Dual Energy CT Physics: Hardware and Image Quality Assessment

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Imaging & Therapy Systems

Outline

1. Physics of Spectral CT Measurements
2. Techniques to Acquire Spectral CT Data
3. Spectral CT Quality
4. What About the Dose?

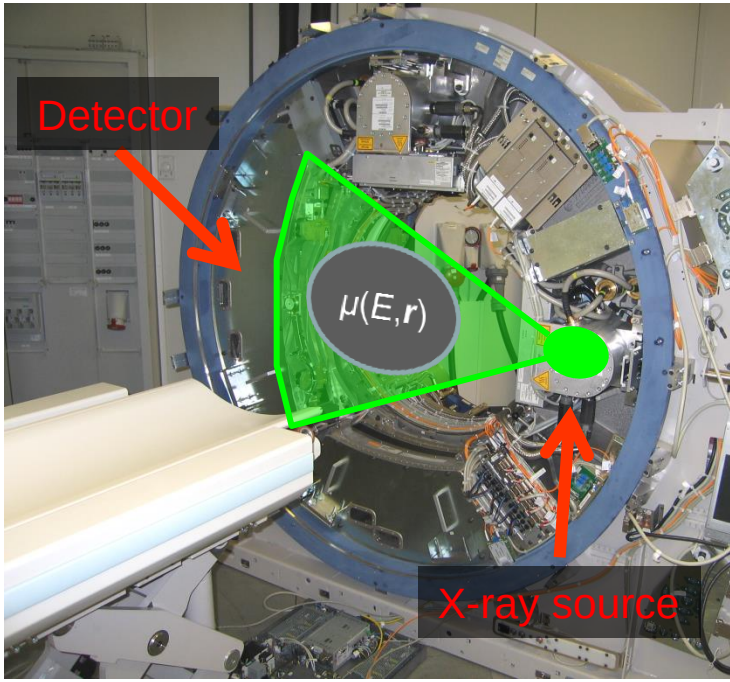
The value of color…

- often not needed in daily life
  - does not matter
  - obvious for known objects
- but there can be surprises …

PHYSICS OF SPECTRAL CT MEASUREMENTS

What Does the Detector Measure? Polychromatic Attenuation Formula

$$A = \frac{I}{I_0} = \frac{\int_E S(E) D(E) e^{-\int_{\{L\}} \mu(E,\vec{r}) d\vec{r}} dE}{\int_E S(E) D(E) dE}$$

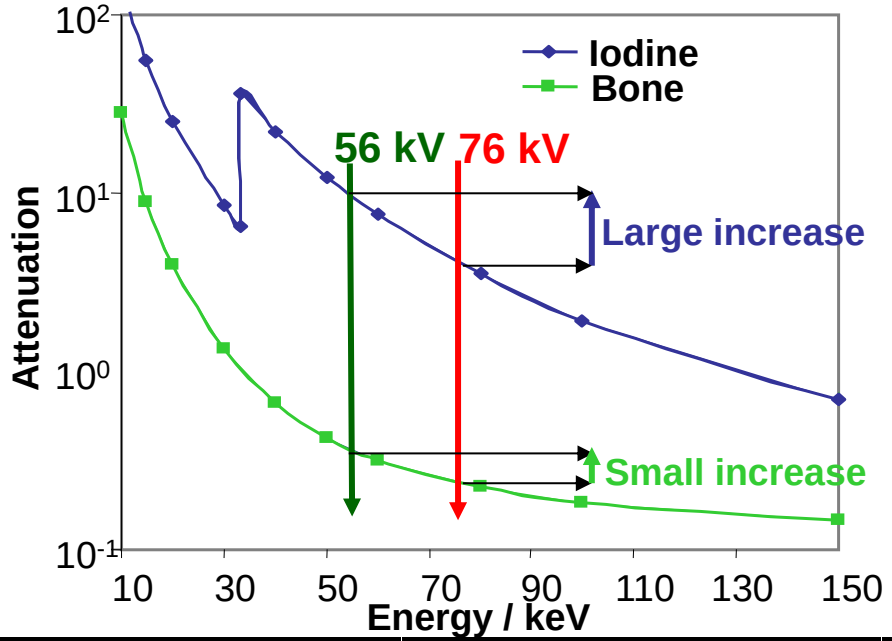


Polychromatic Lambert-Beer law contains

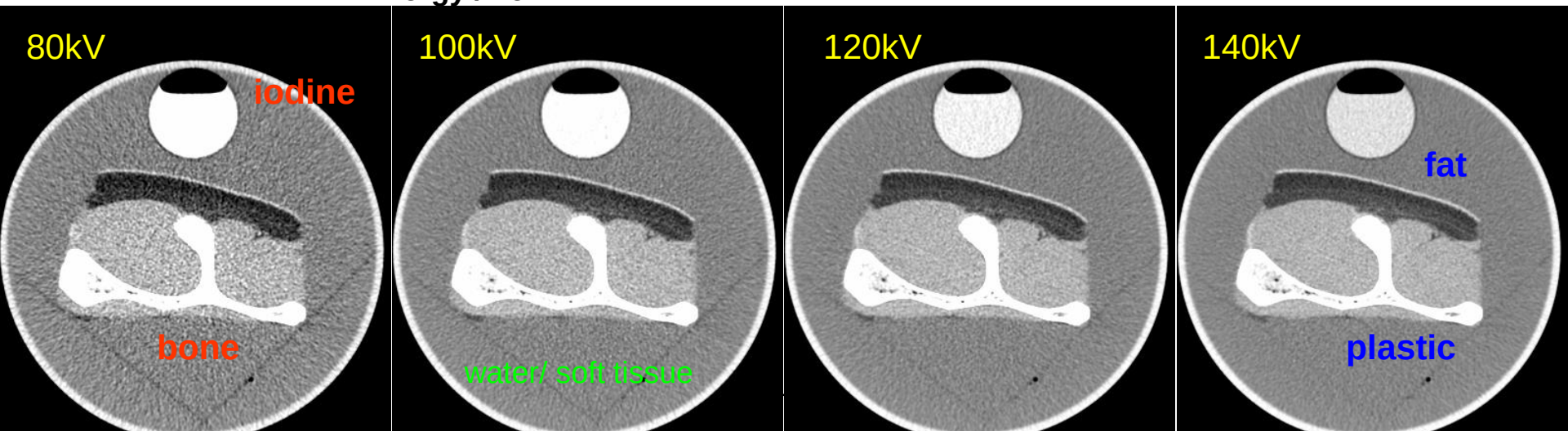
- Input X-ray tube quanta distribution, $S(E)$,
- Spectral responsivity of detector, $D(E)$, and
- Spectral object attenuation, $\mu(E,\mathbf{r})$.

