DUAL ENERGY CT

Principles & Clinical Applications

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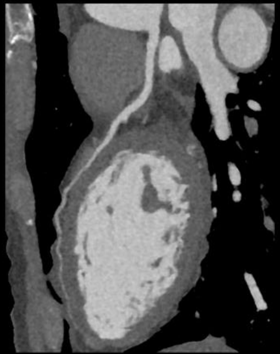
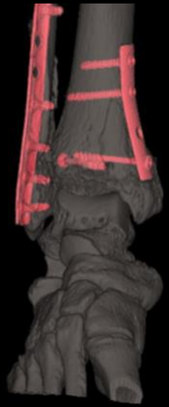
OUTLINE

1. Physics principles of dual energy CT
2. Acquisition & reconstruction
3. Clinical Applications

CONVENTIONAL CT PROVIDES ANATOMICAL INFORMATION, BUT LITTLE ON TISSUE COMPOSITION





BASICS OF CT IMAGING

- CT number depends on **x-ray attenuation** caused by
  - Photoelectric Absorption
  - Compton Scatter
- It is calculated as a function of the **linear attenuation coefficient** μ:

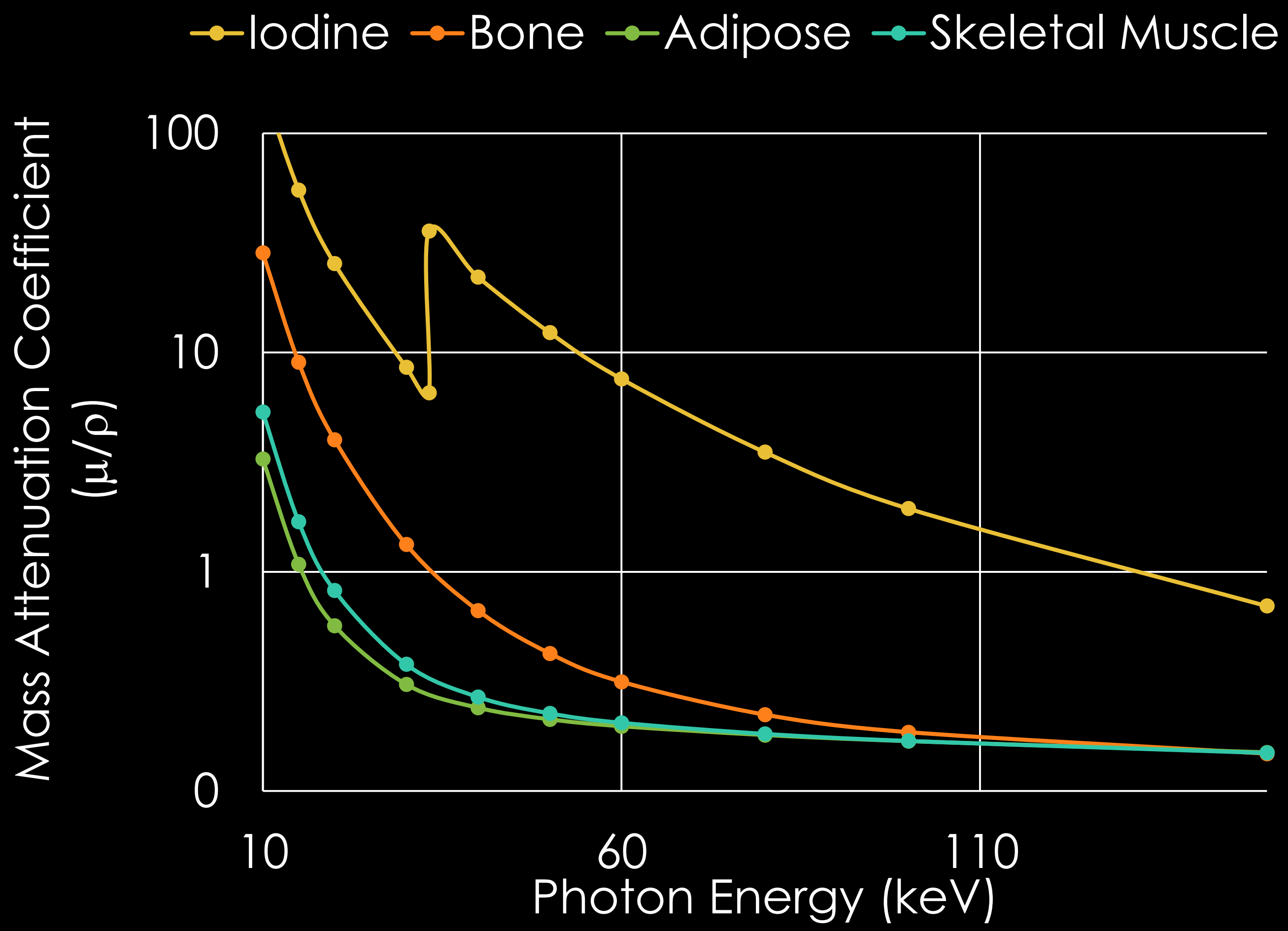
$$\mathrm{HU} = 1000 \times \frac{\mu - \mu_{\mathrm{water}}}{\mu_{\mathrm{water}}}$$

- μ is ***not unique for a material***, but is a function of:
  - Atomic Number (Z)
  - Physical density (g/cm^3)
  - Photon energy
- Different materials may have the same CT number due to their density

BASICS OF CT IMAGING

- The attenuation coefficient varies over x-ray photon energies

- Materials show *different CT numbers* at different energies



ENERGY DEPENDENCE

Soft tissues

- Mainly C, H, N, O
  - Low Z elements
  - No relevant k-edge

Substance	K-Edge (keV)	Atomic Number (Z)
Hydrogen	**0.01**	**1**
Carbon	**0.28**	**6**
Nitrogen	**0.40**	**7**
Oxygen	**0.53**	**8**
Calcium	4.00	20
Iodine	33.20	53

ENERGY DEPENDENCE

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Bone

- Contains calcium
  - Higher Z & k-edge
- Bone absorbs *more* x-rays than soft tissues

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Hydrogen	0.01	1
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ENERGY DEPENDENCE

Soft tissues

- Mainly C, H, N, O
  - Low Z elements
  - No relevant k-edge

Bone

- Contains calcium
  - Higher Z & k-edge
- Bone absorbs *more* lower energy x-rays than soft tissues

Iodine

- Higher Z & k-edge
- Large difference in attenuation as a function of energy

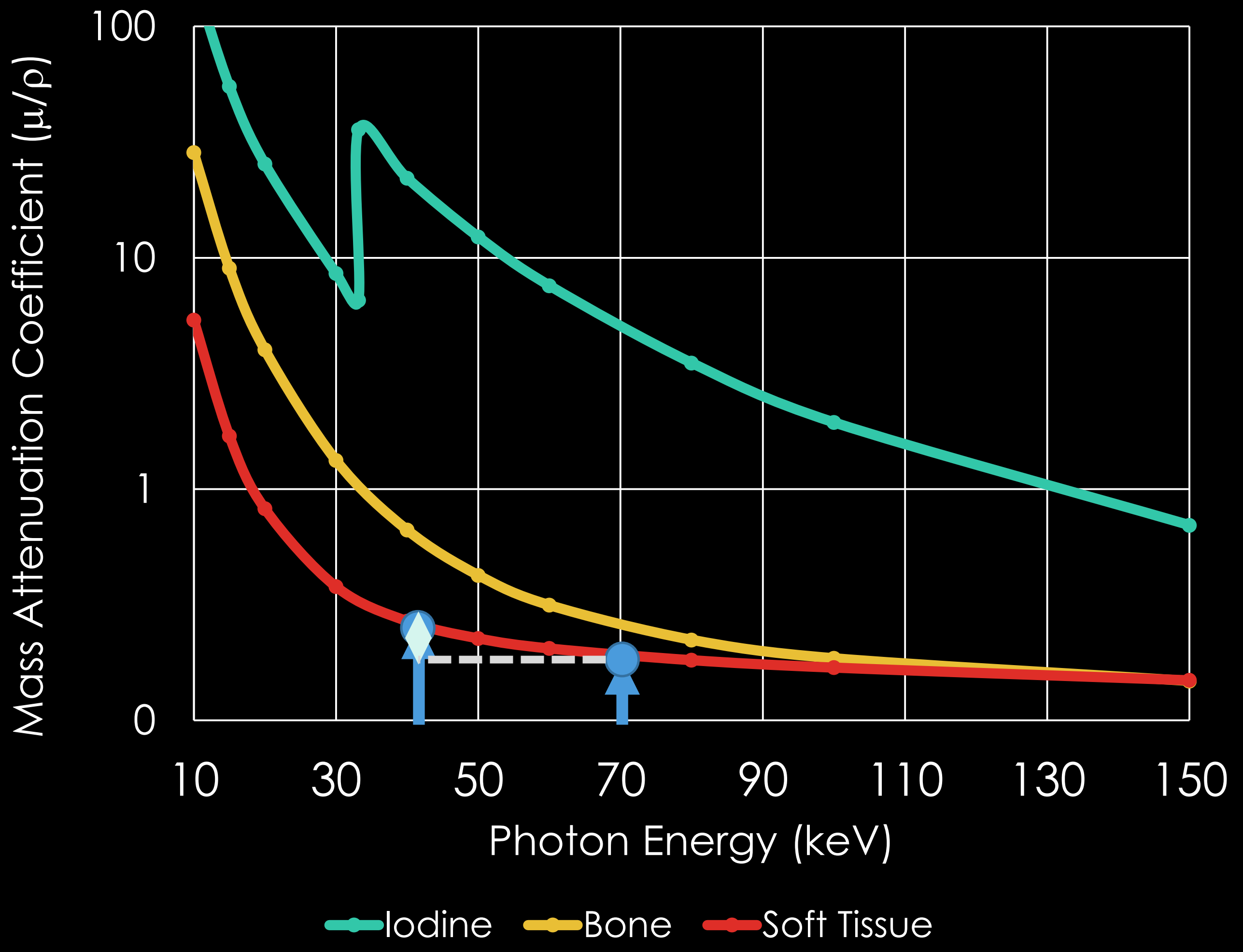
Substance	K-Edge (keV)	Atomic Number (Z)
Hydrogen	0.01	1
Carbon	0.28	6
Nitrogen	0.40	7
Oxygen	0.53	8
Calcium	4.00	20
Iodine	**33.20**	**53**

ENERGY DEPENDENCE

To allow differentiation on DECT, material must have differences in x-ray attenuation at different photon energies

Differences in attenuation and CT number as a function of energy:

- Soft tissue: Low

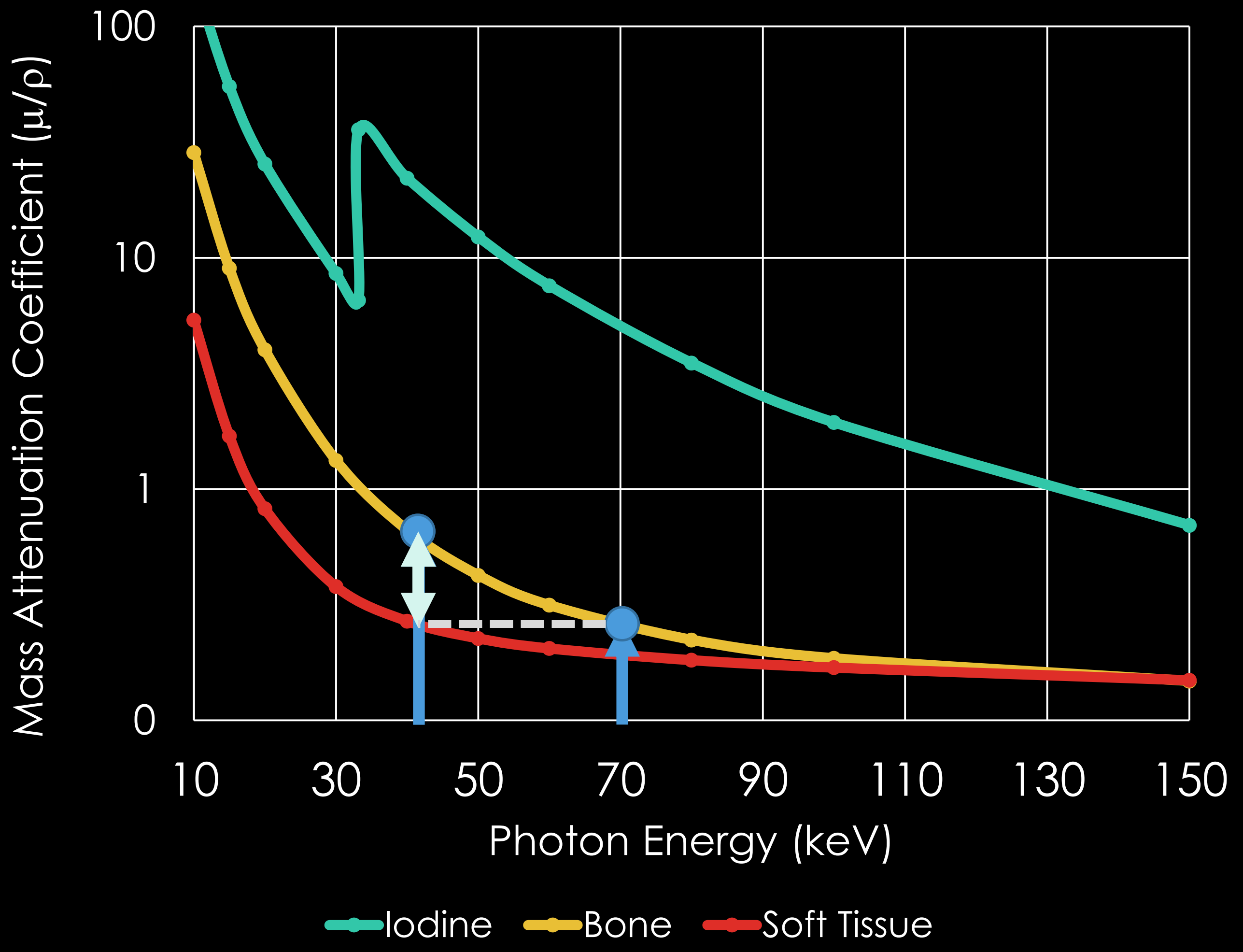


ENERGY DEPENDENCE

To allow differentiation on DECT, material must have differences in x-ray attenuation at different photon energies

Differences in attenuation and CT number as a function of energy:

