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CT Clinical Innovation Center

Multi-energy CT Clinical Applications

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Disclosures

- Research support
  - NIH (EB017095, EB028590, EB028591)
  - Mayo Clinic Discovery Translation Grant
  - Siemens Healthcare
- Board membership
  - ISCT, Vice-president
- Use of off-label medical devices
  - The photon-counting-detector research CT scanner mentioned in this work is not commercially available

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Multi-energy CT image types

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

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

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

⇓

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

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Multi-energy CT Images

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

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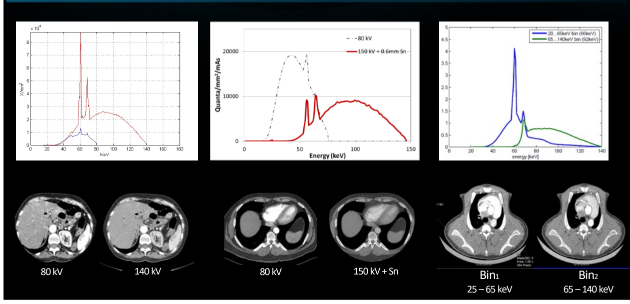
Images at each spectrum or energy bin



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Images at each spectrum or energy bin

- These are the original "source" data
  - Not available on all systems
  - 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

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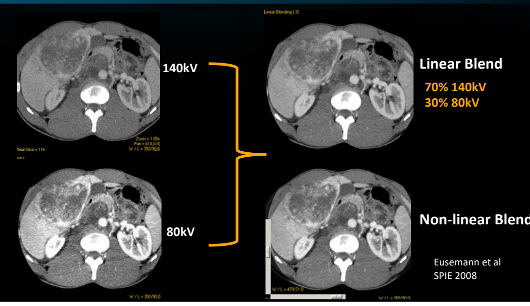
Multi-energy CT Mixed Images



Eusemann et al
SPIE 2008

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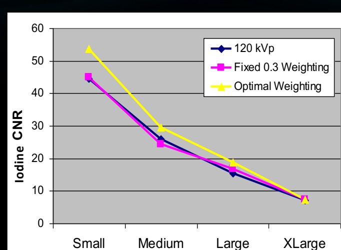
Optimal Weighting

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



Yu et al, Med Phys 2009

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Multi-energy CT Mixed Images

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

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Virtual Monoenergetic Imaging

- Improves iodine contrast and CNR at low keV
  - 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

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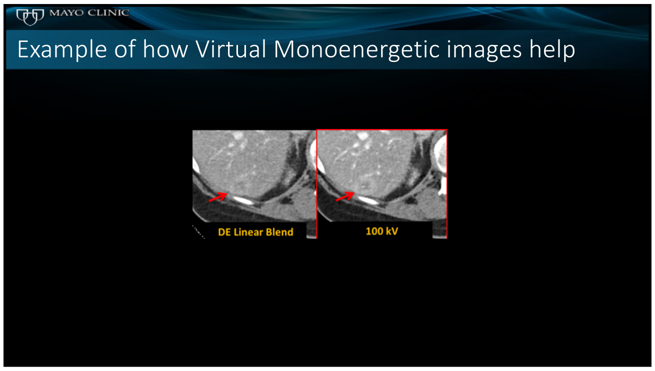

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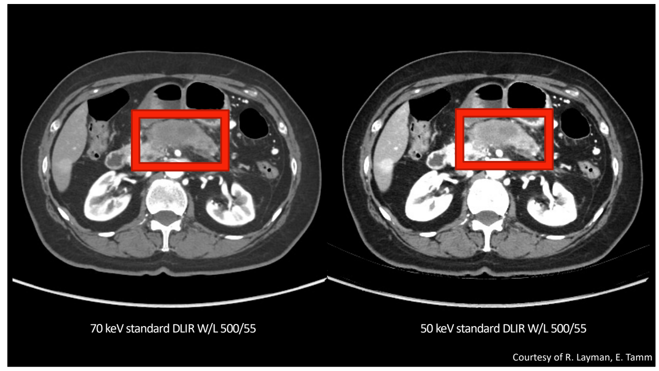