Principle of Dual Energy CT

Materials show different attenuation at different mean energies: $\mu(<E>,\boldsymbol{r})$

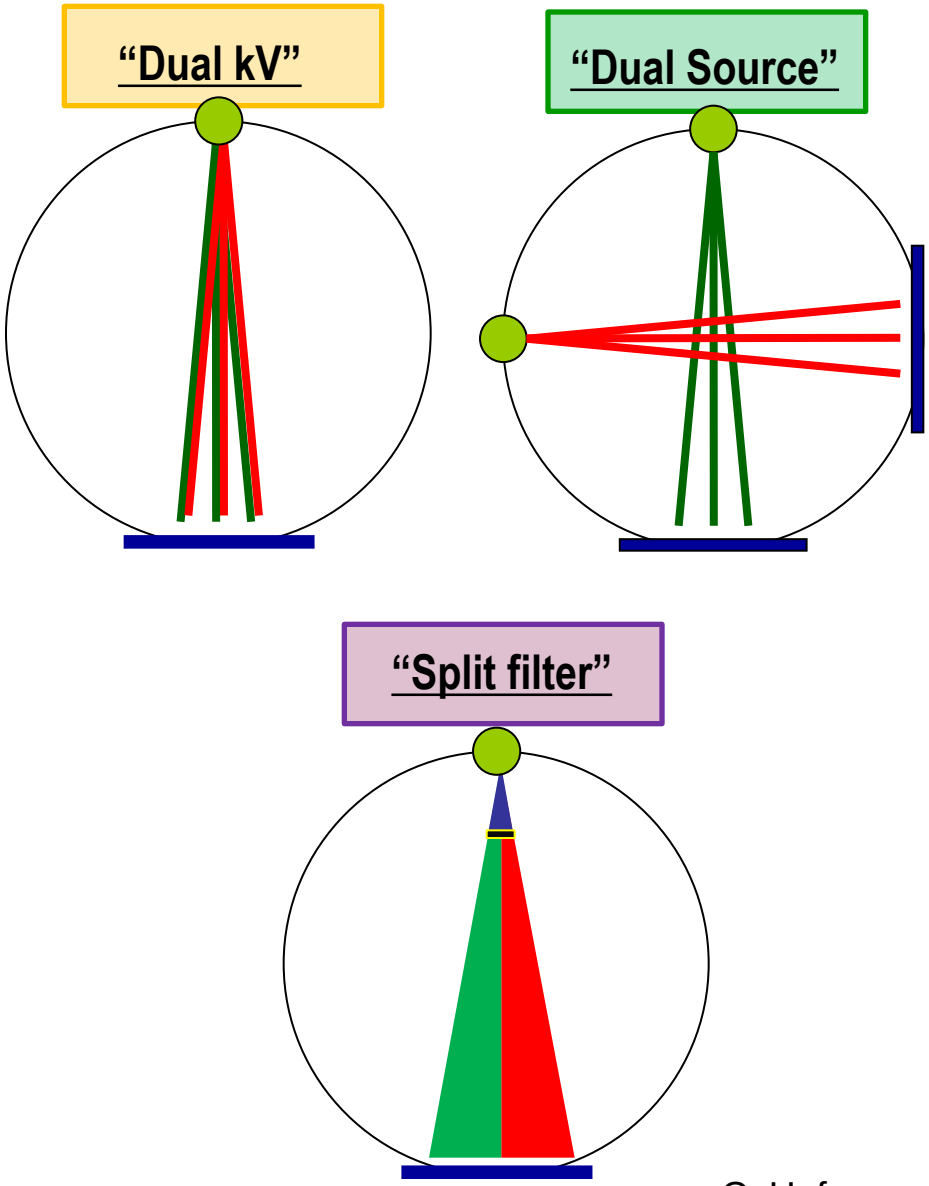


- higher CT-value at 80kV: iodine, bone, metal ...
- higher CT-value at 140kV: fat, plastic, uric acid ...
- (almost) same CT-value: water, soft tissue, blood ...



TECHNIQUES TO ACQUIRE SPECTRAL CT DATA

Spectral Difference Generated by X-ray Source



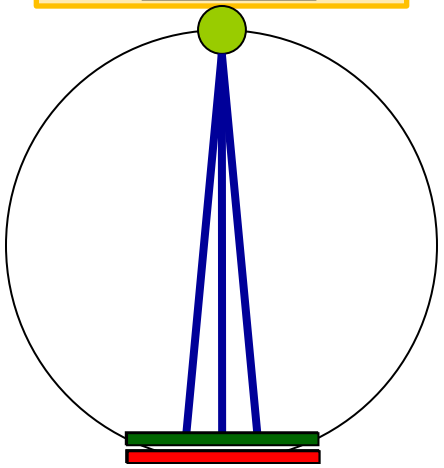
- **Dual Spiral:**
  Two spiral scans at low and high kV, respectively.
- **Slow kV Switching:**
  Switch kV level typically once per gantry rotation (sequence or spiral)
- **Fast kV switching:**
  Switch kV level ~ every millisecond

- **Dual Source**
  Simultaneous scan with 2 tubes

- **Split filter**
  The beam of one source “sees” two different filters

Spectral Difference Generated by Detector

“Energy resolving detector”



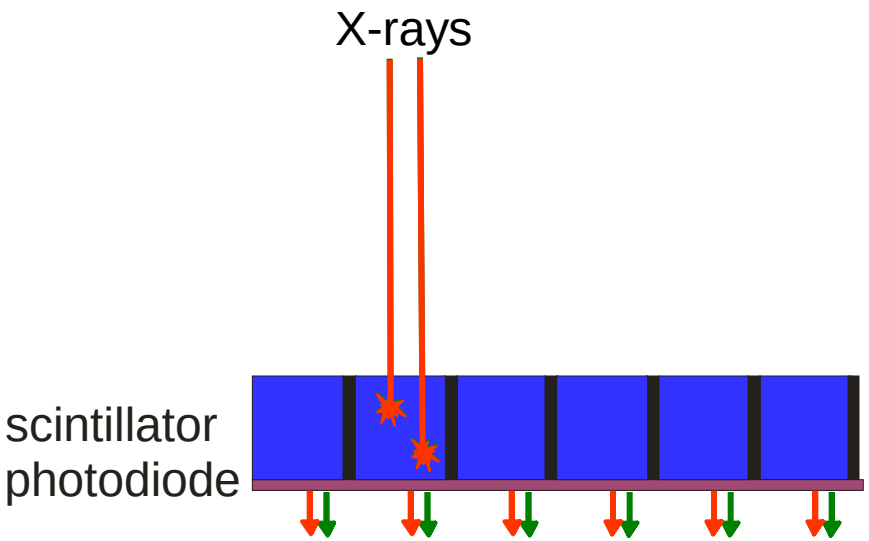
“Photon counting”

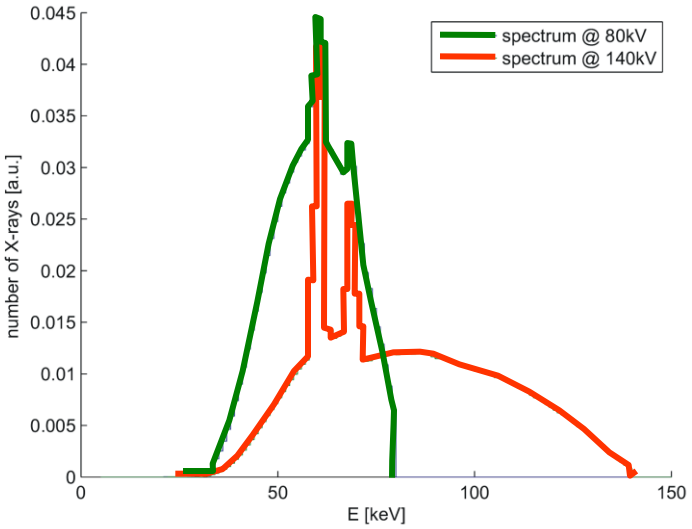
- **Sandwich Detector:**
  - first detector layer for low energy photons
  - second detector layer for high energy photons

- **Quantum Counters:**
  - photon absorbed in semiconductor (CdTe / CdZnTe)
  - photon energy is measured
  - number of photon in each energy bin is counted

