Data Acquisition and Image Formation Methods for Multi-Energy CT

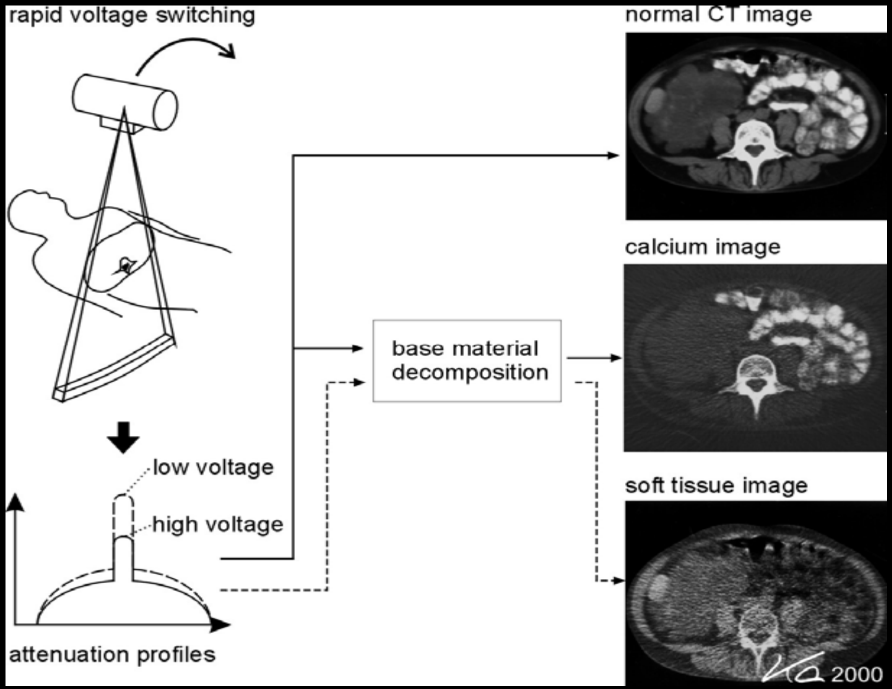
Cynthia H. McCollough, PhD, DABR, FAIMBE, FAAPM, FACR
Professor of Medical Physics and Biomedical Engineering
Director, CT Clinical Innovation Center
Mayo Clinic, Rochester, MN

Clinical Motivation

- CT number depends on x-ray attenuation
  - Physical density (g/cm^3) [electron-density]
  - Atomic number (Z)
- Different materials can have the same CT number if atomic number differences are offset by appropriate density differences
- Multi-energy CT
  - Allows separate determination of density and Z
  - Can provide material composition information

Acquire data with different beam spectra to exploit the energy-dependent nature of CT

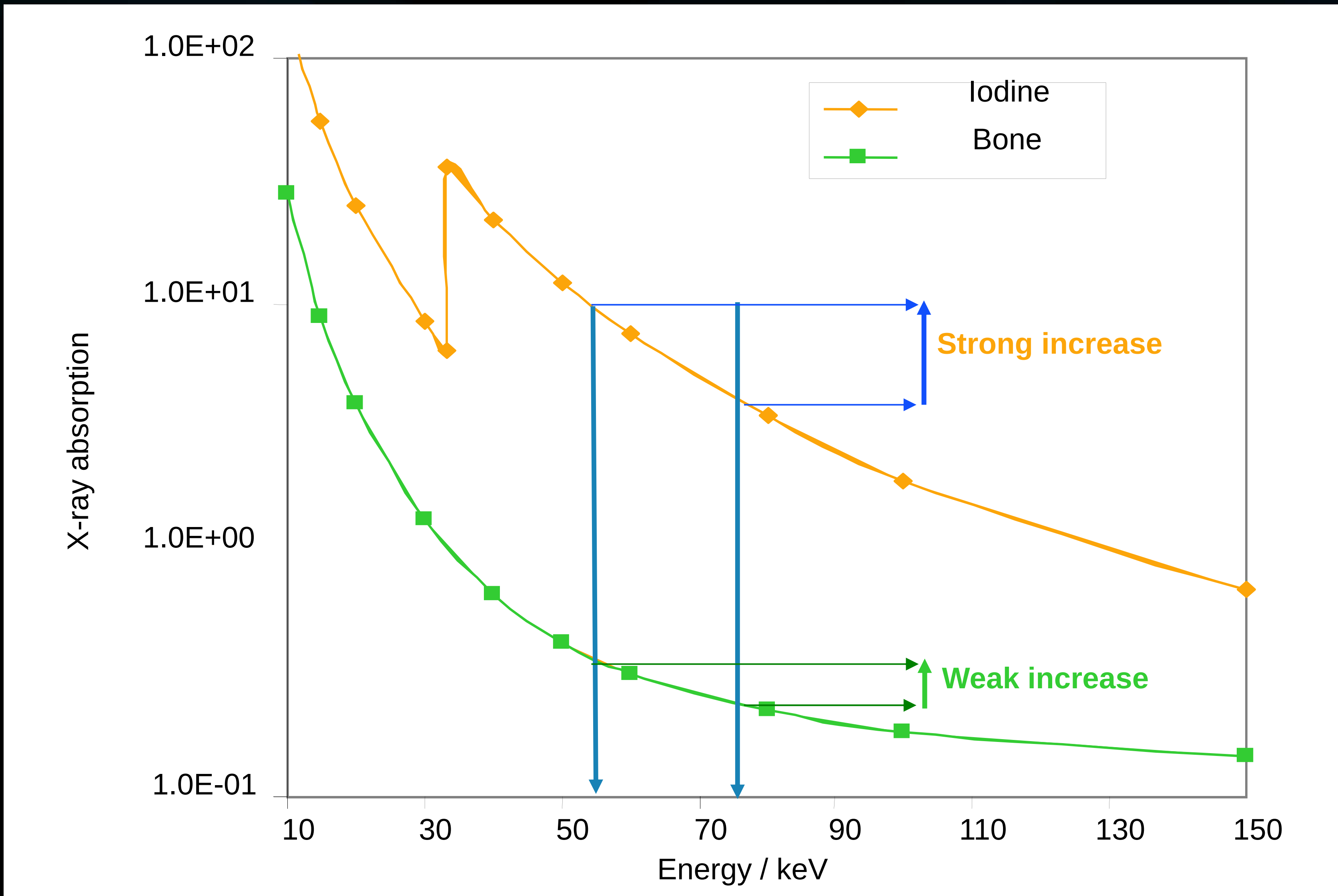
First proposed in 1973 …. by Hounsfield
Clinically implemented by one manufacturer for a short time in mid 80's



Kelcz et al: Med Phys 6, 418-25, 1979
Lehmann et al: Med Phys 8, 659-67, 1981
Kalender et al, Med Phys 13, 334, 1986

Kalender, Computed Tomography, Publicis Corporate Publishing, 2005.

Spectral separation is key!



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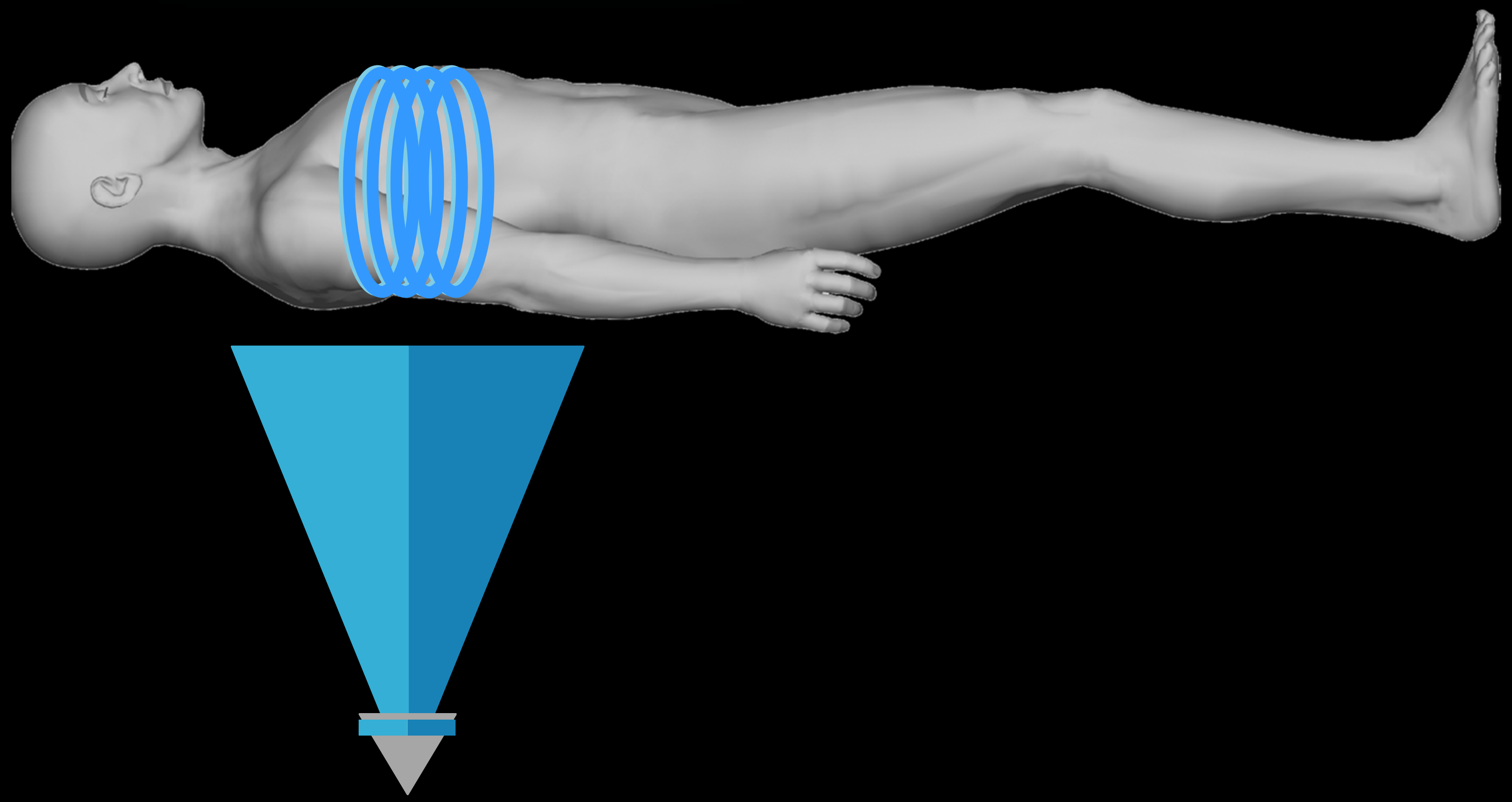
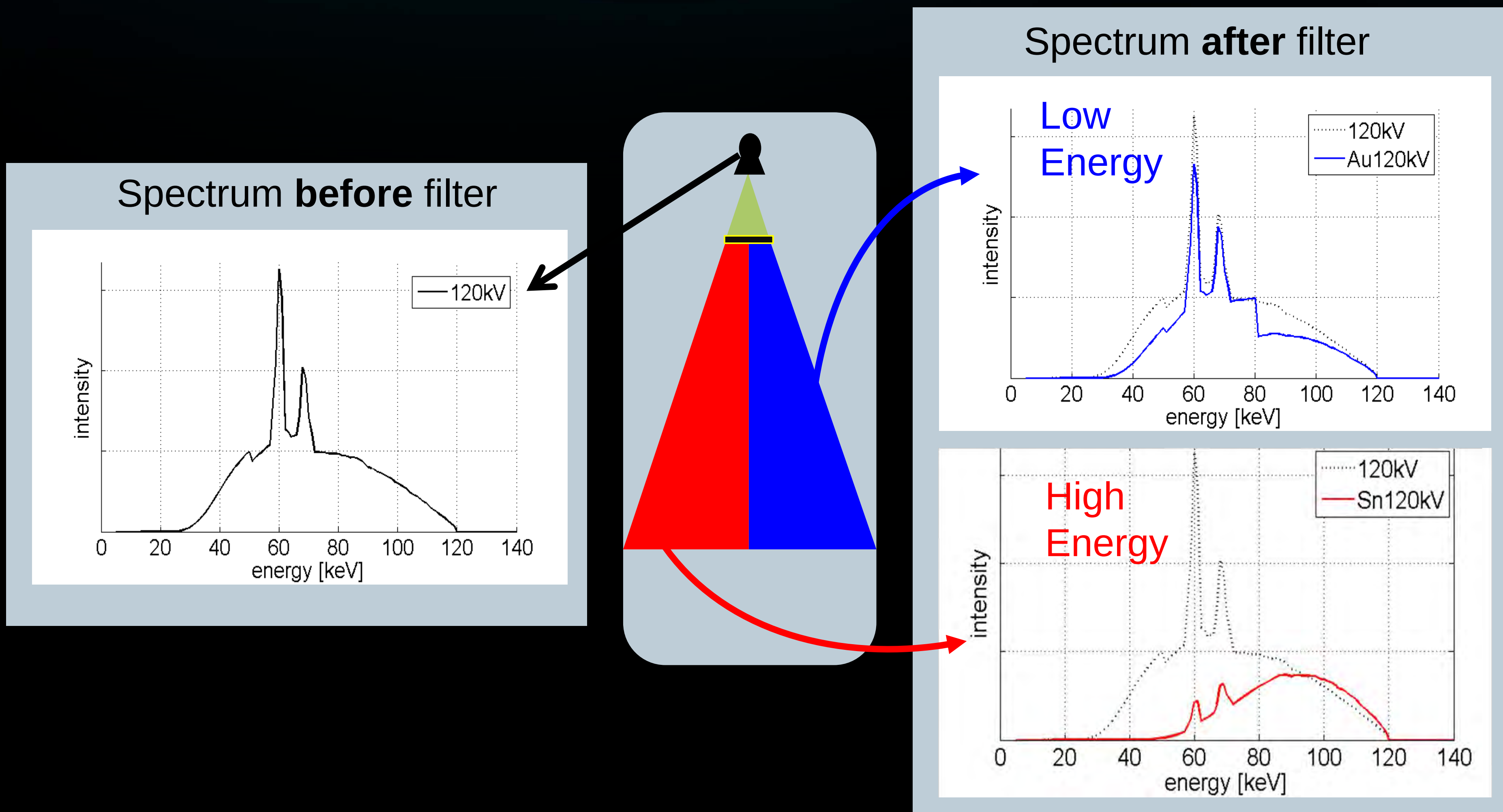
Current Acquisition Methods for Multi-Energy CT: Single Tube Potential

