State of the art CT dose reduction and protocol optimization approaches for children

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Cincinnati Children's
changing the outcome together

COI

AI related grant:

- CCRF ARC

Theranostics grants:

- CONNECT
- Clarity Pharmaceuticals

Purpose

- Innovation in diagnostic CT technology and protocol development has led to significantly reduced pediatric patient dose levels

- This talk will discuss:
  - the key technologies that provide dose reduction
  - use of figure of merits (FOM) for image quality optimization
  - the effect of new, deep learning, CT reconstruction algorithms on image quality and patient dose reduction

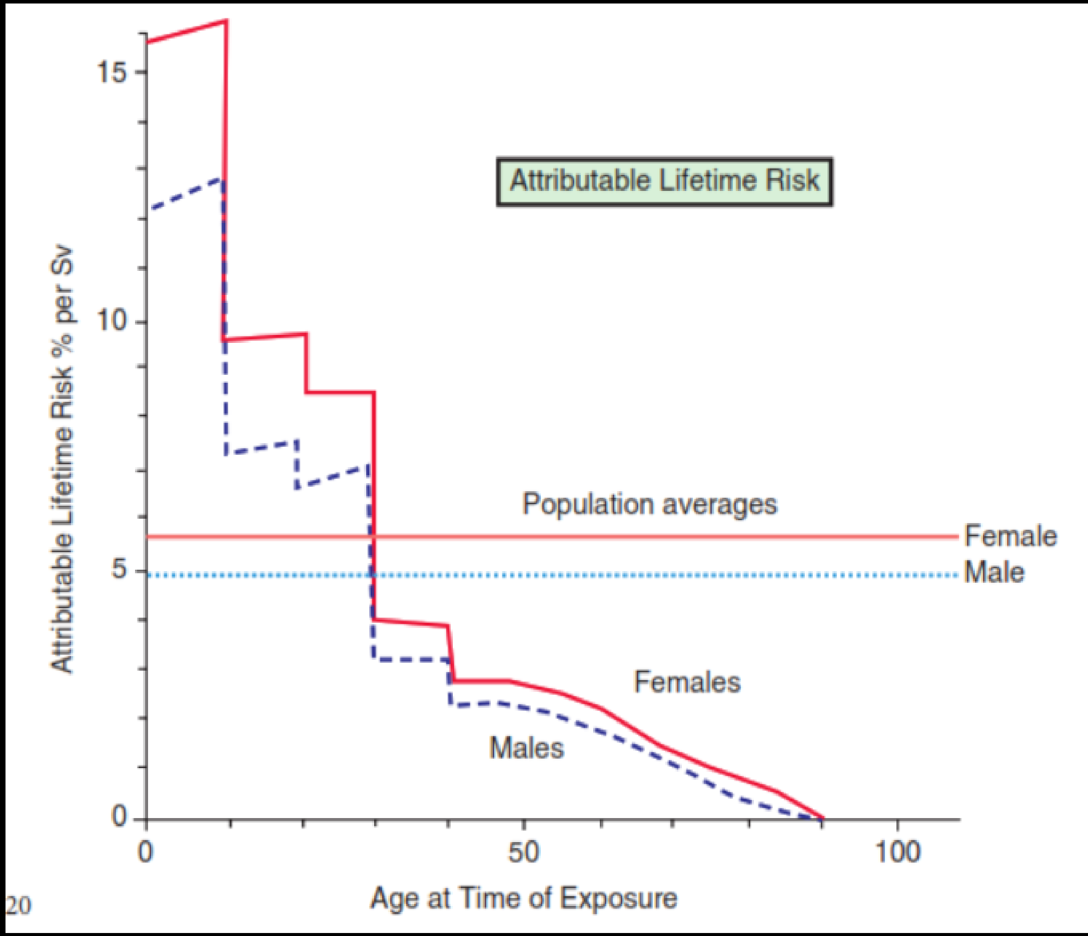
Historical Perspective

- Pediatric sensitivity to radiation
  - It has been 20 years since Hall's paper

> Pediatr Radiol. 2002 Oct;32(10):700-6. doi: 10.1007/s00247-002-0774-8. Epub 2002 Jul 19.

Lessons we have learned from our children: cancer risks from diagnostic radiology

Eric J Hall [1]



- Pediatric protocols have evolved

- Dose reduction has been significant

Appropriateness

- #1 best dose reduction method:
  - Only scan when medically indicated!

- ACR appropriateness criteria
  - Physician/physics committee
  - Indication specific
    - Rank imaging modalities
    - Provides a dose estimate

Relative Radiation Level*	Adult Effective Dose Estimate Range	Pediatric Effective Dose Estimate Range
O	0 mSv	0 mSv
☢	<0.1 mSv	<0.03 mSv
☢☢	0.1-1 mSv	0.03-0.3 mSv
☢☢☢	1-10 mSv	0.3-3 mSv
☢☢☢☢	10-30 mSv	3-10 mSv
☢☢☢☢☢	30-100 mSv	10-30 mSv

Variant 2: **Left lower quadrant pain. Suspected complications of diverticulitis.**

Procedure	Appropriateness Category	Relative Radiation Level
CT abdomen and pelvis with IV contrast	Usually Appropriate	☢☢☢
CT abdomen and pelvis without IV contrast	May Be Appropriate	☢☢☢
CT pelvis with bladder contrast (CT cystography)	May Be Appropriate	☢☢☢☢
MRI abdomen and pelvis without and with IV contrast	May Be Appropriate	O
Fluoroscopy contrast enema	May Be Appropriate	☢☢☢
Fluoroscopy cystography	May Be Appropriate	☢☢☢
MRI abdomen and pelvis without IV contrast	May Be Appropriate	O
US abdomen transabdominal	May Be Appropriate	O
CT abdomen and pelvis without and with IV contrast	Usually Not Appropriate	☢☢☢☢
Radiography abdomen and pelvis	Usually Not Appropriate	☢☢☢
US pelvis transvaginal	Usually Not Appropriate	O

www.acr.org/Clinical-Resources/ACR-Appropriateness-Criteria

Appropriateness

- How is this applicable in RT?
  - It is not a question of if a patient needs a CT but how many
  - Do it right the first time: set the right dose!
    - Too low of dose usually equals non diagnostic exams which lead to repeat exams
    - Carefully position and double check settings

Appropriateness

- How is this applicable in RT?
  - Follow up CTs
    - Is surveillance necessary?
    - How often should these occur?
    - Can follow up be reasonably be performed w/ MRI?

Is Routine Pelvic Surveillance Imaging Necessary in Patients With Wilms Tumor? Cancer January 1, 2013

Sue C. Kaste, DO[1,2,3]; Samuel L. Brady, PhD[1]; Brian Yee, RT(R)(CT), ARRT[1]; Valerie J. McPherson, BS[2]; Robert A. Kaufman, MD[1,3,4]; Catherine A. Billups, MS[5]; Najat C. Daw, MD[6]; and Alberto S. Pappo, MD[2]

90% cured
Most relapses are salvaged
All relapsed patients were symptomatic and didn’t require CT surveillance for detection

Appropriateness

– Follow up CTs

Pediatr Blood Cancer

The Role of Chest Computed Tomography (CT) as a Surveillance Tool in Children With High-Risk Neuroblastoma

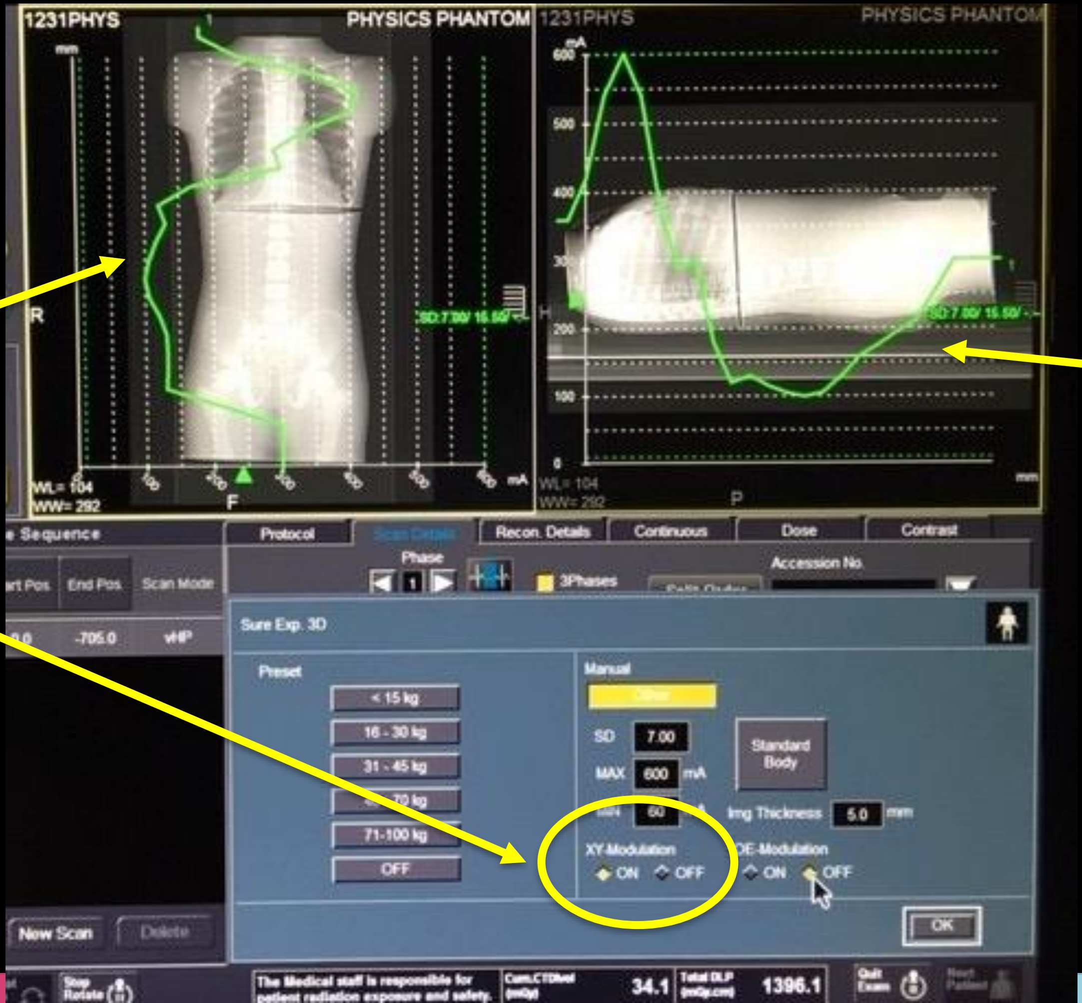
Sara M. Federico, MD,[1,4]* Samuel L. Brady, PhD,[2] Alberto Pappo, MD,[1,4] Jianrong Wu, PhD,[3] Shenghua Mao, PhD,[3] Valerie J. McPherson, BS,[1] Alison Young, MSFNP,[1] Wayne L. Furman, MD,[1,4] Robert Kaufman, MD,[2,4,5] and Sue Kaste, DO[1,2,5]

Relapsed patients only have a 10% salvage rate
Patients' w/o thoracic disease at diagnosis were otherwise symptomatic

– Reduction or removal of chest CT for surveillance leads to 35-40% dose reduction