- Soft tissue: Low
- Bone: Medium

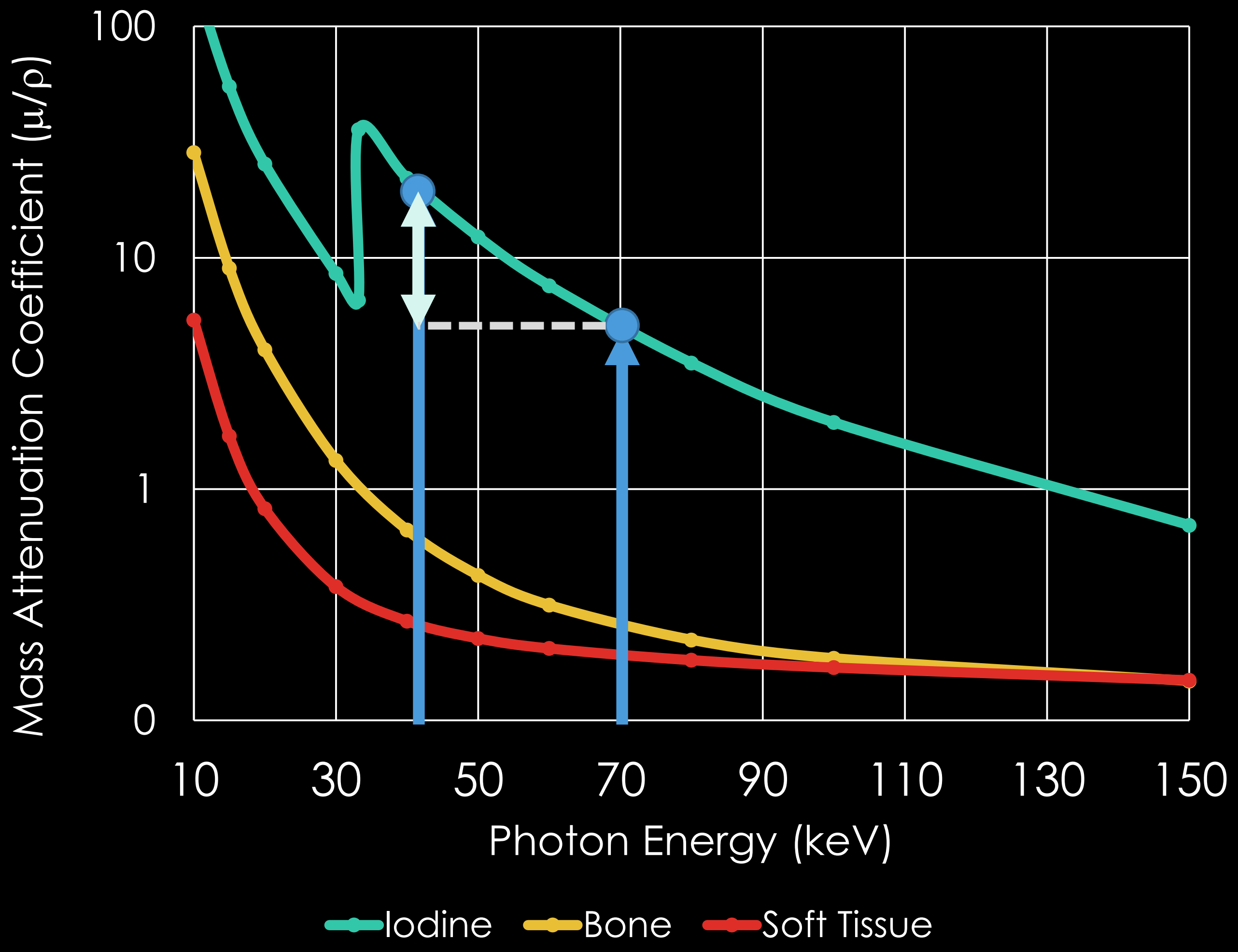


ENERGY DEPENDENCE

To allow differentiation on DECT, material must have differences in x-ray attenuation at different photon energies

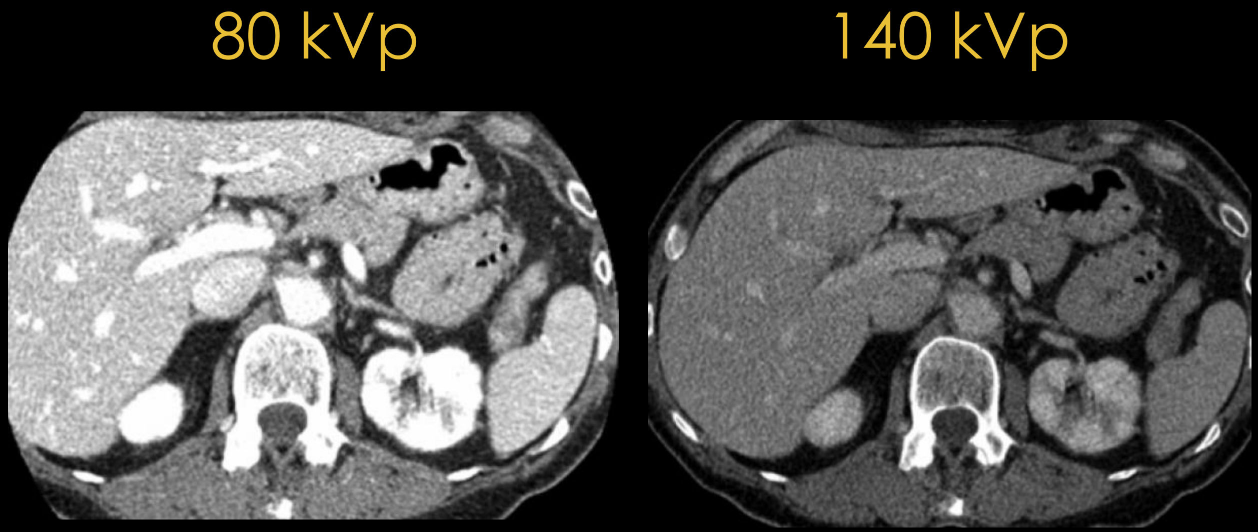
Differences in attenuation and CT number as a function of energy:

- Soft tissue: Low
- Bone: Medium
- Iodine: Large

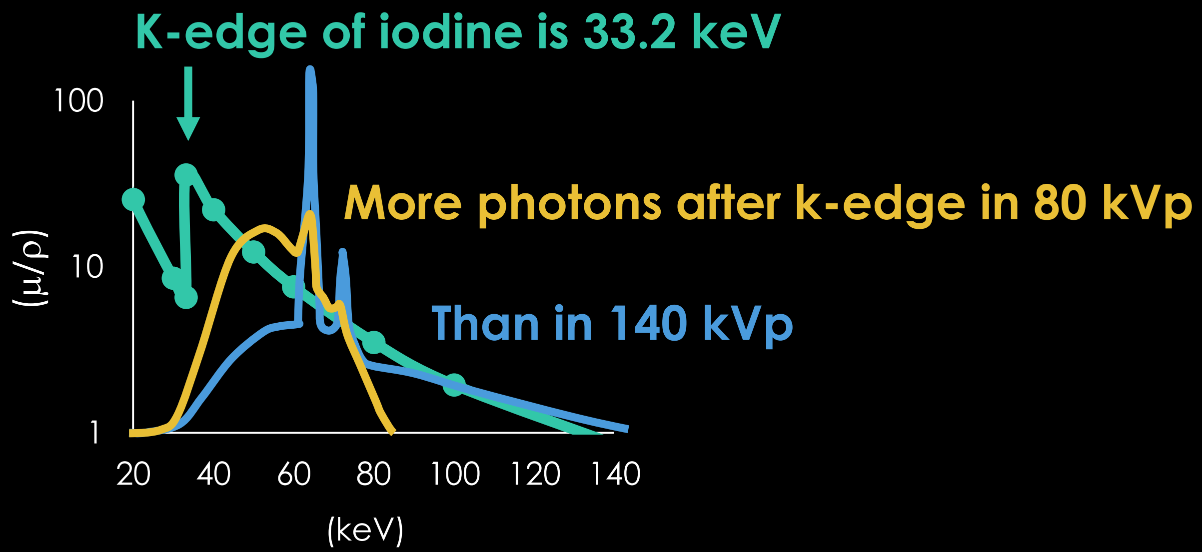


DUAL ENERGY CT

- μ and CT numbers vary at different photon energies
- **Different materials** show **different CT numbers** at **different energies**

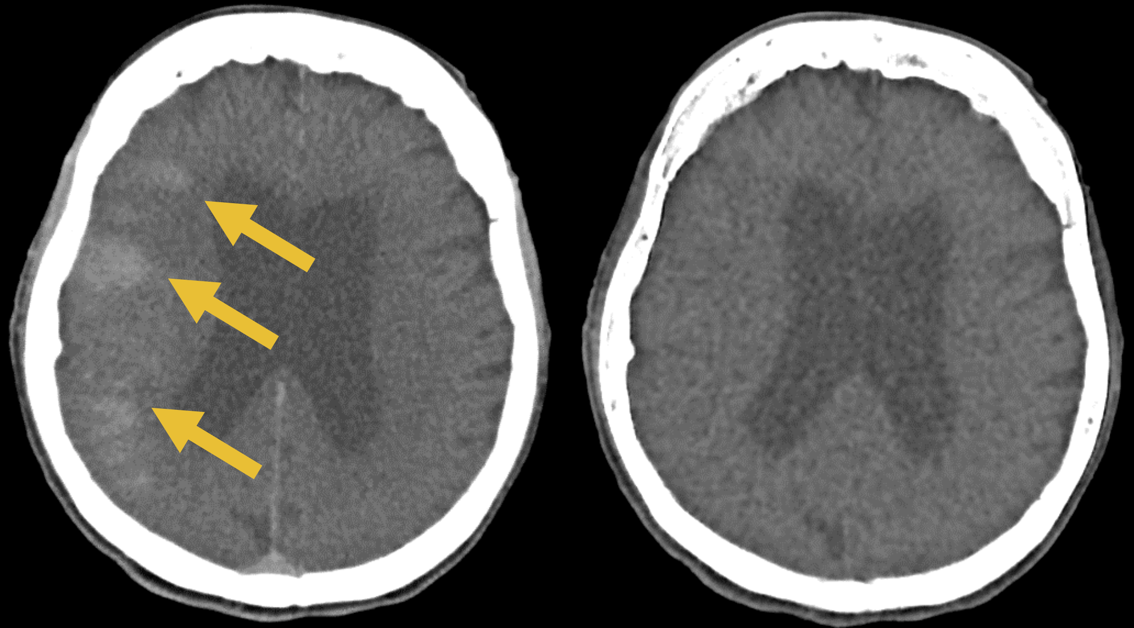


Increased attenuation of iodine on 80 kVp image

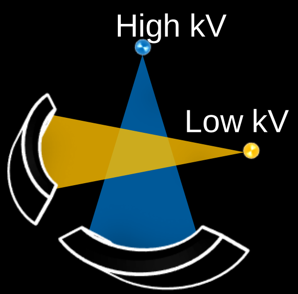
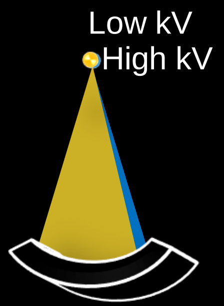
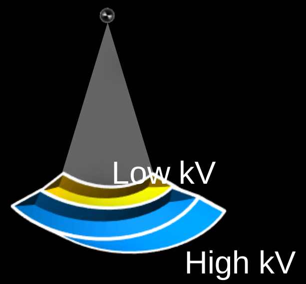
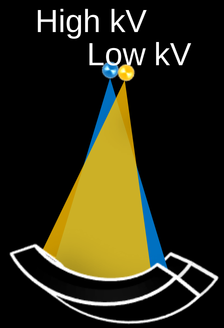


DUAL ENERGY CT

- **Dual energy CT** obtains data with **different beam spectra** to exploit the **energy-dependent nature of the CT number**
- Can provide information on ***material composition***

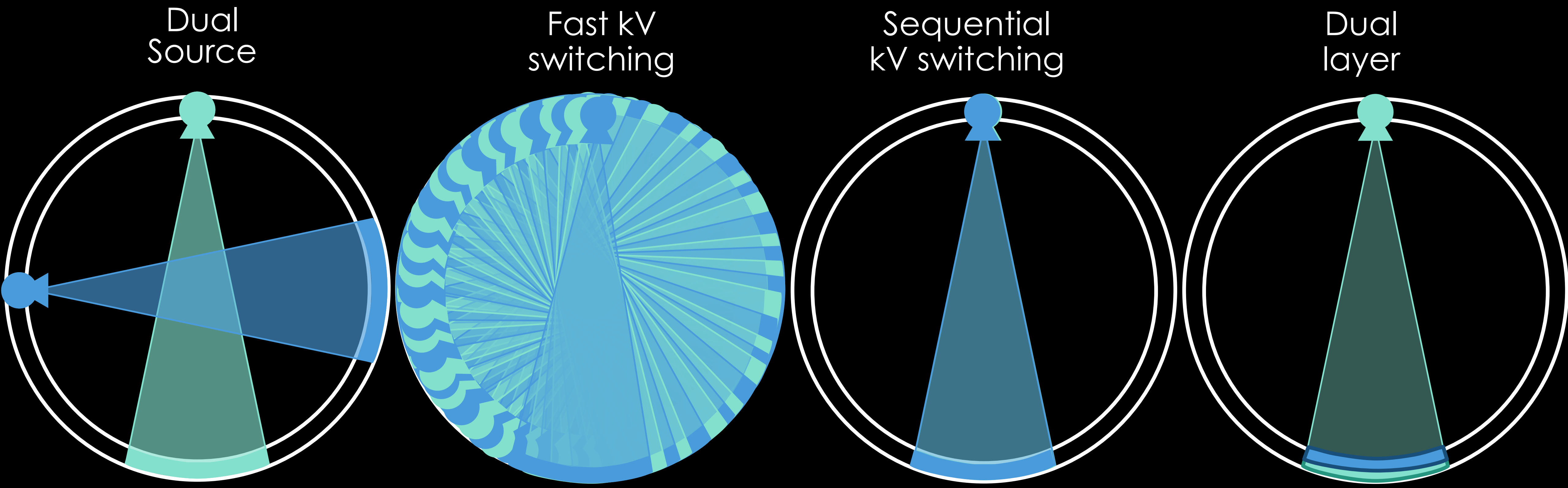


ACQUISITION METHODS

SIEMENS		PHILIPS	Canon	Canon, GE
Dual source	Twin beam	Dual layer	Sequential kV	Fast kV switching
				

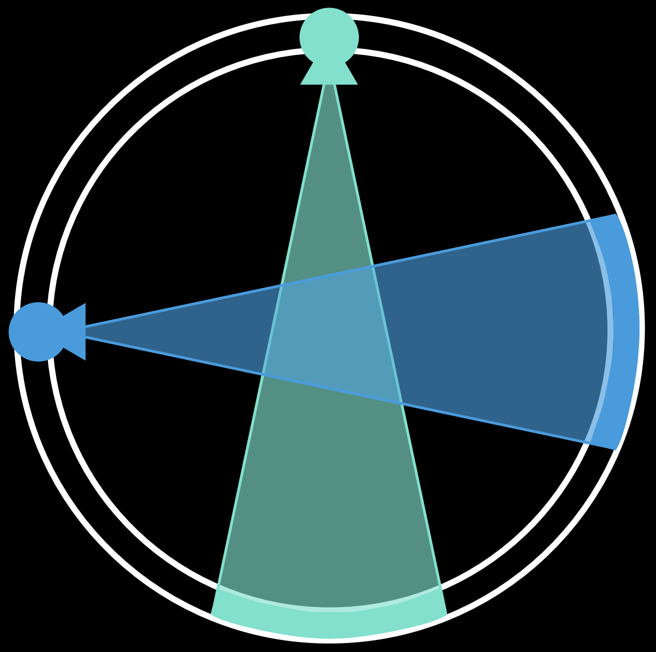
ACQUISITION METHODS FOR DECT

Low Energy
High Energy



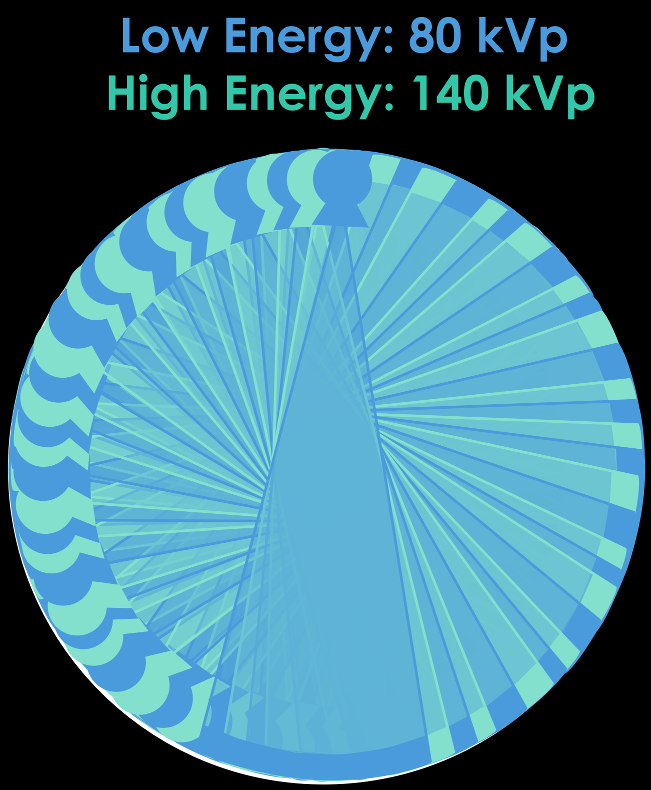
DUAL-SOURCE GEOMETRY (*SIEMENS*)

- Two tubes allow simultaneous collection of dual-kVp data
- Pros:
  - mA & filter selection for each tube
  - Good spectral separation
- Cons:
  - Requires cross-scatter correction
  - Limited FOV