Dual kV:
One X-Ray Source

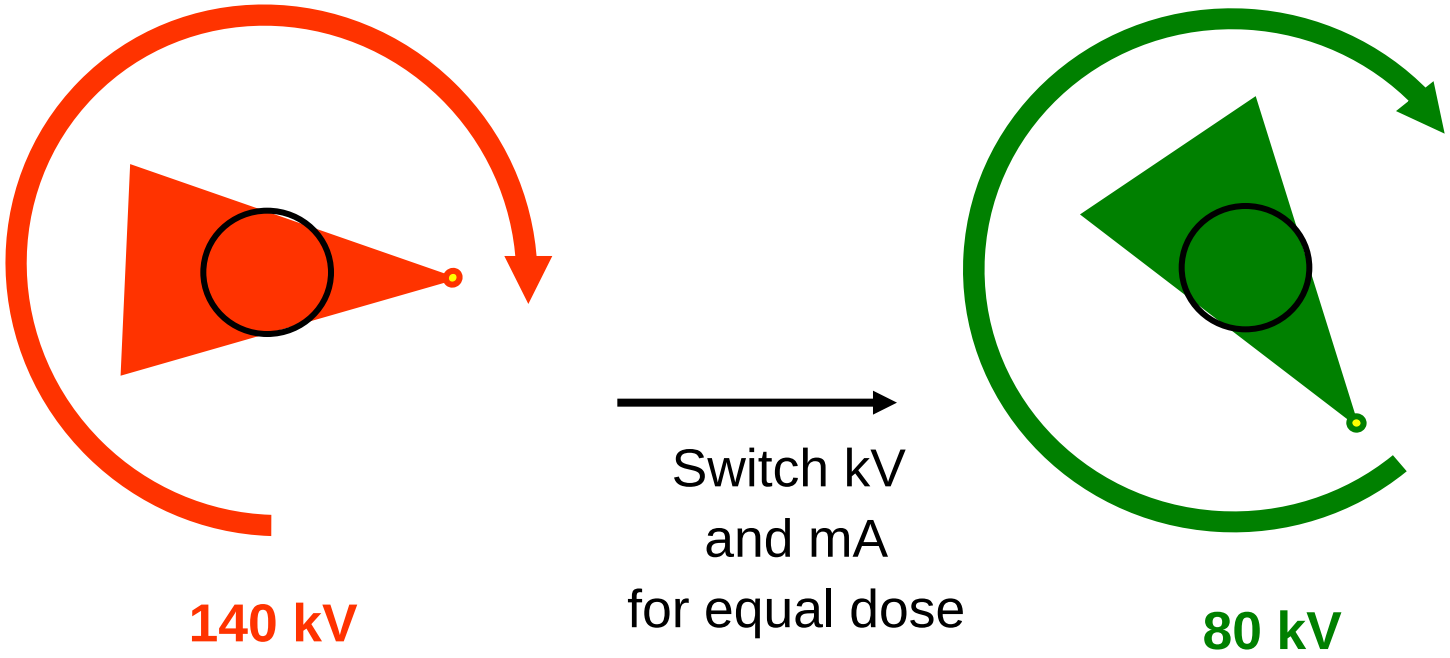
→ Two scans with different kV or kV-switching (fast or slow) during one scan is performed





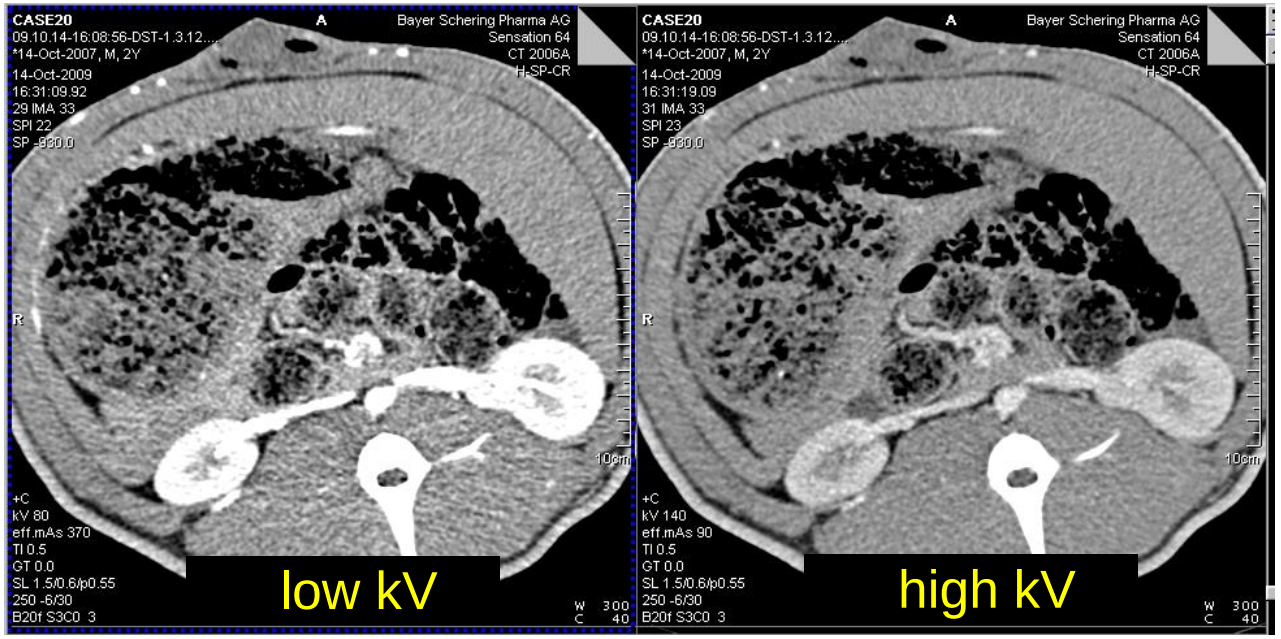
Two Scans with Different kV: Dual Spiral / Slow kV Switching

→ A (partial) scan is performed with one kV-setting (e. g. 140 kV)
→ kV and mA are switched
→ A second (partial) scan is performed at the same z-position, with the other kV-setting (e. g. 80 kV) and the other mA-setting



Two Scans with Different kV: Benefits

→ Simplest approach, providing dual energy for standard CT systems
→ Good spectral separation
→ Spectral optimization possible (e. g. by selective pre-filtration – Zn)
→ Full field of view
→ No cross-scatter problems
→ Similar radiation dose at 140 kV and at 80 kV by mA - adaptation

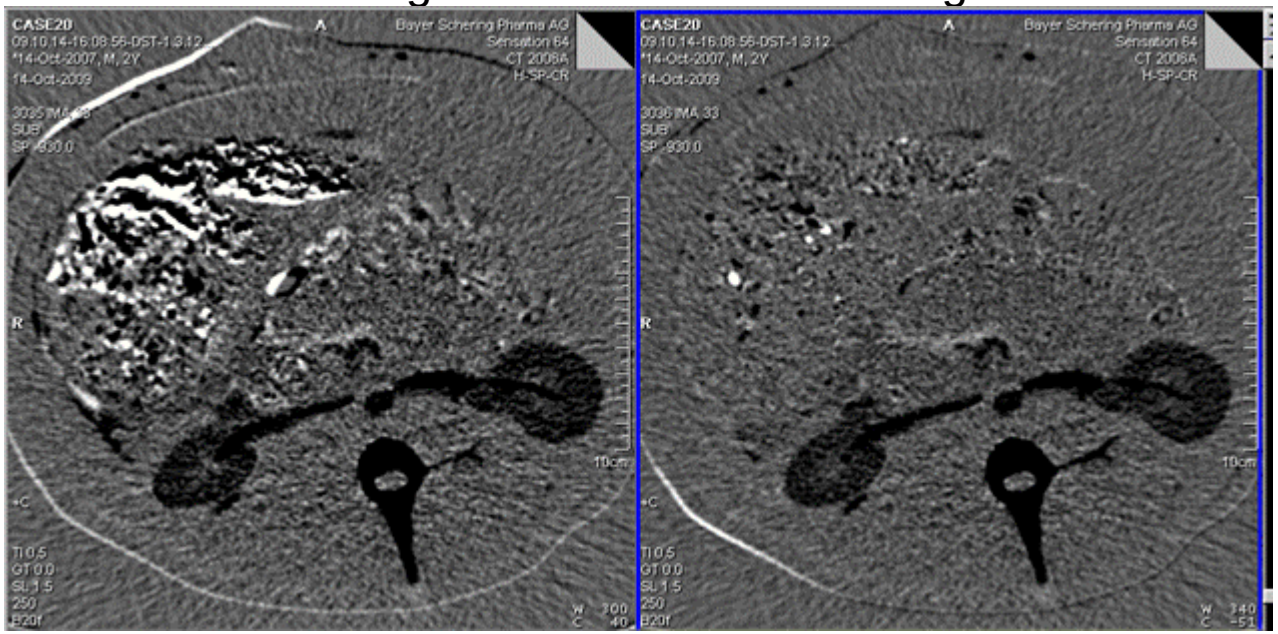


Two Scans with Different kV: Challenges

→ Long duration → motion artifacts, registration problems – can be addressed with registration