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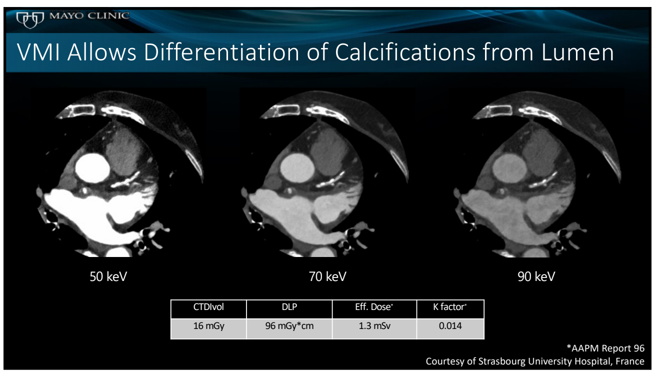

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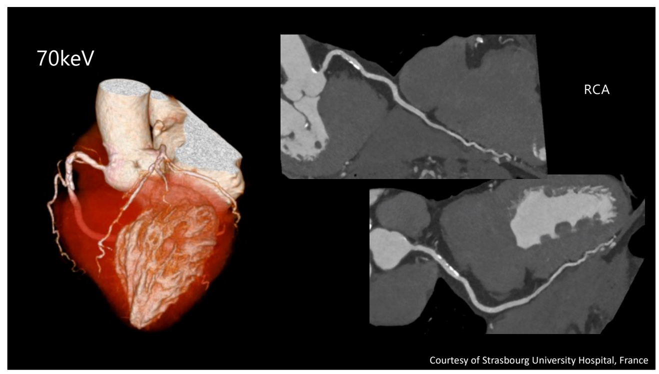

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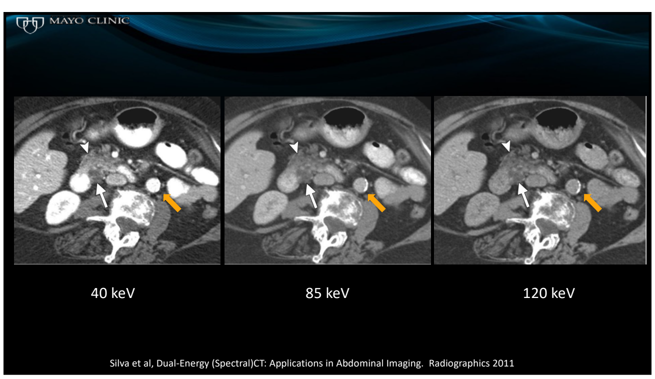

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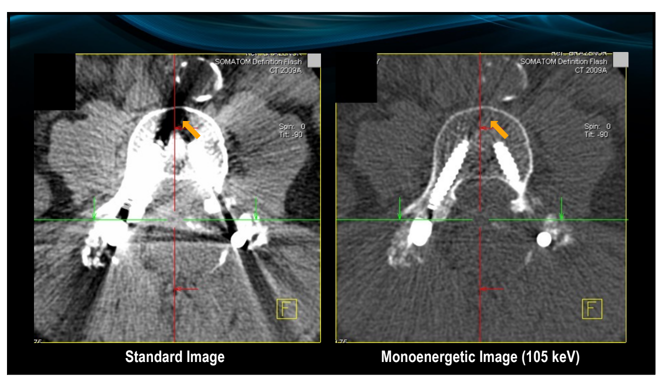

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Virtual Monoenergetic – Metal Artifacts

- Use low keV to visualize iodine
- Use high keV to reduce strength of metal artifacts
- Allows fast and flexible reduction of metal artifacts
- Is not metal artifact correction
  - No metal detection or sinogram correction
- Especially helpful for complex metal objects