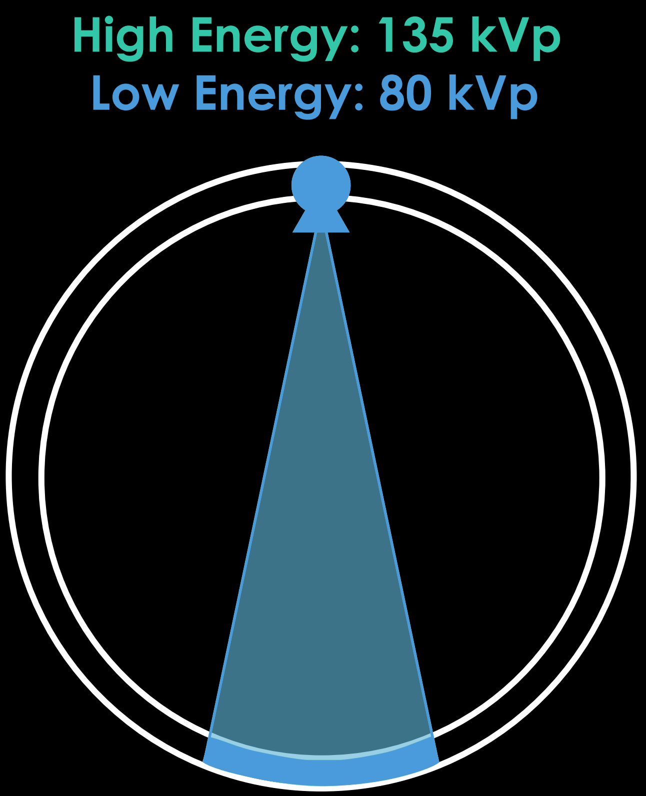
RAPID KV SWITCHING (*GE, CANON*)

- kVp switches (low, high) between views
  - 0.25 ms interval for both kV
- Both data sets acquired within 1 tube rotation
- Pros:
  - Good temporal registration
  - Projection-based algorithm available
- Cons:
  - Longer rotation time = motion artifacts
  - One mA for both kV results in high noise for low kV and high dose for high kV



SEQUENTIAL KV SWITCHING (CANON)

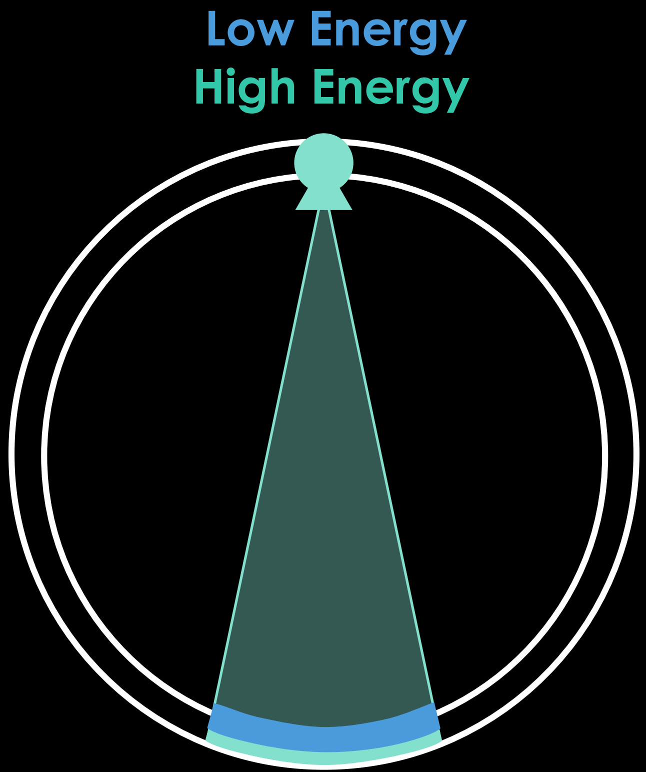
- Consecutive scan of entire scan volume
- Pros:
  - One mA for each kVp for optimal noise and dose
  - Projection-based algorithm available
- Cons:
  - Only possible in broad (320) detectors
  - Delay between both acquisitions may produce cardiac or respiratory motion



DUAL LAYER DETECTORS (*PHILLIPS*)

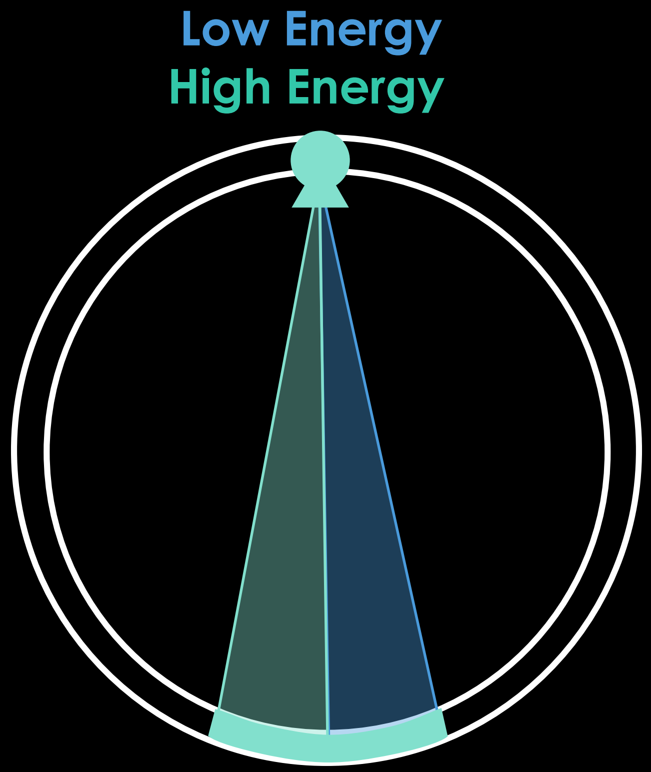
- Differentially absorb low and high energy photons from a single beam

- Top : absorbs lower energies, transparent to higher energies
- Bottom : absorbs high energy photons
- Pros:
  - Perfect temporal matching
- Cons:
  - Broad spectral overlap causes limited contrast in spectral information



SPLIT BEAM FILTRATION (*SIEMENS*)

- Beam is prefiltered with 2 different materials: Gold (Au) & Tin (Sn)
- Beam is split into a high (Sn) and low Au) energy x-ray spectrum
- Pros:
  - Perfect temporal matching
- Cons:
  - Greater x-ray output is necessary as the pre-filtration absorbs ~ 2/3 of the radiation
  - Pitch values are limited to the 0.25–0.45 range, requiring a longer scan time (9 s for lung)



RADIATION DOSE?

- Dose concerns
- Double the dose?
- Individual scans don't need high dose
- DECT has similar doses to single energy CT

Table 1. Reported CT abdomen doses of DECT and SECT in mean CTDIvol

Study	DECT (mGy)	SECT (mGy)
Takeuchi et al [26]	10.9	11.8
Jepperson et al [23]	12.7	20.0
Dubourg et al [22]	12.8	20.1
Shuman et al [25]	12.8	14.4
Ascenti et al [21]	17.6	15.0
Lin et al [24]	21.8	20.1

CTDIvol = CT dose index in a volume; DECT = dual-energy CT; SECT = single-energy CT.

Grajo, et al, J Am Coll Radiol, 2017

DECOMPOSITION OF μ

- The **attenuation coefficient** μ of a material can be decomposed into 2 functions:

$$\mu(r,E) = \underbrace{a_p(r) \cdot E^{-3}}_{\text{Photoelectric Effect}} + \underbrace{a_c(r) \cdot f_{KN}(E)}_{\text{Compton Effect}}$$

(Alvarez and Macovski, 1976)

- μ can also be decomposed to contributions from **2 basis materials**:

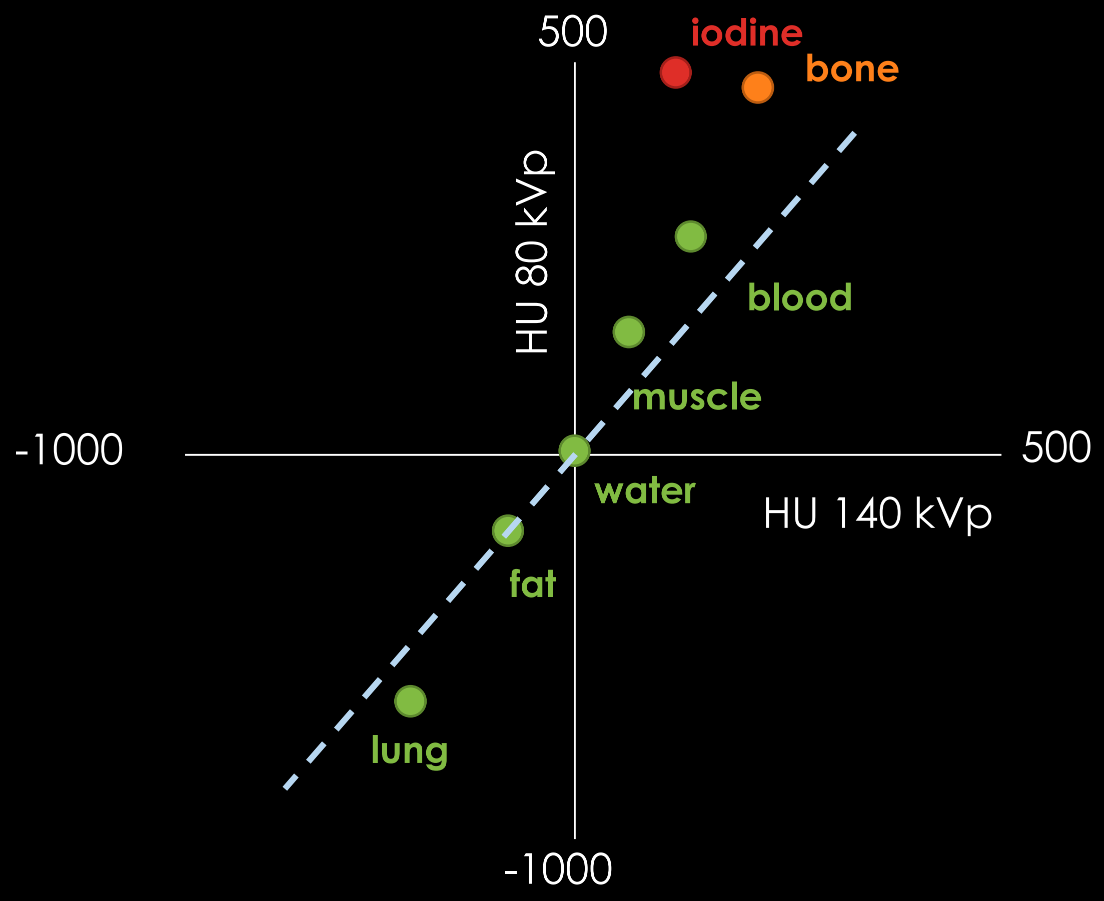
$$\mu(r,E) = \underbrace{a_1(r) \cdot \left(\frac{\mu}{\rho}\right)_{1,E}}_{\text{Basis Material \#1}} + \underbrace{a_2(r) \cdot \left(\frac{\mu}{\rho}\right)_{2,E}}_{\text{Basis Material \#2}}$$

(Lehman et al, 1981)

- To solve for the 2 basis materials, measurements from **2 energy spectra** are required

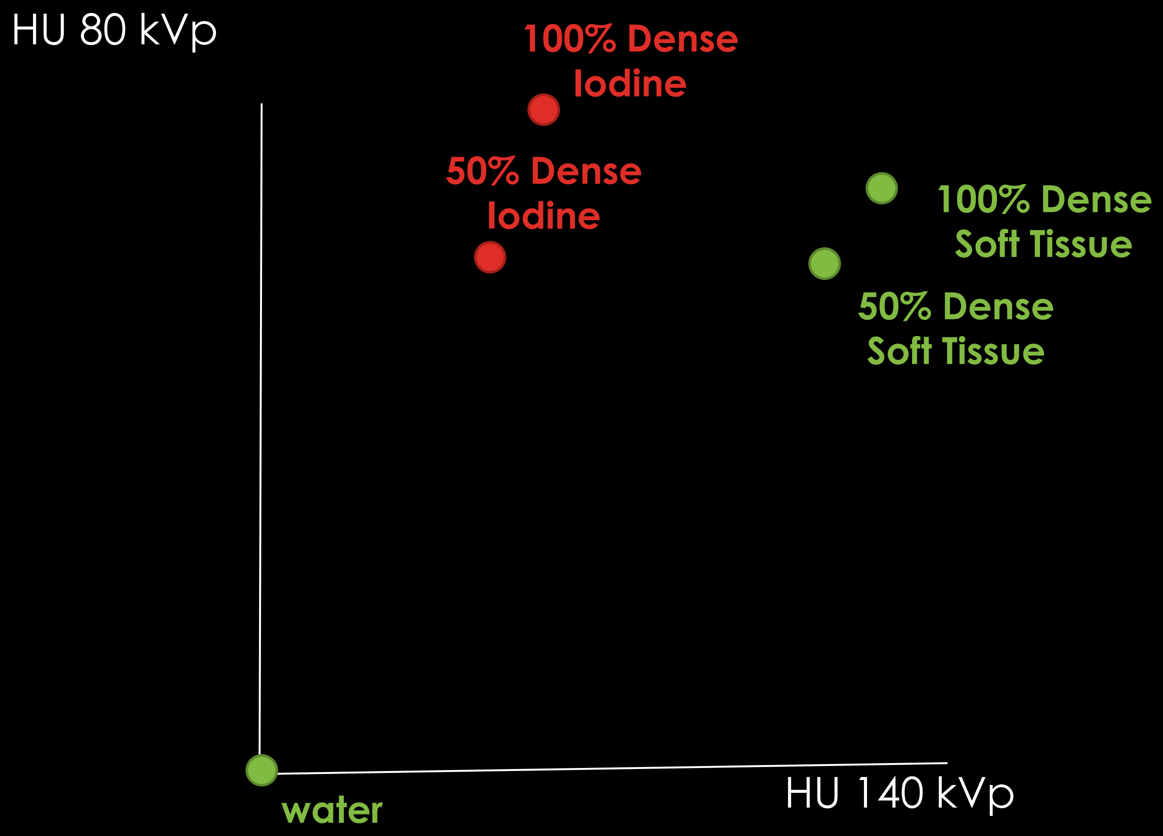
MATERIAL DECOMPOSITION

- The CT numbers of materials in high and low energy images can be plotted



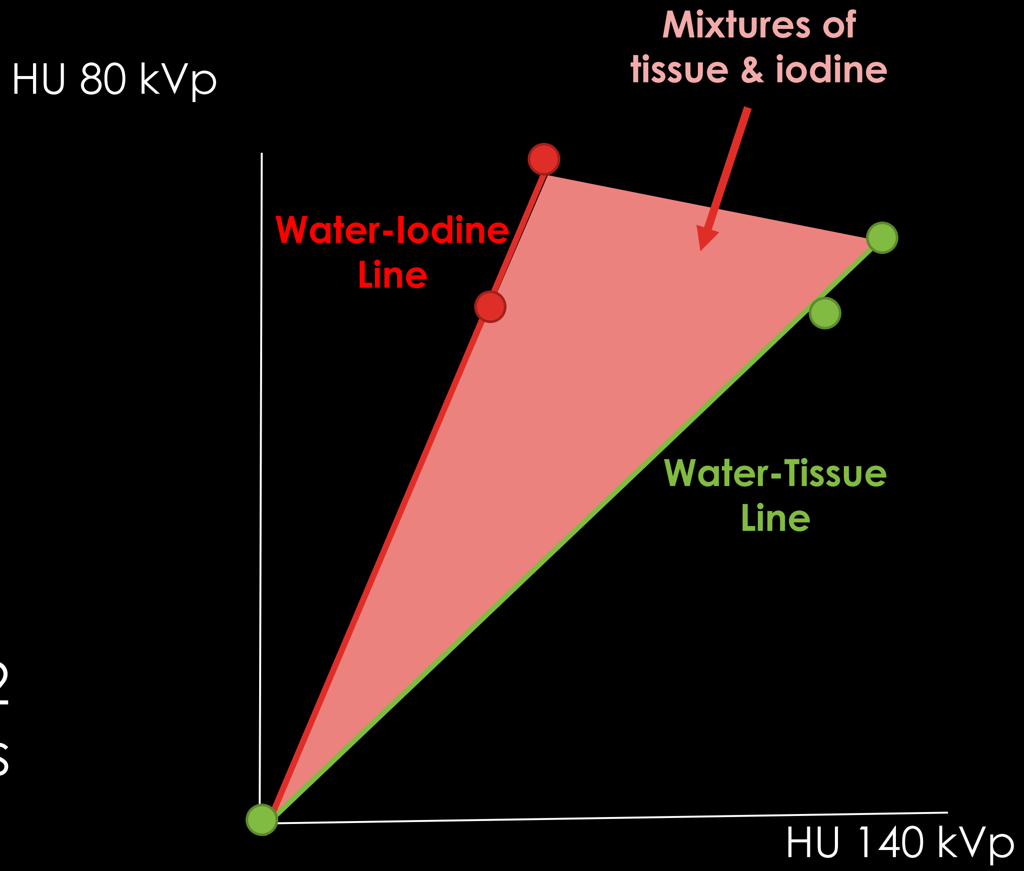
2 MATERIAL DECOMPOSITION

- Assumes:
  - The human body is a mixture of 2 different materials
    - Ex: water and iodine
    - Basis materials should have different spectral properties



