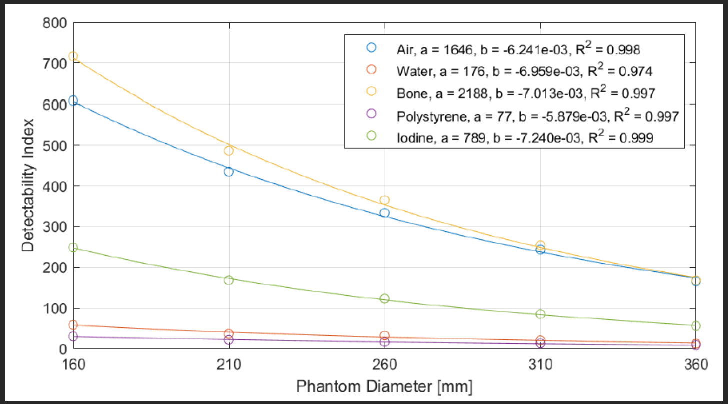
Patient Weight (lbs)	Contrast Volume (ml or cc)
130 and less	80 (minimum amount to load)
140	86
150	92
160	98
165	101
170	104
175	107
180	110
190	116
200	122
210	129
220	135
230	141
240	147
250 and larger	150 (max amount to load)

- Just due to beam hardening, we see a HUGE reduction in CT number with increasing patient size
  - -5 HU per cm of WED!



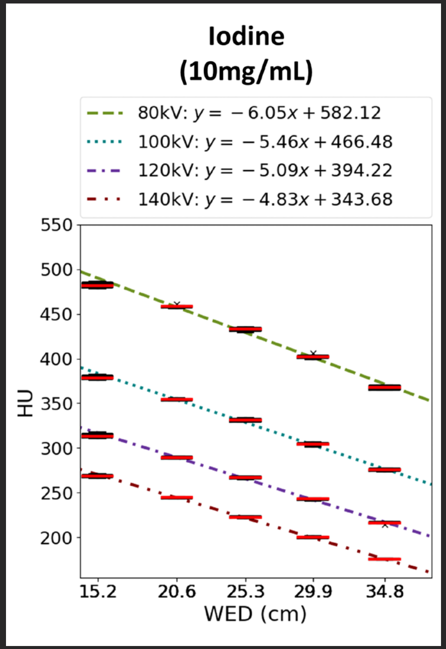
Parameterizing Size-Based Variations in CT Number
AAPM ePoster Library. Rose S. 07/12/20; 302594; BReP-SNAP-I-36 Topic: Multi-detector CT

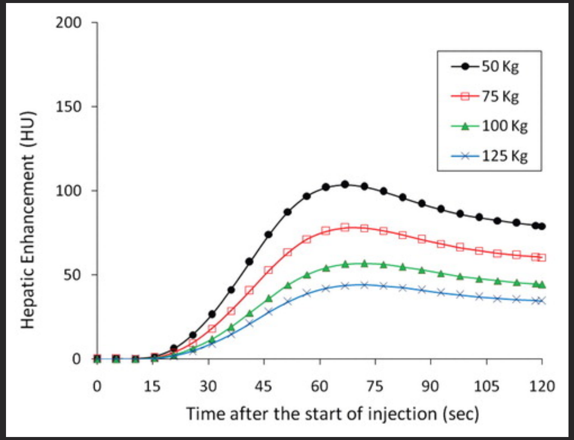
Special considerations for large patients



CNR down from vendor increasing noise via AEC

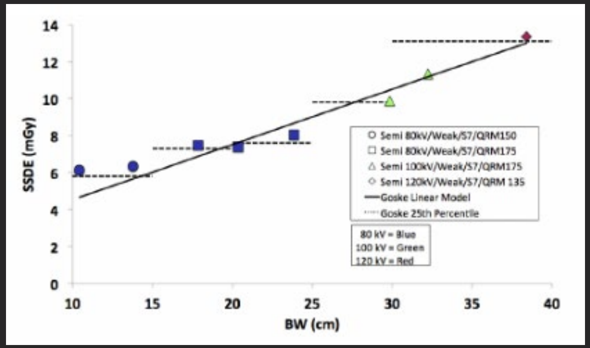
Contrast down from beam hardening





Contrast down from less I density

Contrast down from kV up



@Prof_TimStick's Actionable information

- Since we cannot change kV in rad onc, consider increasing IV contrast for larger patients and decreasing it for smaller patients
- If you cannot change kV or IV contrast volumes, consider using AEC quality targets to account for patient size
    - Decrease noise for larger patients

Thank You.

Feel free to contact me at
tszczykutowicz@uwhealth.org

(at this AAPM meeting, we have a symposium with 2 radiologists and a CT tech later today, attend for more CT knowledge!)