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Data space for operations

- Projection based
  - Requires access to projection data
  - No beam hardening effect
    - In theory, but in practice it remains due to calibration requirements
- Image based
  - Easy to implement, projection data not necessary
  - Beam hardening effect can't be totally removed
    - In theory, but in practice is reasonably well corrected for
- Both approaches can utilize machine learning

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Classification vs. Quantification

- Material classification
  - Uric acid urinary stone differentiation (vs non-uric acid urinary stones)
  - Gout differentiation (vs pseudo-gout)
  - Silicone differentiation (vs dense soft tissue)
  - Bone differentiation (vs iodine)
- Material characterization/quantification
  - Virtual non-contrast (Iodine removal)
  - Virtual non-calcium (Bone removal)
  - Perfused blood volume
  - Electron density and effective atomic number

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Material Classification

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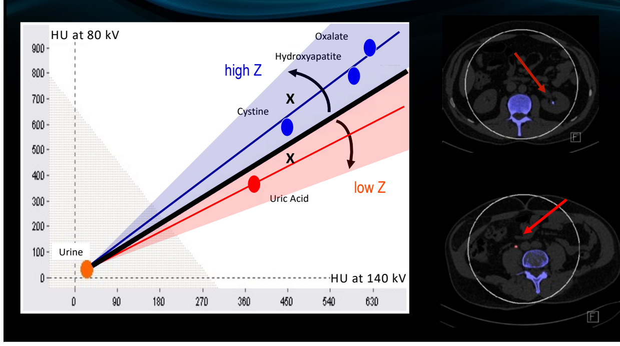

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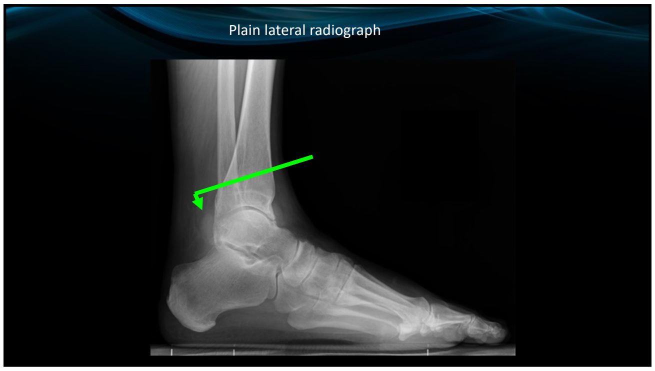

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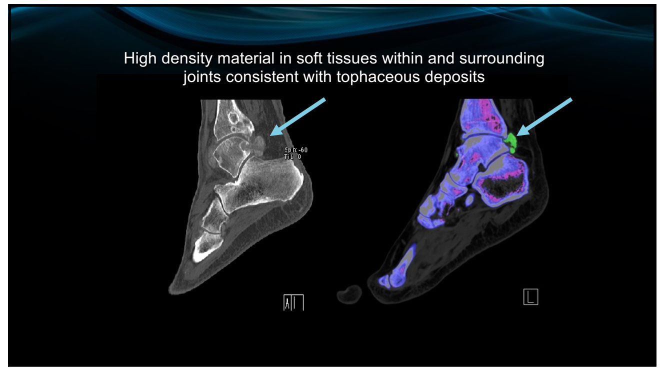

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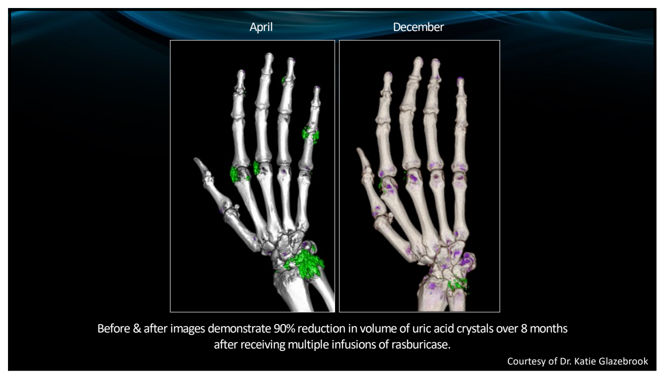