2 MATERIAL DECOMPOSITION

- Assumes:
  - The human body is a mixture of 2 different materials
    - Ex: water and iodine
    - Basis materials should have different spectral properties
  - Voxels are composed of these 2 materials in different proportions

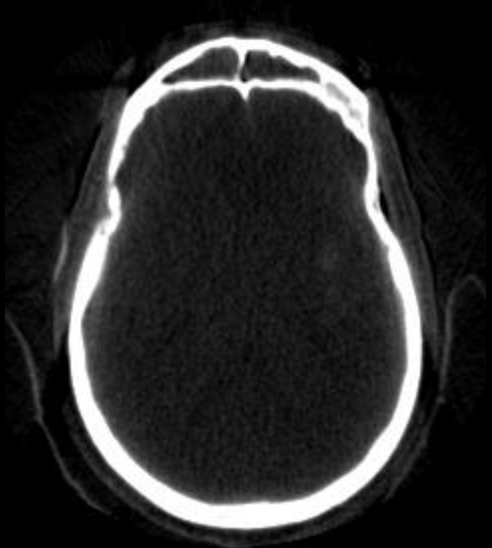


BASIS MATERIAL DECOMPOSITION

I/H2O
Water subtracted
Iodine remains

H2O/I
Water remains
Iodine subtracted

Ca/H2O
Water subtracted
Calcium remains



H2O/Ca
Water remains
Calcium subtracted

DUAL ENERGY PROCESSING

- Source images
  - 80 & 140 kVp images
- Blended images
  - Combine low and high energy images
  - Emulate single-energy 120 kVp images
    - Improved image contrast
- Energy selective images
  - Virtual monoenergetic images
    - Improved image contrast + Metal artifact reduction
- Material selective images
  - Basis material images
  - Material specific or cancelled images
    - Iodine image, water image, bone image
  - “virtual non-contrast” scans

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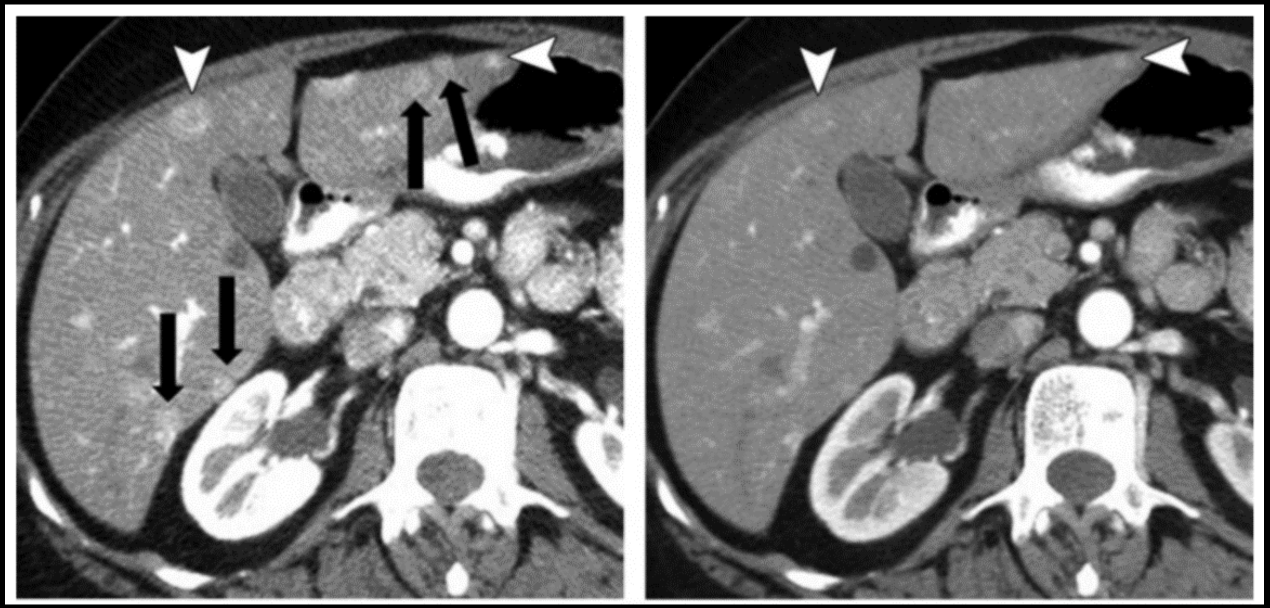
SOURCE IMAGES

Increased conspicuity of hepatic lesions on lower-kV images

80 kVp 140 kVp

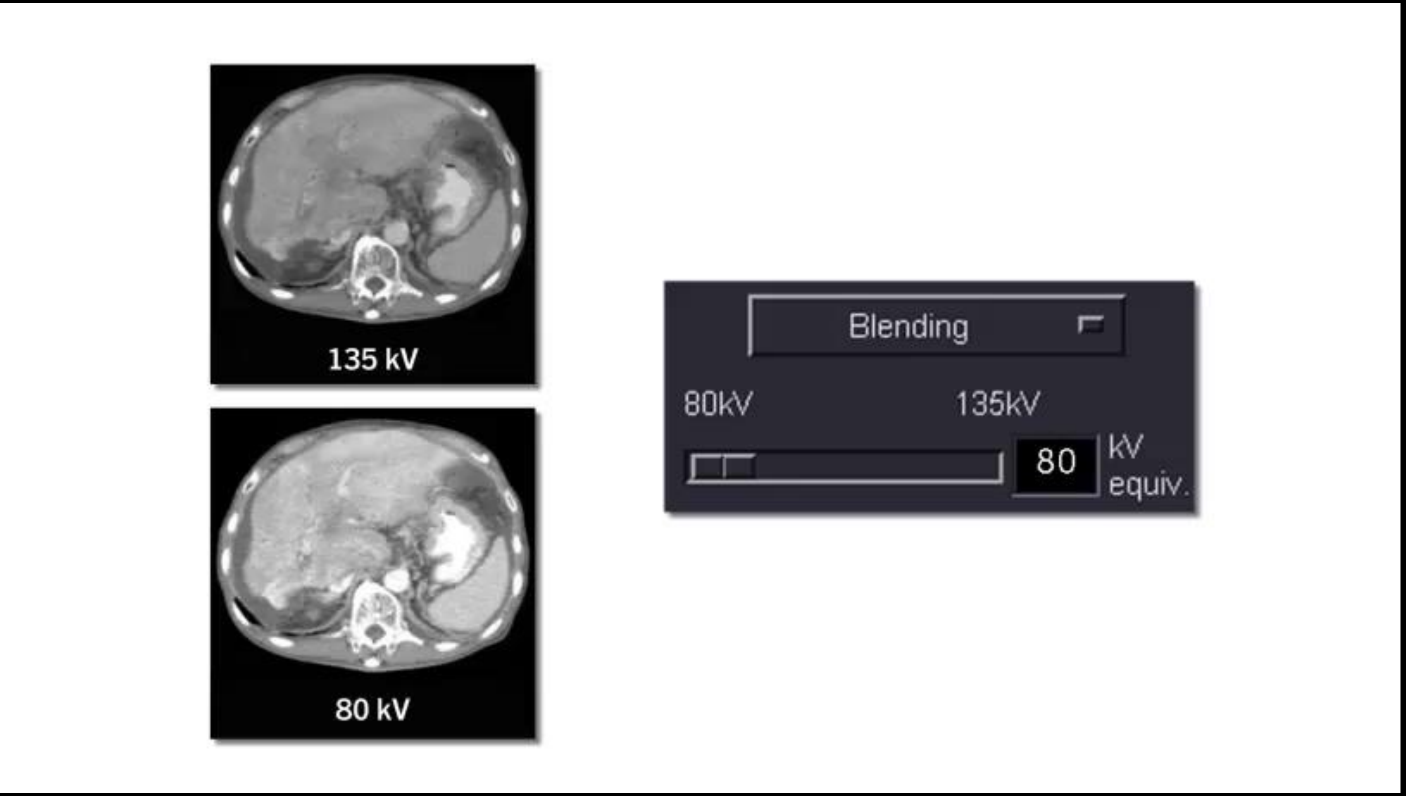


Lesions are better visualized on 80 kVp (arrowheads)
or ONLY visualized on 80 kVp (arrows)

Coursey, et al, Radiographics, 2010

BLENDING

- High and low kV images can be **blended** to generate a **weighted kV equivalent image** at any level within the acquired kV range



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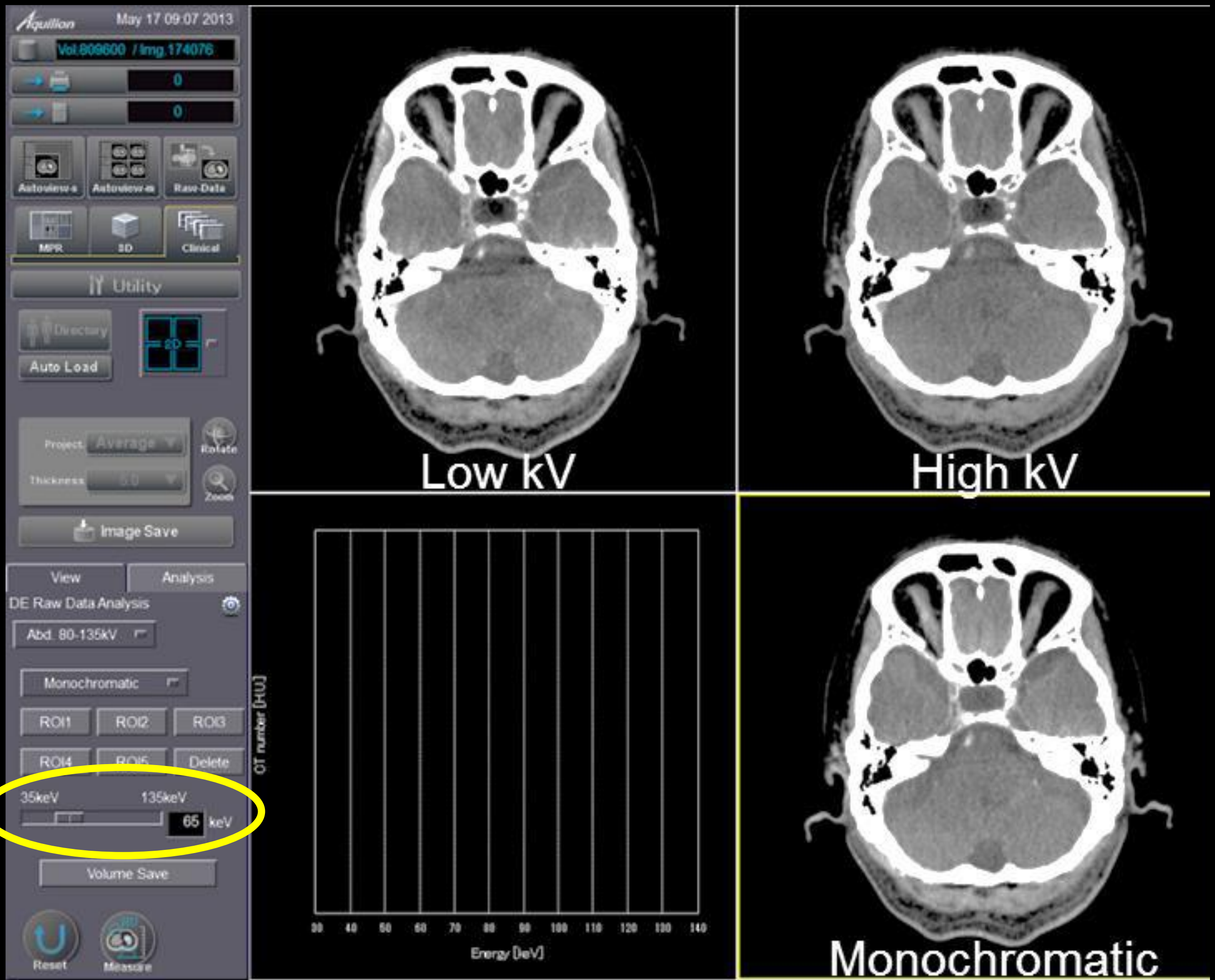
MONOCHROMATIC IMAGING

- Dual-energy CT data can be decomposed to form a **simulated monochromatic image**

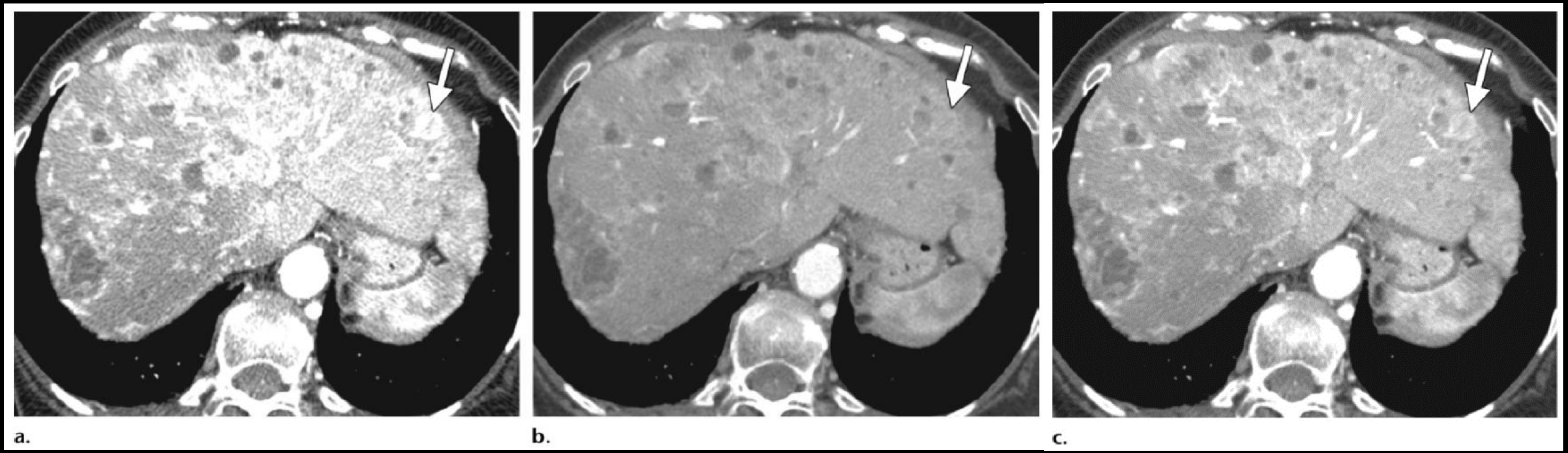
- Monochromatic images can be chosen between 35 keV and 135 keV