Difference image high kV – low kV

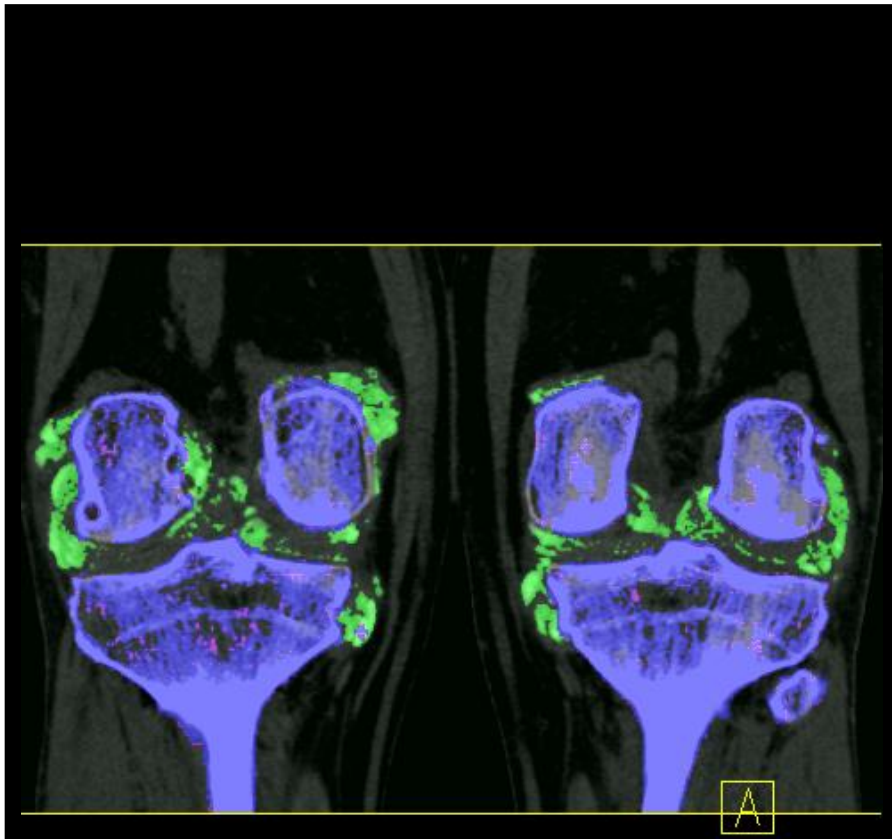
without registration with registration



→ Applications with contrast agent limited by blood flow dynamics – only late phase scans lead to reasonable results

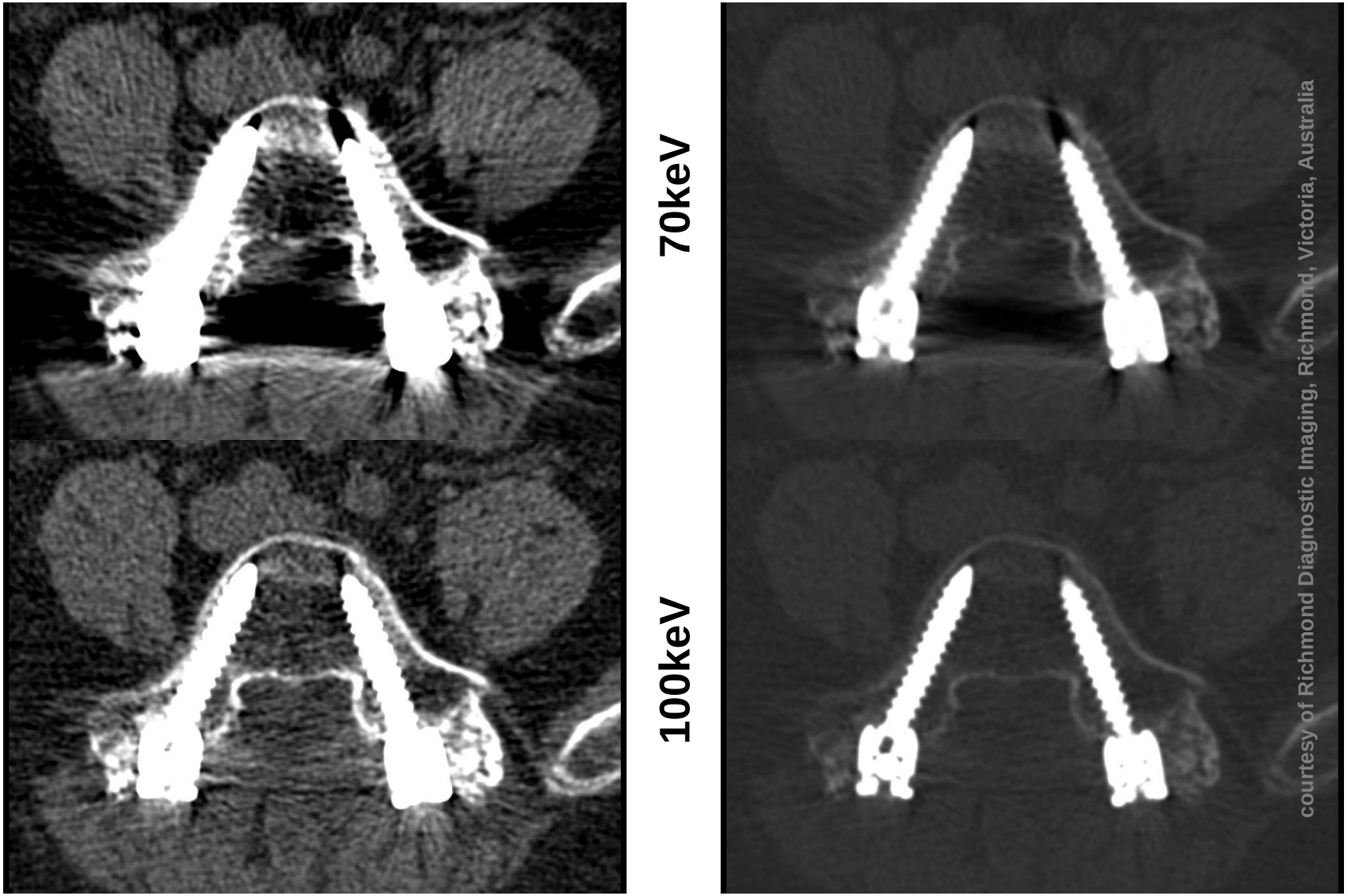
Dual Spiral Dual Energy – Possible Applications: Gout

- The spectral behavior of uric acid is different from that of bone.
- Left: CT image with color LUT. Blue: bone / green: uric acid.