Tube Current Modulation

- The #2 best dose reduction methodology in CT



X&Y axis Modulation

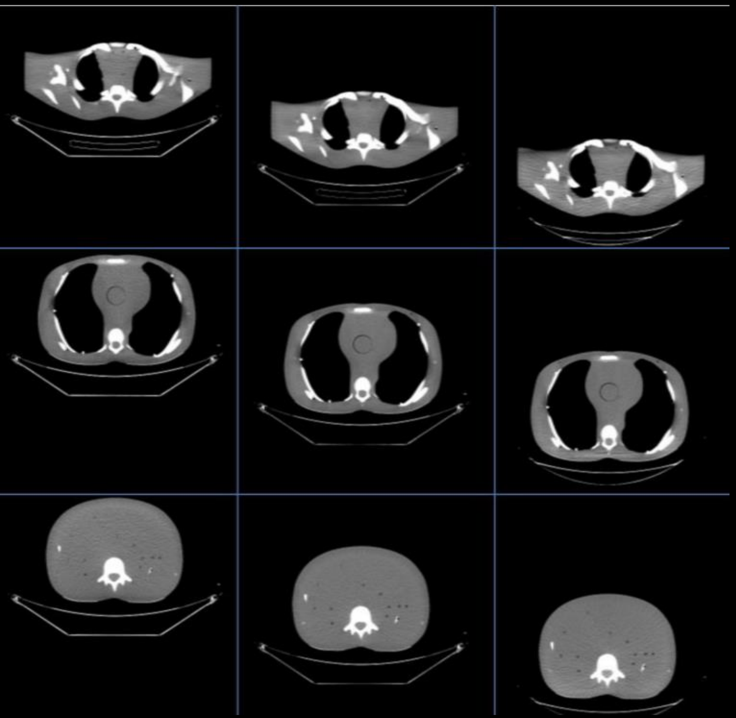
Z axis Modulation

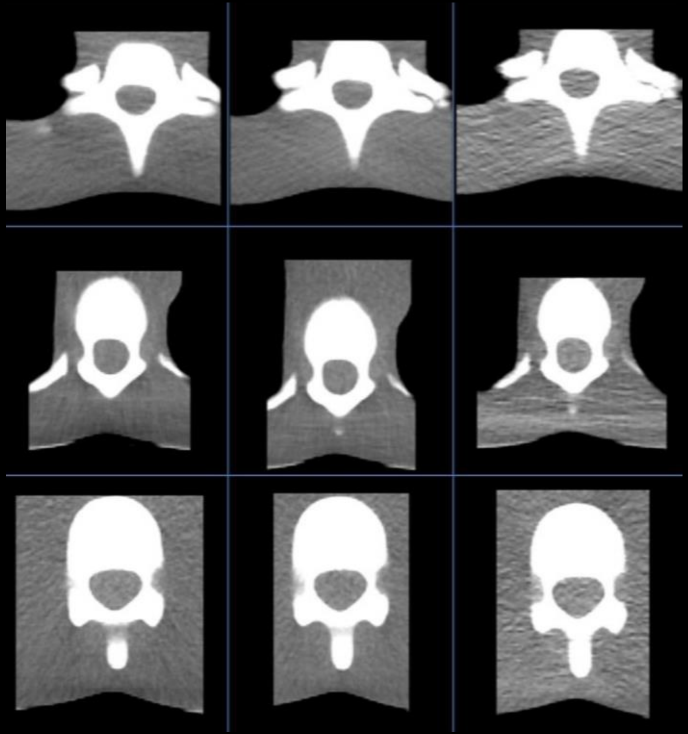
Organ Dose Modulation

- Organ dose modulation reduces mA over anterior portion of the body
  - Used to reduce eye lens, thyroid, and breast dose
  - Used along with TCM for additional dose reduction NO IQ PENALTY

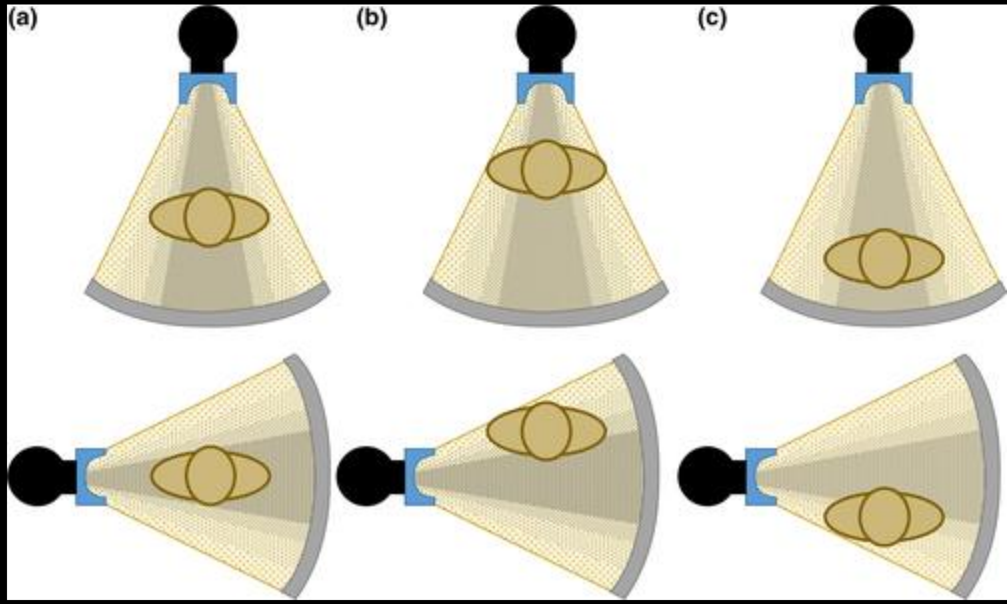
Centering Patient

- Affects patient dose when using TCM
  - Patients lower in the gantry lead to beam hardening and photon starvation artifacts





Images belong to Timothy Szczykutowicz, PhD



Barreto et al. JACMP 2019 20(6); 141-151

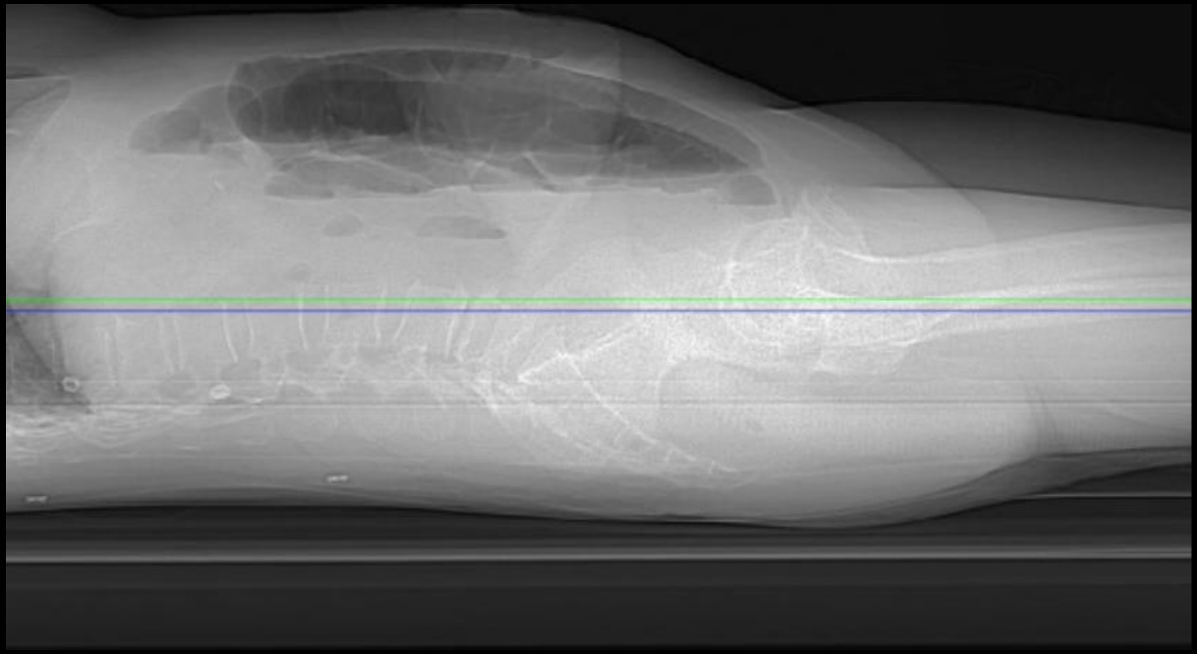
Centering Patient

- How is this applicable in RT?
  - May be difficult to find a patient’s actual center
    - Due to immobilization devices
    - OR nontypical supine positions

Buszek et al. Advances in Radiation Oncology 2019 4(2):362-266

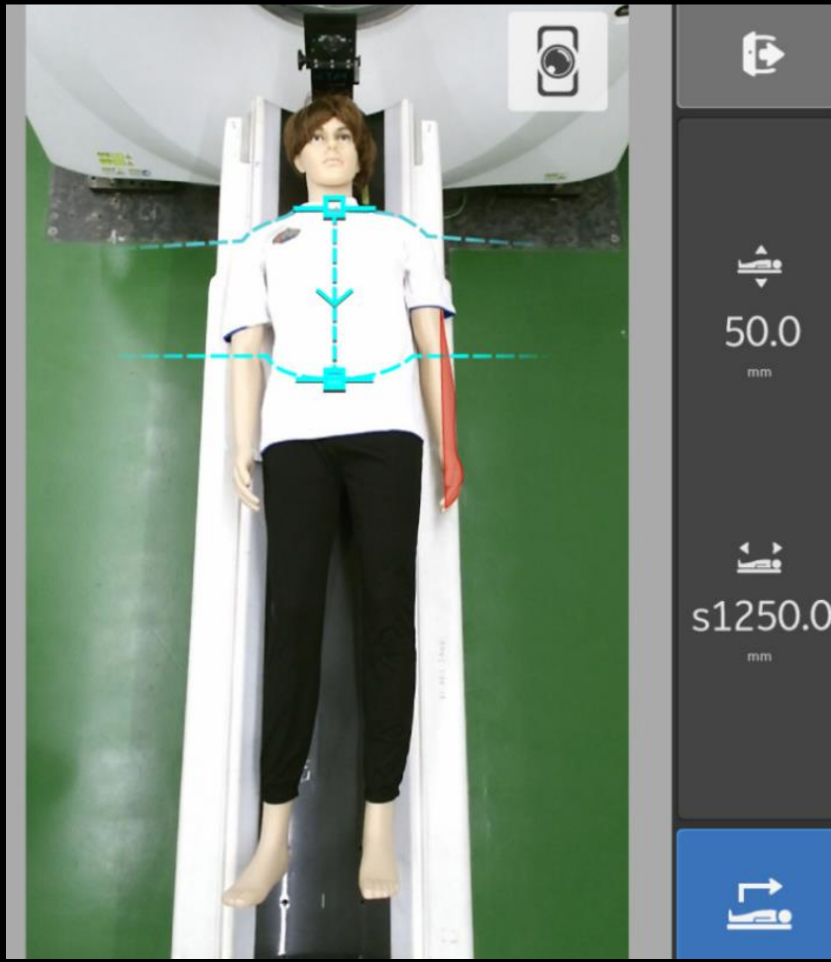
Centering Patient

- Patient centering verification based on attenuation map
  - Some CT vendors will allow a single click move to center
  - Others require technologists' manual intervention