Split Beam Filtration

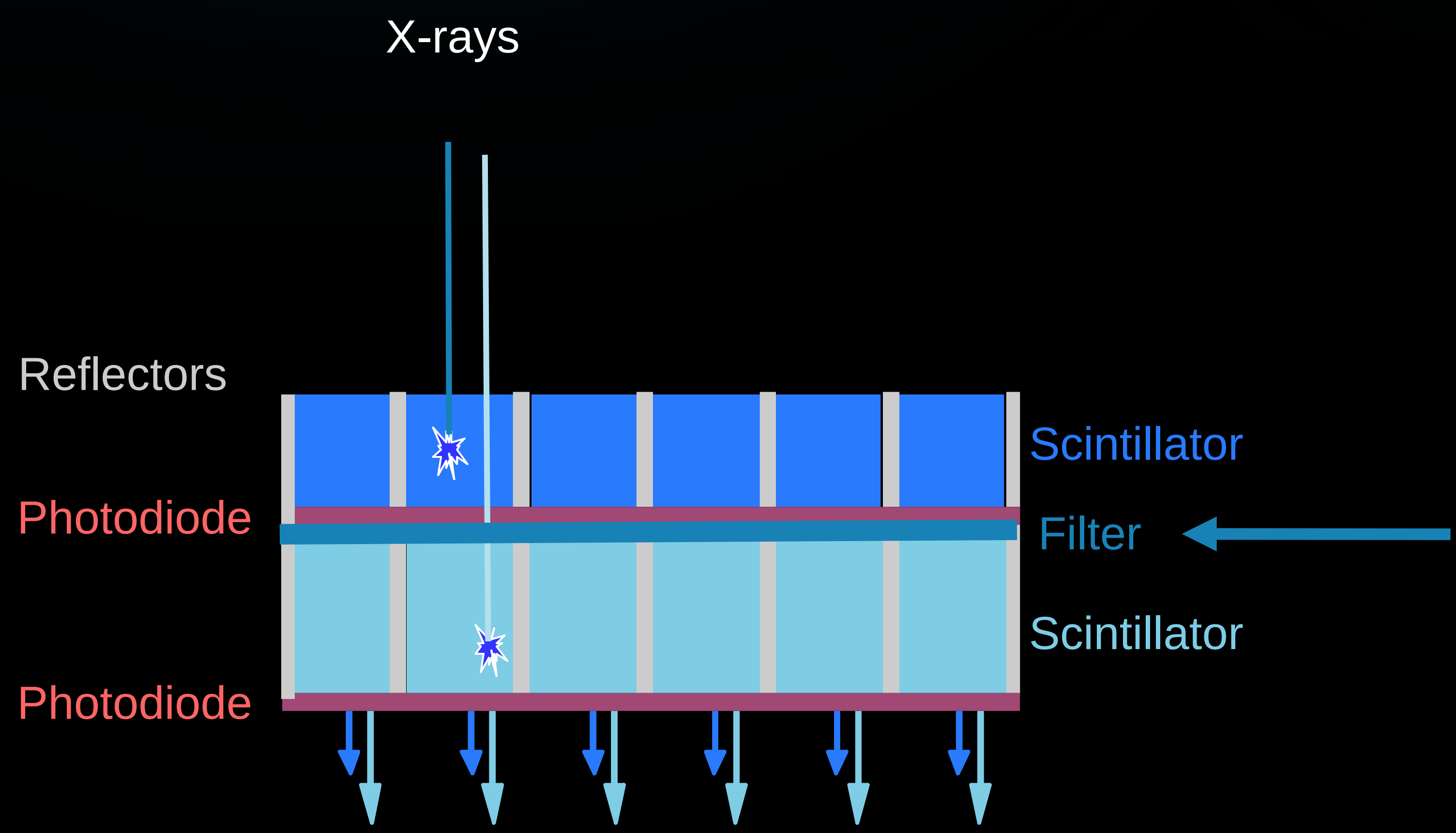
- Single spiral acquisition over entire scan volume
- One spectrum lags the other by half a rotation



Spectra: Split Beam Filtration

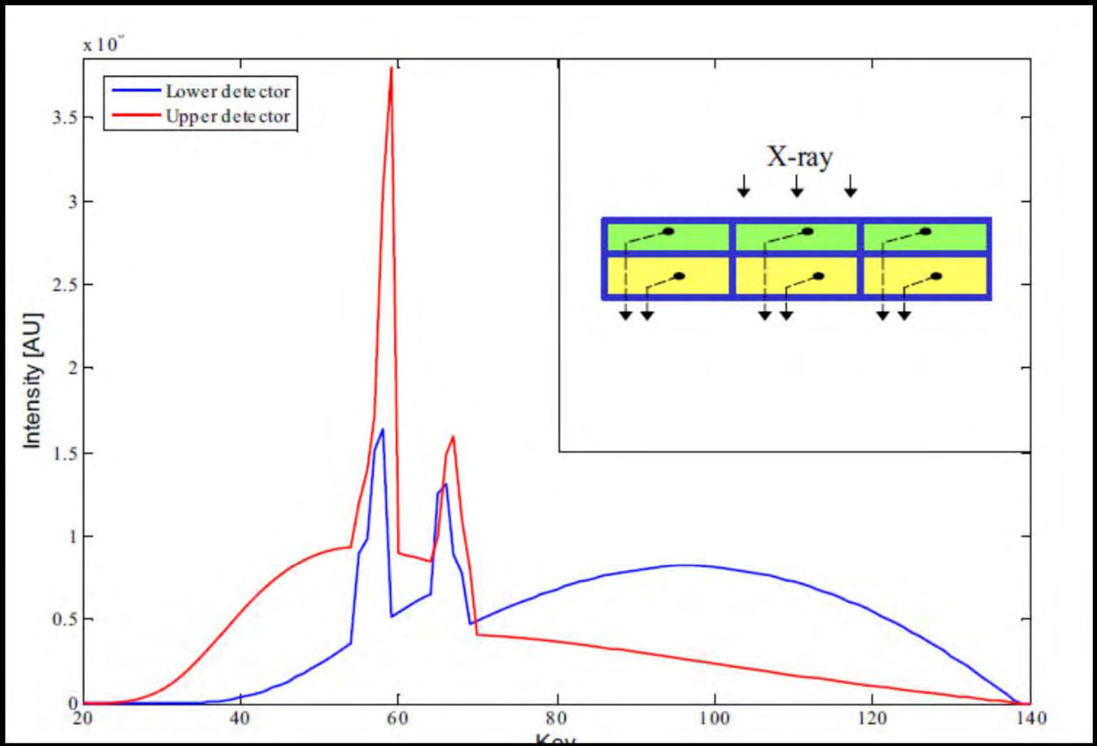


Dual Layer Detectors



Low energy spectrum
High energy spectrum

Spectra: Dual Layer Detectors



Raz Carmi et al, Material Separation with Dual-Layer CT. IEEE NSSCR 2005

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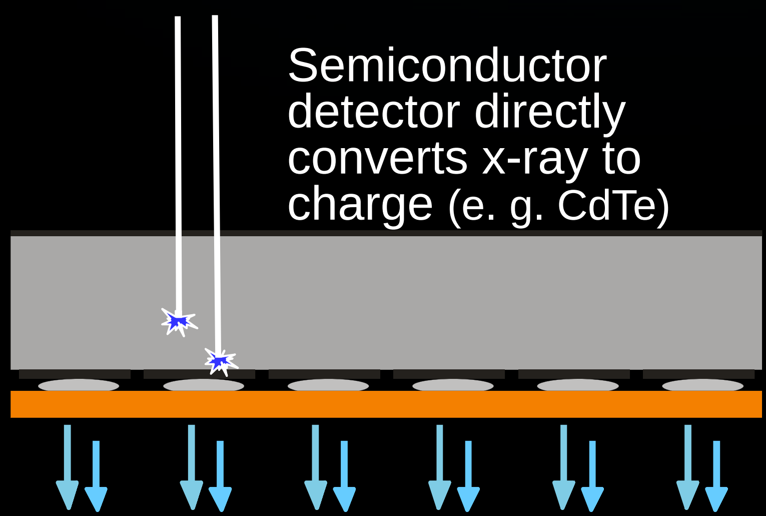
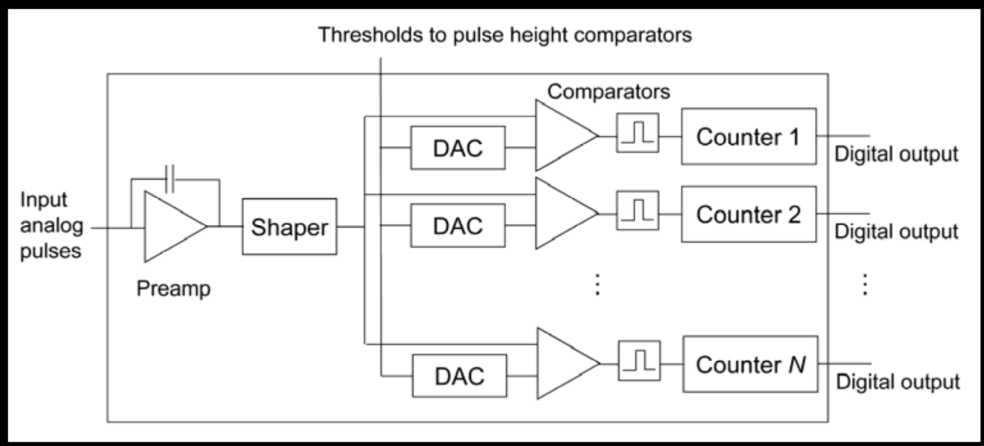
Photon Counting Detectors

X-rays



Two or more energy levels

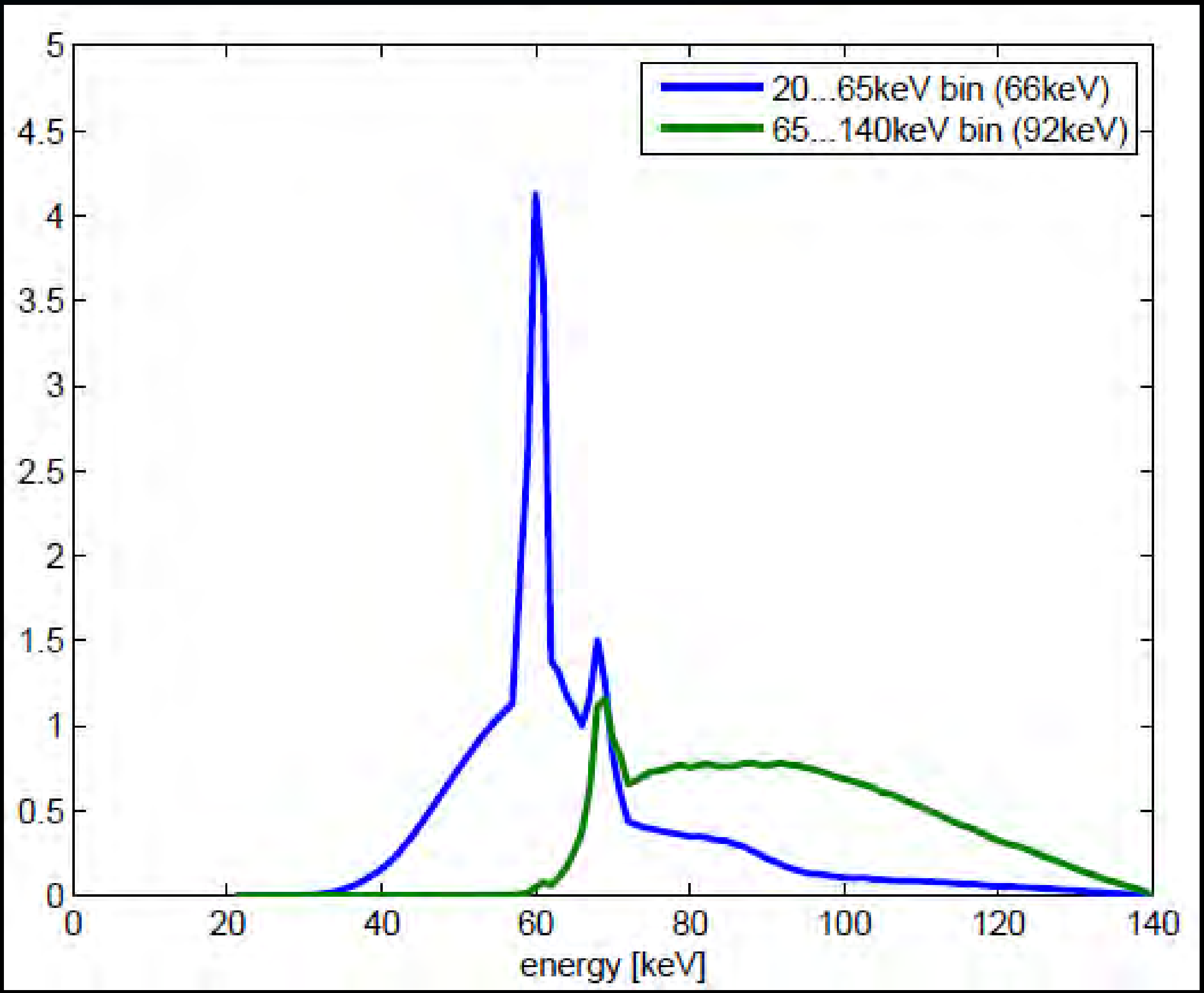
Signals are “binned” according to energy level



* Courtesy Ken Taguchi, John Hopkins

Low Energy Bin
High Energy Bin

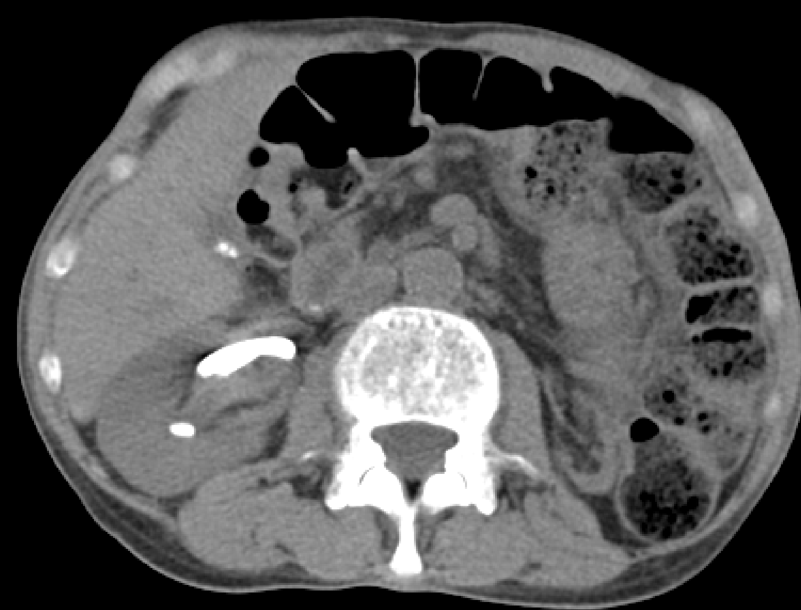
Spectra: Photon-counting, 2 energy bins



In vivo results

- 63 year old female (30 cm lateral width at kidney)
- Non-contrast-enhanced CT of the abdomen

Mixed DSCT



PCCT - T_{low}

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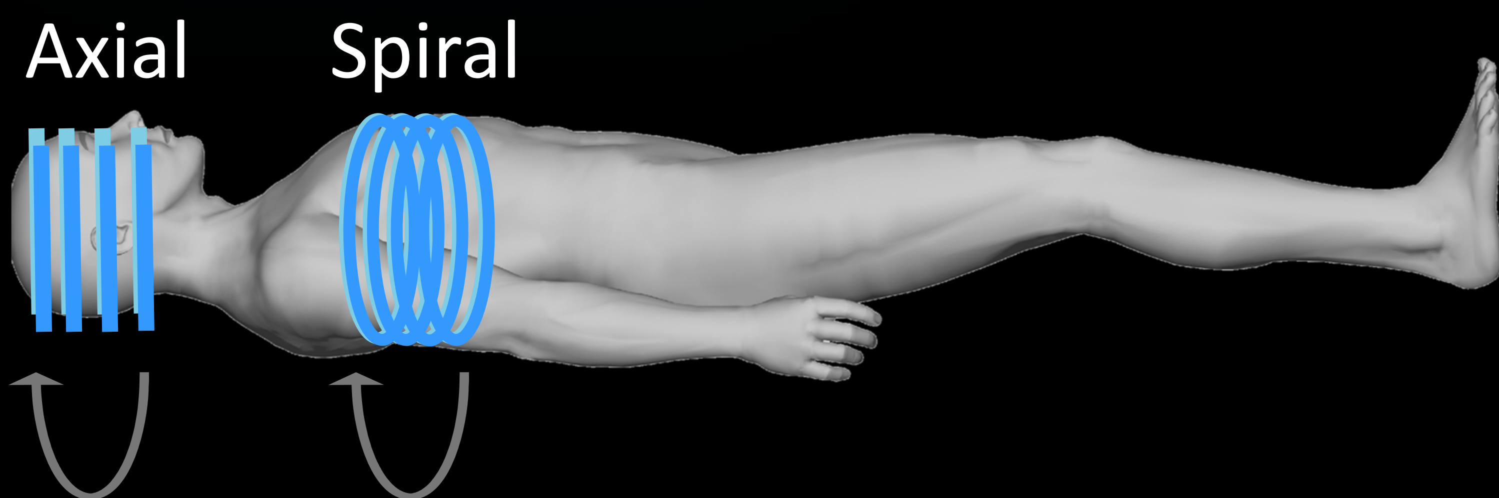
Current Acquisition Methods for Multi-Energy CT: Dual Tube Potential