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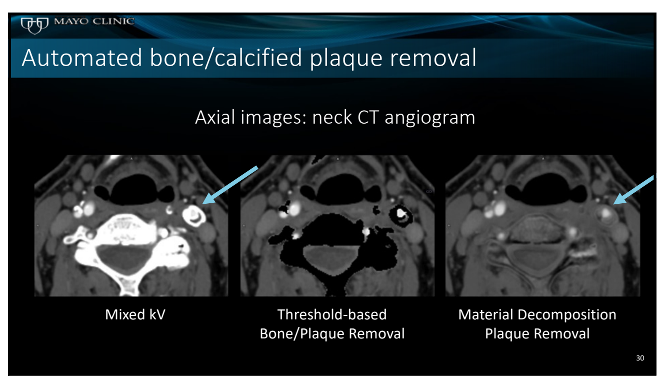

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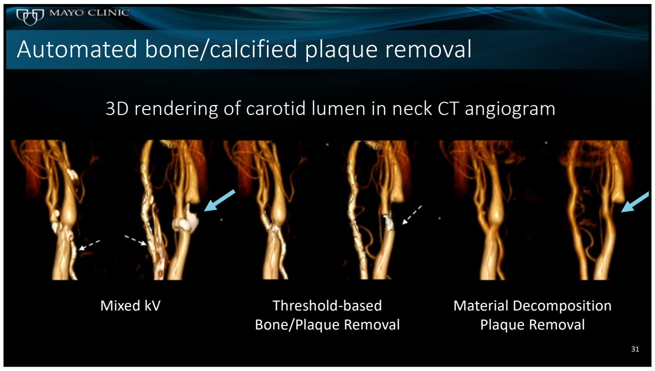

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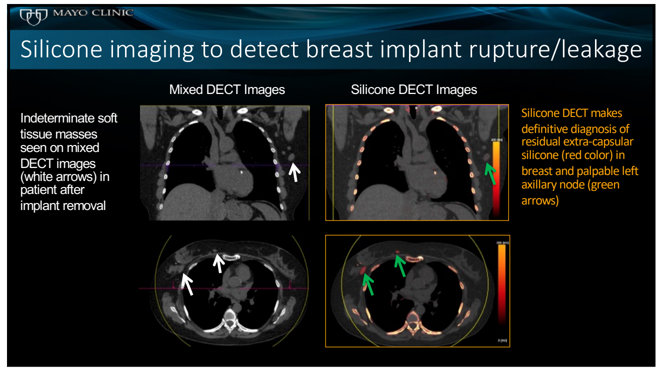

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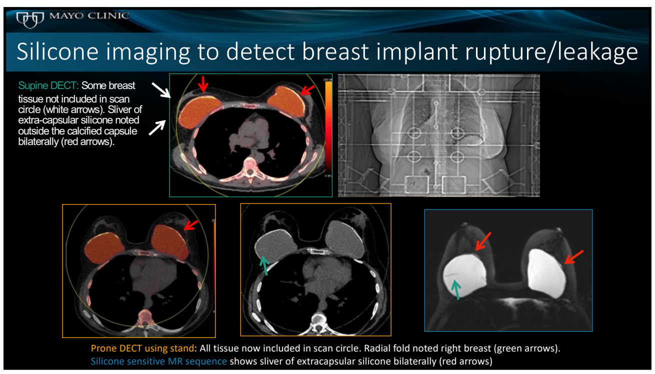

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Material Quantification

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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

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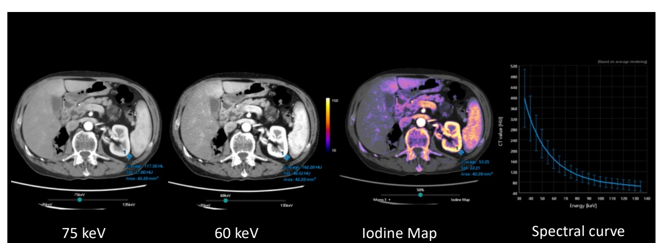