Centering Patient

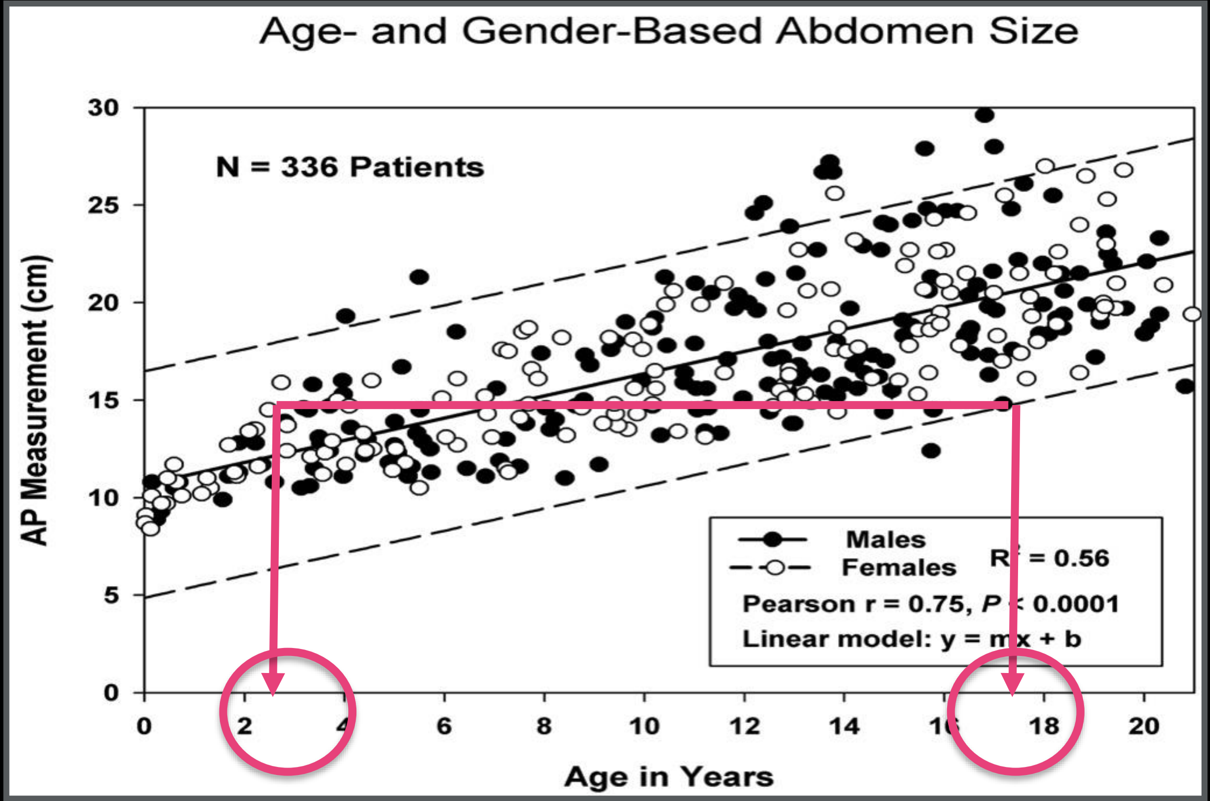
- AI algorithms + camera
  - Visual light based cameras identify anatomical landmarks
  - Provide centering & position guidance
  - Consistent scan coverage
    - Appropriate scan coverage helps reduce unnecessary patient dose



GE AI-based Auto Positioning, white paper

Patient Size

- Same age patients vary dramatically in size
  - Abdomen of smallest 17-yr-old and largest 3-year-old are same size
  - Use patient cross sectional size not age or even weight when setting protocols



Kleinman; AJR 194(6) 2010; 1611-1619

Patient Size

- Use of scan projection radiograph (SPR) to set protocols
  - Measure patient attenuation or “size”
  - Protocol selected based on measured size

- Use of SSDE to better approximate patient dose
  - SSDE is calculated for body (TG 204 & 220) and the head (TG 293)

$$SSDE = CTDI_{vol} \cdot f_{size}$$

  - Where f_{size} can be found by measuring patient attenuation or effective dia.

Low kV Imaging

- Why do we use low kV imaging in Radiology?
  - Lower radiation dose to the patient
  - Better tissue contrast differentiation
  - Why does the dose go down?
    - Dose increases/decreases linearly with mA, but quadratically with kV
  - If we reduced kV by 40: $\left(\frac{80\ kV}{120\ kV}\right)^2$ we get 56% dose reduction
  - If we reduce mA by 40: $\left(\frac{80\ mA}{120\ mA}\right)$ we get 33% dose reduction

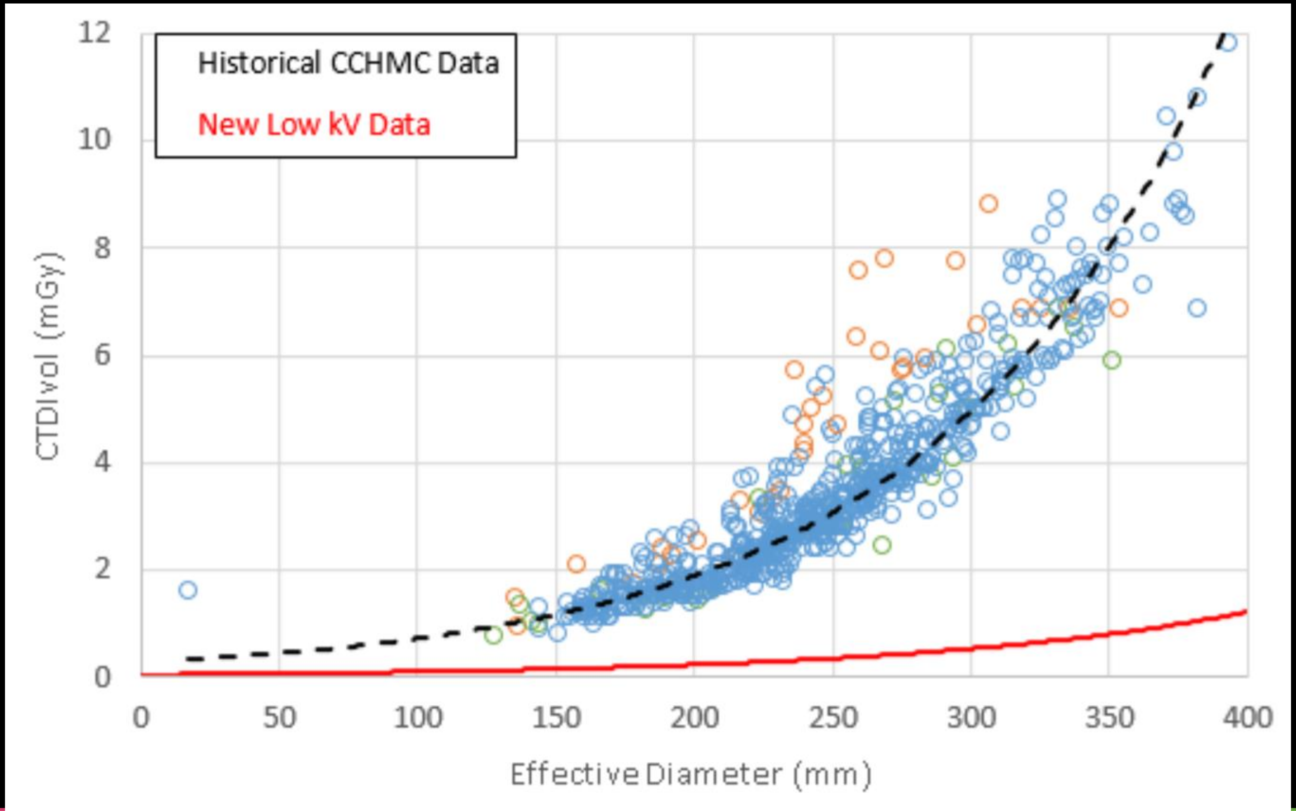
Remember:

Changing mA affects dose/noise

Changing kV affects dose/noise, image contrast, AND CT #

Low kV Imaging

- Lower kV requires high mAs capacity
  - Modern scanners use high tube current (e.g., 1200 mA) w/ low kV
  - Deliver lower dose for all patient sizes

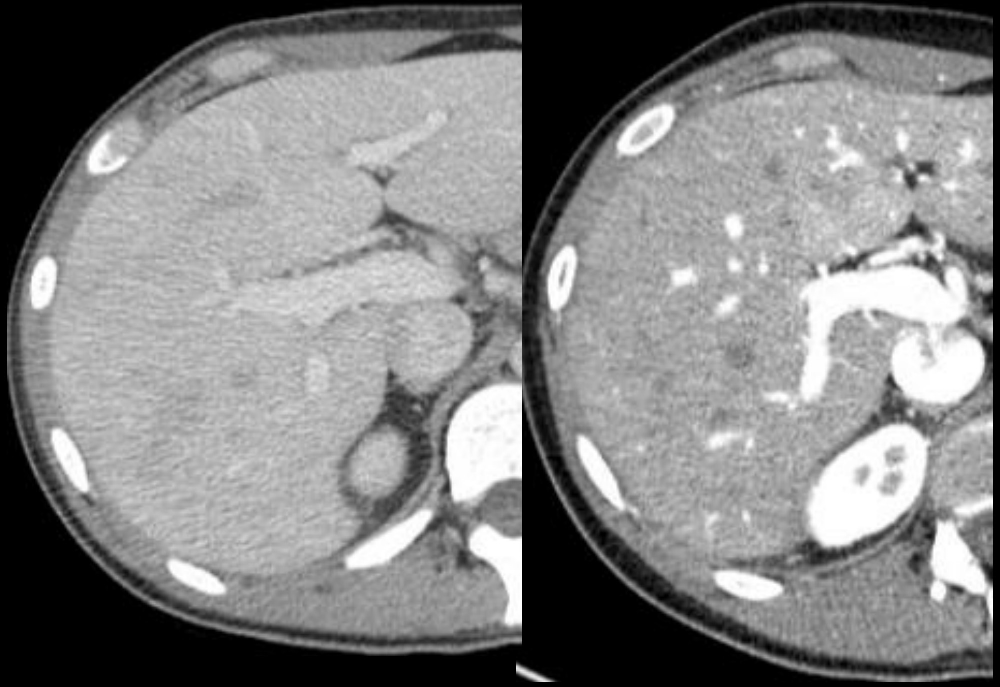


Low kV Imaging

- Lower kV requires more mAs for similar exposure/noise
  - What is the correct mAs/eff mAs

- Don't match noise, match CNR!
  - CNR improves with lower kV even though noise increases
  - Noise may be higher at lower kV than at 120 kV