Slow kVp switching

- Consecutive scans of entire scan volume



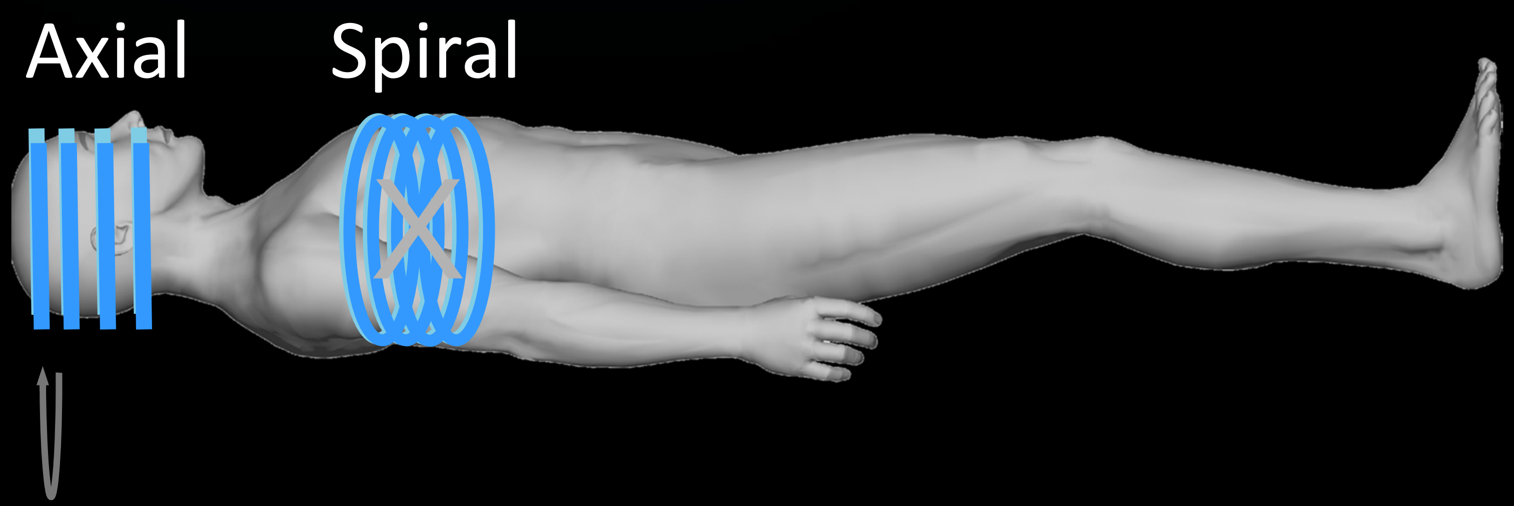
Inter-scan delay = scan time + table move time

Unacceptable motion misregistration for most cases
May be acceptable for large volume acquisitions
(entire volume scanned in one rotation)

Low kVp
High kVp

Slow kVp switching

- Consecutive scans of one anatomic section

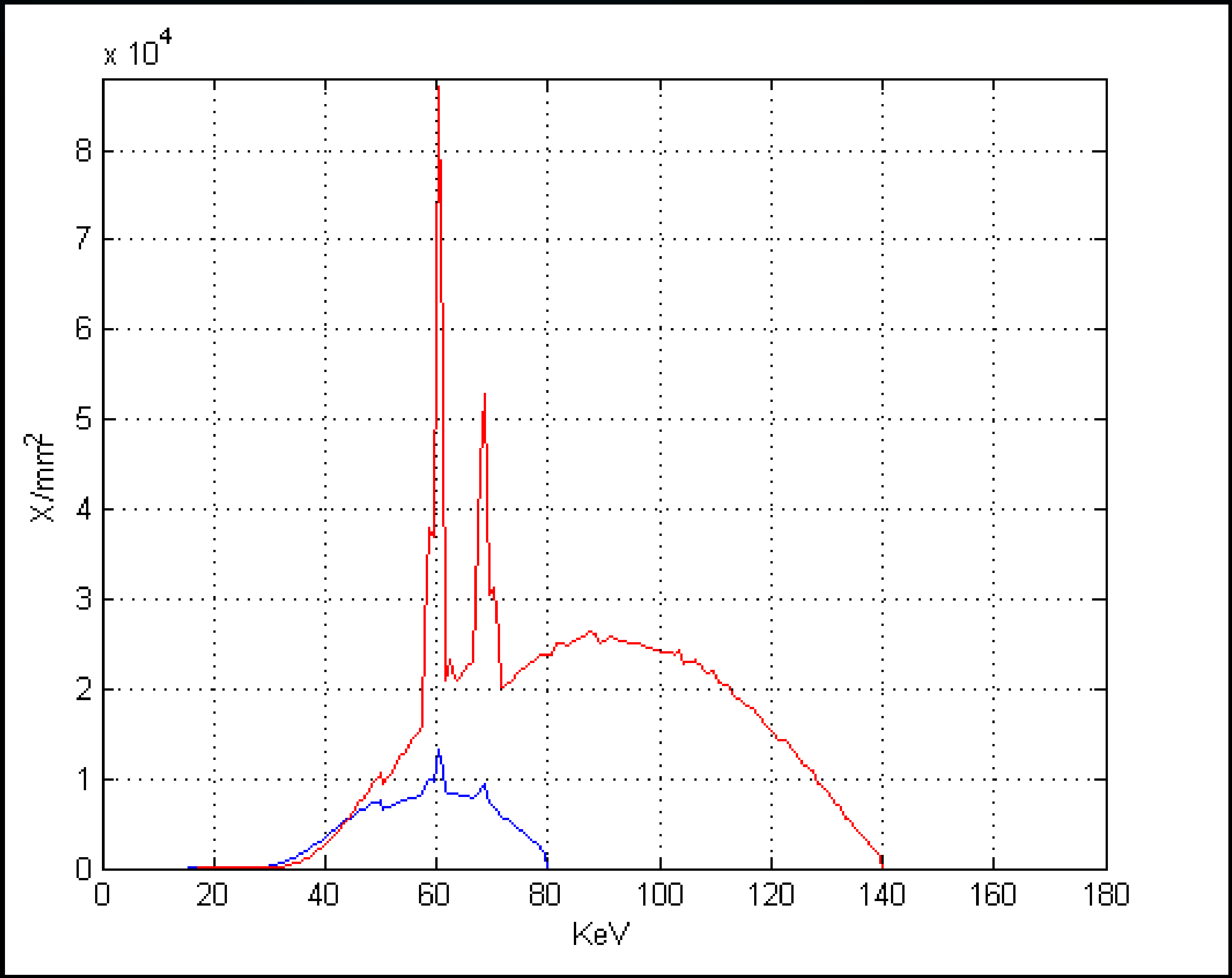


Inter-scan delay = rotation time + kV switching time

Motion misregistration will limit many applications

Low kVp
High kVp

Spectra: Dual Tube Potentials



Rapid kVp switching

- Tube potential switched between successive views

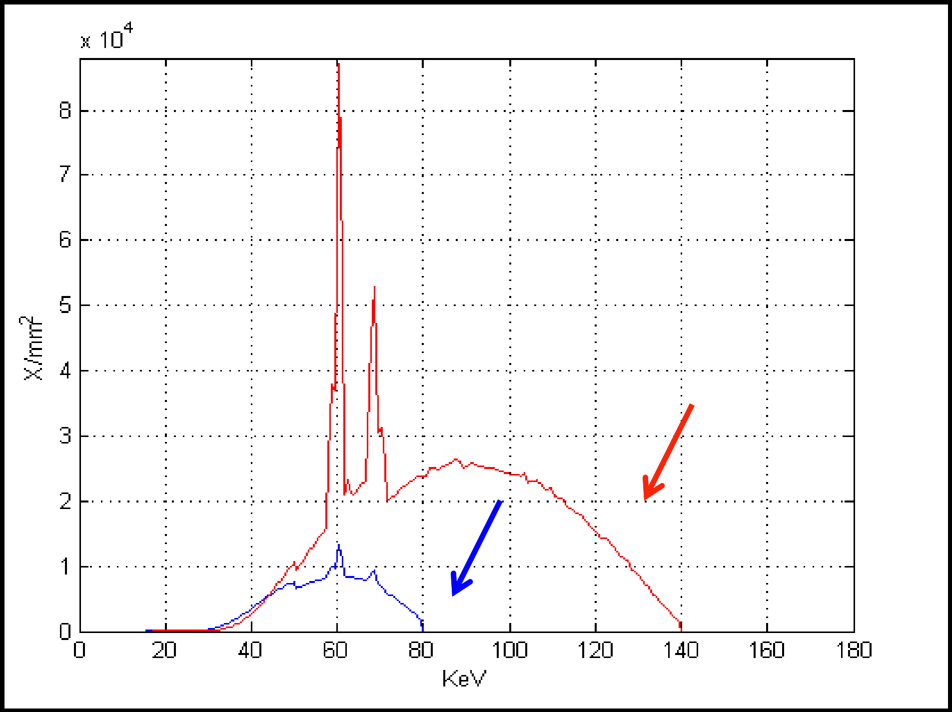
Axial or spiral acquisitions

Temporal resolution = Essentially unchanged

Low kVp
High kVp

Spectra: Rapid kV switching

?



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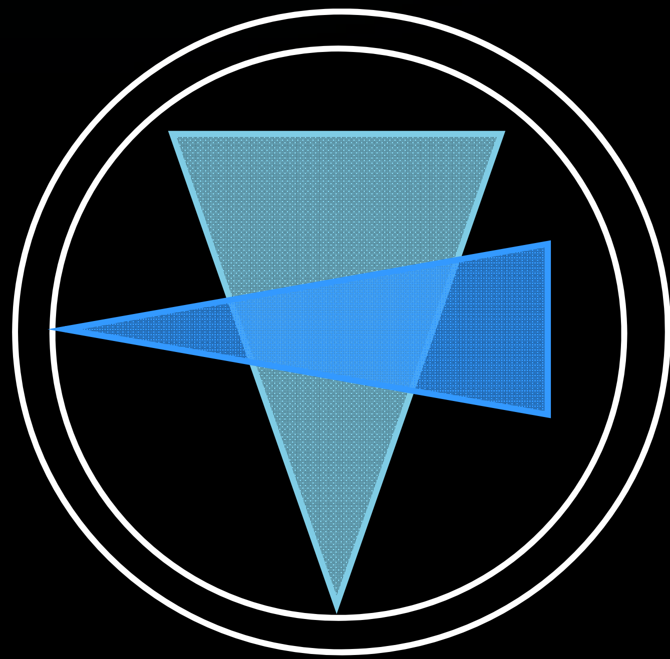
Dual-source geometry

- Two tubes/generators allow simultaneous collection of dual-kVp data

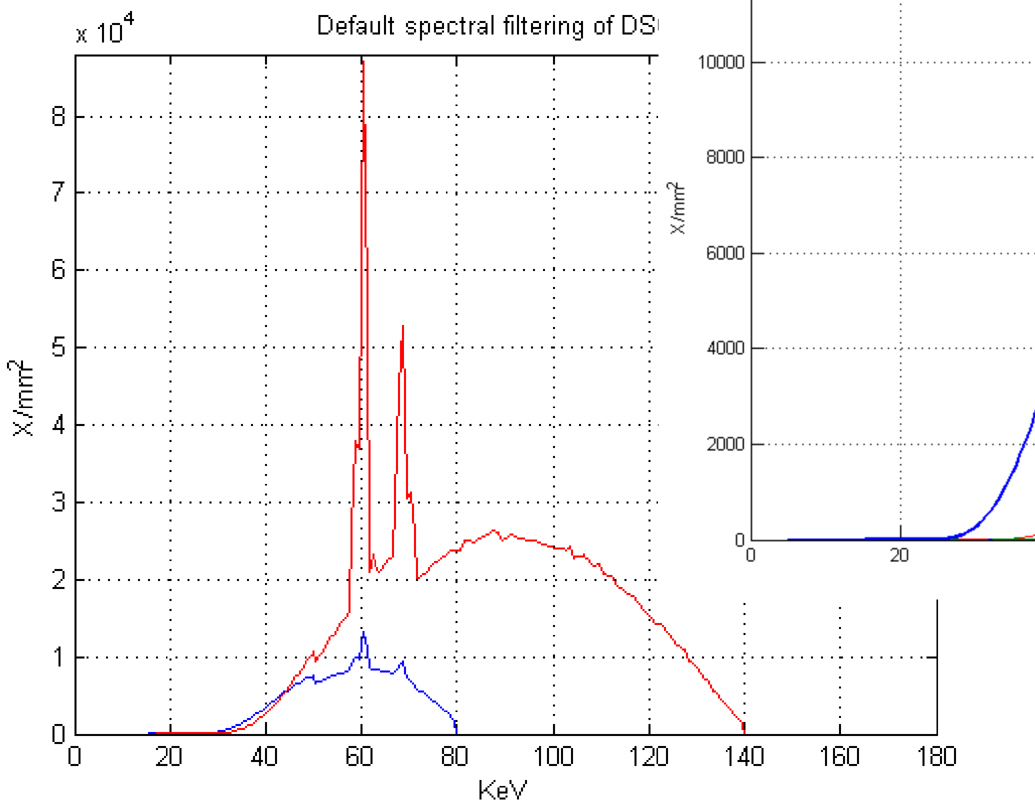


Axial or spiral acquisitions

Temporal resolution = Unchanged

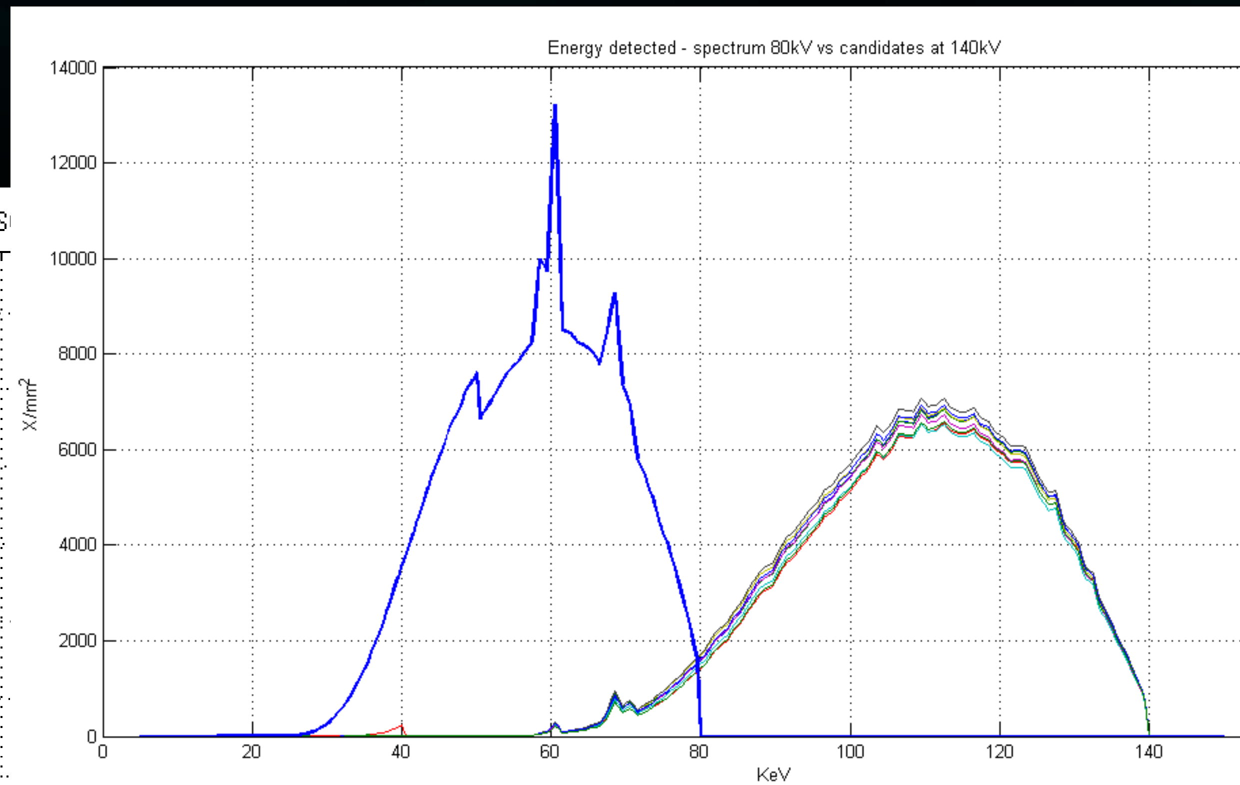
Low kVp
High kVp

Spectra: Dual-source geometry



No added filtration

High kVp: 400% spectral overlap of low kVp



Added Sn filtration

High kVp: ~ 4% spectral overlap

Primak et al. Med Phys 2009

Image Rendition Methods

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Multi-energy CT Images

- Low / High energy source images
  - 80 kV and 140 kV images
- Mixed (blended) images
  - Combine low and high energy images together
  - Linear and non-linear blending
- Material selective images
  - Iodine image, water image, bone image
- Energy selective image
  - Virtual monoenergetic (monochromatic) images