CTDIvol	DLP**	Eff. Dose*	K Factor*
11 mGy	752 mGy*cm	11 mSv	0.0145

*AAPM Report 96
**Spectral CT of the Chest, Abdomen and Pelvis reflected in DLP
Courtesy of Prof. Roy & Pr. Ohana, University Hospital of Strasbourg

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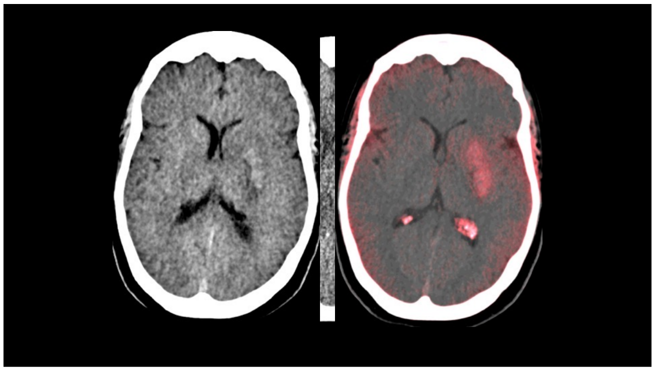

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Virtual Non-Calcium Images

- 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

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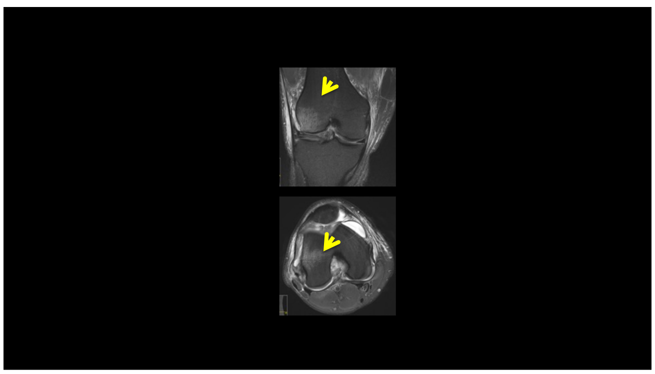

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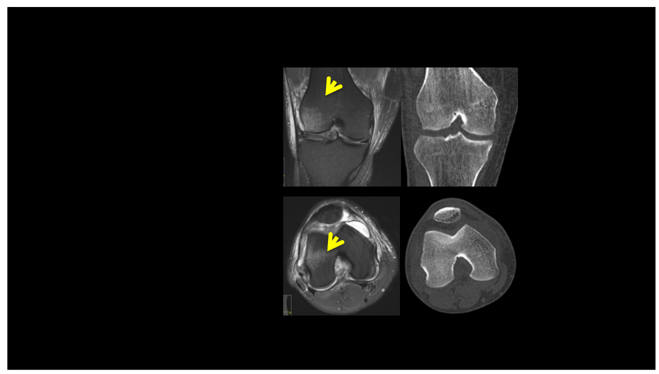

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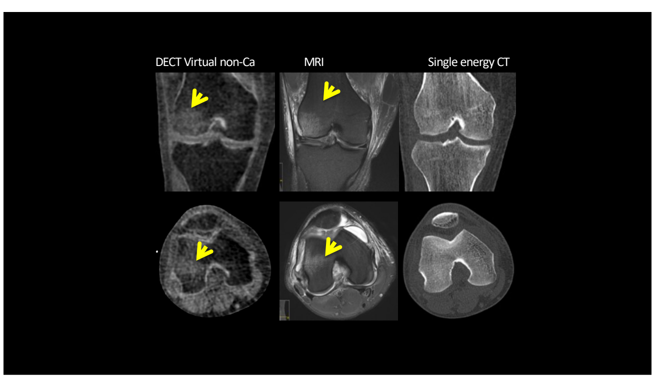