Same Patient



120 kV 100 kV

31% dose reduction

Fletcher, AAPM 2010

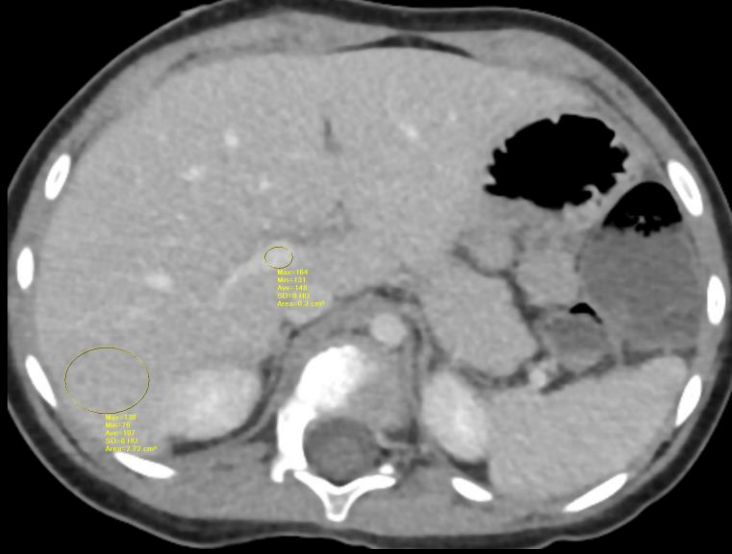
Yu et al. Med Phys 57(1) 2010; 234-24

Low kV Imaging

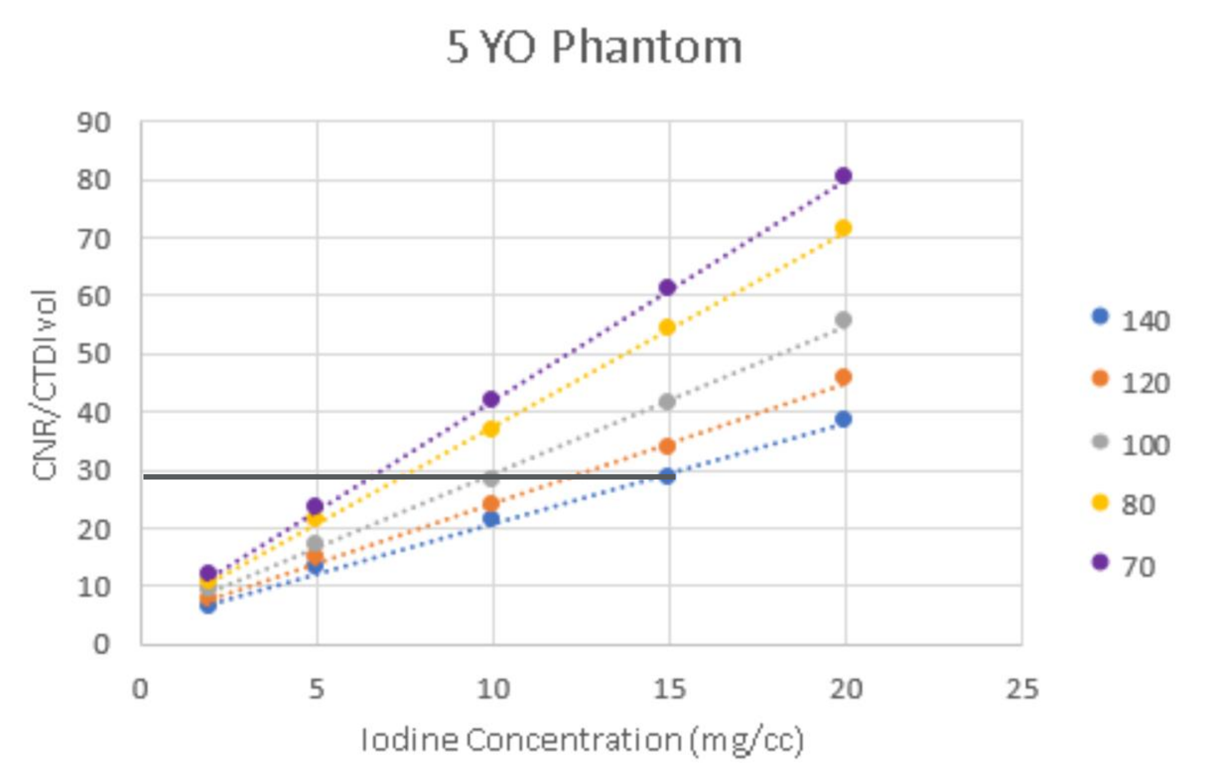
- Rule of thumb
  - Routine body imaging @ 70 kV
    - < 30 cm AP+LAT (CCHMC)
    - Typically, neonates (< 15 kg)
  - Routine body imaging @ 80 kV
    - 30-60 cm AP+LAT (CCHMC)
    - Typically, toddlers to large teenagers
  - Routine body imaging @ 100 kV
    - > 60 cm AP+LAT (CCHMC)
    - Typically, large teenagers young adults

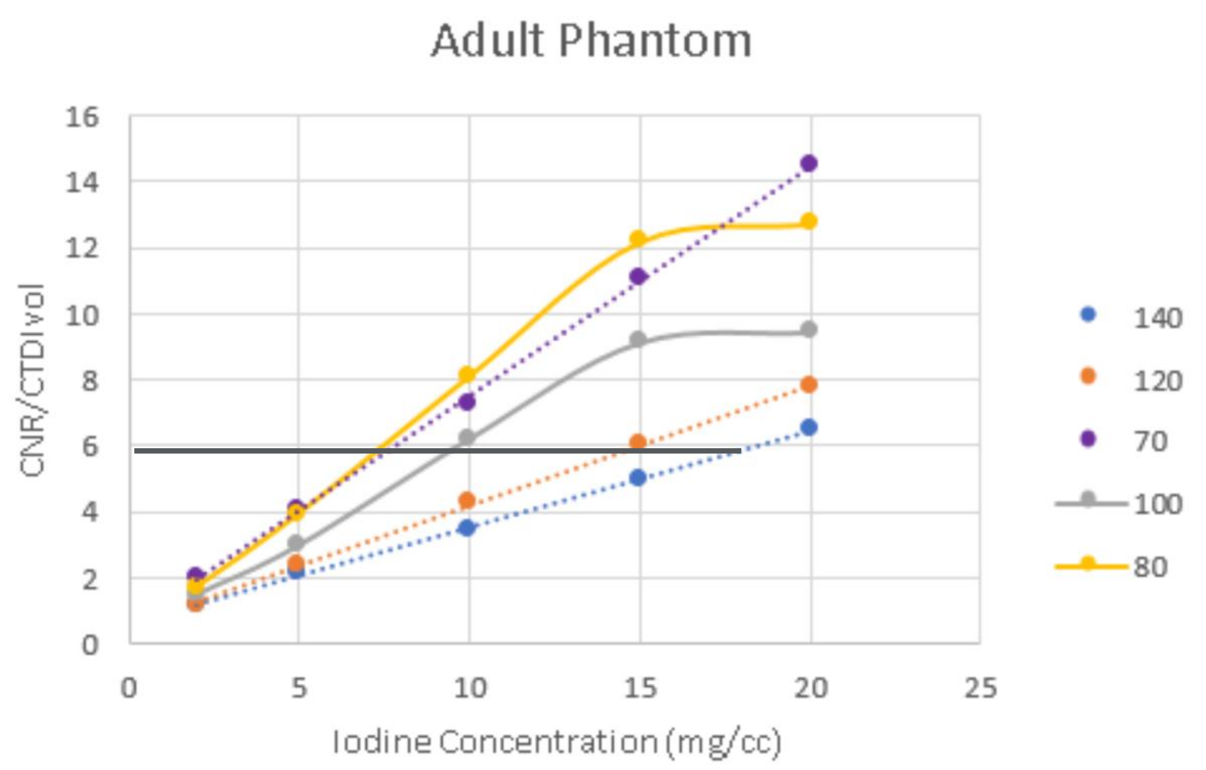
- Rule of thumb
  - Routine imaging @ 100 kV
    - Heads < 5 years old
  - Routine imaging @ 120 kV
    - Heads > 5 years old

Low kV Imaging



- Lower kV protocols may lead to lower IV contrast
  - This is largely true for all pediatric patients
  - Limited for adults





Low kV Imaging

- How is this applicable in RT?
  - When changing kV, CT number changes for high attenuating material
    - Bone & contrast infused tissues
  - Less change for soft tissue
    - Water and Air CT #s stay the same for all kV's

$$HU = \left(\frac{\mu_{material} - \mu_{water}}{\mu_{water}}\right) \times 1000$$

  - Minimize CT # changes to keep changes in Tx dose by <1%*
    - Changes in soft tissue #s are more detrimental to Tx doses than to bone
    - Suggest that CT # changes be kept to:
      - ± 20 HU for soft tissue &
      - ± 50 HU for the lung and bone

*Davis et al. BJR 2017 90(1076):20160406

Low kV Imaging

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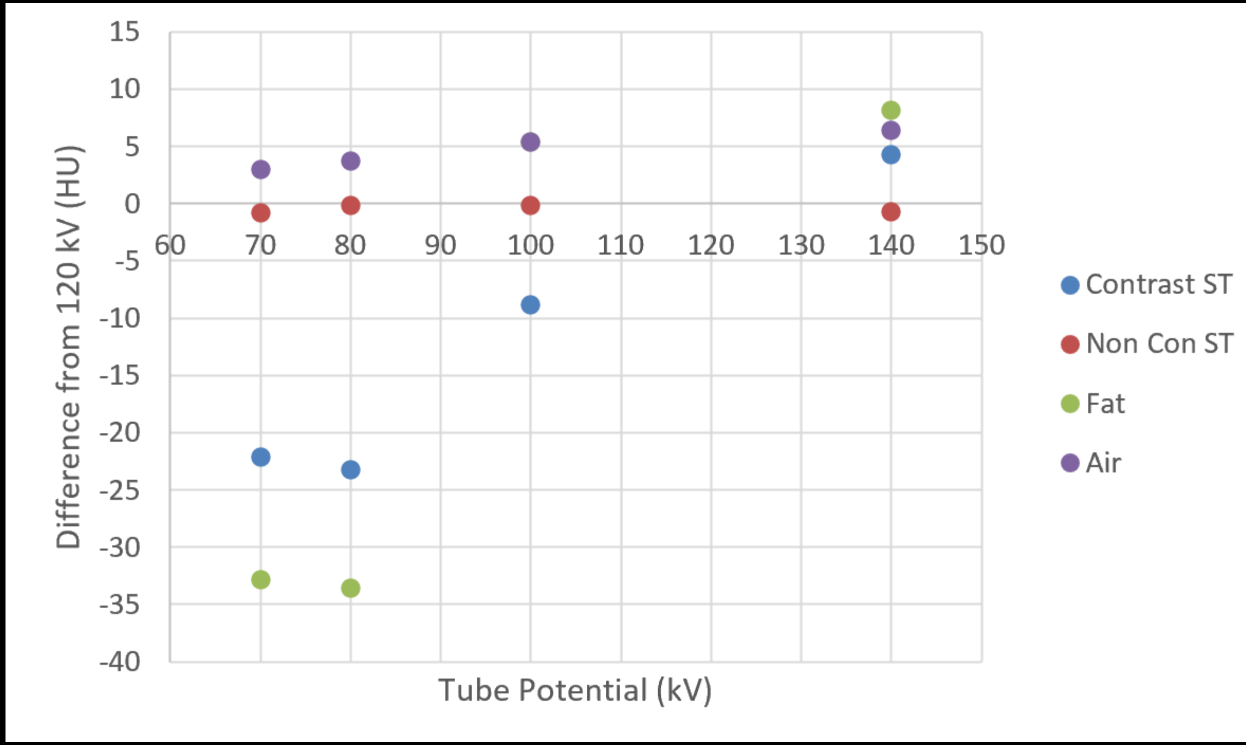
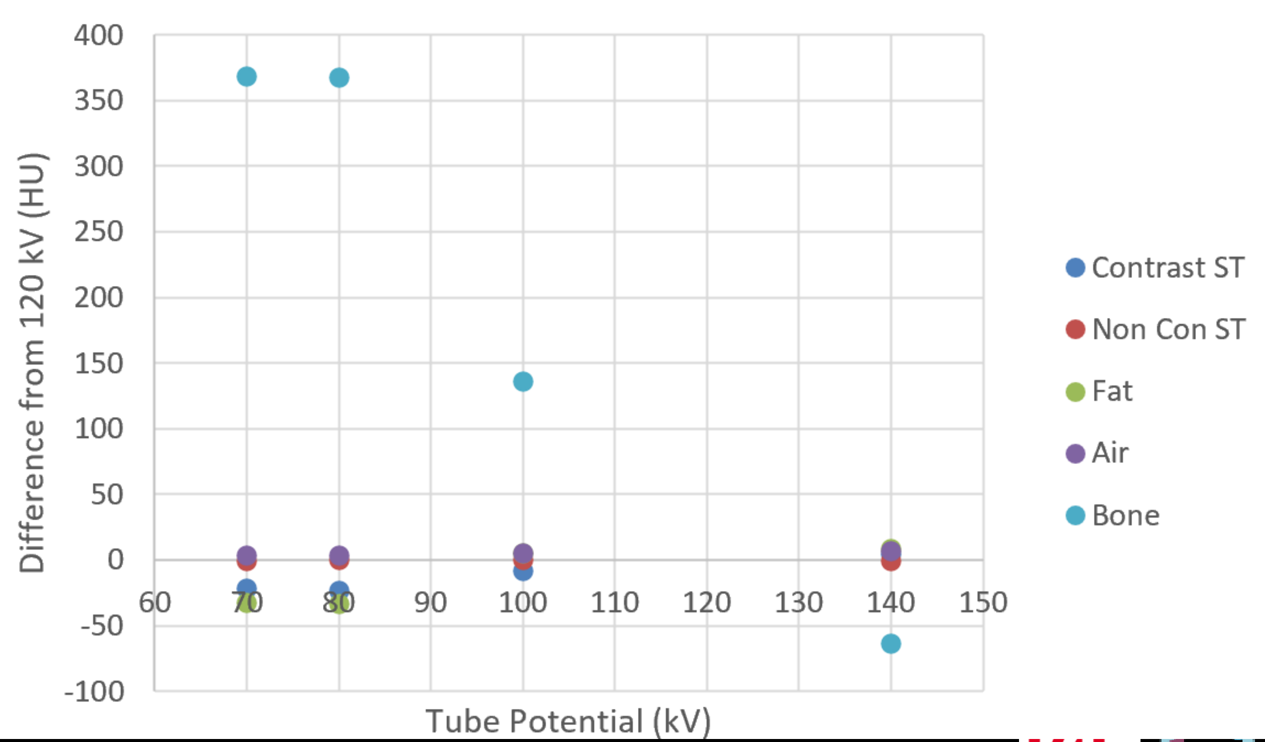
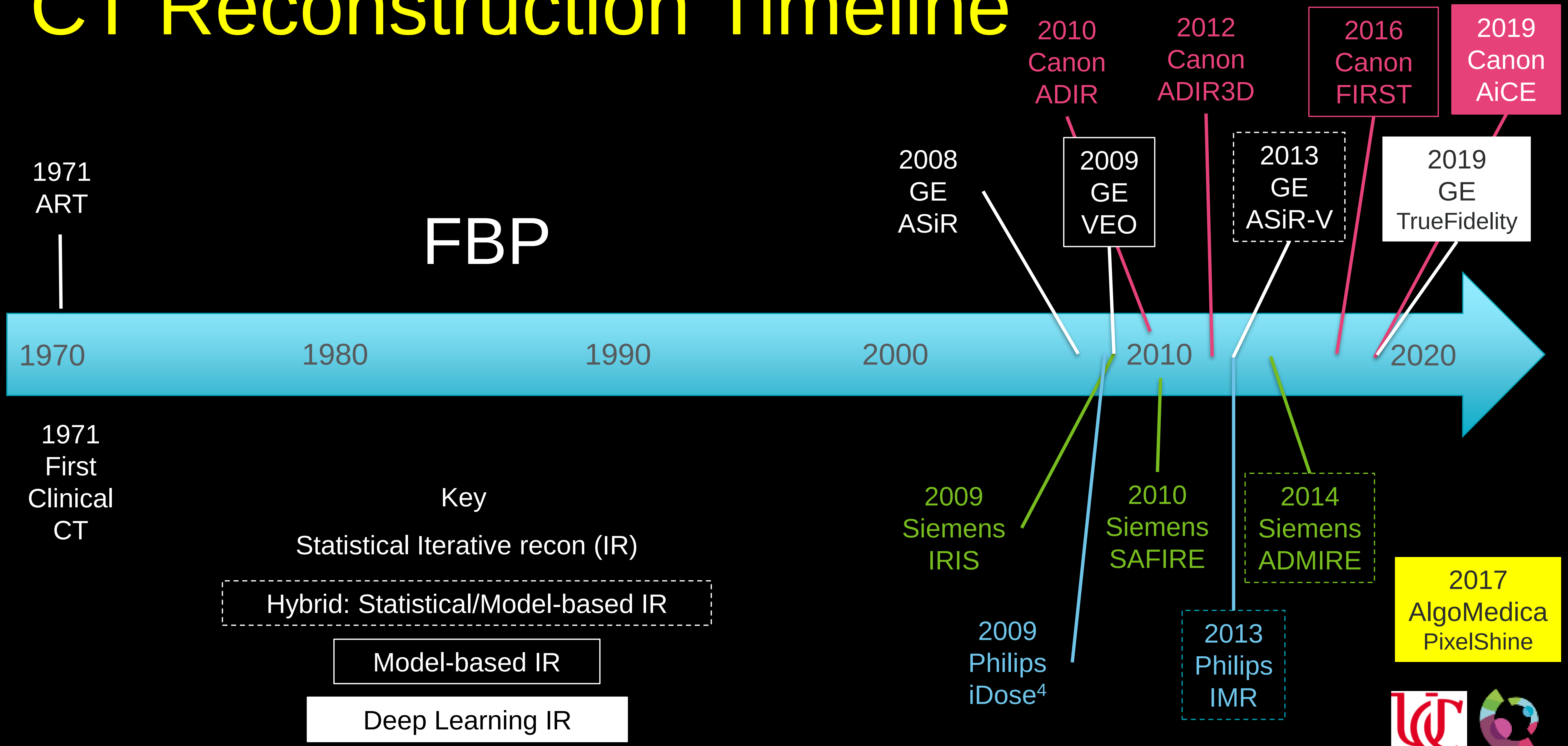
  - ± 20 HU for soft tissue &
  - ± 50 HU for the lung and bone