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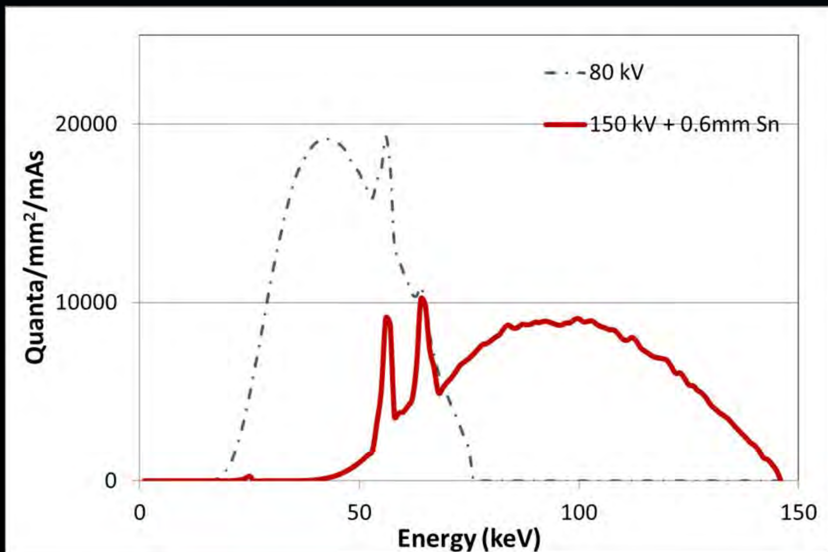
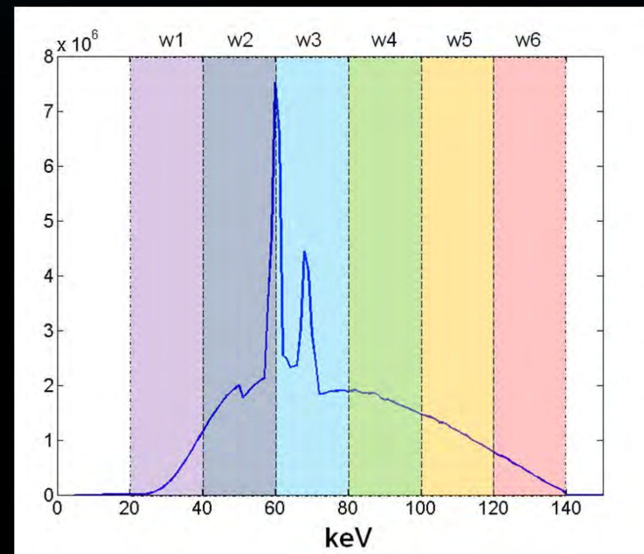
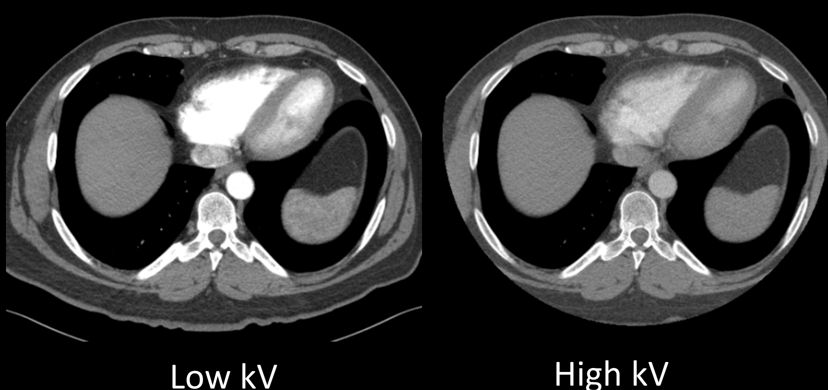
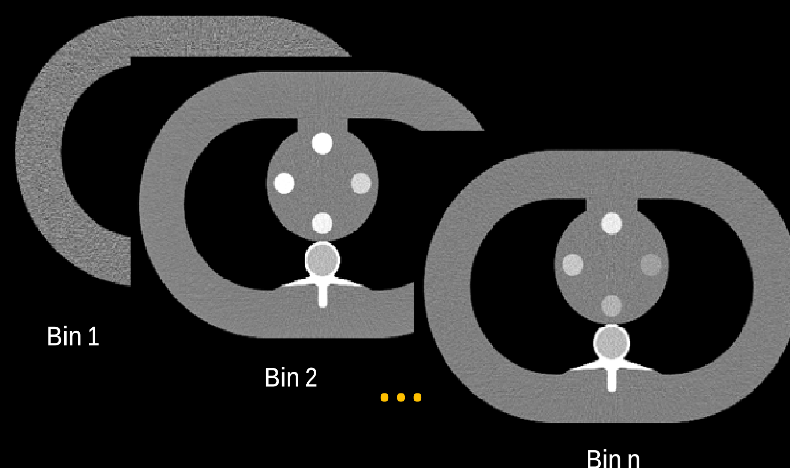
Images at each spectrum or energy bin









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Images at each spectrum or energy bin

- These are the original “source” data
  - Archive is possible for subsequent post-processing
    - If needed in future for comparison to future exam
    - If new algorithms arrive
  - Not typically viewed by radiologist
  - Used for trouble shooting

Multi-energy CT Images

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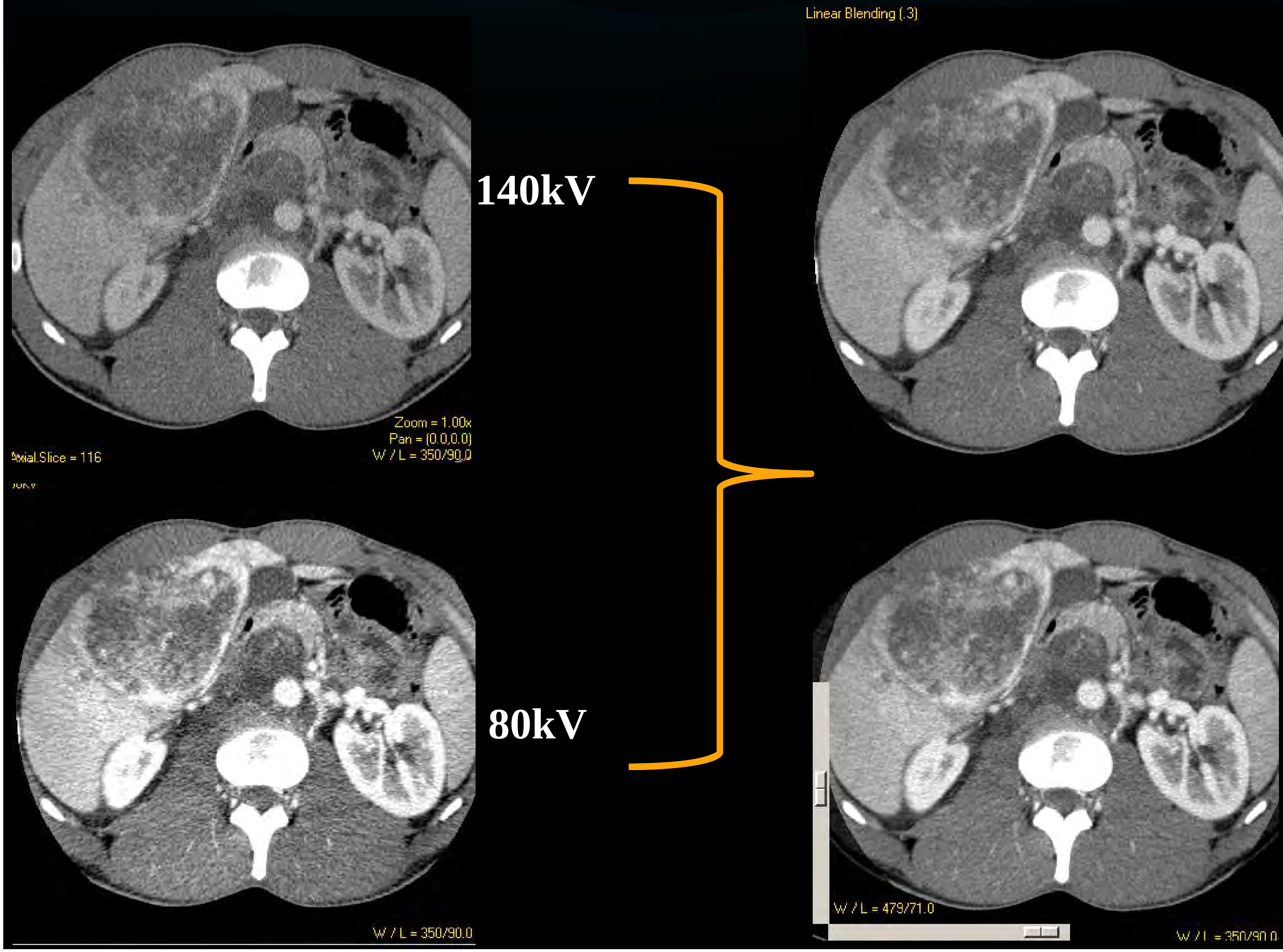
Multi-energy CT Mixed Images



Linear Blend

70% 140kV
30% 80kV

Non-linear Blend

Eusemann et al SPIE 2008

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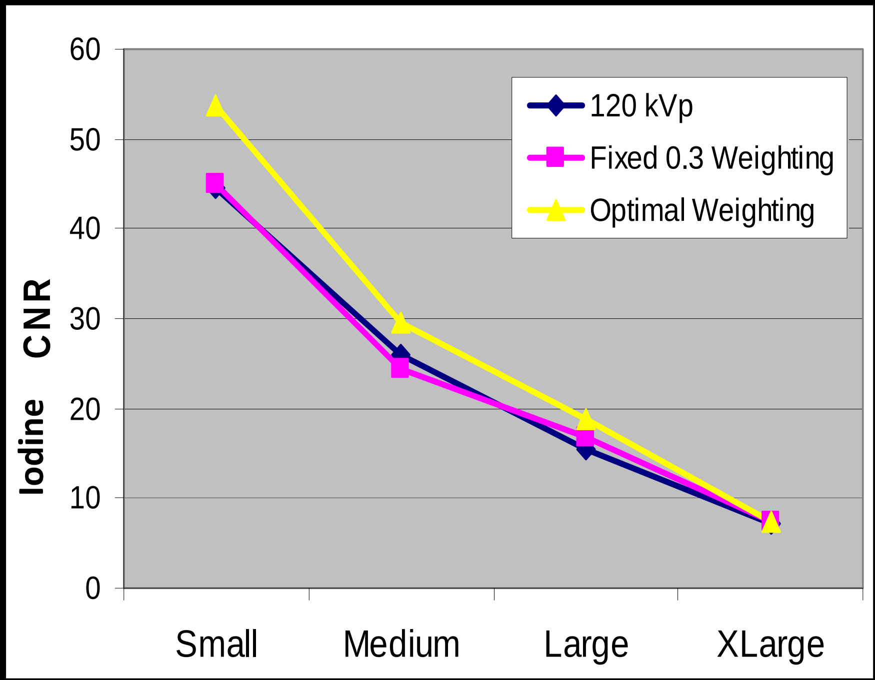
Optimal Weighting

- Optimal weighting depends on
  - Spectra or energy bins
  - Dose partitioning
  - Patient size
  - Material of interest



Yu et al, Med Phys 2009

Multi-energy CT Mixed Images

- These are the “routine” images
  - Must archive these
  - Shared with clinicians
  - Used for general reading of the case
  - Typically emulate single-energy source images at 120 kV
  - Always viewed by radiologists

DECT need not increase dose

Single Energy (120 kV)

March 2009

CTDIvol: 18.65 mGy

Indication: HCC

35 – 36 cm

lateral width

Dual Energy Mixed

April 2009

CTDIvol: 15.59 mGy

Multi-energy CT Images

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Material Decomposition Methods

Parameter	Options
Data space	Projection or image space

Data space for operations

- Projection based
  - Requires access to projection data
  - Requires data consistency between low/high energy projections
  - No beam hardening effect
    - In theory, but in practice it remains due to calibration requirements
- Image based
  - Easy to implement, projection data not necessary
  - No data consistency problem
  - Beam hardening effect can’t be totally removed
    - In theory, but in practice is reasonably well corrected for

Material Decomposition Methods

Parameter	Options
Data space	Projection or image space
μ-decomposition	PE-Compton or basis material

Decomposition of X-ray Linear Attenuation Coefficient

- In diagnostic energy range and for low-Z materials, μ can be described by 2 independent basis functions
  - PE and Compton (Alvarez and Macovski, 1976; Heismann et al. 2003)

$$\mu(r,E) = a_1(r) \cdot \frac{1}{E^3} + a_2(r) \cdot f_{KN}(E)$$

  - Two basis materials (Lehman et al, 1981; Kalender et al , 1985; Liu et al, 2009)

$$\mu(r,E) = a_1(r) \cdot \mu_1(E) + a_2(r) \cdot \mu_2(E)$$

Material Decomposition Methods

Parameter	Options
Data space	Projection or image space
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K-edge	with or without K-edge

Material Decomposition Methods

Parameter	Options
Data space	Projection or image space
μ-decomposition	PE-Compton or basis material
K-edge	with or without K-edge
Prior constraint on material composition	With or without prior assumptions on volume or mass: “3-material decomposition”