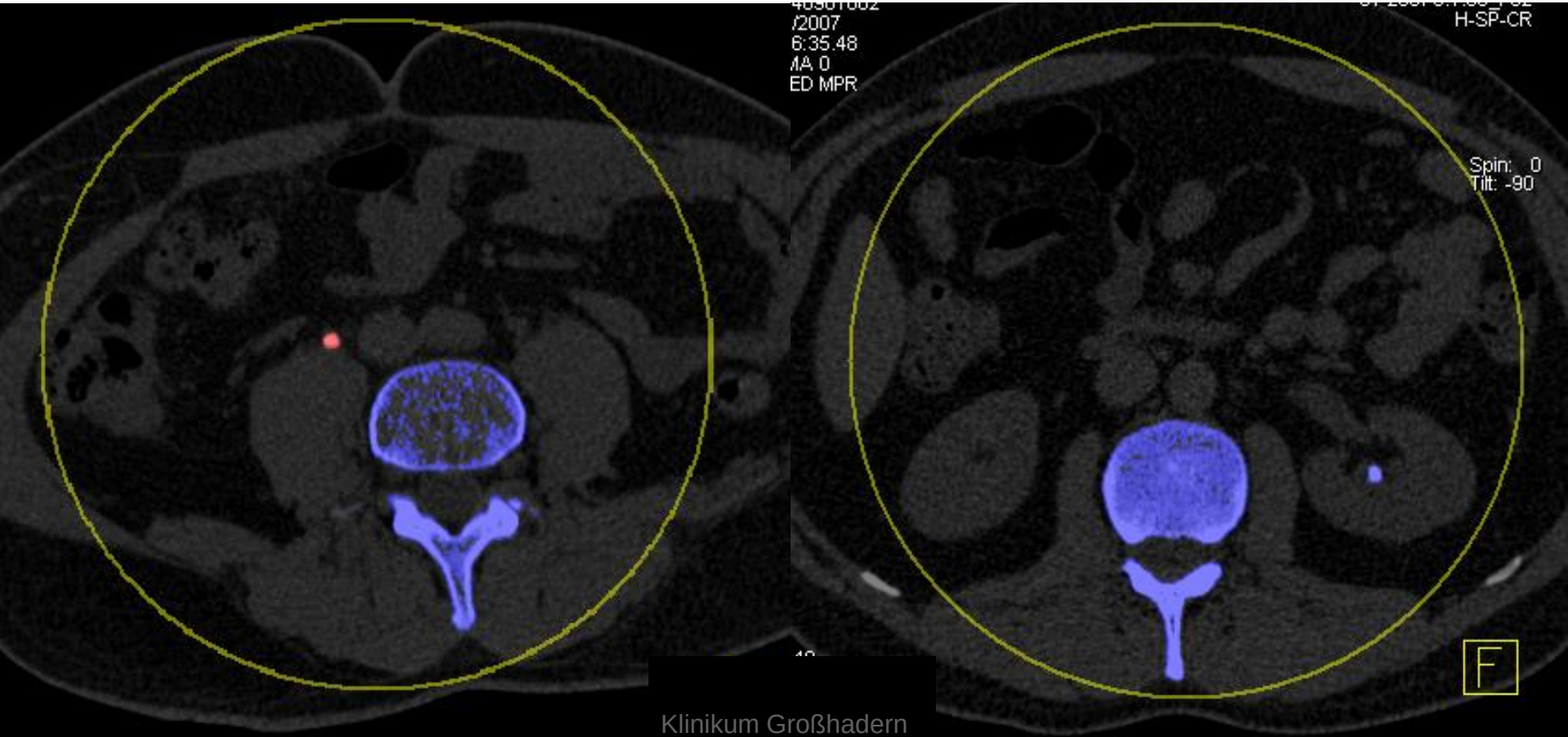
Vancouver General Hospital, Canada

Dual Spiral Dual Energy – Possible Applications: Improved Metal Visualization with Monoenergetic

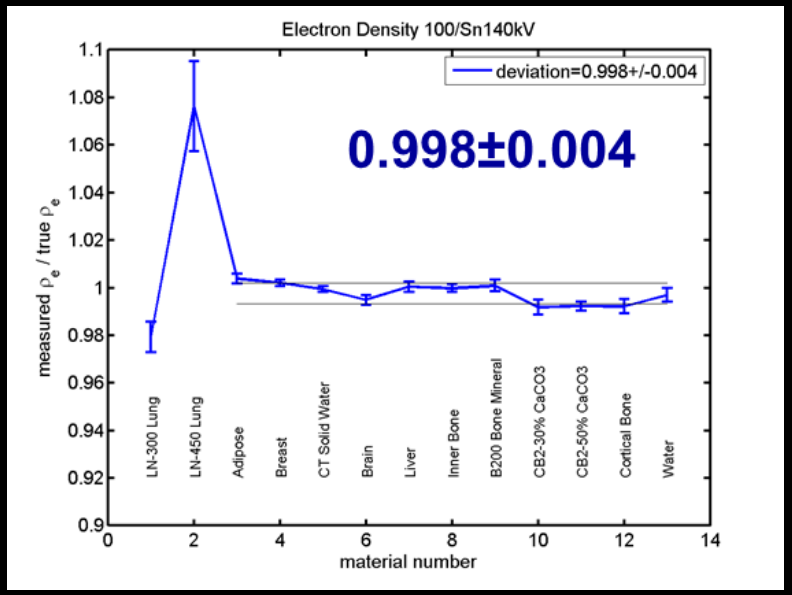


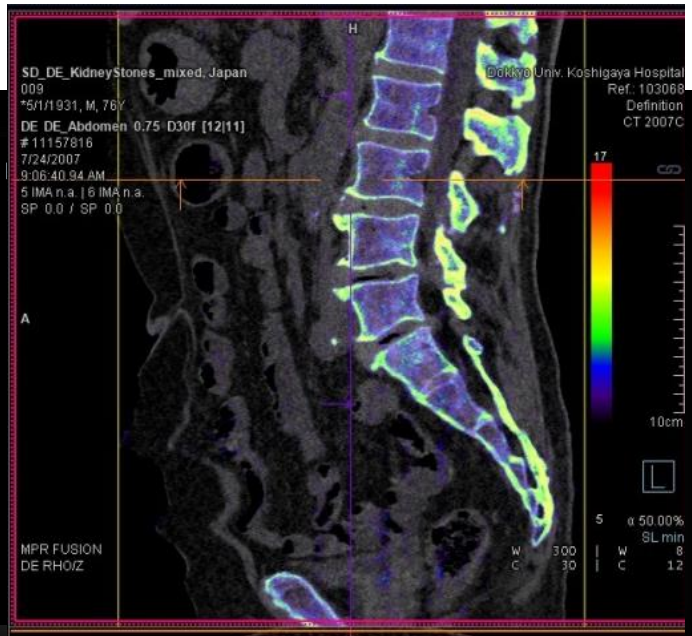
Dual Spiral Dual Energy – Possible Applications: Kidney Stones

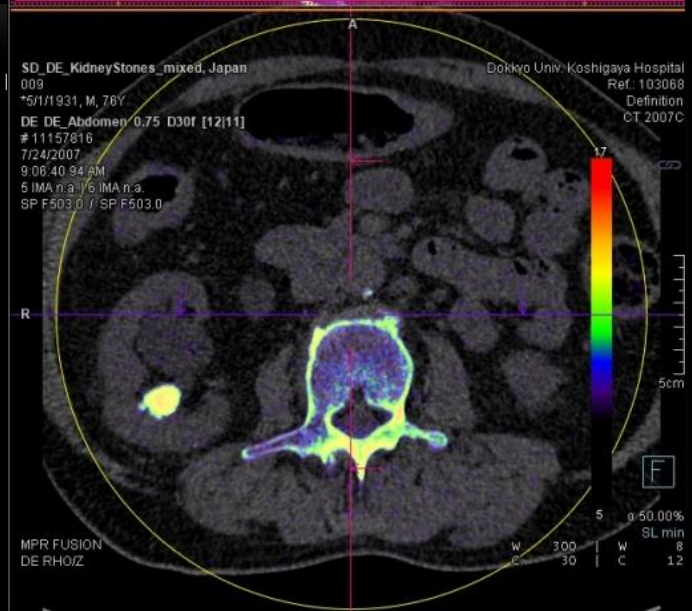
- Discriminate between uric acid stones (dissolvable) and other stones
- Uric acid-containing stones are labelled in *red*, non uric acid-containing stones are labelled *blue*



Dual Spiral Dual Energy – Possible Applications Electron Density and eff. Z



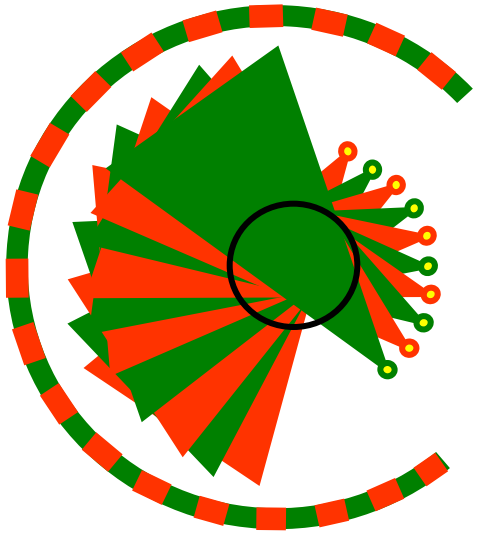




Calculation of electron density ρ_e and effective Z for dose calculation in radiation treatment planning!