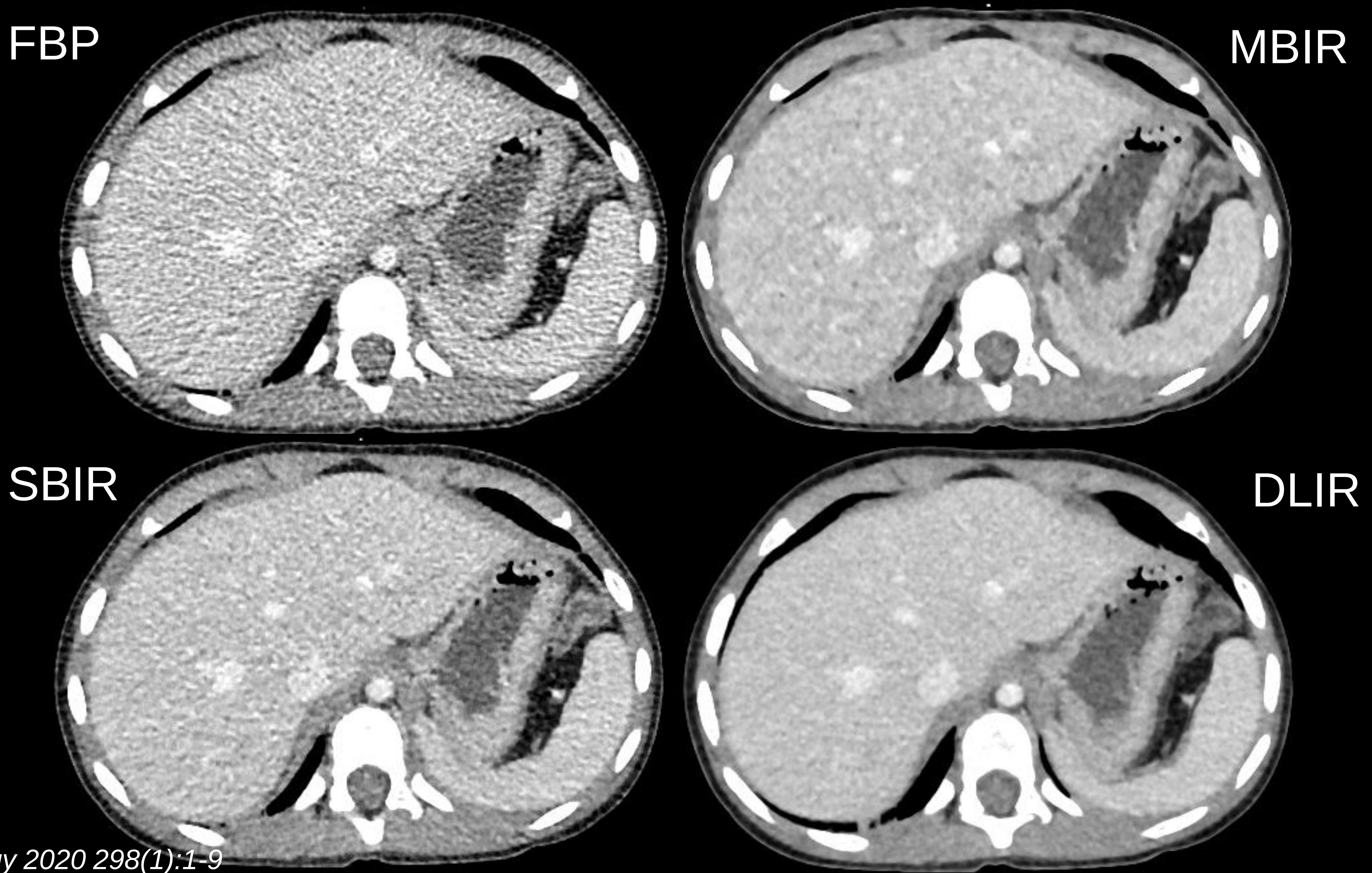
Davis et al. BJR 2017 90(1076):20160406

CT Reconstruction Timeline



Beister et al, Physica Medica, 2012, 28:94-108

Image Reconstruction-Options



Brady et al. Radiology 2020 298(1):1-9

CT DLIR-CCHMC Experience

- How is this applicable in RT?
  - No measurable difference in CT # between DLIR and IR
  - Noise reduction, CNR improvement do not affect dose planning accuracy
  - Additionally: shown to improve organ segmentation time/accuracy

> J Med Imaging (Bellingham). 2019 Oct;6(4):043504. doi: 10.1117/1.JMI.6.4.043504. Epub 2019 Oct 24.

Deep learning-based image quality improvement for low-dose computed tomography simulation in radiation therapy

Tonghe Wang [1], Yang Lei [1], Zhen Tian [1], Xue Dong [1], Yingzi Liu [1], Xiaojun Jiang [1], Walter J Curran [1], Tian Liu [1], Hui-Kuo Shu [1], Xiaofeng Yang [1]

REVIEW article

Front. Oncol., 01 October 2019
Sec.Radiation Oncology
https://doi.org/10.3389/fonc.2019.00977

Deep Learning: A Review for the Radiation Oncologist

Luca Boldrini[1], Jean-Emmanuel Bibault[2*], Carlotta Masciocchi[1], Yanting Shen[3] and Martin-Immanuel Bittner[4]

CT DLIR-CCHMC Experience

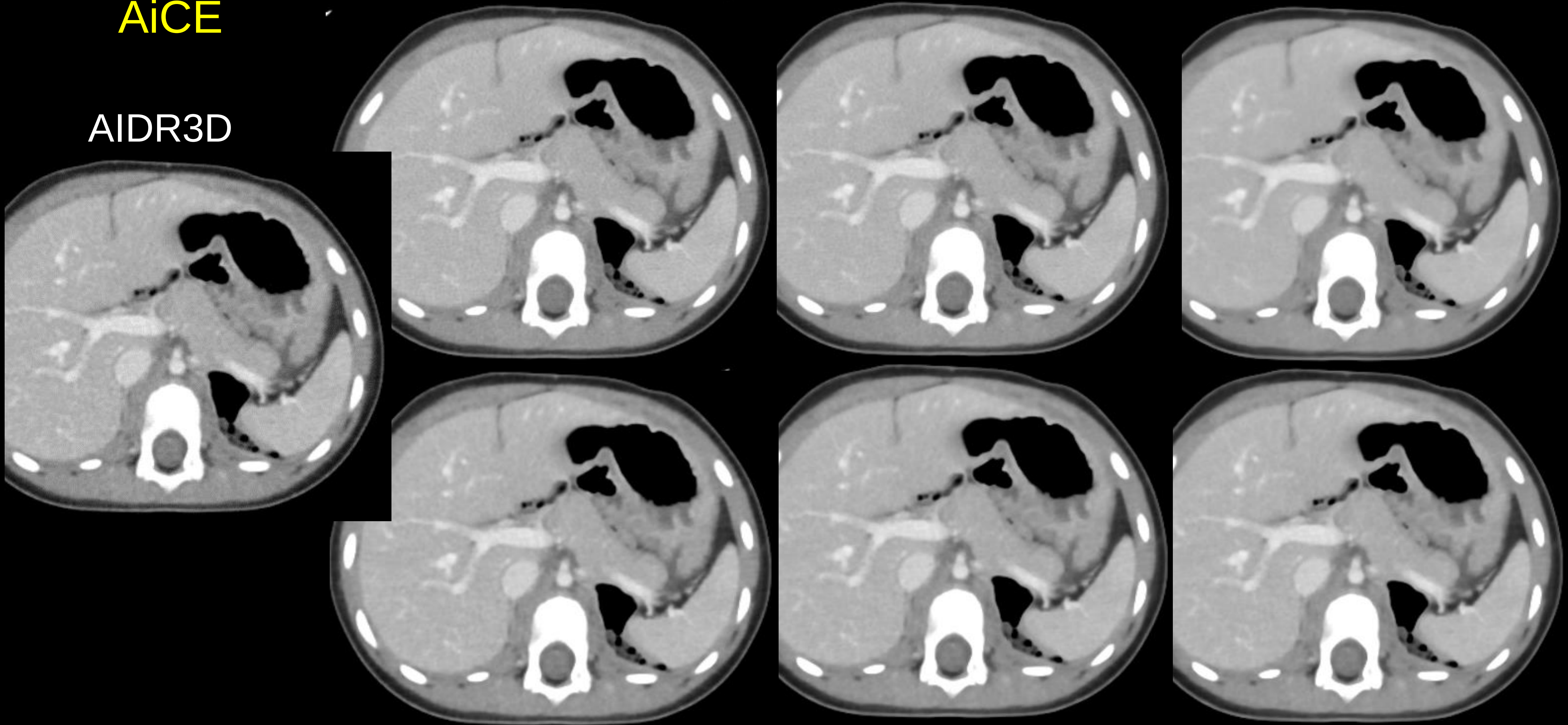
- Two vendors, two installs, two years apart
  - Canon's AiCE installed on Aquilion One Genesis
  - GE's TrueFidelity installed on Revolution Apex