Three Material Decomposition

- Two measurements, three unknowns
- Additional assumption needed:
  - Volume conservation
    - Not always true, e.g. salt-water mixture
  - Mass conservation

$$\mu_m = m_1\mu_{m1} + m_2\mu_{m2} + m_3\mu_{m3}$$

$$m_1 + m_2 + m_3 = 1$$

Liu et al, Quantitative imaging of element composition and mass fraction using dual-energy CT: Three-material decomposition. Med Phys. 2009

Material Decomposition Methods

Parameter	**Options**
Data space	Projection or image space
μ-decomposition	PE-Compton or basis material
K-edge	with or without K-edge
Prior constraint on material composition	With or without prior assumptions on volume or mass: “3-material decomposition”
Task	Quantifying material density in a mixture or classifying materials

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Classification vs. Quantification

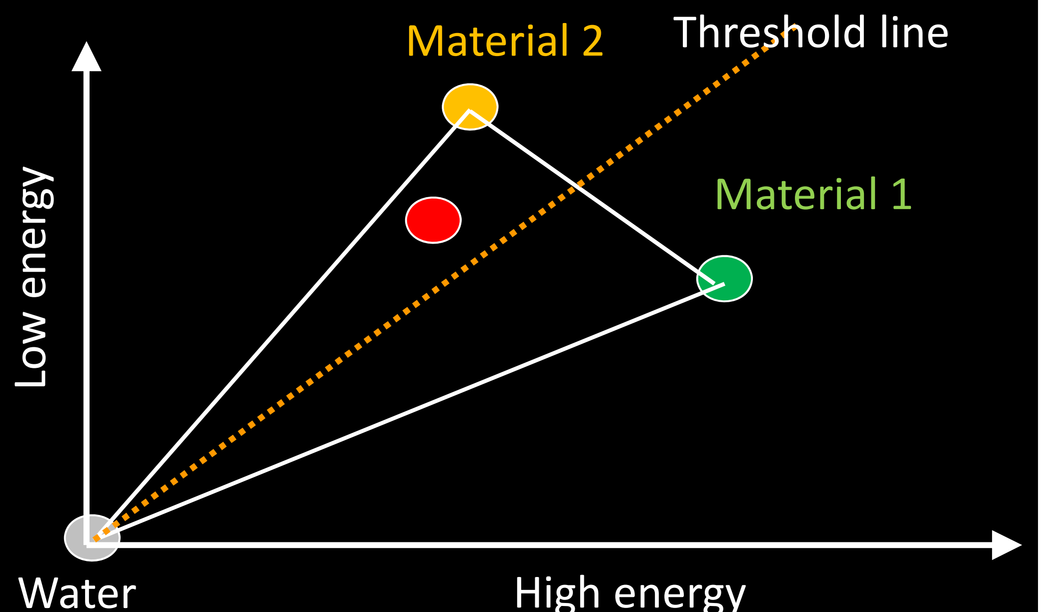
- Material classification
  - Kidney stone characterization
  - Gout detection and quantification
  - Silicone breast implant leakage
  - Automated bone removal in CT angiography
  - Plaque removal
- Quantifying material density
  - Blood pool imaging (Perfused blood volume)
  - Virtual non-contrast (Iodine removal/iodine image)
  - Virtual non-calcium (Bone removal/bone image)

Material Classification

- Common clinical questions related to material classification
  - Uric acid vs. non-uric stones
  - Bone vs. iodine
  - Uric acid crystals vs. calcium-containing crystals
  - Silicone vs. tissue

$$DEratio = CT\#_{Low}/CT\#_{High} \approx f(Z)$$

Independent of concentration



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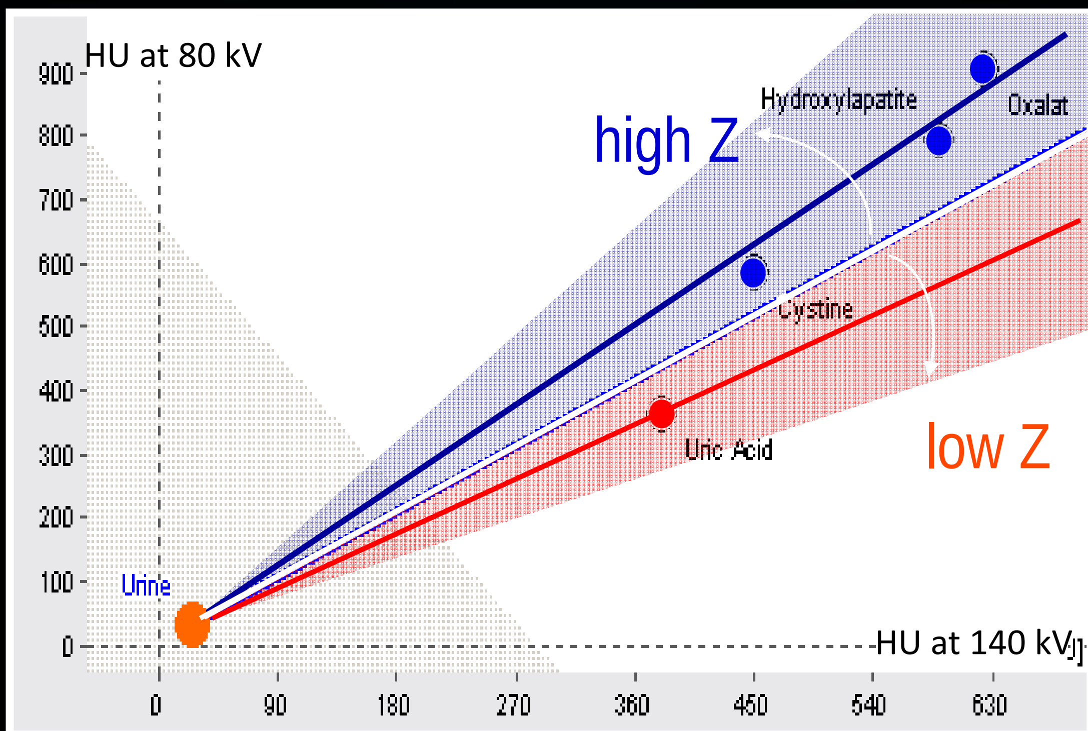
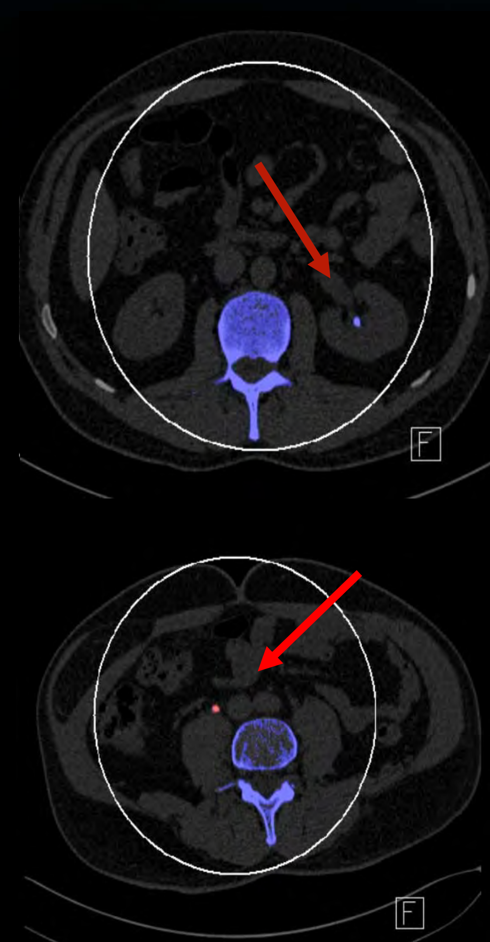
Dual Source DECT – UA vs Non-UA

- Numerous publications on stone composition differentiation using dual energy CT
- Both *in vitro* and *in vivo* studies
- High accuracy, sensitivity and specificity reported
- Used in routine clinical practice

HU at 80 kV



HU at 140 kV



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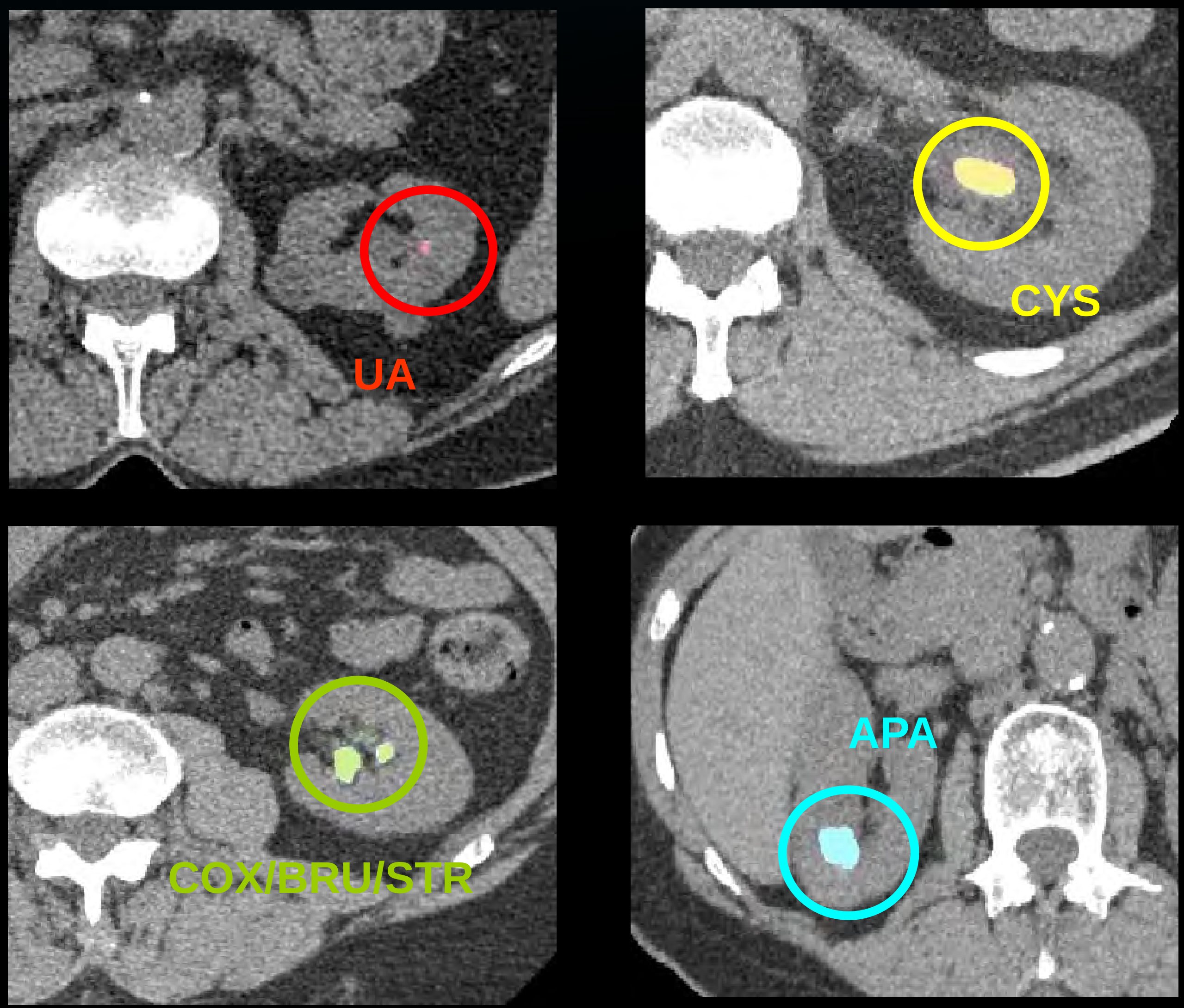
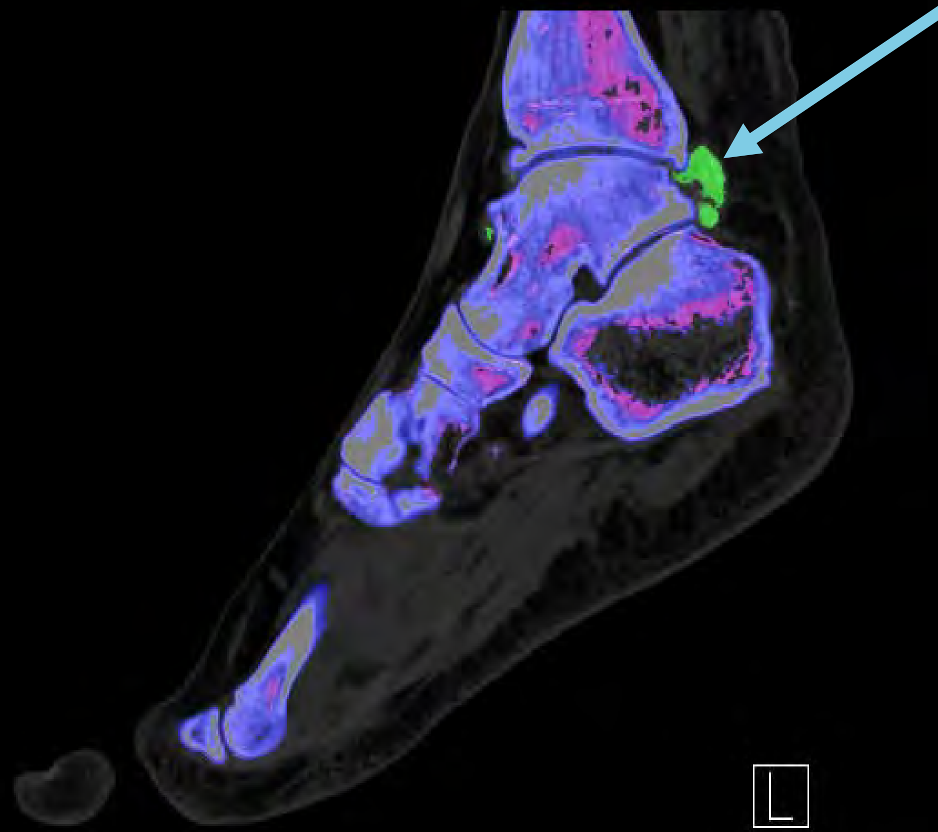
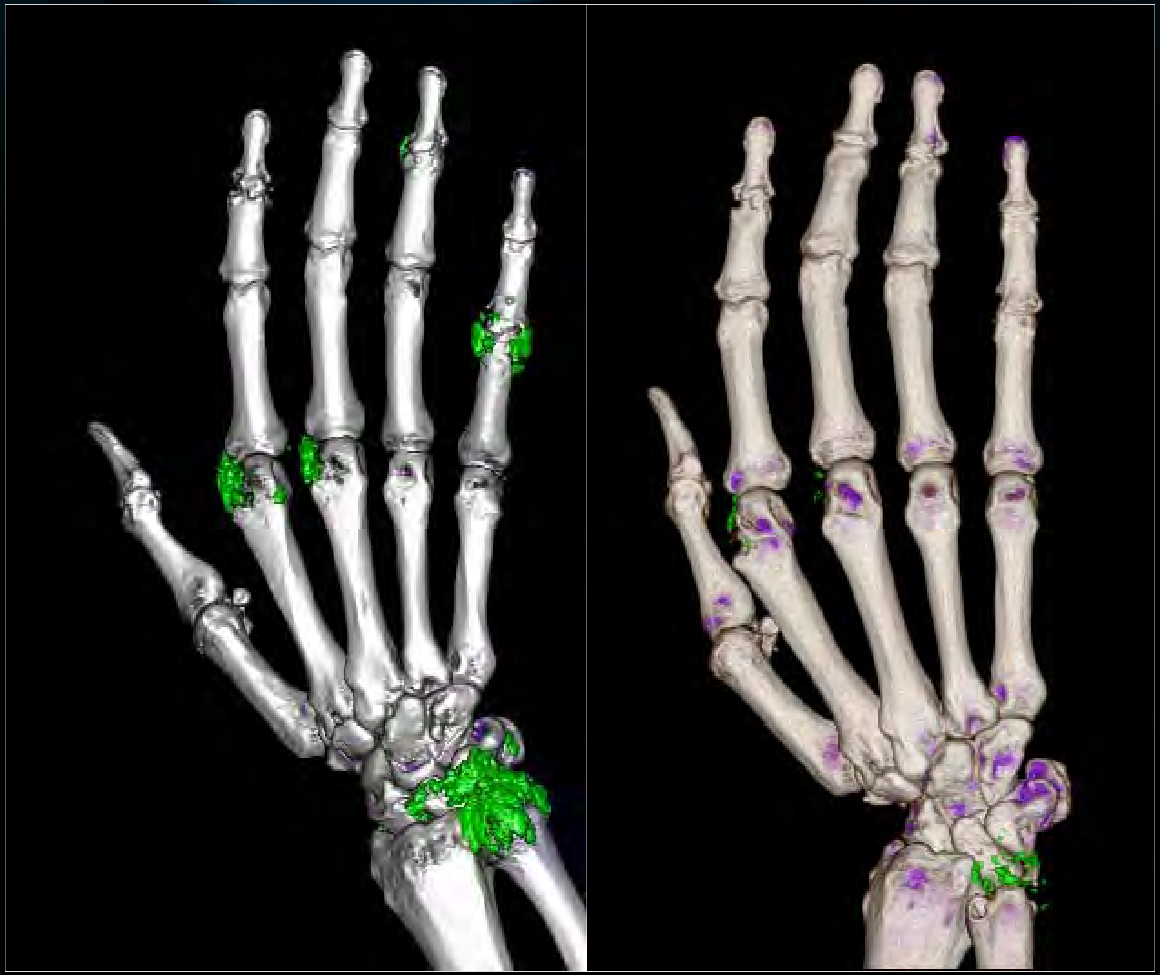
Color-coded stones from in vivo study



High density material in soft tissues within and surrounding joints consistent with tophaceous deposits



April December



Before & after images demonstrate 90% reduction in volume of uric acid crystals over 8 months after receiving multiple infusions of rasburicase.