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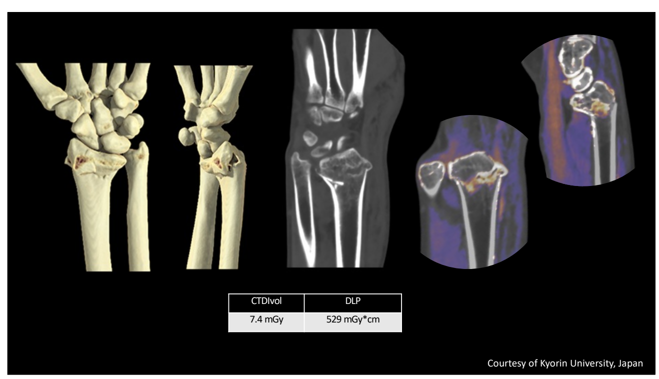

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Perfused Blood Volume (Blood Pool Imaging)

- Assessment of blood distribution with one scan 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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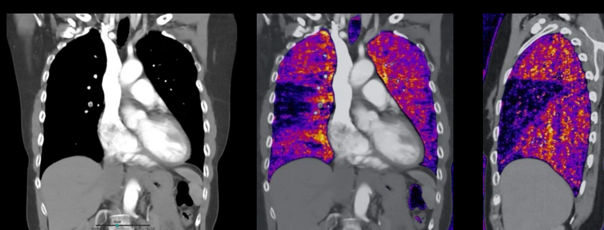

CTDIvol	DLP	Eff. Dose*	K factor*
9 mGy	323 mGy*cm	4.5 mSv	0.014

*AAPM Report 96

Courtesy of Kyorin University, Japan

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Effective atomic number and electron density maps

- Proton therapy requires accurate knowledge of the stopping power for the tissues/materials that are traversed
- SECT cannot discriminate between changes in density and chemical composition, limiting accuracy of stopping power ratio (SPR) calculations
- DECT can be used to calculate maps of electron density and effective atomic number

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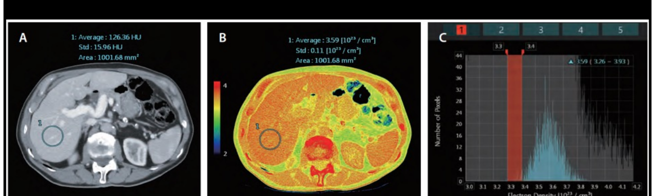

Deep Learning Spectral CT, Boedeker K et al., (2019)

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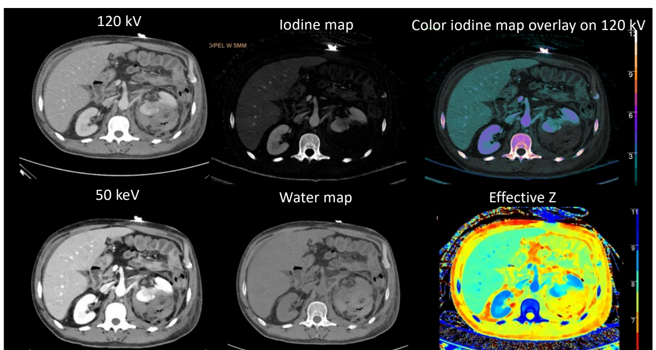

Courtesy of Xinhui Duan

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Dosimetry considerations

- Doses used in dual-energy CT (DECT) are comparable to those for single-energy CT (SECT) for similar levels of image quality in “routine” images
  - Some systems are more dose efficient (e.g., photon counting detector systems), providing lower dose capabilities
  - Some systems limit tube current modulation capabilities for DECT, decreasing optimization in some body regions
  - Technology continues to improve. Know your scanner’s technology
- Conventional CT dosimetry methods apply
  - However, attenuation to calibration energy is required for energy-sensitive dosimeters (e.g., TLD, OSL, MOSFET)
- Effective dose estimation methods apply similarly to DECT and SECT

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Image quality considerations