- Two different approaches to implement DLIR
  - AiCE install occurred first (2019)
  - We needed to sort through all the reconstruction options
    - Learn radiologist preference(s)
    - Test for diagnostic confidence

Canon's AiCE

Body Sharp Mild | Body Sharp Standard | Body Sharp Strong

AIDR3D



Body Mild | Body Standard | Body Strong

GE's TrueFidelity

FBP

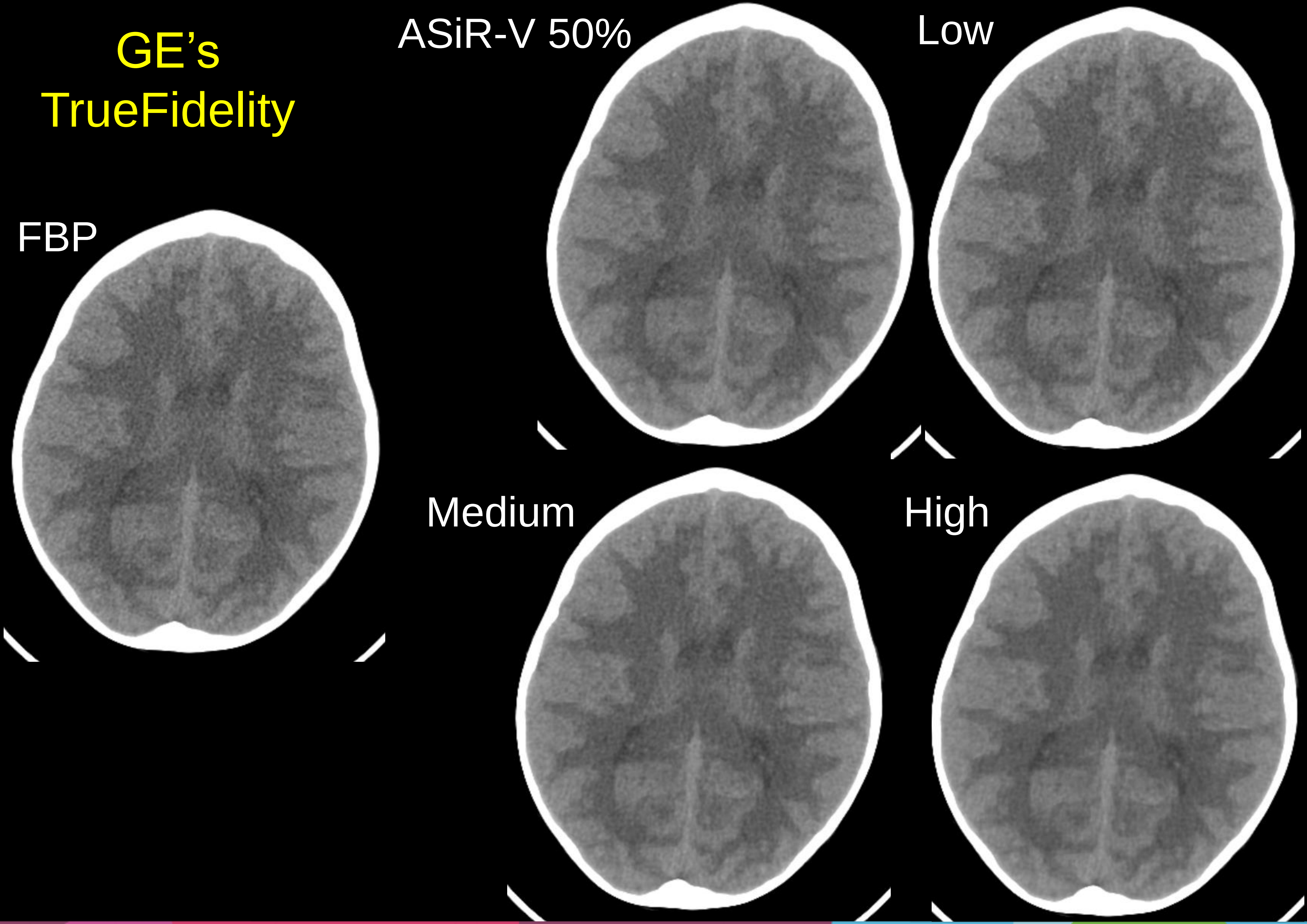
ASiR-V 50%

Low

Medium

High

GE's TrueFidelity



Objective Observer Preference

- To learn radiologist preference(s) & test for diagnostic confidence
  - We selected a variety of patient ages/sizes for reconstruction
    - Total was ~130 exams
      - Each patient was reconstructed using clinical SBIR + 6 DLIR options
  - Each exam was evaluated
    1. Mathematical observer/rater [using a non-prewhitening-matched mathematical-observer model with eye filter (d'_{NPWE})]
    2. Human observer/rater
    3. Took all data and did an ROC analysis

Brady et al. Radiology 2020 298(1); doi.org/10.1148/radiol.2020202317

Objective Observer Preference

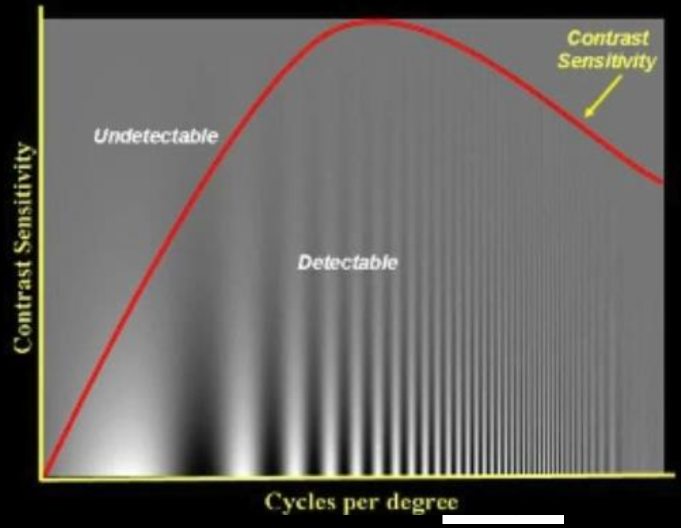
- Objective model: non-prewhitening matched detection index observer model (d'_{NPWE}):

$$d'_{NPWEi} = \frac{\left[2\pi \cdot \int_0^{Nyquist} |W(f)|^2 \cdot TTF(f)^2 \cdot E(f)^2 \cdot df\right]^2}{2\pi \cdot \int_0^{Nyquist} \left[|W(f)|^2 \cdot TTF(f)^2 \cdot E(f)^4 \cdot NPS(f) + N(f) \cdot NPS(f)\right] df}$$

  – Eye Function: models the eye response to spatial freq

  – $E(f) = \rho^{1.5} \cdot e^{-C \cdot \rho^2}$; $\rho = f \cdot \frac{\pi}{180} \cdot \frac{d_v \cdot SFOV}{DFOV(cm)}$

    - d_v = 50 cm & C = 3.22*



*Richard S, Siewerdsen JH. Med Phys. 2008;35(11):5043-53.
*Solomon J, Samei E. J Med Imaging (Bellingham). 2016;3(3):035506.

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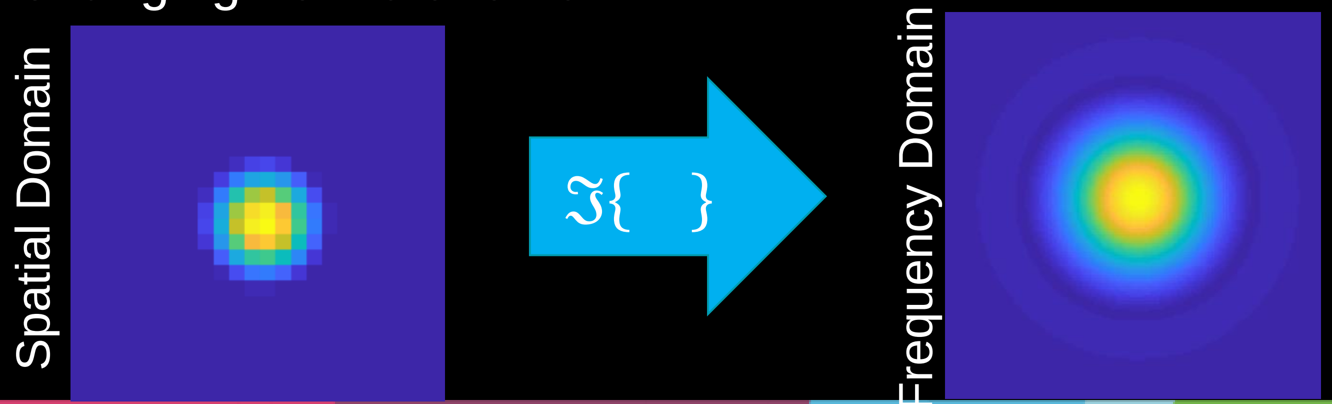
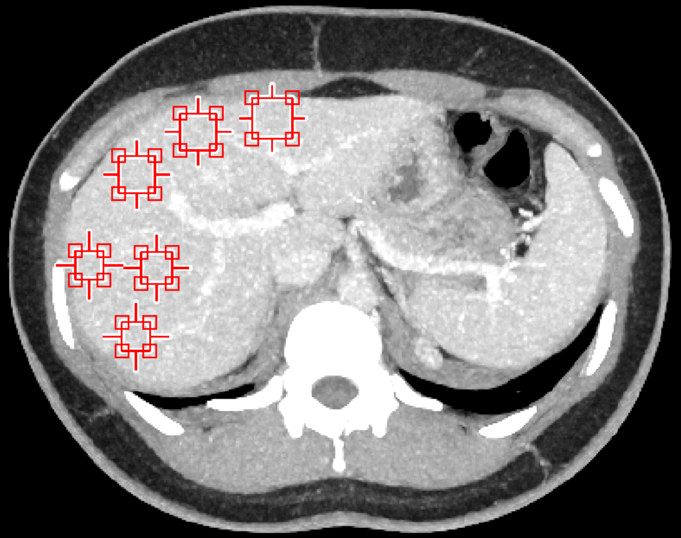
  – $W(f)$ is the task function, i.e., the Fourier transform of the signal to be detected
    - Circular objects ranging from 0.5 to 10 mm