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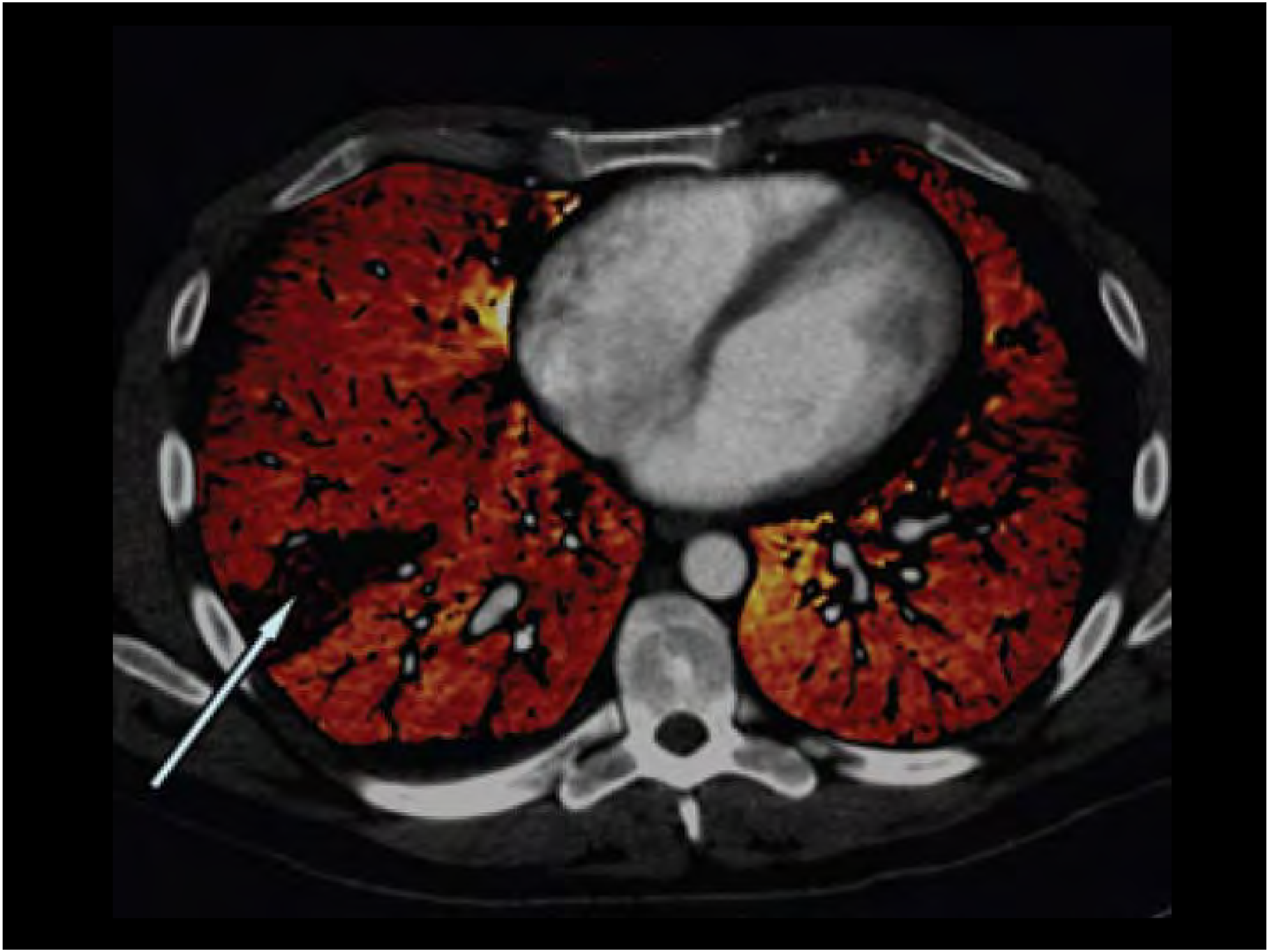
Automated Bone Removal in CT Angiography

- CT angiography is a minimally invasive technique to determine location, size, and patency of arteries and veins
- Overlying bony anatomy interferes with useful visualization techniques (eg MIP and VRT)
- Manual or semi-automated bone removal can be labor intensive and/or operator dependent

Perfused Blood Volume (Blood Pool Imaging)

- Assessment of blood distribution with a measurement made at a single time point
  - Perfusion measurements require temporal measurements
- Quantitative assessment of perfused blood volume shown to serve as a surrogate marker for ischemia/infarct and to correlate with direct measures of perfusion and flow



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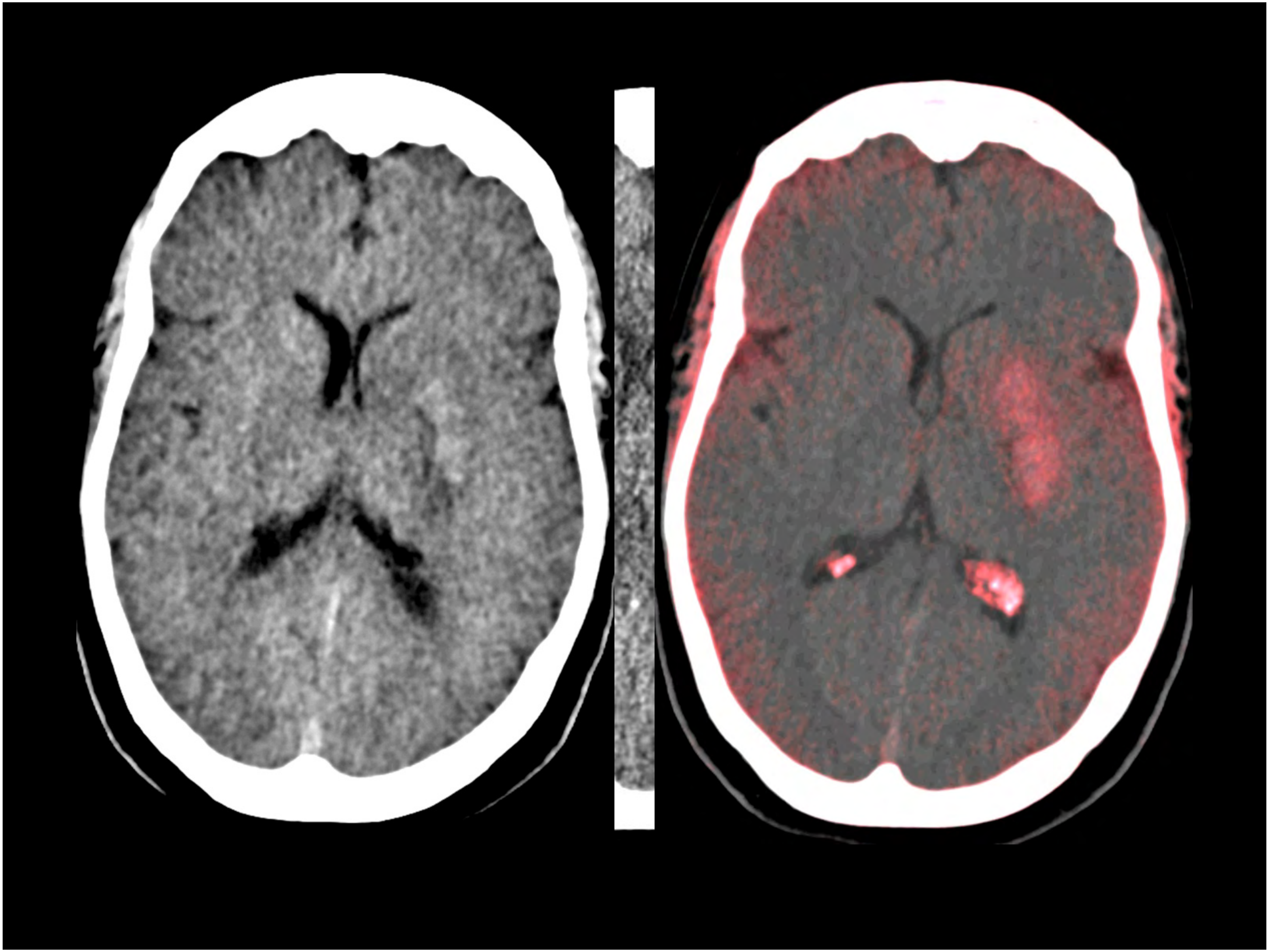
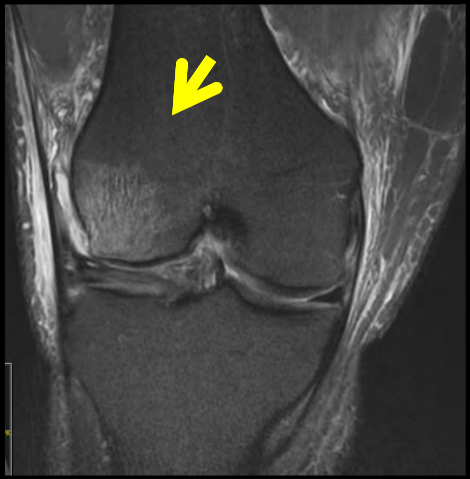
Virtual Noncontrast Images

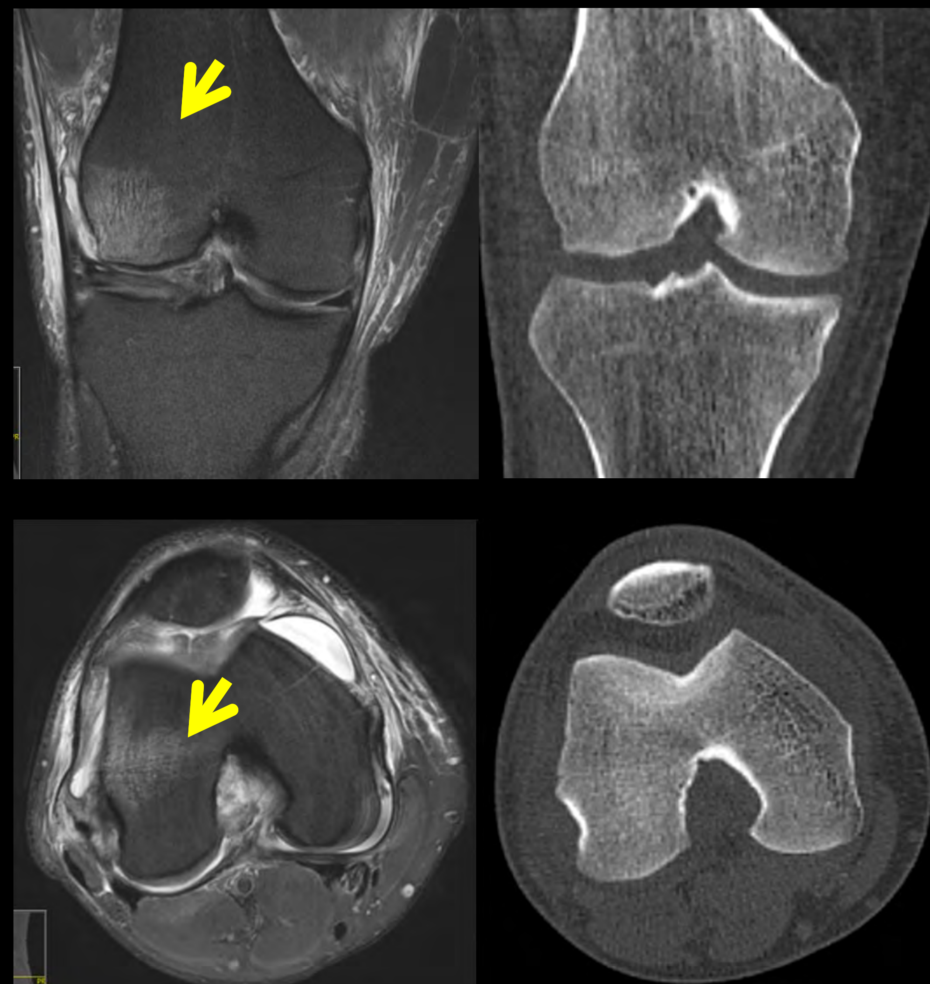
- Scans performed without contrast media not routinely included in most contrast-enhanced exams
- Unexpected findings (e.g. modestly enhancing renal masses) may be un-interpretable without a non-contrast scan for comparison
- Identification and digital suppression of iodine signal can create a perfectly registered "virtual" non-contrast scan