MONOCHROMATIC IMAGING

For improved noise & contrast resolution

80 kVp | 140 kVp | Monochromatic



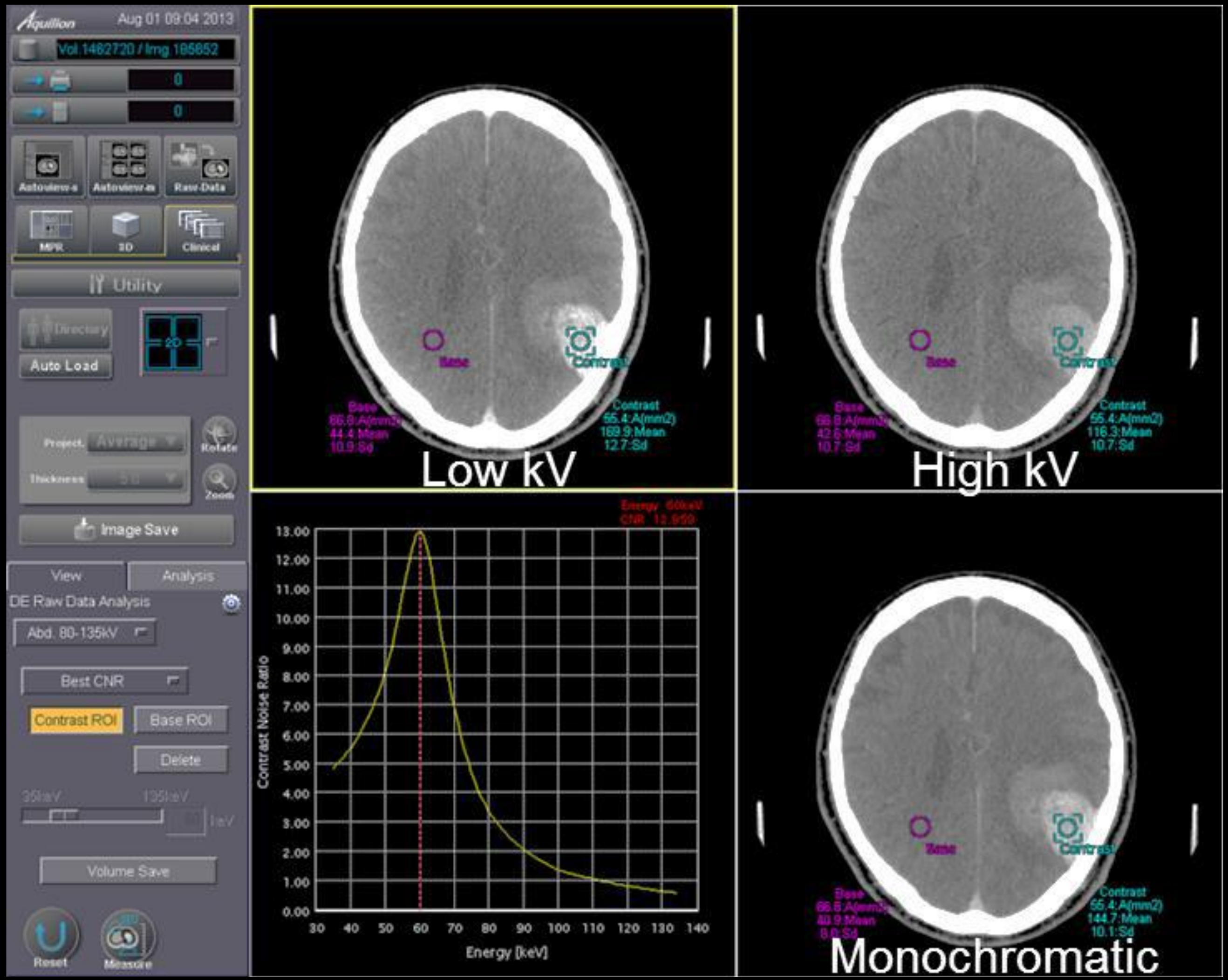
Visible, but noisy | Difficult to see | Decreased image noise & improved contrast resolution

Arrows = Enhancement of hypervascular metastasis

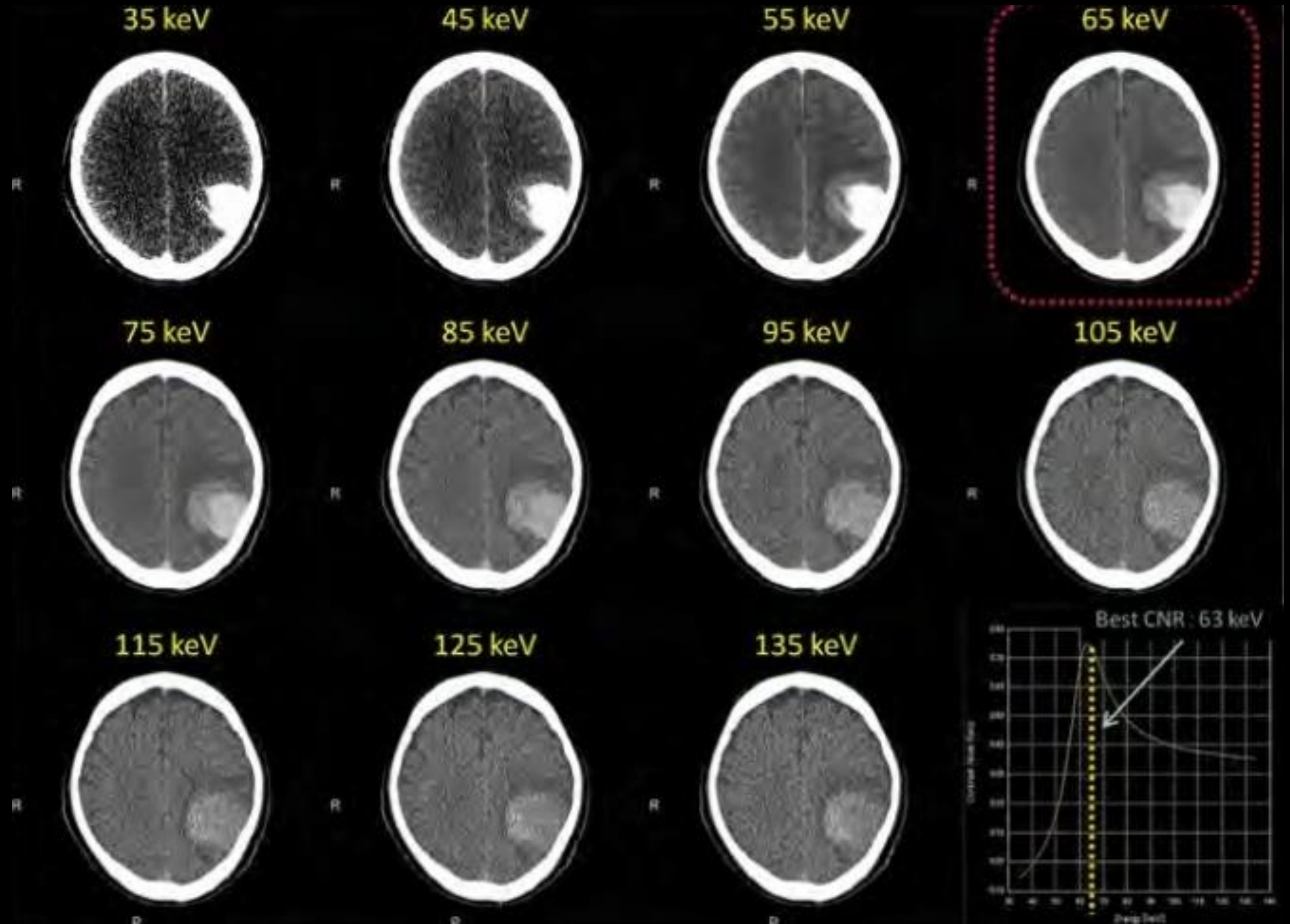
Silva, et al, Radiographics, 2011

BEST CONTRAST-TO-NOISE RATIO (CNR)

- Automatic CNR calculation after placement of two ROIs:
  - 1. Contrast ROI
    - on enhancing tissue
  - 2. Base ROI
    - on least enhancing tissue
- Automatic display of best monochromatic CNR image

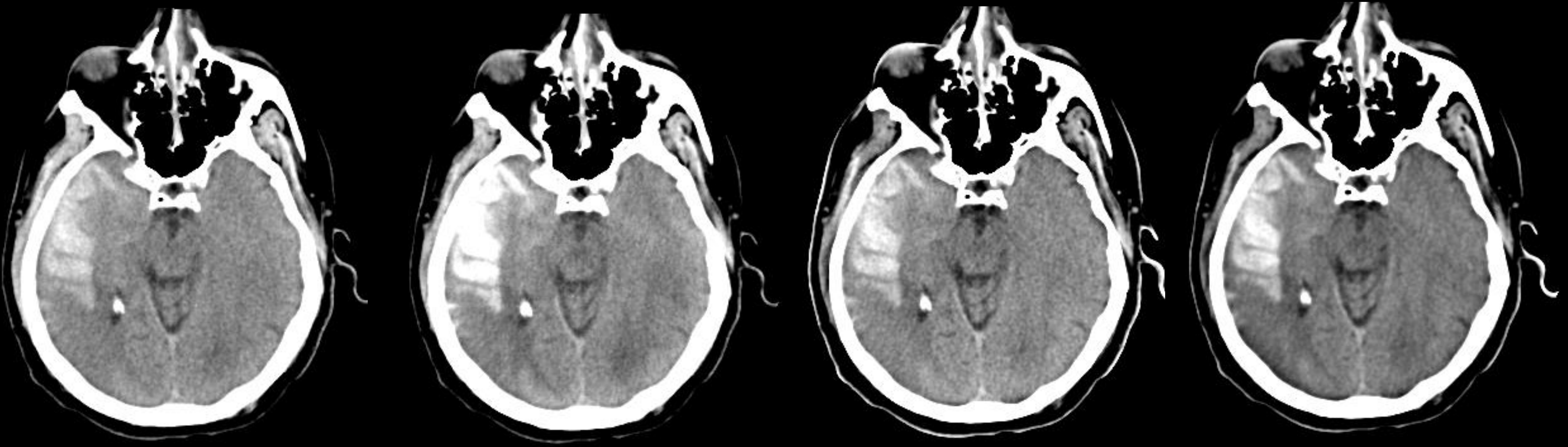


BEST CONTRAST-TO-NOISE RATIO (CNR)



BLENDING & BEST CNR

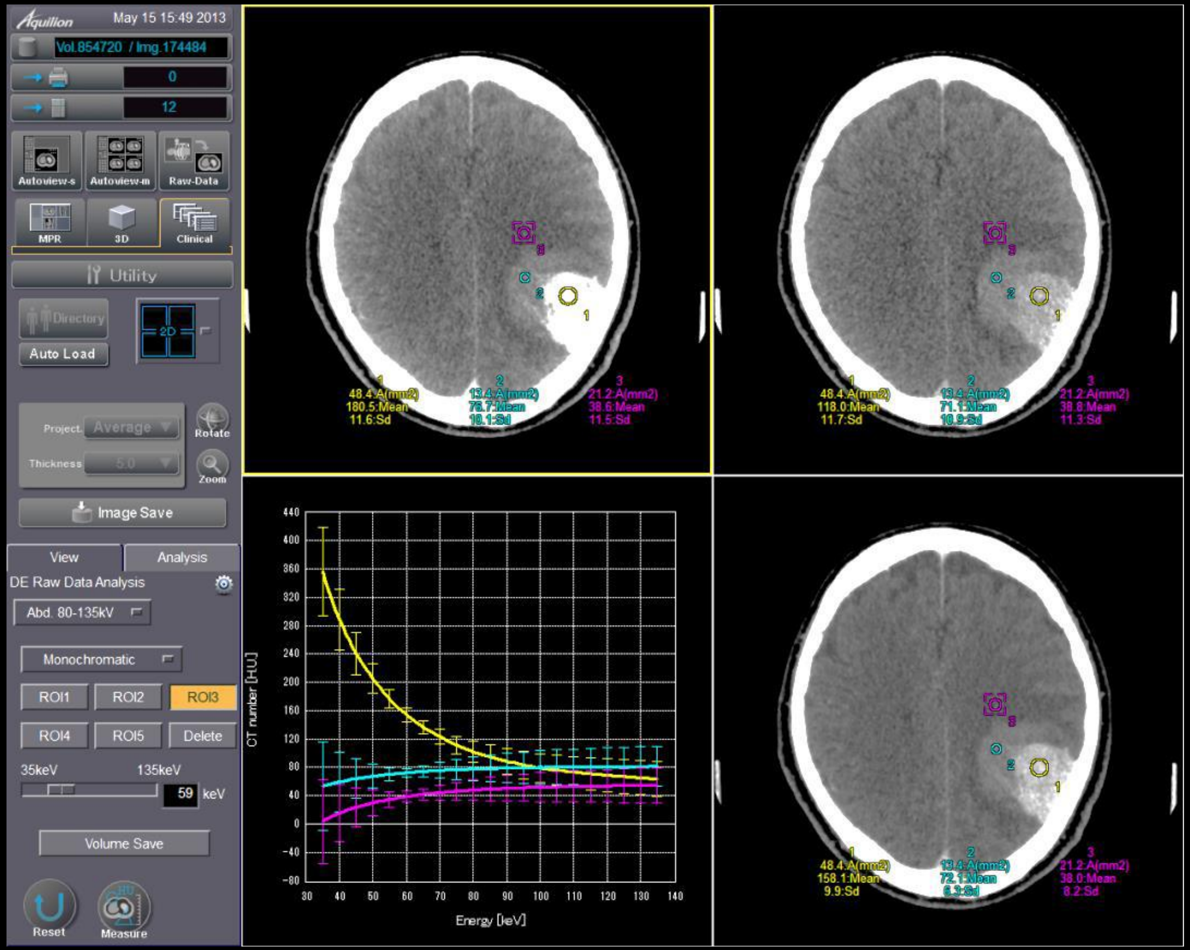
135 kVp | **80 kVp** | **Blended 120 kVp** | **Best CNR (66 keV)**



MONOCHROMATIC IMAGING

For attenuation curves (HU)

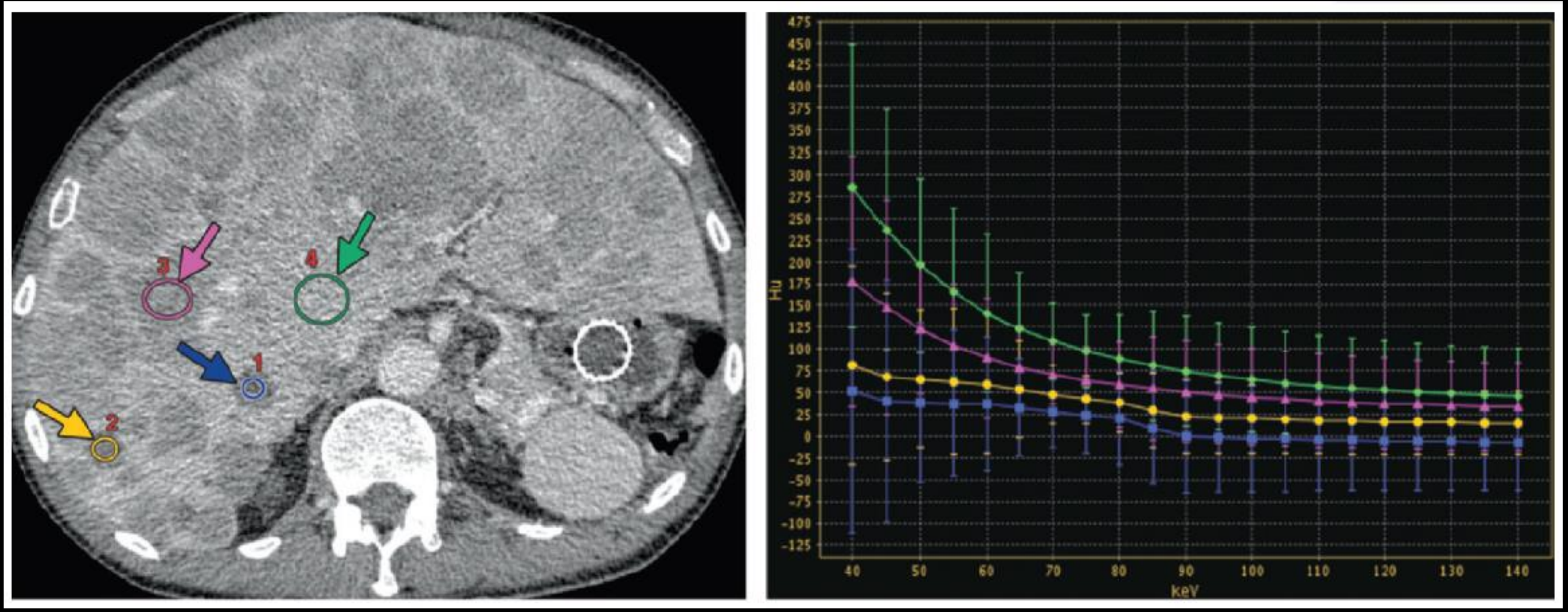
- Multiples ROI's can be placed for calculation of HU values for each keV
- ROI values are color coded and plotted across an HU/keVgraph
- Useful tools for tissue analysis