- Material decomposition strongly amplifies noise
  - Impacts all energy-specific and material-specific images
- Increased spectral separation decreases this noise amplification
- Several types of noise reduction techniques are used commercially
  - Algorithms to exploit noise correlations in the energy and/or spatial domains
  - Performed using projection and/or image data
  - Iterative and machine-learning approaches available
  - Can alter spatial frequency content of noise and appearance of noise texture
- Technology continues to improve. Know your scanner’s technology

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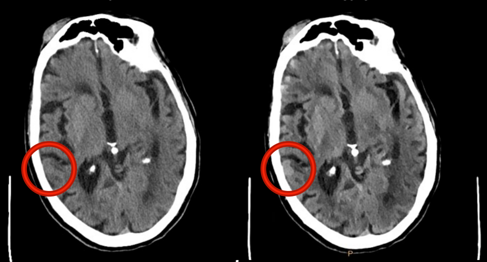
89-year-old male evaluated for stability of right retrobulbar hematoma



59.3 mGy CTDIvol

Courtesy of Xinhui Duan

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Dose comparisons must control for image quality

- Claim: Use of virtual non-contrast (VNC) images from contrast-enhanced DECT scans can cut dose in half by avoiding the need for true non-contrast-enhanced scan
  - Image quality in VNC images is not the same as in true non-contrast images
  - If the decreased quality of VNC images is acceptable, a greatly decreased dose in true non-contrast images would also be acceptable. the dose that one can “save” from using VNC is only equal to the dose needed to match the lower quality of the VNC image.
- To compare dose, must match or account for differences in
  - Noise, noise texture, spatial resolution in high, medium, and low contrast tasks, temporal resolution, contrast-to-noise-ratio, …

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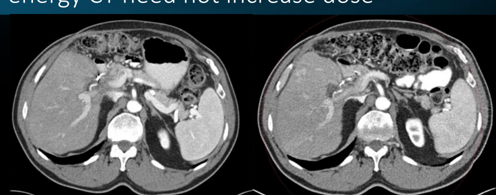
Multi-energy CT need not increase dose



Single Energy (120 kV)		Dual Energy Mixed
March 2009	Indication: HCC 35 – 36 cm lateral width	April 2009
CTDIvol: 18.65 mGy		CTDIvol: 15.59 mGy

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Virtual Monoenergetic (monochromatic) Imaging

CTDIvol	DLP	Eff. Dose*	K factor*
14 mGy	4 mGy*cm	1.3 mSv	0.0059

*AAPM Report 96
Courtesy of Strasbourg University Hospital, France

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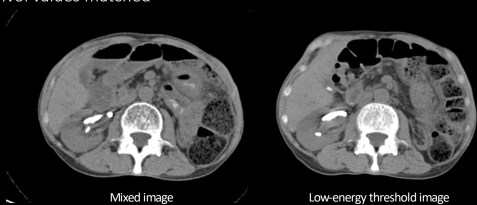
Photon counting detector (PCD) CT

- Under IRB, patients scanned using PCD-CT after their clinical scan
- CTDIvol values matched



Mixed image
Energy integrating detector CT

Low-energy threshold image
Photon counting detector CT

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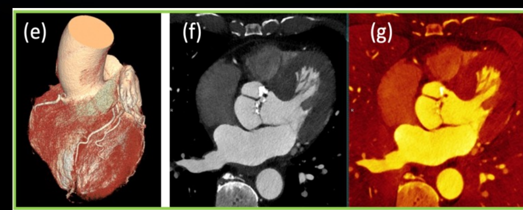
Cardiac photon-counting-detector multi-energy CT

- CTDIvol lower than energy-integrating detector dual-source CT



VRT
55 keV VMI
Iodine Map

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Conclusions

- Multi-energy CT
  - can differentiate materials of different effective atomic numbers, making possible new clinically relevant CT applications
  - is moving firmly into the mainstream of clinical CT imaging
- Dual-energy CT disappeared from clinical consideration in the 1980s, but with the tremendous advances that have taken place since that time, modern CT technology is now capable of taking full advantage of the fundamental physics — and clinical promise — that Godfrey Hounsfield envisioned in 1973

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