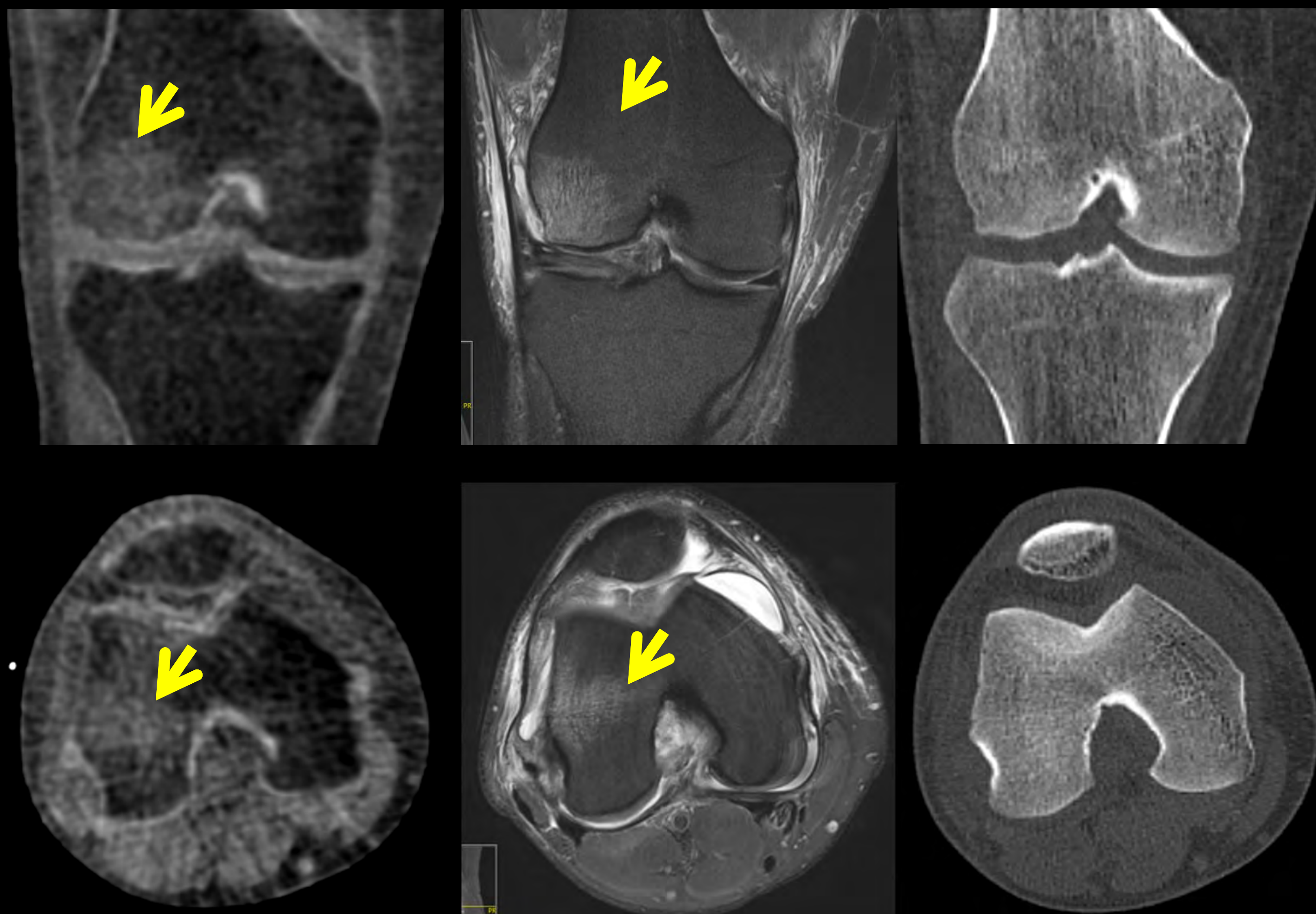
Virtual Non-Calcium Images

- Traumatic or oncologic bone lesions (bruising, edema, bone marrow lesions) cannot be appreciated on CT in the presence of bright calcium signal
- Identification and digital suppression of calcium signal can allow appreciation of these findings, previously observed only with MRI





DECT Virtual non-Ca | MRI | Single energy CT



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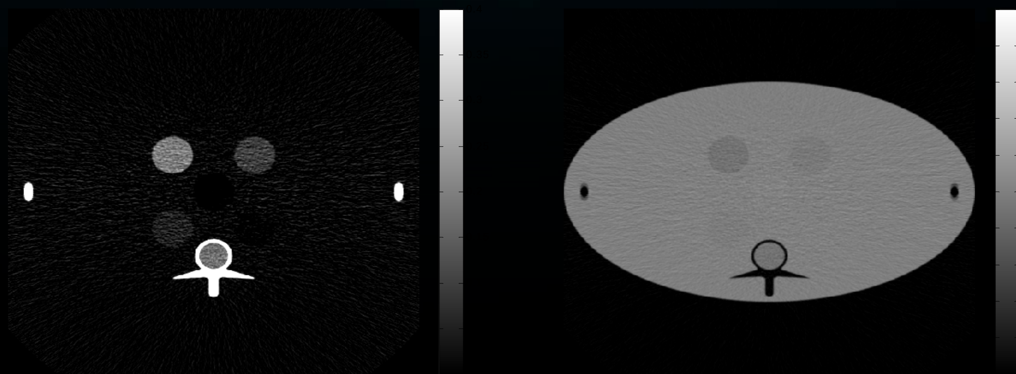
Virtual monoenergetic images

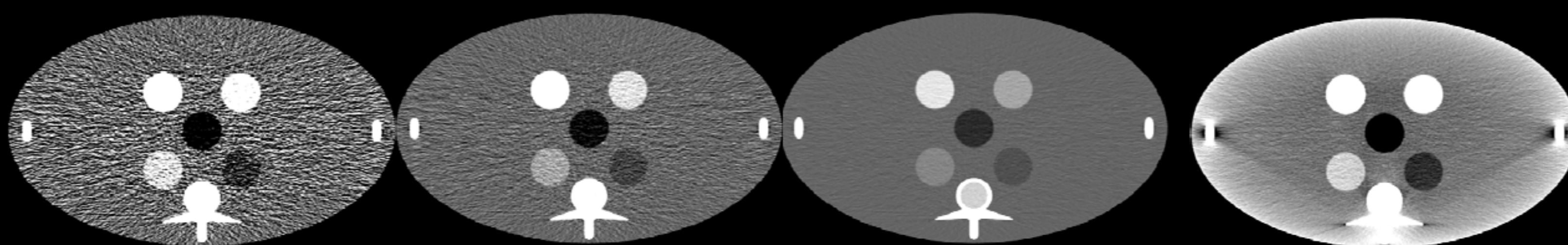
- Decompose source data into basis material maps
  - Pixel values represent density of each material
- Look up mass attenuation coefficients (μ/ρ) for each basis material at the photon value of interest
  - E.g. 40 keV, 70 keV, 180 keV
- Calculate linear attenuation coefficient from density material maps and mass attenuation coefficients

Virtual Monoenergetic Imaging

Basis material or PE-Compton map after material decomposition

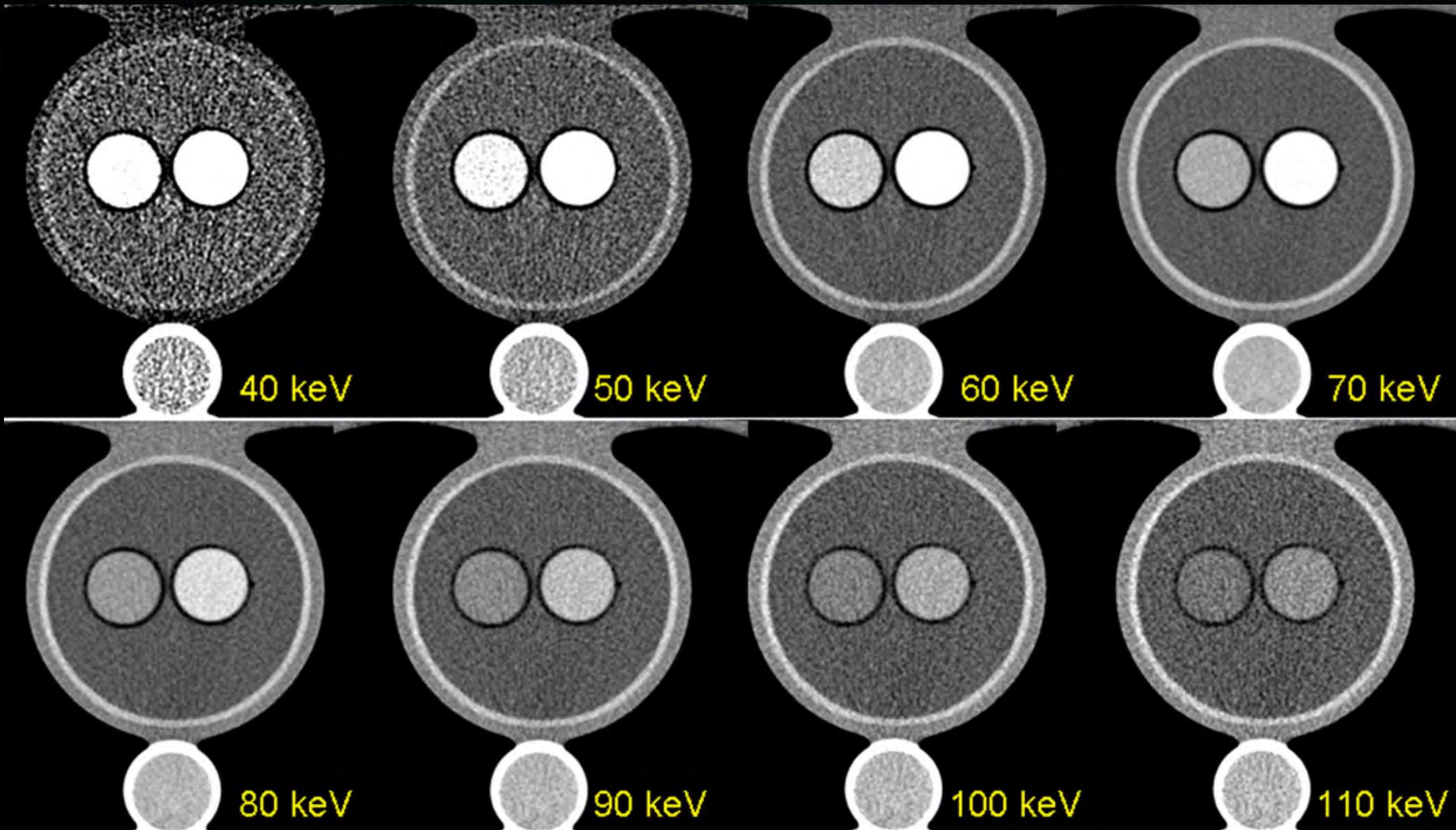


Synthesize mono-energetic images using density maps and mass attenuation coefficients



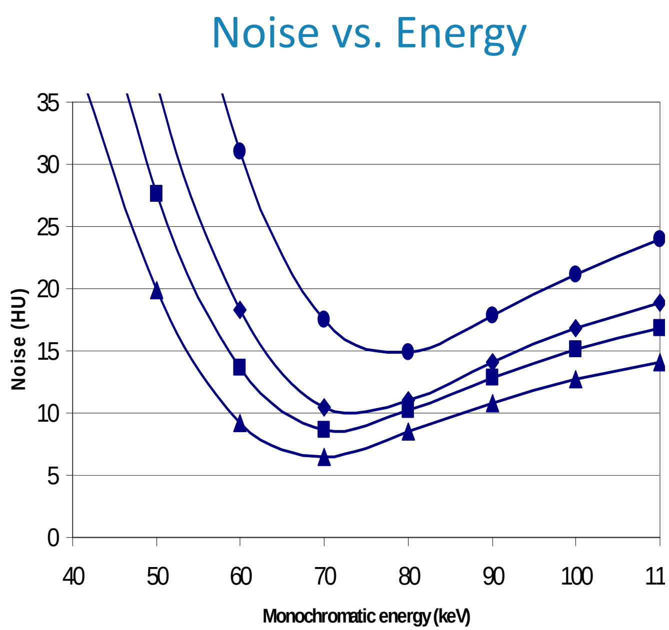
20 keV | 40 keV | 60 keV | 120 kV

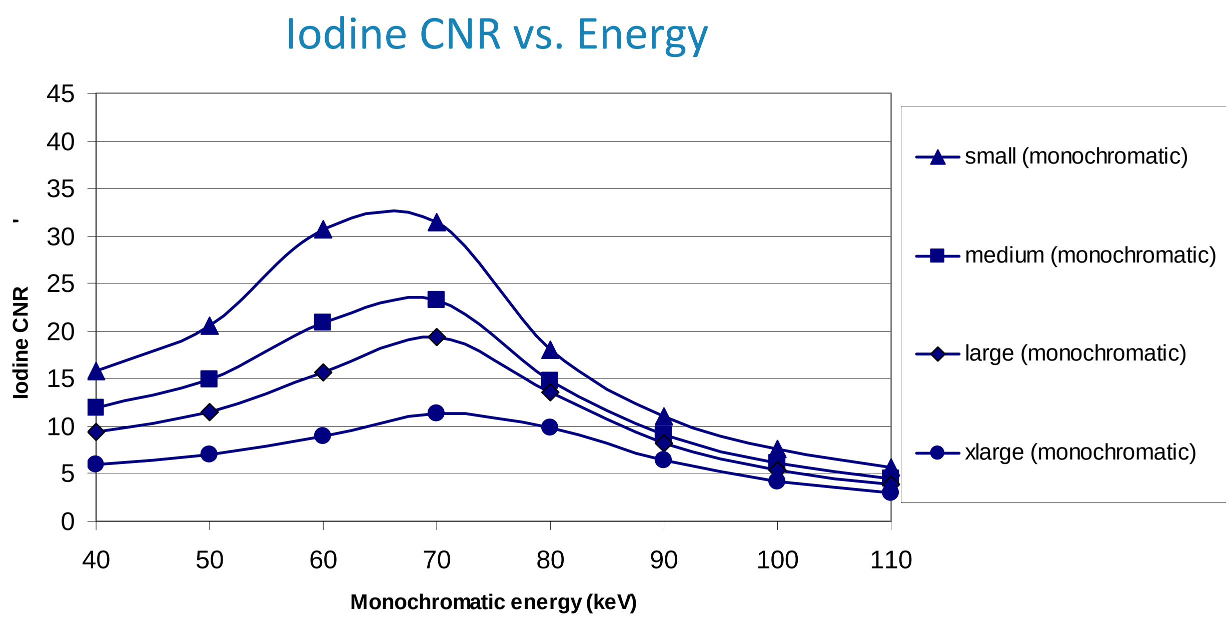
Monoenergetic Images



Yu et al, Virtual monochromatic imaging in dual-source dual-energy CT: Radiation dose and image quality, Med Phys. 2011