Fast kV-Switching During One Scan

- → The tube voltage (kV) is switched between two readings (e.g. from 140 kV to 80 kV)
- → Two „interleaved“ data sets with different kV-settings are simultaneously acquired
- → Has already been implemented in a medical CT scanner in 1986



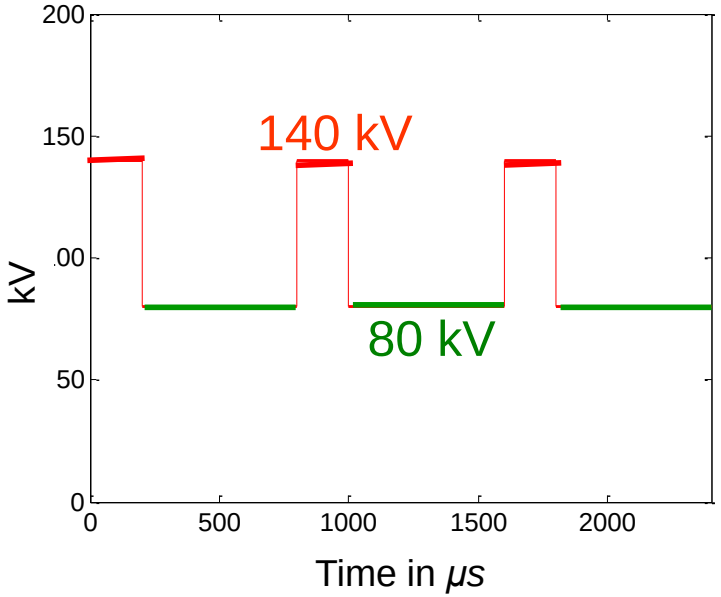
140 kV
80 kV

Fast kV-Switching During One Scan: Benefits

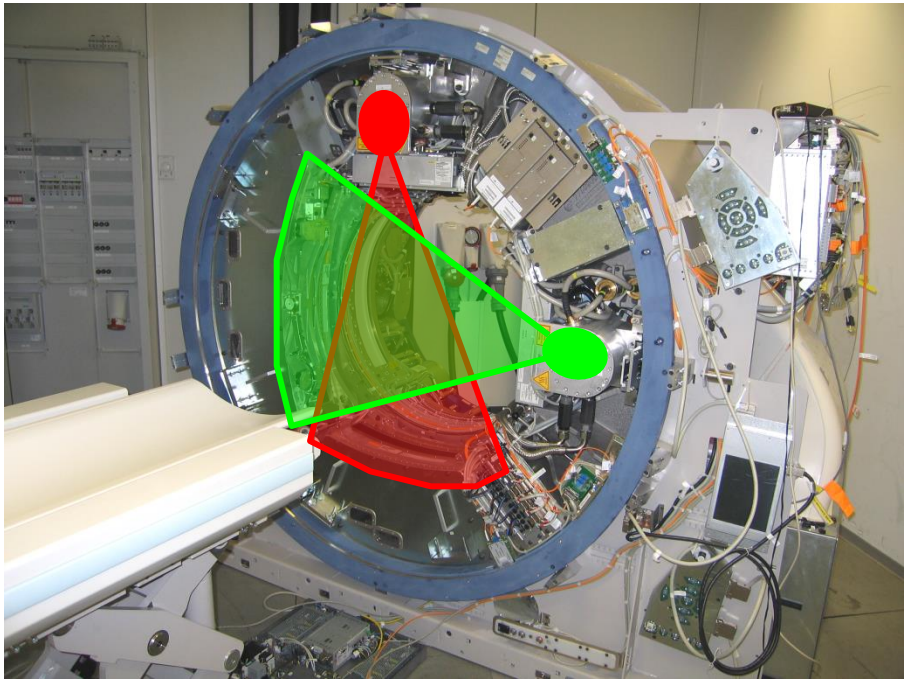
- → Good spectral separation
- → Full field of view
- → No cross-scatter problems
- → Raw-data based evaluation techniques possible
- → No motion artifacts, no registration problems due to simultaneous data acquisition
- → No problems with varying concentrations of contrast agent

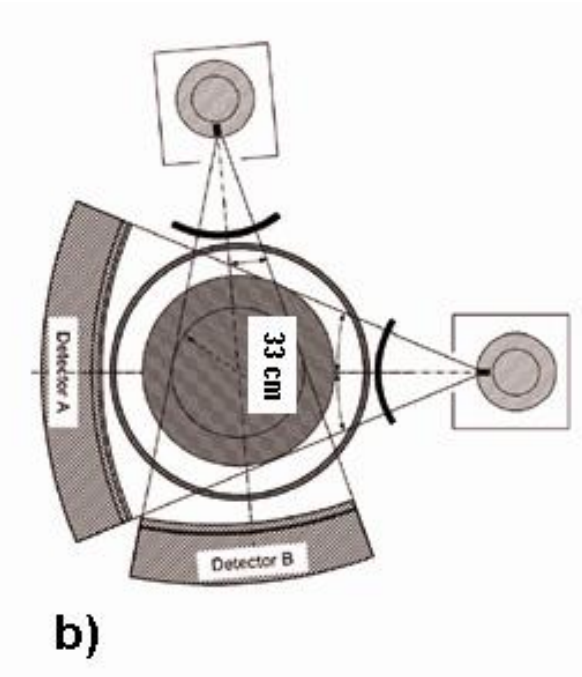
Fast kV-Switching During One Scan: Challenges

- → Today: switching every 250 - 500 *µs* → slower rotation (≥ 0.5 -1s) preferred, challenging for fast moving organs such as lungs and heart
- → Only kV-switching, no mA-switching → equal dose problematic
  Way out: 1 reading at 140 kV, ~ 2-3 readings at 80 kV
  But: reduced total number of readings
- → Currently, no anatomical dose modulation possible
- → No spectral optimization by different pre-filtration possible



Dual Source Dual Energy





Dual Source Dual Energy:

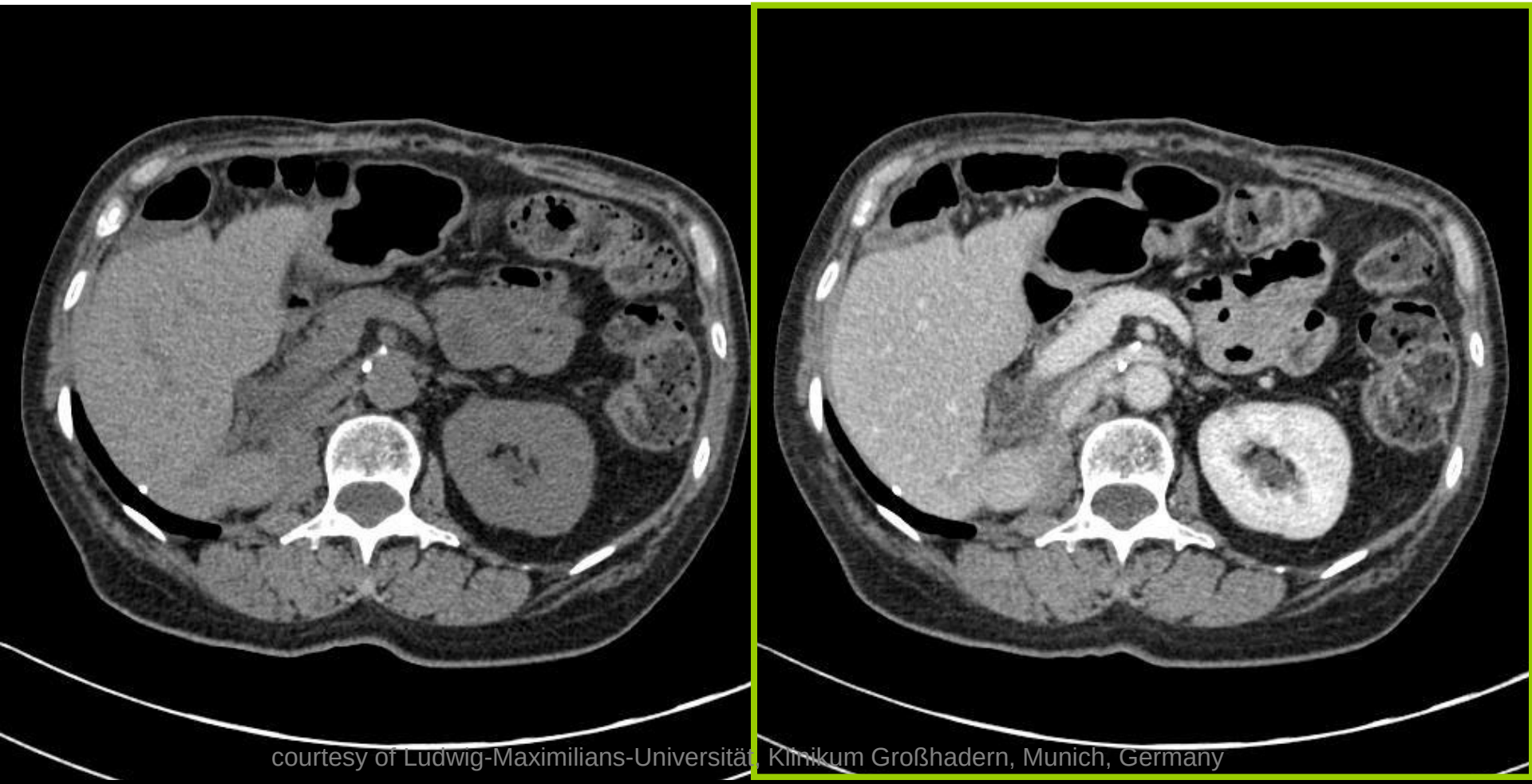
Benefits:

→ (Nearly) simultaneous data acquisition
→ Same dose at 140 kV and at 80 kV due to mA – adaptation
→ Good spectral separation, spectral optimization possible
→ Short rotation times for fast moving organs possible
→ Applications with contrast agent are possible also in early phase due to high temporal resolution and fast acquisition times

Challenges:

→ Data acquisition not fully
→ Raw-data based evaluation difficult
→ Reduced field of view of the second detector
→ Cross-scattered radiation, in particular for larger patients

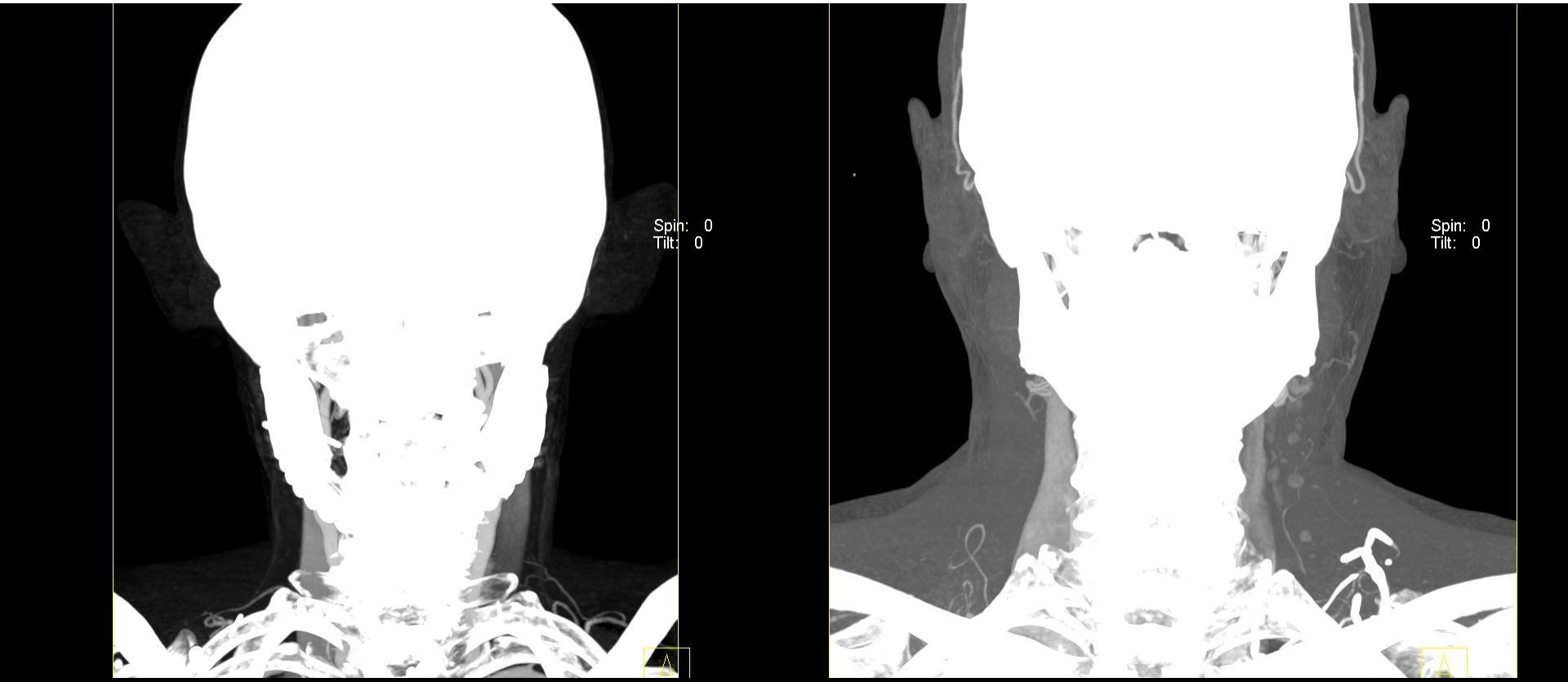
Dual Source Dual Energy – Possible Applications: Virtual Unenhanced CT (Liver VNC)



courtesy of Ludwig-Maximilians-Universität, Klinikum Großhadern, Munich, Germany

- With this approach one can calculate the VNC images which represent the patient without the iodine enhancement.
- Furthermore, it allows to quantify iodine-uptake, revealing important information if a tumor is benign or malignant.

Dual Source Dual Energy – Possible Applications: Reliable Head Bone Removal



Without any user interaction, bone can be subtracted, also in complicated anatomical situations like carotids in base of the skull, vertebral arteries etc.