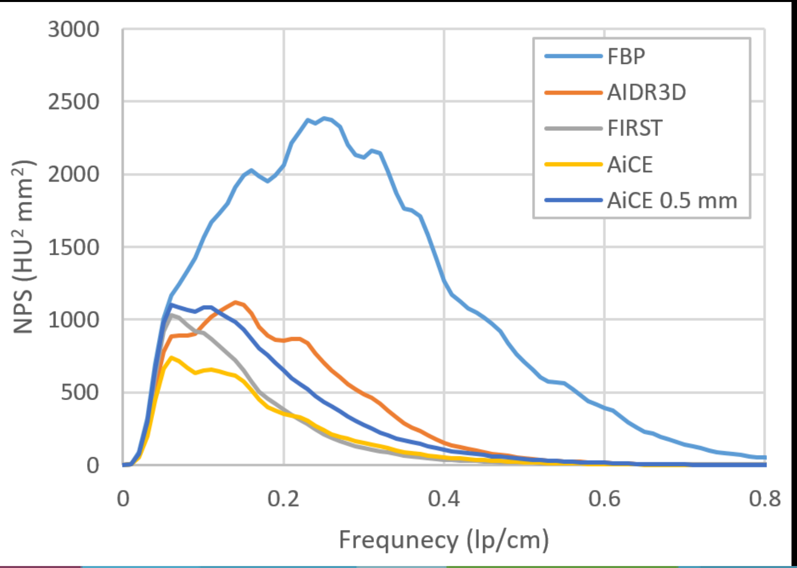


Objective Observer Preference

- Noise Power Spectrum [NPS(f)]
  - Patient images imported into IMQUEST, Duke University

$$d'_{NPWEi} = \frac{\left[2\pi \cdot \int_0^{Nyquist} |W(f)|^2 \cdot TTF(f)^2 \cdot E(f)^2 \cdot df\right]^2}{2\pi \cdot \int_0^{Nyquist} [|W(f)|^2 \cdot TTF(f)^2 \cdot E(f)^4 \cdot \mathrm{NPS}(f) + N(f) \cdot NPS(f)]\, df}$$





Objective Observer Preference

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$$d'_{NPWEi} = \frac{\left[2\pi \cdot \int_0^{Nyquist} |W(f)|^2 \cdot TTF(f)^2 \cdot E(f)^2 \cdot df\right]^2}{2\pi \cdot \int_0^{Nyquist} \left[|W(f)|^2 \cdot TTF(f)^2 \cdot E(f)^4 \cdot NPS(f) + N(f) \cdot NPS(f)\right] df}$$

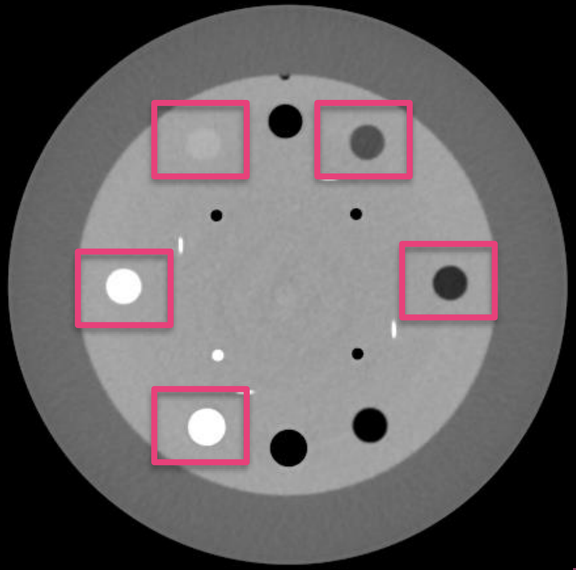
  – $N(f)$ is a scalar to model the human inefficiency caused by cognitive inconsistency
    - Defined as 60% of NPS based on prior studies*

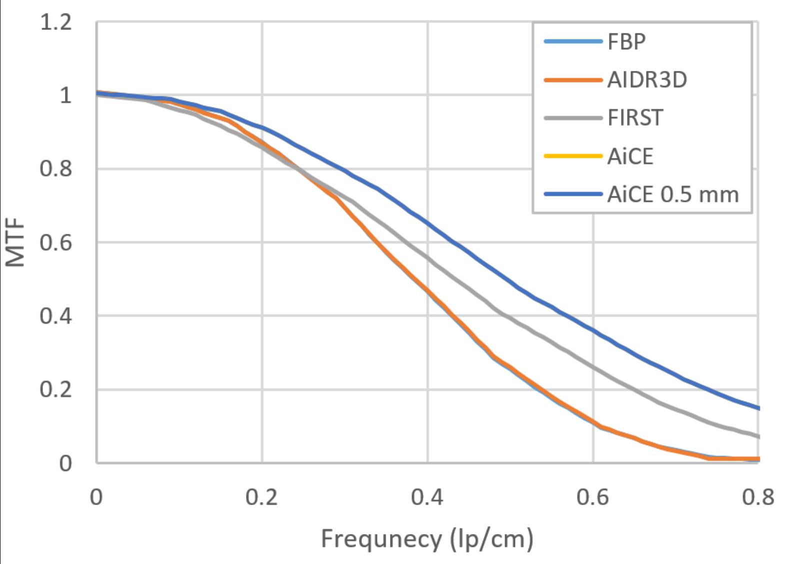
**Burgess AE. Semin Nucl Med. 2011;41(6):419-36.*
**Chen B, et al. Proc SPIE Int Soc Opt Eng. 2016;9783*

Objective Observer Preference

- Task Transfer Function [TTF(f)]
  - CatPhan 600 Phantom imported into IMQUEST, Duke University

$$d'_{NPWEi} = \frac{\left[2\pi \cdot \int_0^{Nyquist} |W(f)|^2 \cdot TTF(f)^2 \cdot E(f)^2 \cdot df\right]^2}{2\pi \cdot \int_0^{Nyquist} [|W(f)|^2 \cdot TTF(f)^2 \cdot E(f)^4 \cdot NPS(f) + N(f) \cdot NPS(f)]\, df}$$





Objective Observer Preference

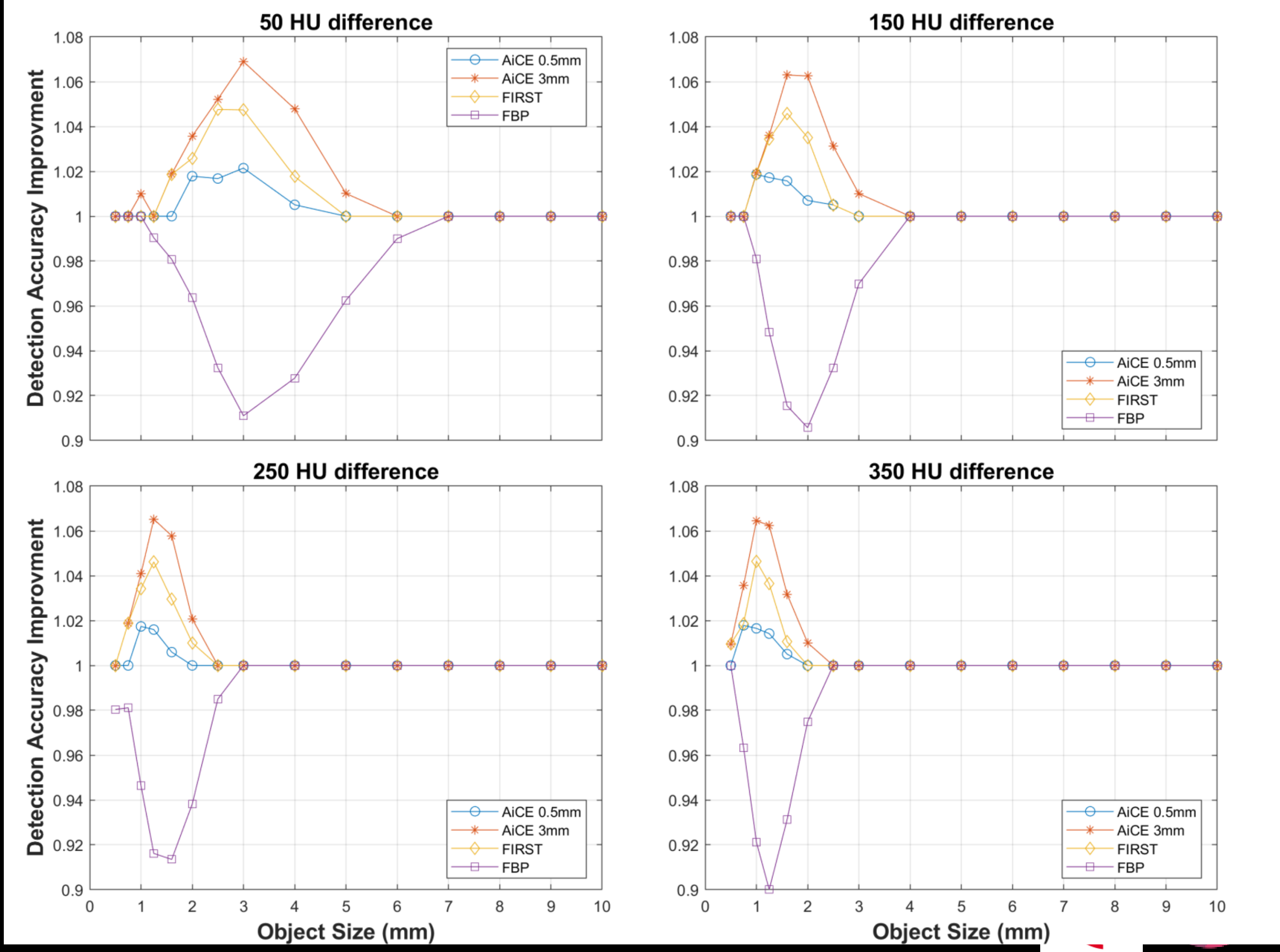
- Non-prewhitening matched detection index observer model (d'_{NPWE})
  - Used as a metric of SNR
- Use d'_{NPWE} *to calculate* an area under the curve (A_z) score

$$A_z = \frac{1}{2} \cdot \left[1 + \frac{2}{\sqrt{\pi}} \cdot \int_0^{d'_{NPWEi}/2} e^{-x^2} dx \right]$$

  - Used as a metric for detection accuracy
    - Calculated at each object size (0.5 to 10 mm)
    - Calculated at each contrast difference level (50 to 350 HU; increments of 100 HU)