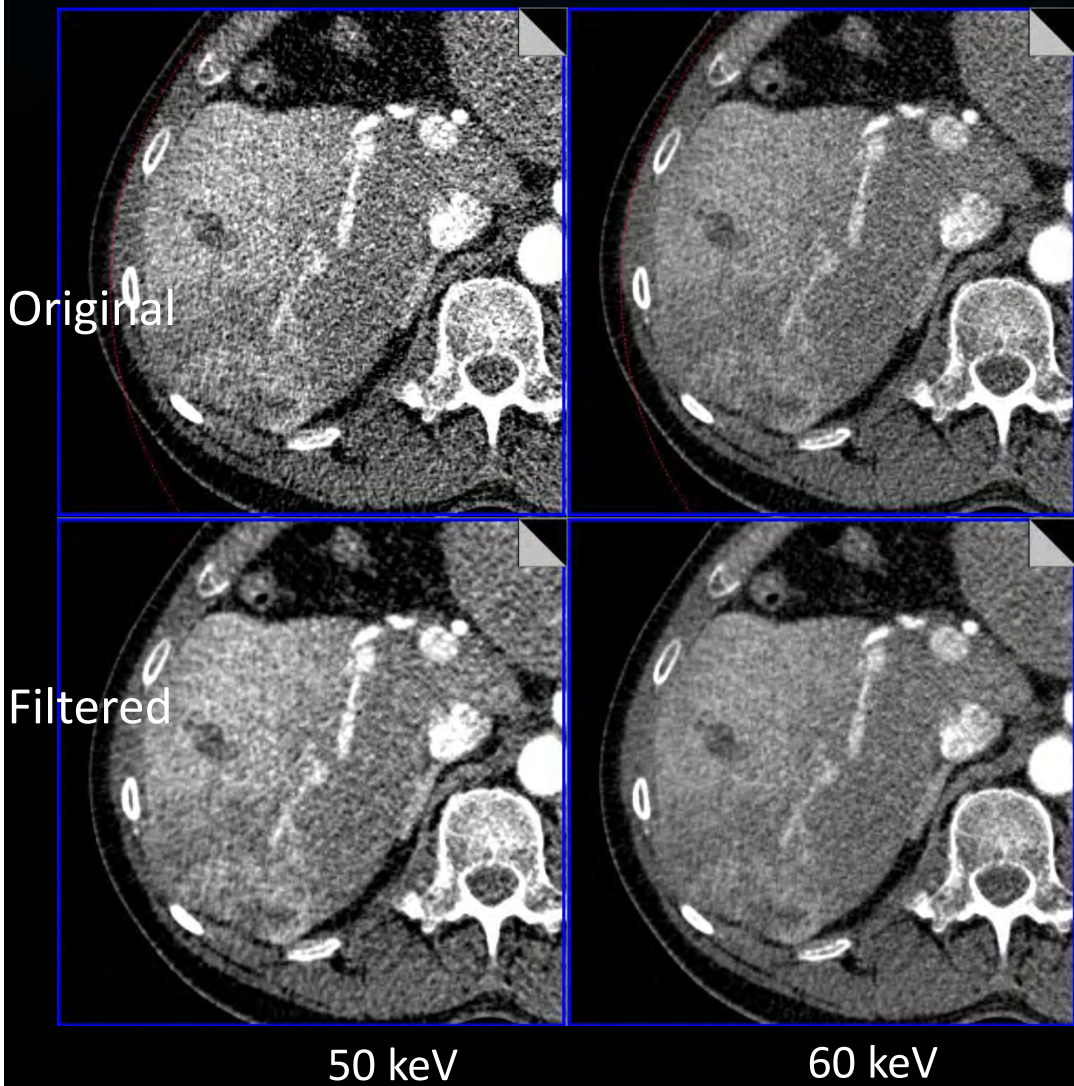
Optimal Monoenergetic Energy

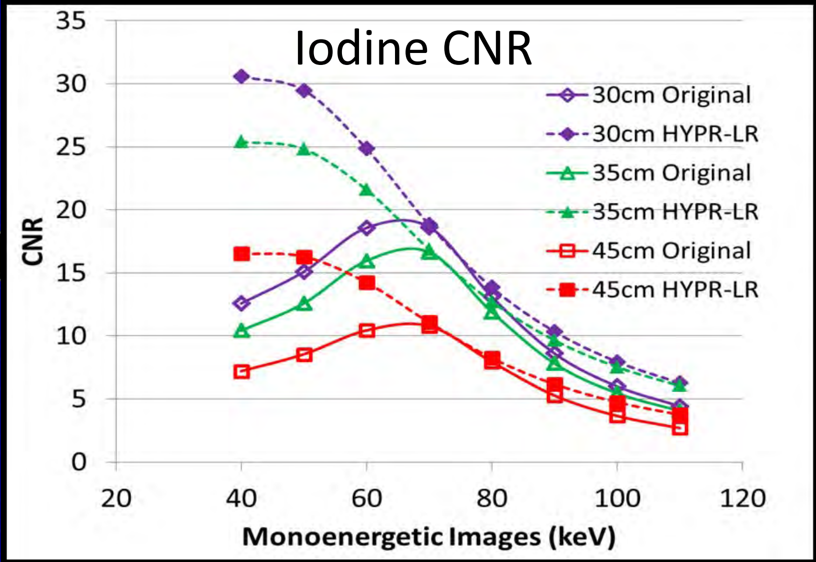




Yu et al, Med Phys 2011

Energy-domain noise reduction on monoE images



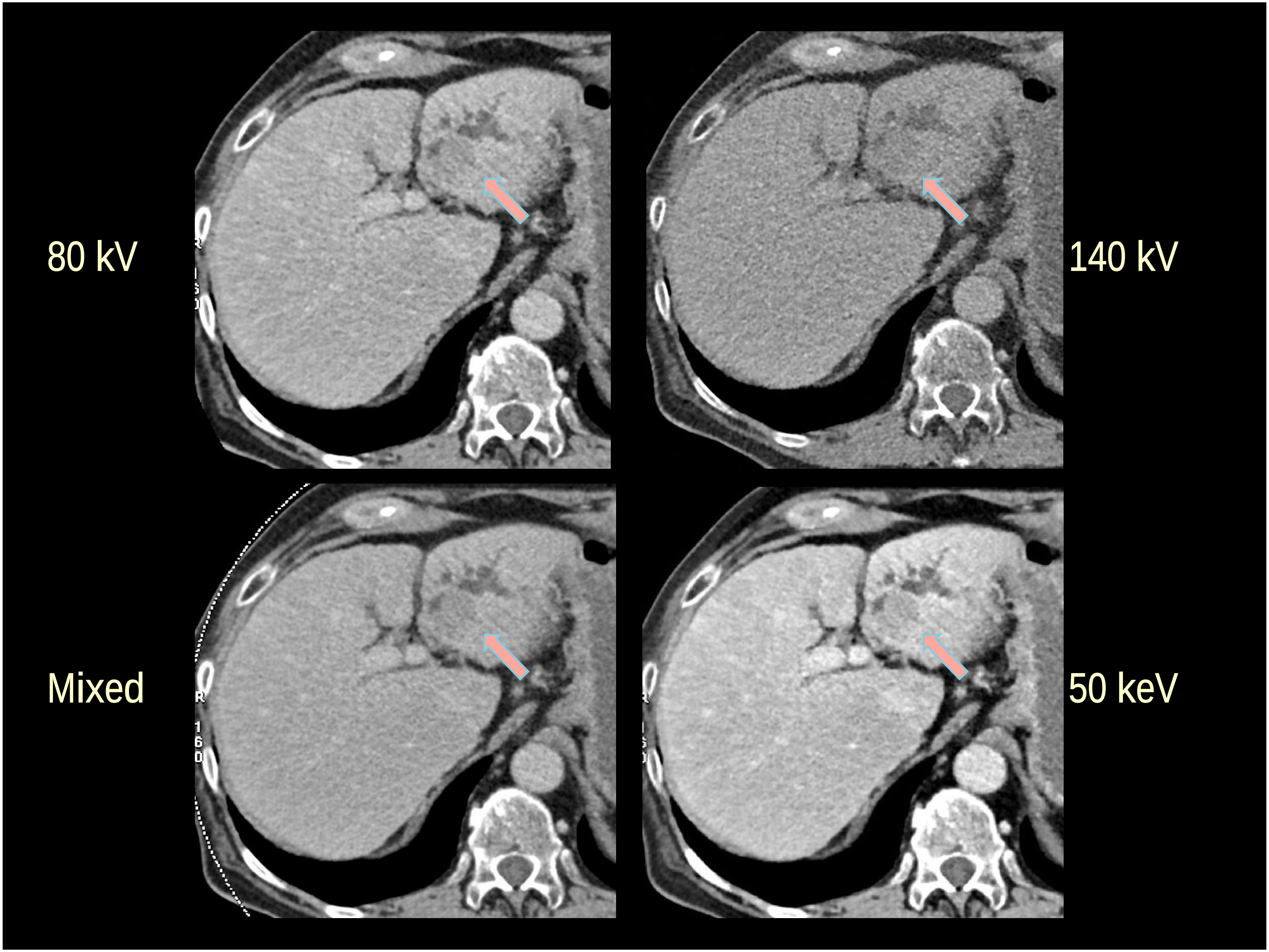


Leng et al, Radiology, 2014

Virtual Monoenergetic Imaging

- Improves iodine contrast
- With energy domain noise reduction*, can be used to improve iodine CNR
  - Increase conspicuity of subtle lesions
  - Allow use of less iodinated contrast media
  - Compensate for poor venous access resulting in slow injection rates
- Reduces metal artifacts

* Leng et al. 2011


80 kV
140 kV
Mixed
50 keV

Virtual Monoenergetic – Metal Artifacts

- Use high keV to reduce strength of metal artifacts
- Use low keV to visualize iodine

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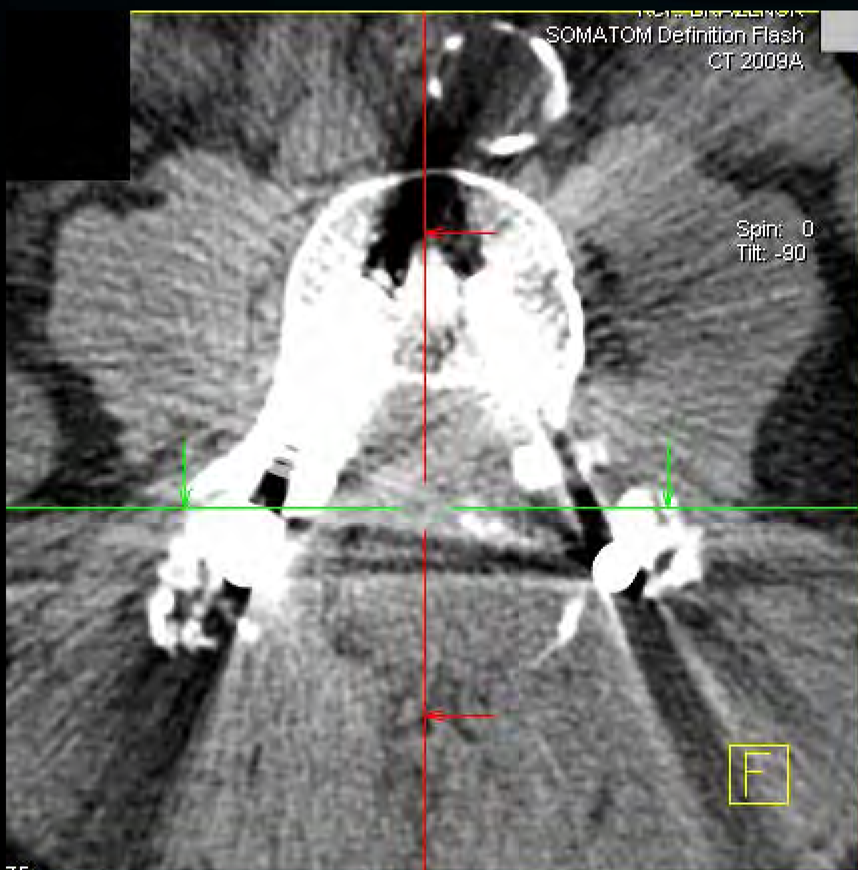


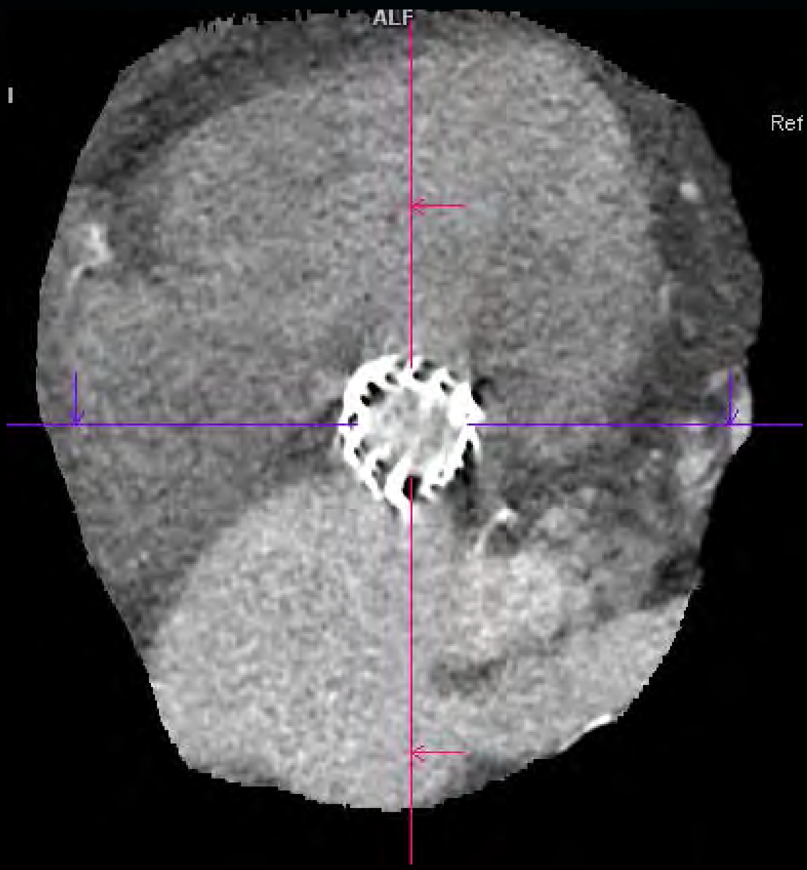
Standard Image

Monoenergetic Image (105 keV)

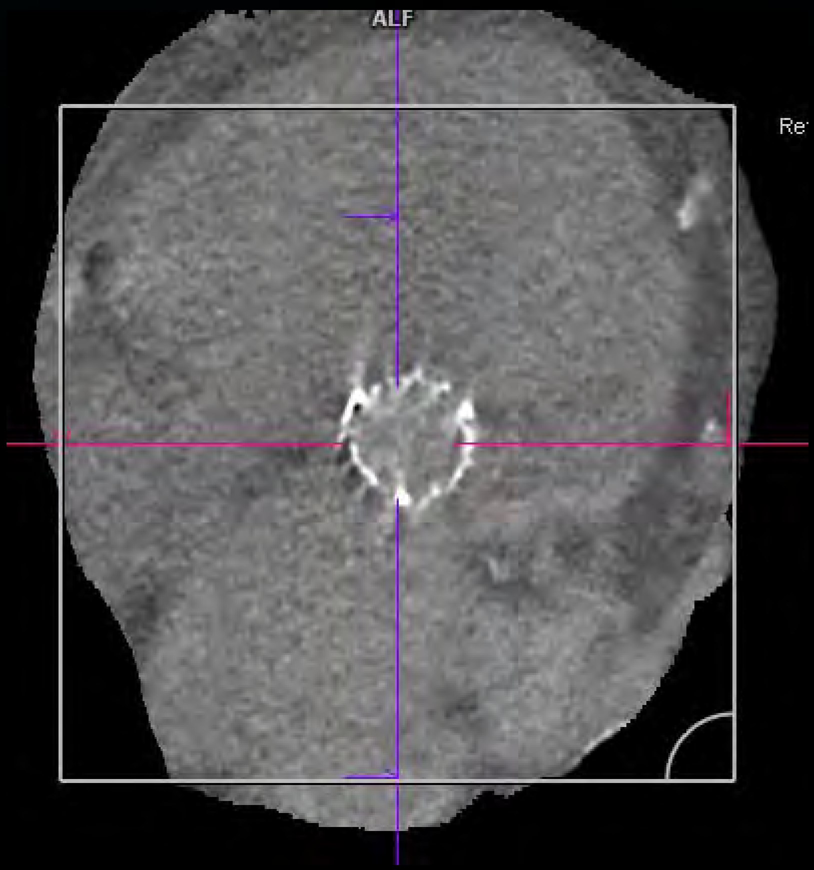
Virtual Monoenergetic – Metal Artifacts

- Use high keV to reduce strength of metal artifacts
- Use low keV to visualize iodine
- Is not metal artifact correction, but allows fast and flexible reduction of metal artifacts

Transaortic Valve Replacement



70 keV



130 keV

Summary: Multi-energy CT Image Types

- Non-material specific images
  - Low/high kV images
  - Mixed images
  - Virtual monoenergetic images

⇓

- Mixed: Provide "routine" set of images for interpretation
- MonoE: Reduce artifacts and improve quantitative accuracy
- MonoE: Improve iodine CNR and dose efficiency

- Material specific imaging
  - Basis material decomposition
  - PE-Compton decomposition
  - K-edge imaging (photon-counting multi-energy)

⇓

- Expand clinical applications
  - Material classification (e.g., bone/iodine, uric acid/non-uric acid)
  - Material quantification (e.g., iodine, bone, high-Z contrast agent)