MONOCHROMATIC IMAGING

- Using iodine as a biomarker for **tumor viability** allows quantitative assessment of response to therapy by analyzing **spectral attenuation curves**

The flatter attenuation curves for two lesions (blue & yellow) indicate ***less iodine content*** than a third lesion (pink) and normally enhancing hepatic parenchyma (green)



Silva, et al, Radiographics, 2011

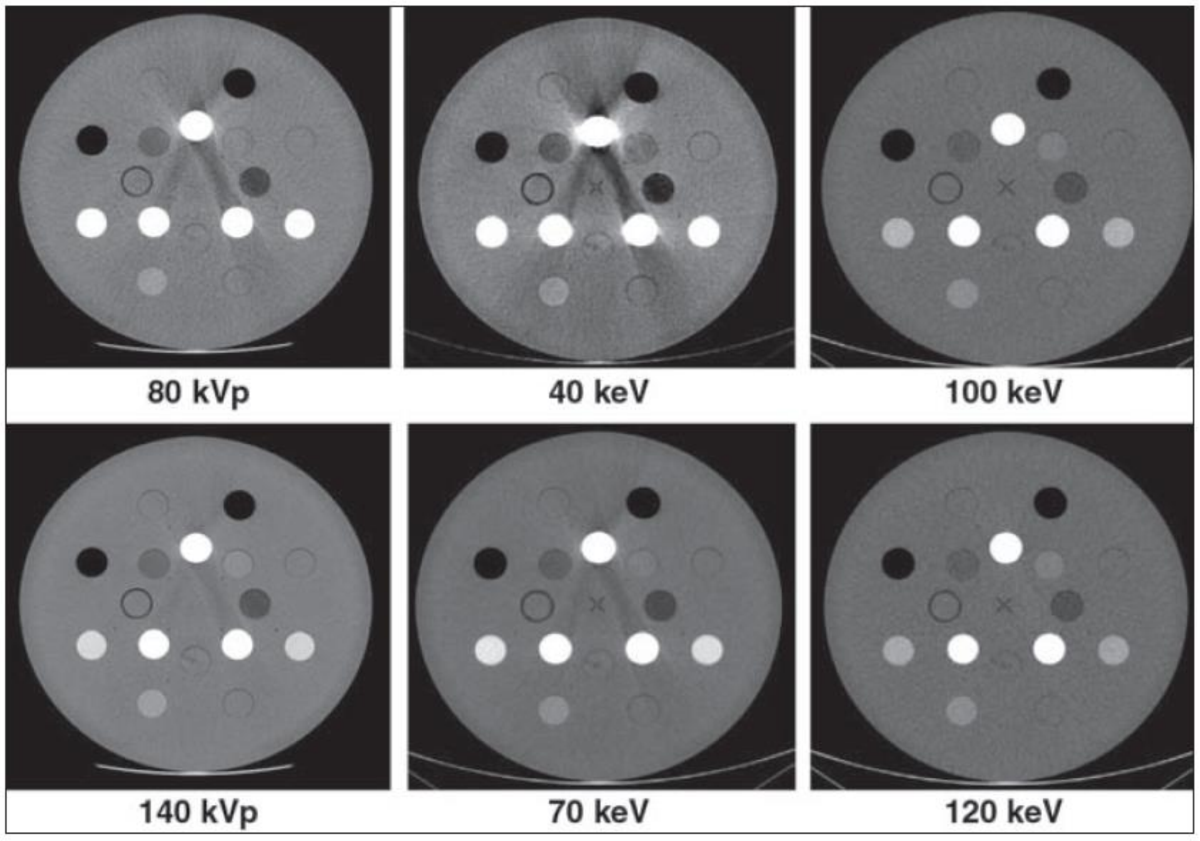
MONOCHROMATIC IMAGING

For reducing beam-hardening artifacts

- Polychromatic x-ray beams become hardened when passing through dense materials

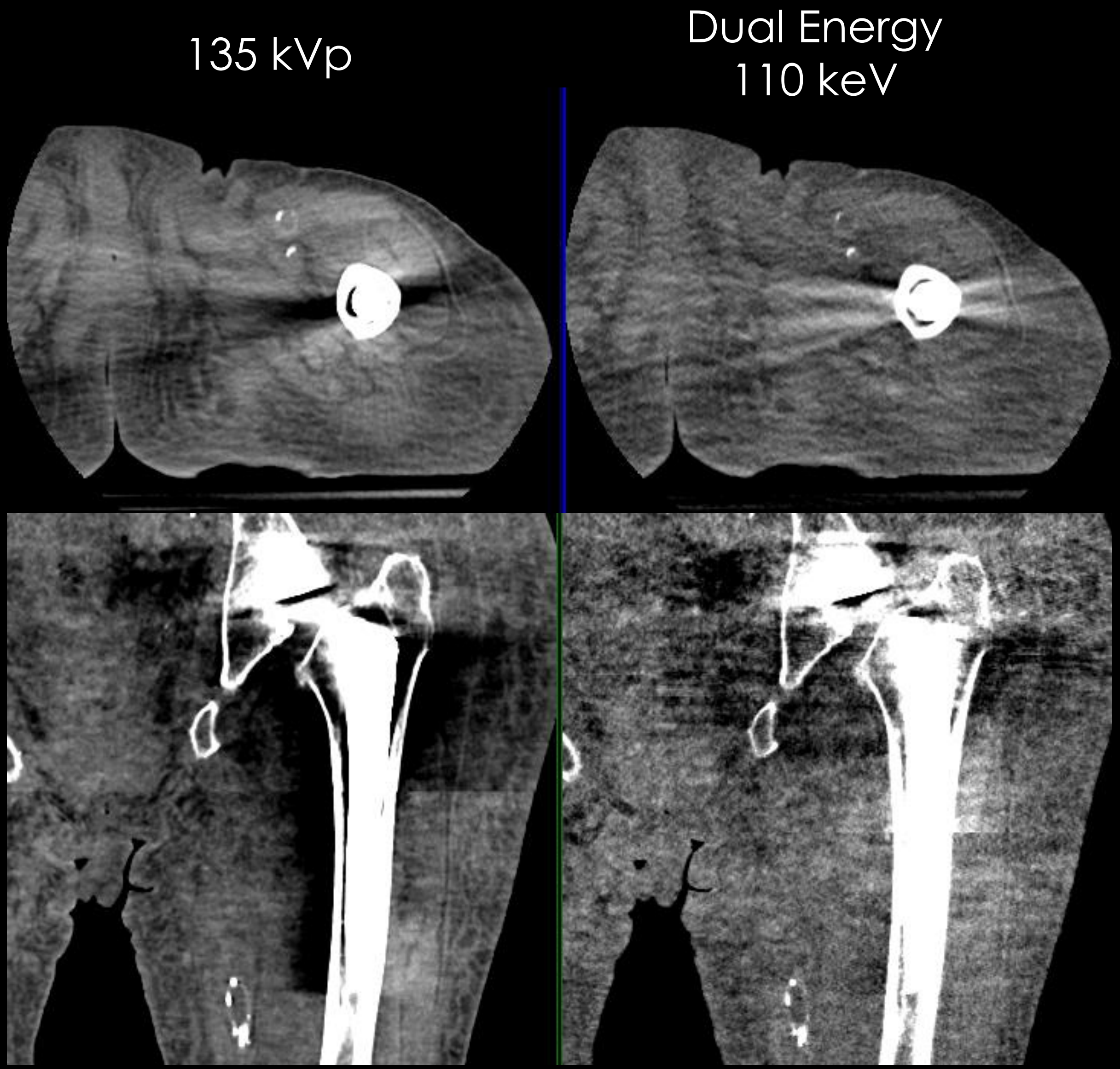
- Monochromatic x-ray beams do not

- The HU would not change if monochromatic x-ray beam were available and used at CT



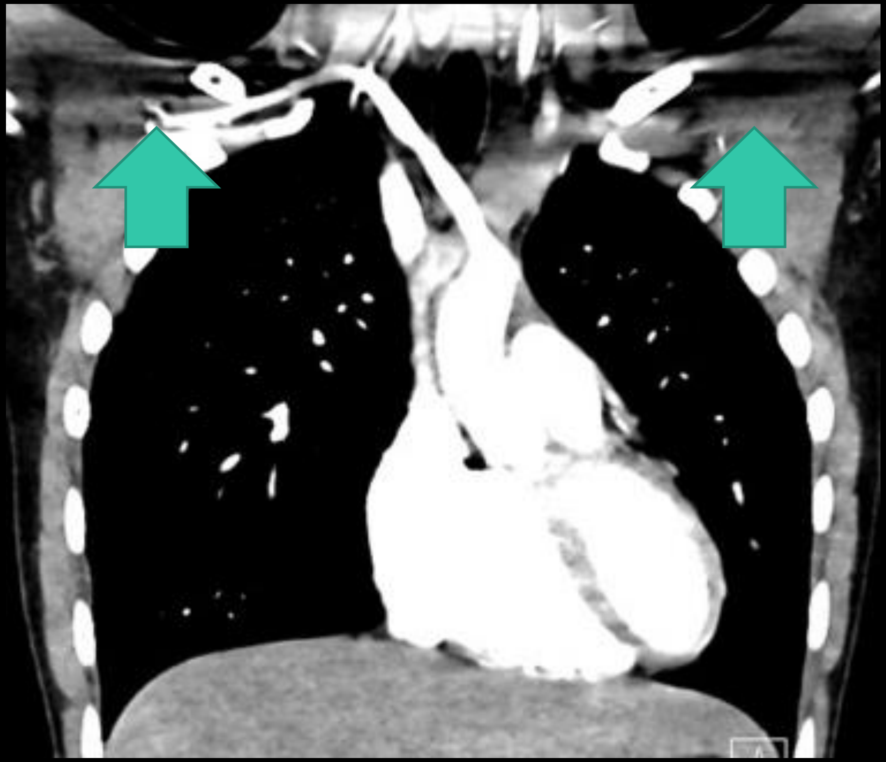
Yu, et al. AJR, 2012

MONOCHROMATIC IMAGING



MONOCHROMATIC IMAGING

40 keV: Beam hardening & photon starvation artifacts in thoracic inlet and shoulder are **pronounced**



60 keV: Artifacts are **reduced** in **higher keV images**

DUAL ENERGY PROCESSING

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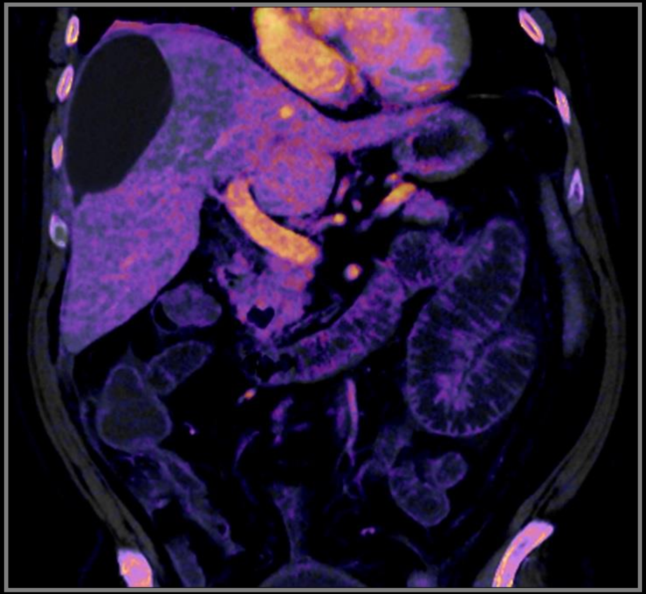
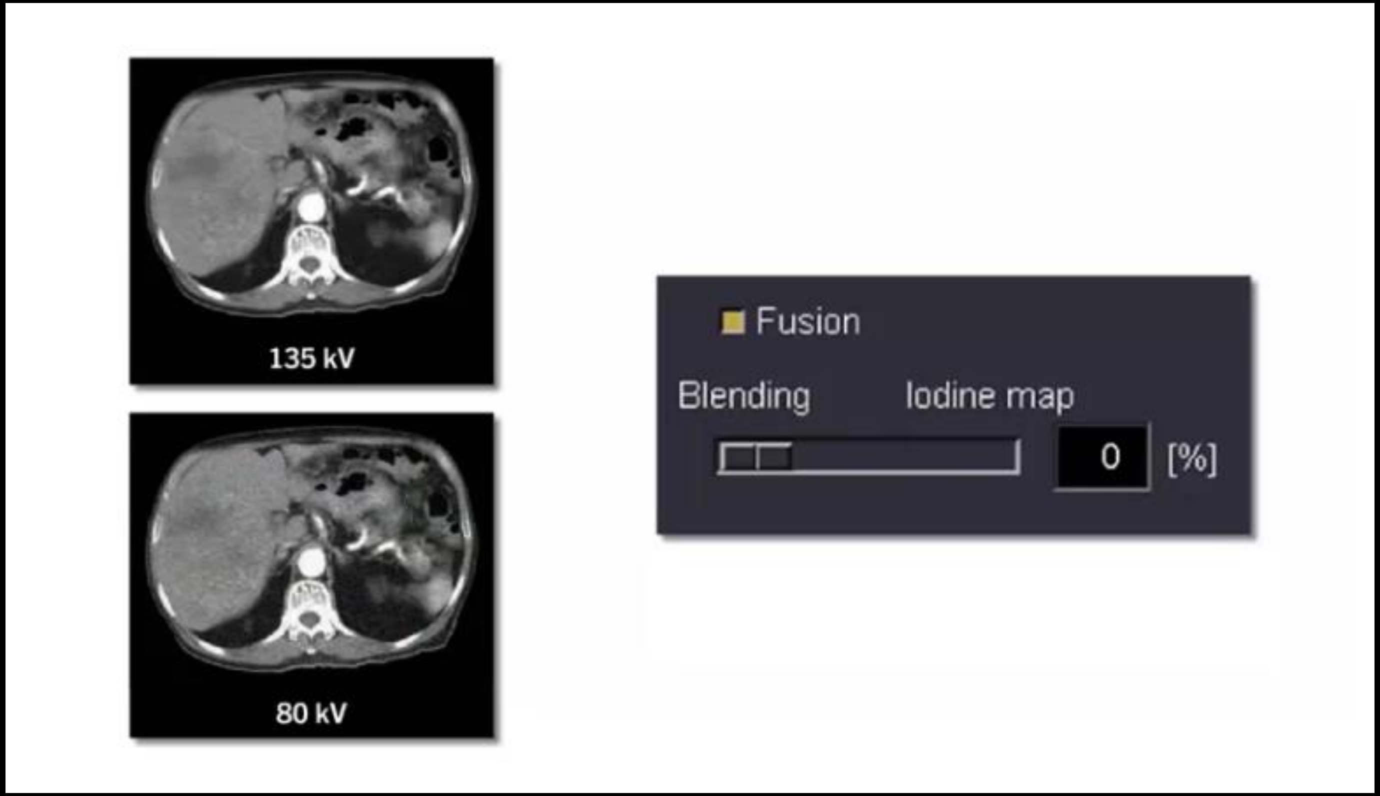
IODINE MAP