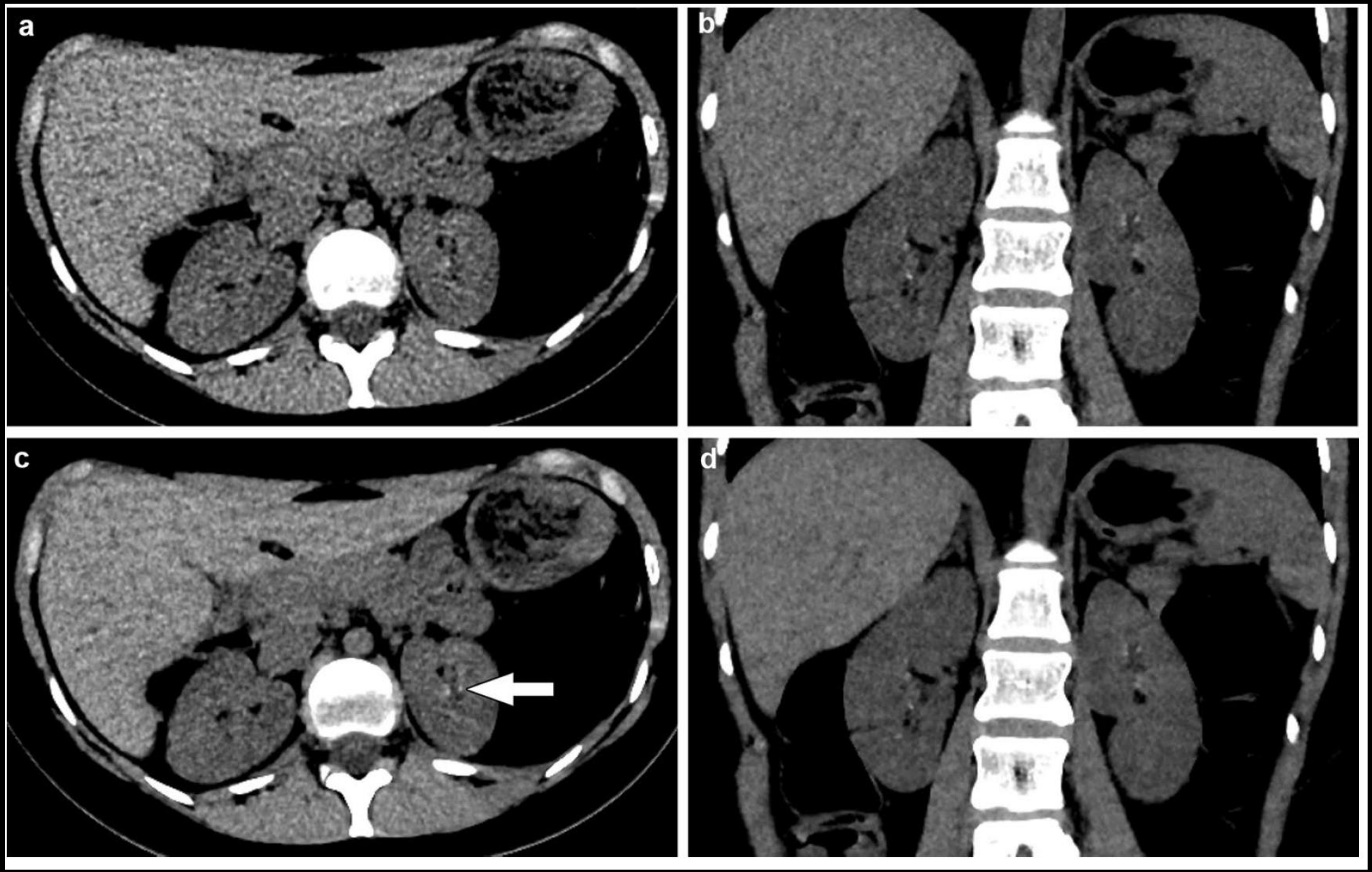
Mathematical Evaluation

- Mathematical observer study
  - *AUC* scores normalized to AIDR3D (SBIR)
    - 5mm thick images
  - *AUC* scores averaged over all patients
  - Results:
    - DLIR > MBIR > SBIR
    - DLIR(0.5 mm) > SBIR(5 mm)



Brady et al. Radiology 2020 298(1); doi.org/10.1148/radiol.2020202317

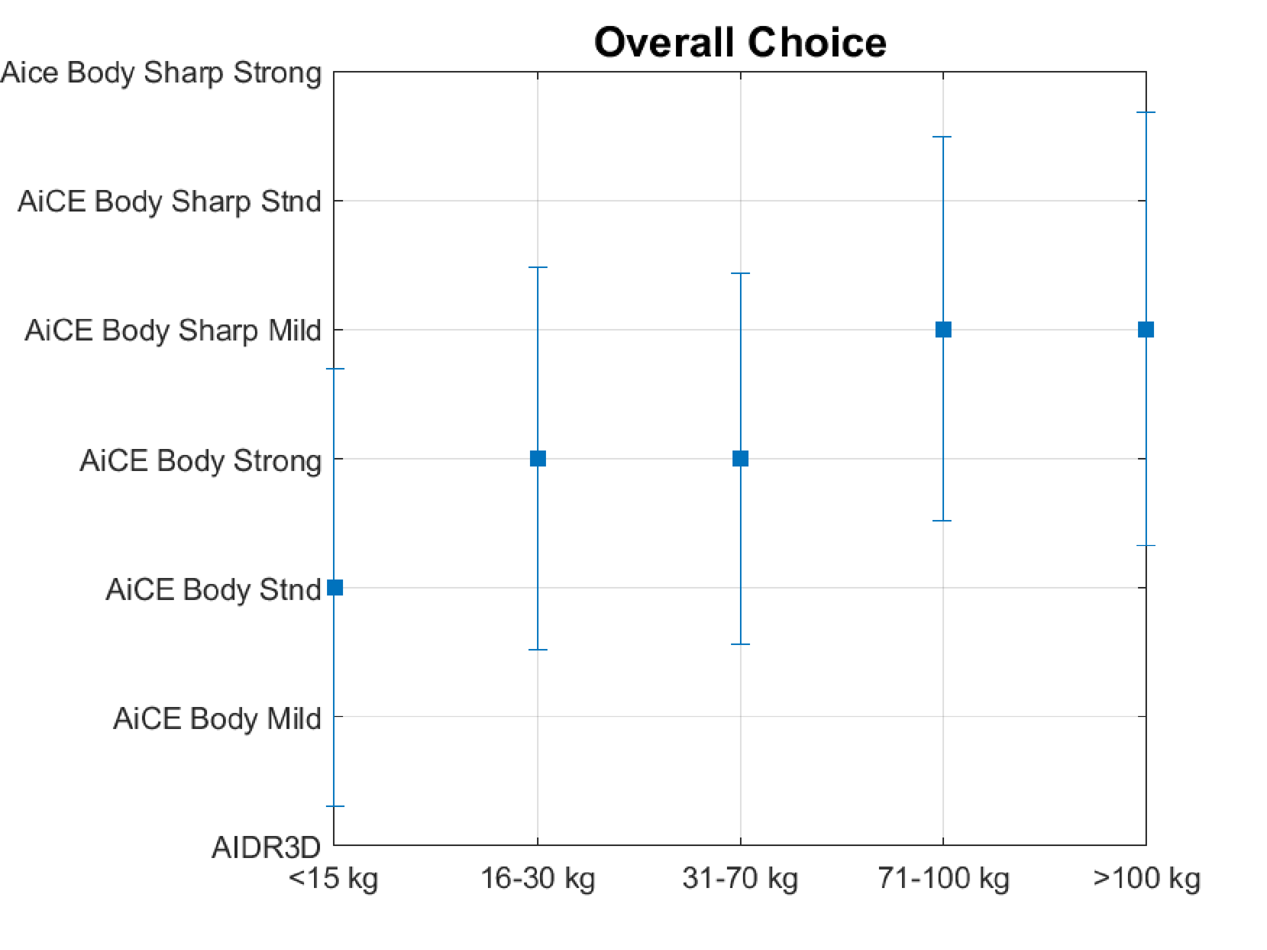
Object Detection



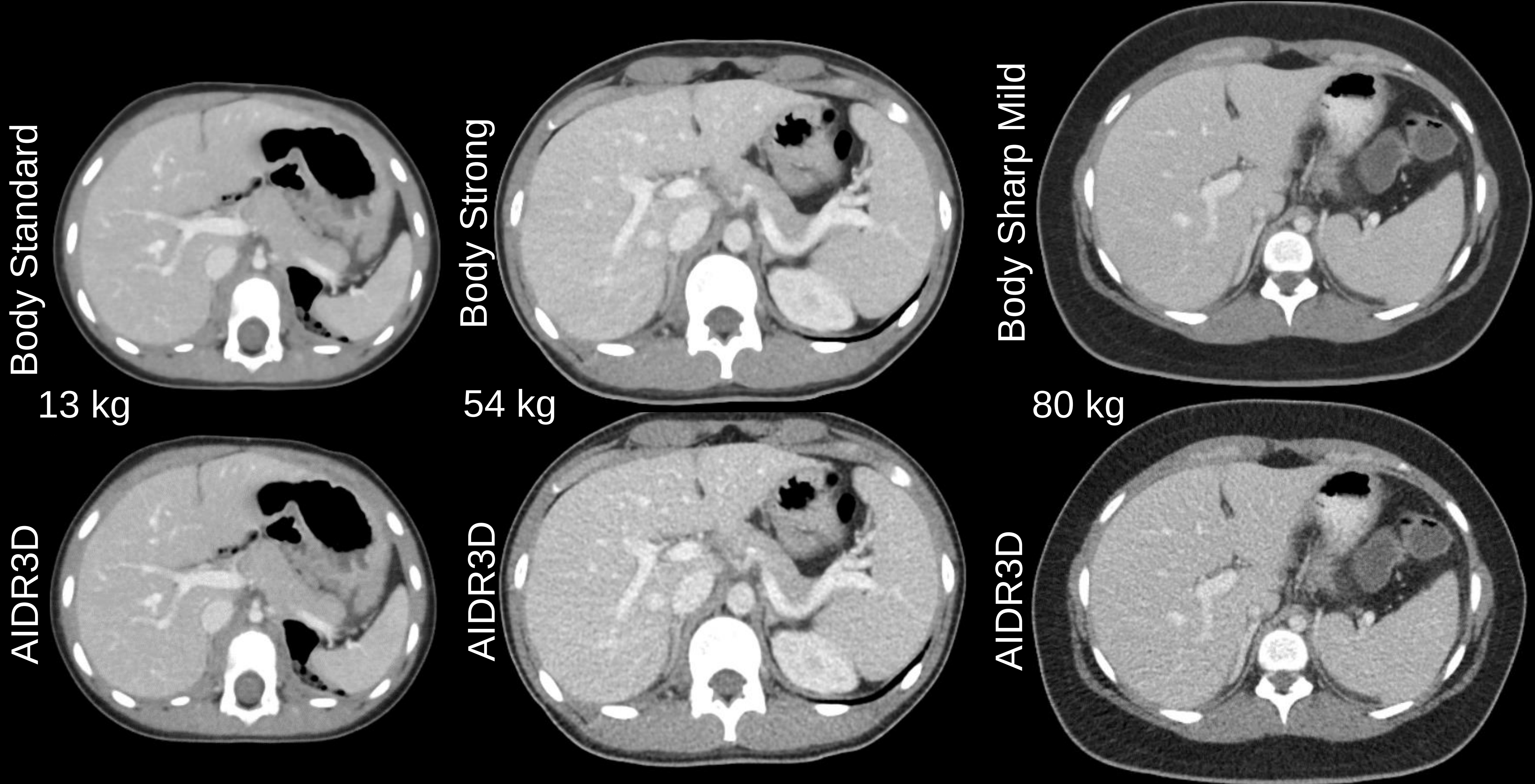
22-year-old woman with flank pain. Axial and coronal reformatted images reconstructed with iterative reconstruction (a and b) and deep learning reconstruction (c and d) show multiple calculi in both kidneys. One of the two stones in the upper pole of the left kidney is not visible in the axial image reconstructed using iterative reconstruction (a) and is visible on the deep learning reconstruction image (white arrow in c). All stones are visible on both reconstructions in the coronal plane. Note the decreased image noise in the deep learning reconstruction image

Thapaliya et al. Abdom Radiol 2022 47(1):265-271; doi.org/10.1007/s00261-021-03274-7

Observer Preference



- Is there a preference for the use of DLIR by patient size/weight?
- When considering all aspects of the image, in a blinded observer study, the participants demonstrated DLIR preference by patient weight


Body Standard
13 kg
AIDR3D
Body Strong
54 kg
AIDR3D
Body Sharp Mild
80 kg
AIDR3D

AiCE-Body Standard

TrueFidelity-Medium

Conclusions

- Use tube current modulation!
  - Use organ dose modulation if available
- Center your patients
- Create size-based protocol
- Reduce kV where possible (be careful of CT # change)
  - Dose reduction & CNR improvement
  - Potential reduction of IV/oral contrast concentration
- Adopt DLIR when possible

Thank you

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