- Iodine distribution
- Color map display



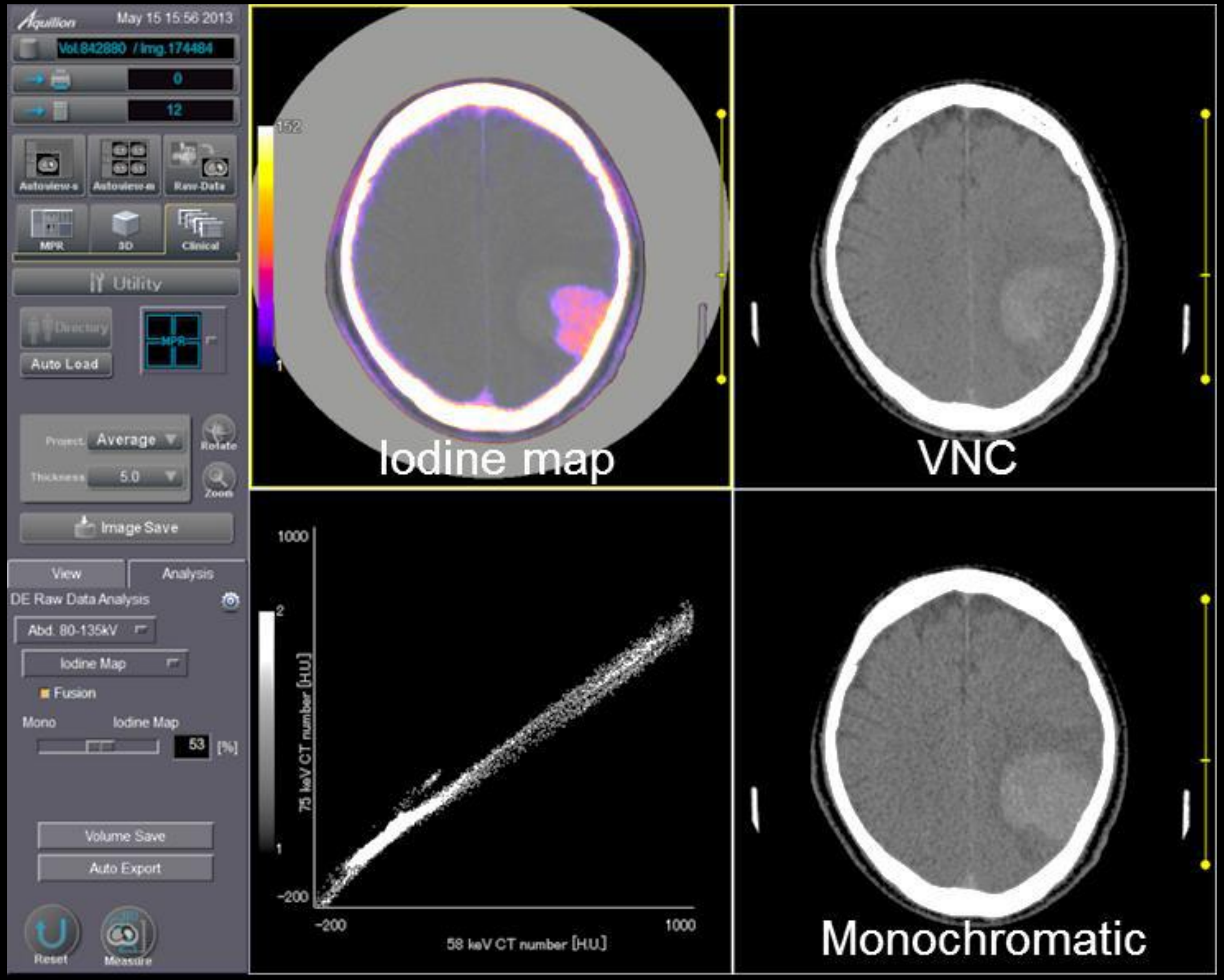


IODINE SUBTRACTION

- Iodine subtracted images

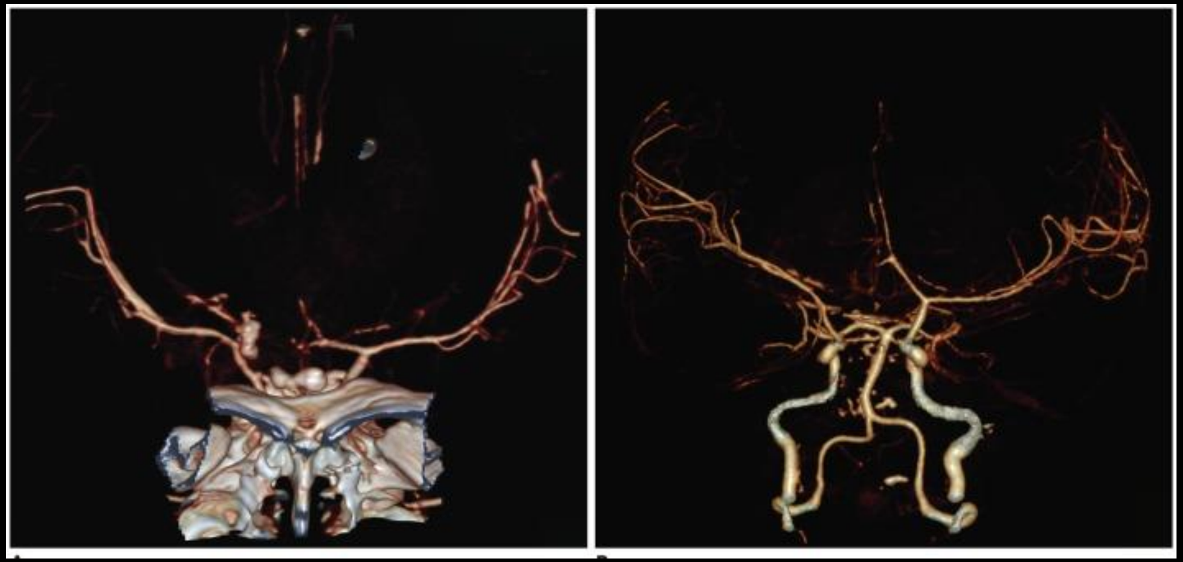
IODINE MAP & SUBTRACTION

- Iodine distribution is displayed as a **color map**
- Adjustable fusion between mono and iodine map
- Virtual Non-Contrast (VNC) image is also generated



BONE REMOVAL

- Bone can hamper interpretation of intracranial vessels
- DECT can remove bone with 3-material decomposition



- DECTA is useful for facilitating interpretation of vessels in surgically treated aneurysms
  (Postma, et al. Curr Radiol Rep. 2015)
- Compared to conventional CTA, visualization of aneurysms and calcified aneurysms was superior with DECTA
  (Watanabe, et al, Neuroradiology 2014)

CLINICAL APPLICATIONS

Table 3: Clinical Applications of DE CT Material Decomposition

Body Region	Iodine	VNC*	Calcium	Fat	Uric acid	Other Materials
Head and neck	Hemorrhage vs contrast-medium extravasation, intracranial hemorrhage of unknown etiology, tumoral invasion of cartilaginous structure	++	Bone removal	...	...	Xenon (paranasal sinus imaging)
Chest	Pulmonary perfusion, pulmonary emboli, pulmonary nodules	++	Cardiovascular plaque	...	...	Xenon and krypton (ventilation imaging)
Abdomen	Lesion detection and characterization, tumor staging, metal-related artifact reduction, fibrosis	+++	Aortic and mesenteric plaque, calcifications vs contrast medium, kidney stones	Liver fat quantification, fat-containing lesions	Kidney stones	Iron (hemochromatosis)
Musculoskeletal	...	+	Bone mineral density, bone marrow edema	Marrow fat	Gout	Tendons and ligaments

*+ = occasionally used, ++ = frequently used, +++ = very frequently used.

Patino, et al, Radiographics, 2016

DE STONE ANALYSIS

- Characterize renal stones for treatment planning
- Uric acid kidney stone differentiation
- A slope of HU characterizing each material is graphed with low and high kV
- Either Uric Acid or "Other"
  - Calcium oxalate
  - Calcium phosphate
  - Struvite
  - Cystine

High kV Low mA - 135kV 75mAs

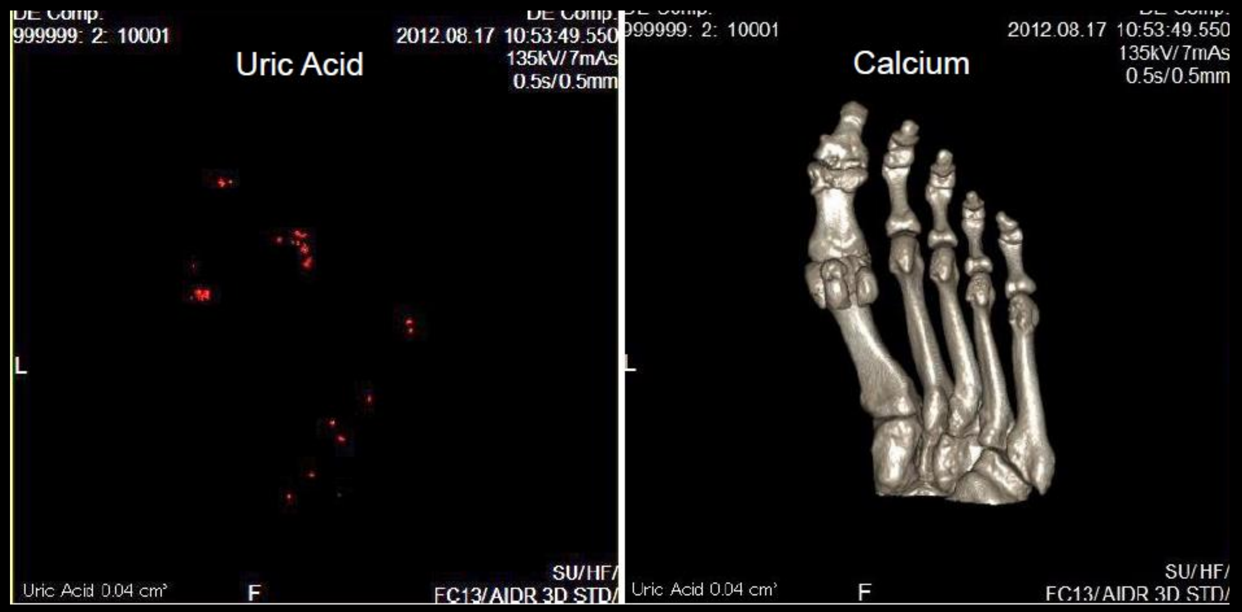
Low kV High mA - 80kV 350mAs

Canon America Medical Systems

GOUT COMPOSITION ANALYSIS

- Identification of monosodium urate crystal deposits

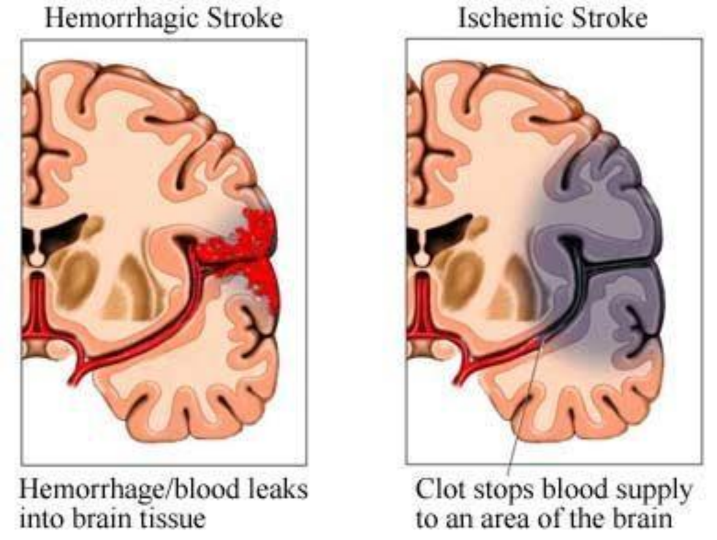


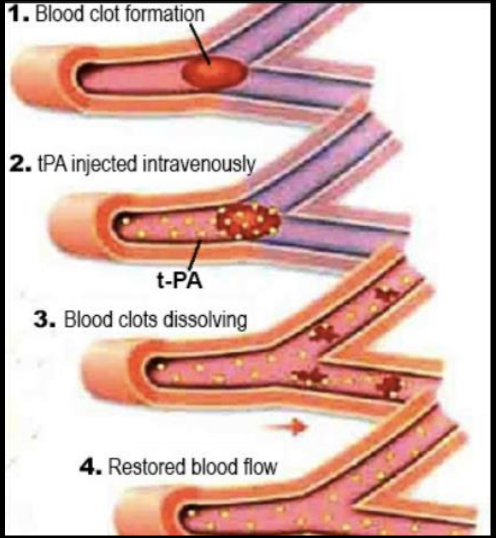


Canon America Medical Systems

DECT IN STROKE IMAGING

- Patients with ischemic stroke may be treated with tissue plasminogen activator (tPA)
  - Helps break up clot that caused stroke
  - Can only be used up to 4 hours after onset of symptoms
- Risk of posttreatment intracerebral hemorrhage
- Monitoring of patients: ICU for 24 hours
  - Follow up CT within 24 hours to asses for complications from tPA
  - Hemorrhage may be obscured by iodinated contrast staining from prior cerebral CT angiogram study
  - Differentiation of contrast and hemorrhage may influence decision to continue or reverse tPA



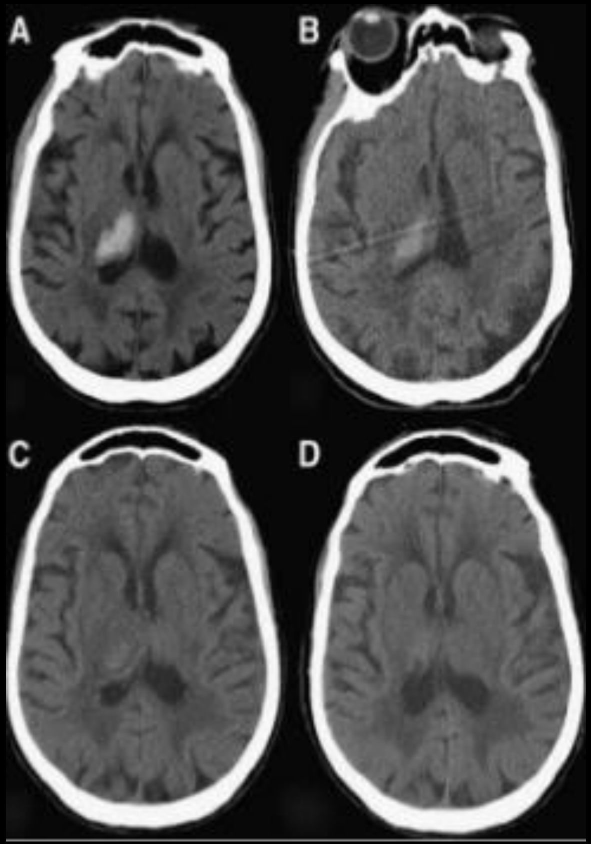


DECT IN STROKE IMAGING

- Attenuation of intracranial blood depends on concentration of hemoglobin protein molecules

ICH Stage	Appearance	HU
Hyperacute (immediate)	Isodense	40-60
Acute (1-3 days)	Hyperdense	60-90
Sub acute (3-14 days)	Isodense	30-40
Chronic (>14 days)	Hypodense	< 30

Gray matter: 30-35 HU
White matter: 25-30 HU

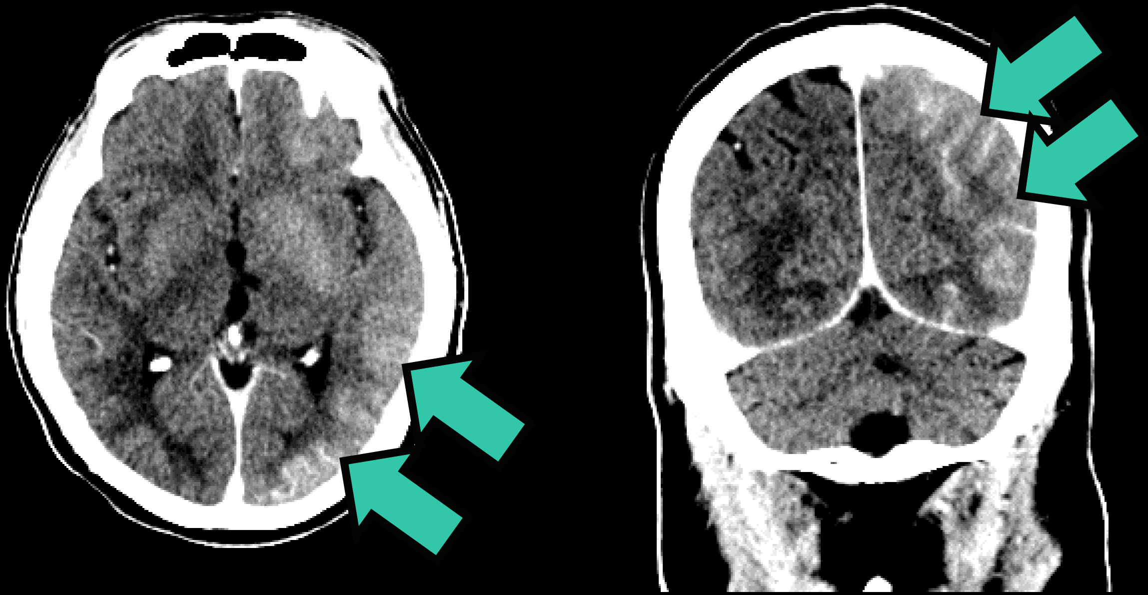


- ***Acute bleeds*** appear *hyperdense* due to increased density from clot formation
- After a few weeks, lysis occurs and HU returns to normal
- May appear hypodense if have tissue loss

Alotaify, Brain Hemorrhage vs Infacrtion in CT & MRI

CLINICAL STROKE CASE

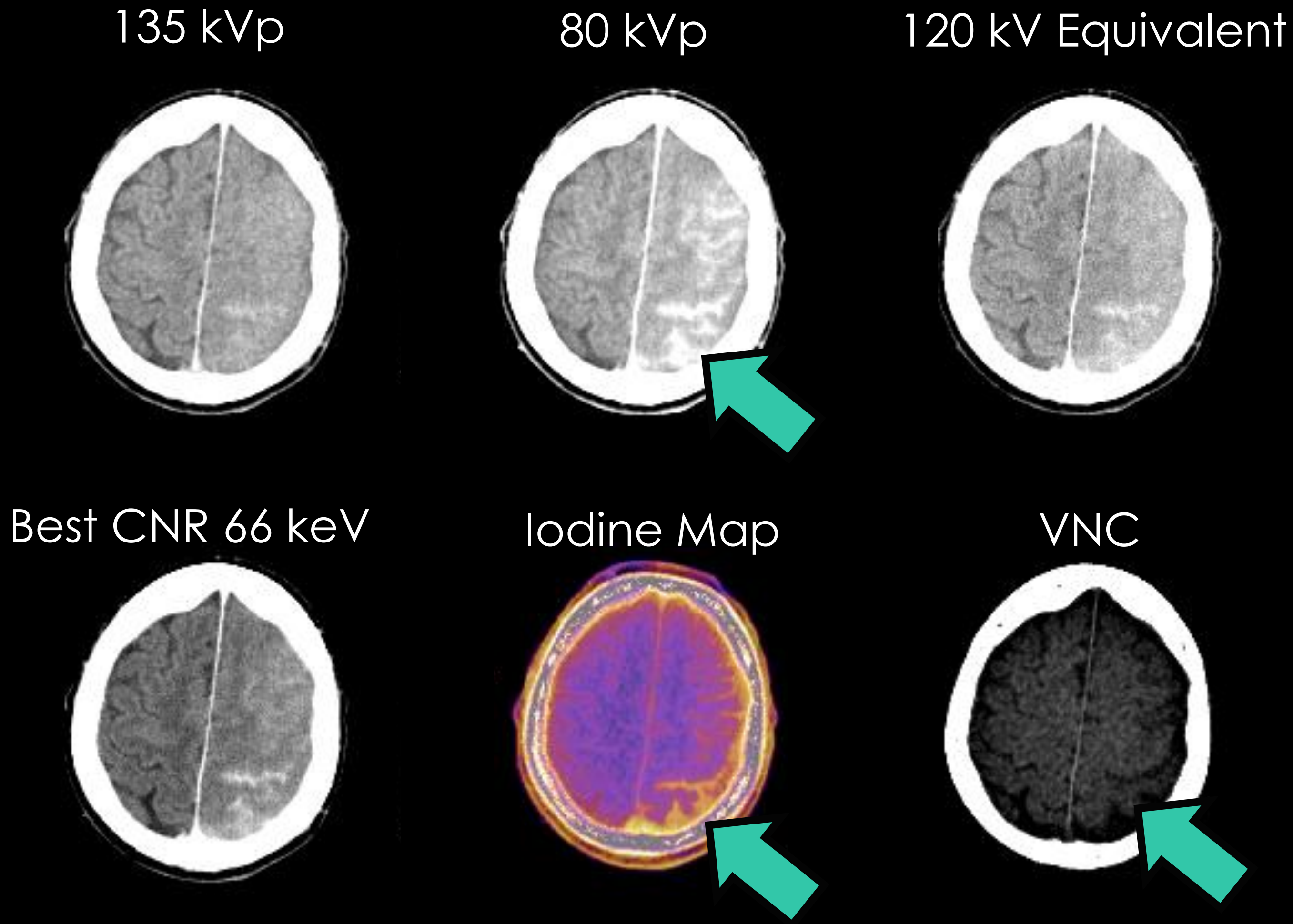
- 61 year old male presented with stroke symptoms
- Brain Perfusion CT ordered
  - IV Contrast administration
  - Identified narrow arteries in neck
- 7 hours later
- Stroke symptoms worsened
  - Single energy CT ordered
  - Stroke evolved



Are hyperdensities due to **hemorrhagic transformation** or **residual contrast material** from prior CT?

Ordered a dual energy CT…

CLINICAL STROKE CASE

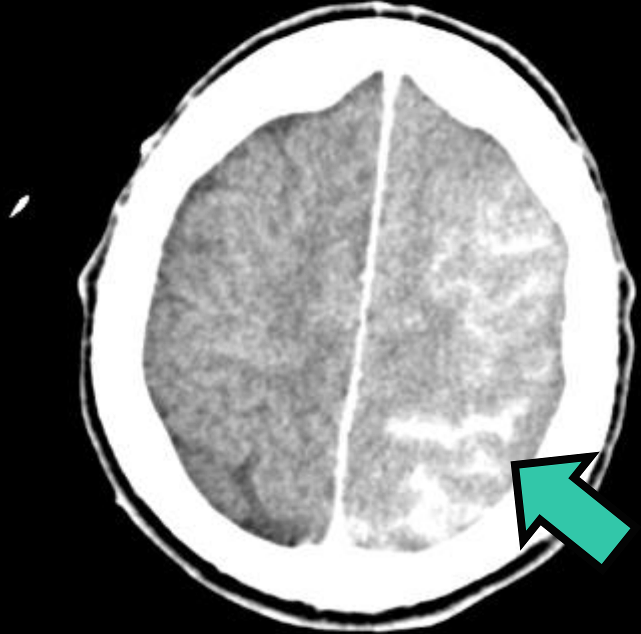


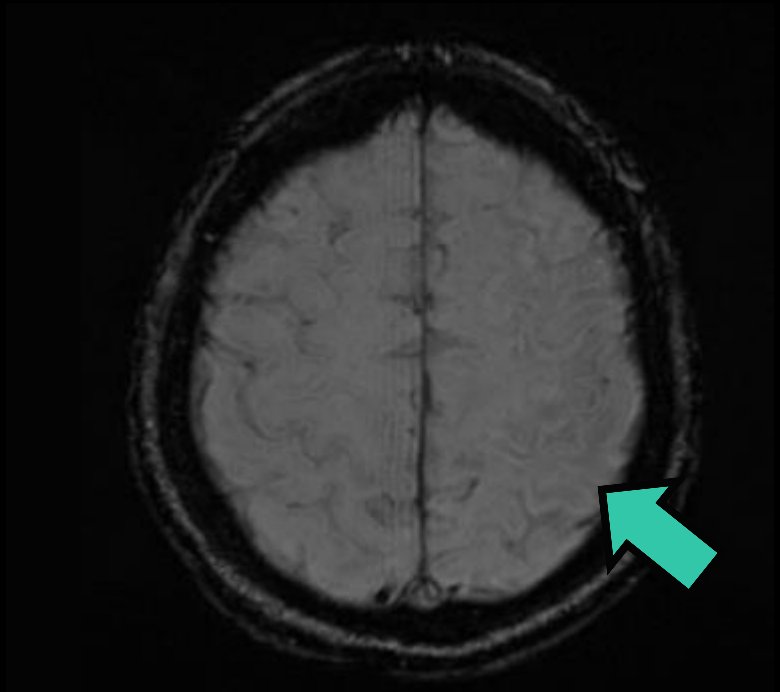
DECT demonstrated hyperdensities to be contrast material from perfusion CT

No evidence of subarachnoid hemorrhage

CLINICAL STROKE CASE

- Confirmed on next day MRI





The differentiation of contrast from blood permitted continuation of anticoagulation with the intent of preventing new clot formation or propagation of the infarction

RADIATION DOSE?

Dual-Energy Brain Volume

No.	Protocol	#of scan(s)	kVp	CTDIvol (mGy)	DLP (mGy.cm)
1	DualScano	1	120		
2	DualScano	1	120		
3	DE-Vol	1	135	54.60 (Head)	872.90 (Head)

Single-Energy Brain Helical

No.	Protocol	#of scan(s)	kVp	CTDIvol (mGy)	DLP (mGy.cm)
1	DualScano	1	120		
2	DualScano	1	120		
3	Helical	1	120	65.70 (Head)	1256.30 (Head)

DECT acquired both image sets with ***less*** dose than conventional CT

HU ACCURACY AND REPRODUCIBILITY

- Clinical applications rely on **accurate material differentiation**

- **Can we rely on material differentiation with DECT**?
  - HU Information
    - Visual representation
    - Quantitative measurements

- Stroke:
  - Blood, Iodine, *mixtures* of blood + iodine

HU ACCURACY AND REPRODUCIBILITY

- Gammex Multi Energy CT Phantom
- 19 inserts representing different dimensions and concentrations of iodine, calcium, blood, adipose and other materials

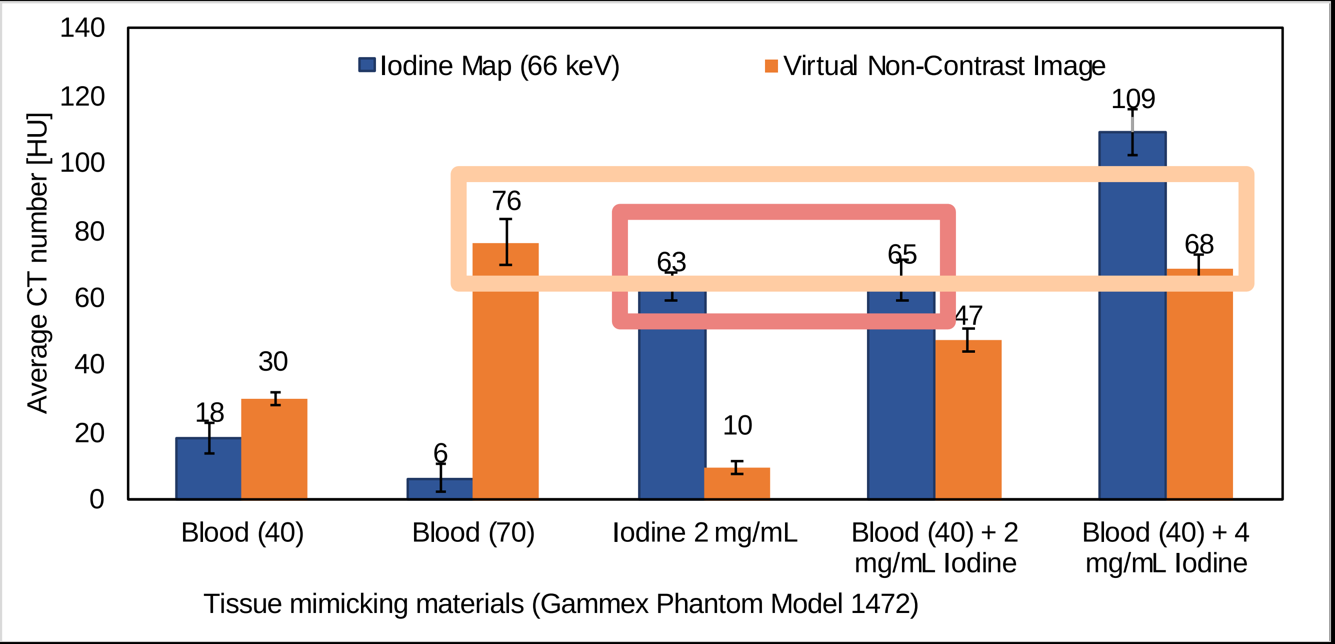
Material:	HE CT Solid Water®
Interchangeable Inserts:	18 solid inserts plus 1 true water container, each tagged with a CT-visible rod identification code
4 Iodine Inserts with Variable Concentrations:	4 inserts with concentrations of 2.0, 5.0, 10.0, and 15.0 mg/mL
3 Iodine Inserts with Variable Diameters:	5.0 mg/mL concentration at diameters of 2.0, 5.0, and 10.0 mm
3 Calcium Inserts:	Calcium concentrations of 50, 100, and 300 mg/mL
3 Blood [iron] Inserts:	Blood-mimicking material at relative electron densities of 1.03, 1.07, and 1.10
2 Blood [iron] with Iodine Inserts:	Blood-mimicking material plus iodine at 2.0 and 4.0 mg/mL
3 Tissue-Mimicking Inserts:	High-Equivalency Brain, High-Equivalency Adipose, High-Equivalency CT Solid Water

https://www.sunnuclear.com

IODINE MAP & VNC

- **HUs *overlap*** in:
  - **Iodine map**
    - Iodine 2 mg/mL &
    - Blood (40)+ Iodine (2 mg/mL)
  - **VNC**
    - Blood (70) &
    - Blood (40)+ Iodine (4 mg/ml)

➢ Need ***both*** **iodine map** and **VNC** to differentiate iodine & blood

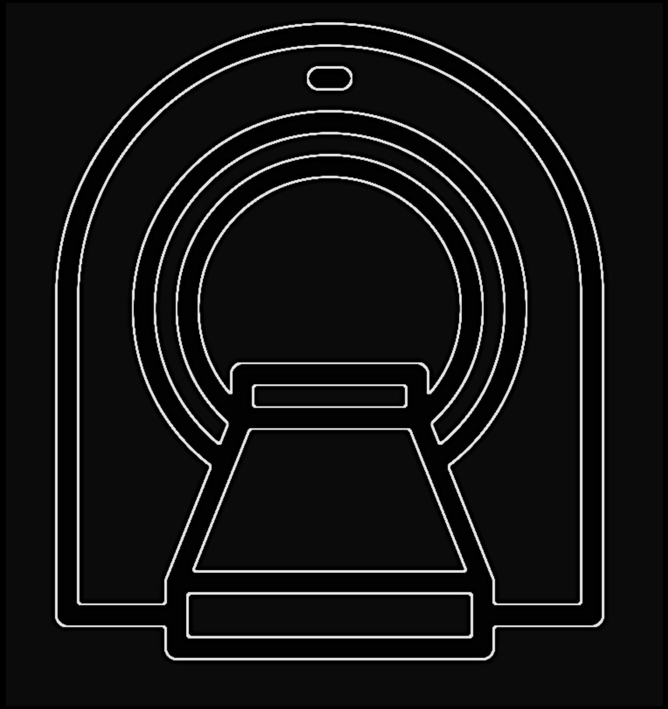


Data obtained & graphs created by PhD student Catherine Olguin, MS

CHALLENGES

Technology

- Further optimization
  - Material decomposition
- More versatile DECT applications
  - Expanded clinical utility



CHALLENGES

Workflow

- Scanner accessibility
  - Scheduling
  - Longer reconstruction time
- Technologist training
  - Scan acquisition & post-processing
- Physician & Radiologist training
  - Protocoling & ordering
  - Additional information made available

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