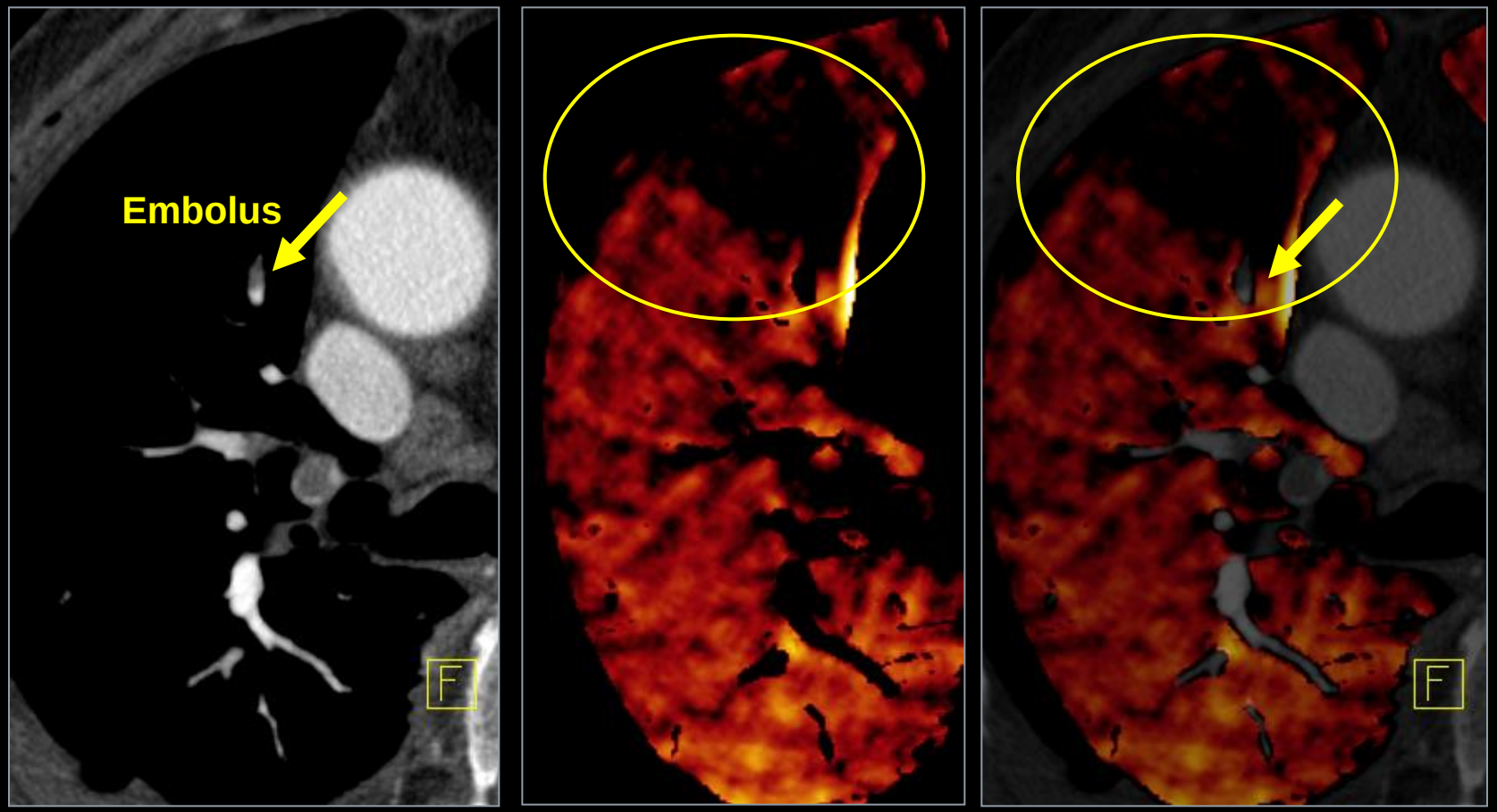
courtesy of Friedrich-Alexander University Erlangen-Nuremberg - Institute of Medical Physics / Erlangen, Germany

100kV/Sn140kV

Dual Source Dual Energy – Possible Applications: Lung Perfused Blood Volume (PBV)

- **Quantification of iodine to visualize perfusion defects in the lung**
- Avoids registration problems of non-dual energy subtraction methods

80/140kV Mixed Image | Iodine Image | Mixed image + iodine overlay

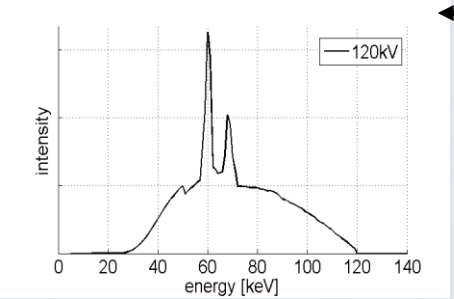


Courtesy of Prof. J and M Remy, Hopital Calmette, Lille, France

Split Filter

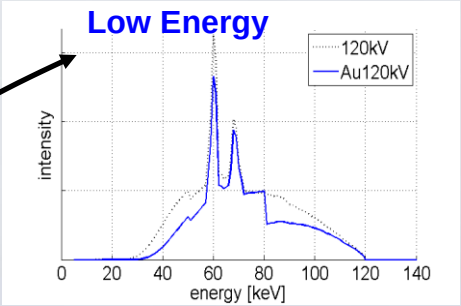
Tube voltage:
120kV

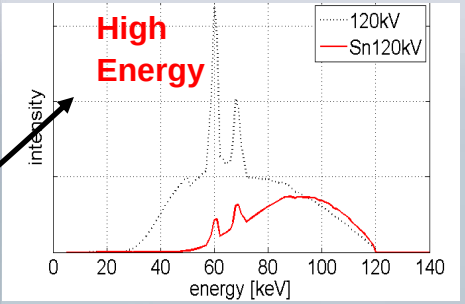
Spectrum before filter



Moveable
Split Filter

Spectrum after filter





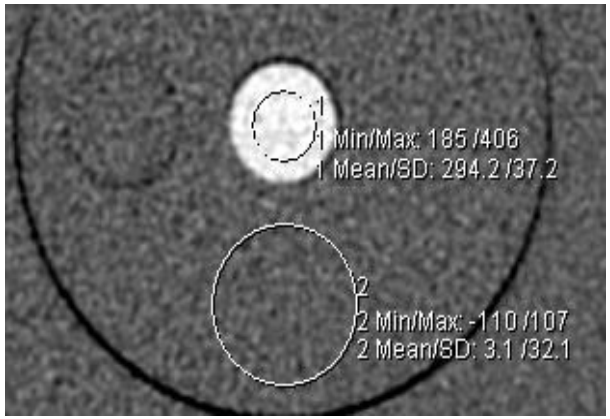
Split filter

Gold (Au, 0.05mm)
Tin (Sn, 0.6mm)

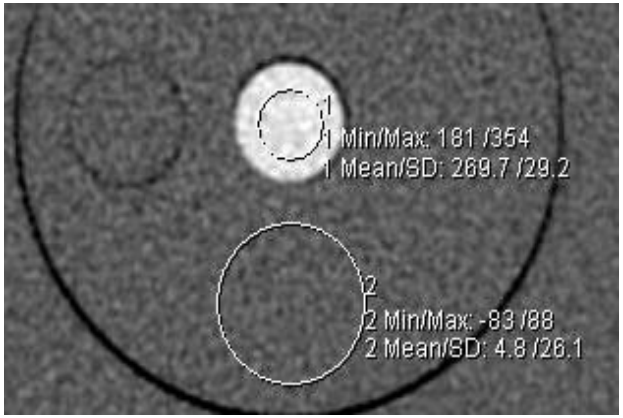
Split Filter: Benefits

→ (Nearly) simultaneous data acquisition
→ Short rotation times for fast moving organs possible
→ Full field of view for both high and low energy
→ dose modulation (reduction) techniques possible (tube current)
→ Dose neutral compared to 120 kV
→ Almost the same applications possible as in Dual Source Dual Energy

30cm phantom, default abdomen protocol, same dose



120 kV



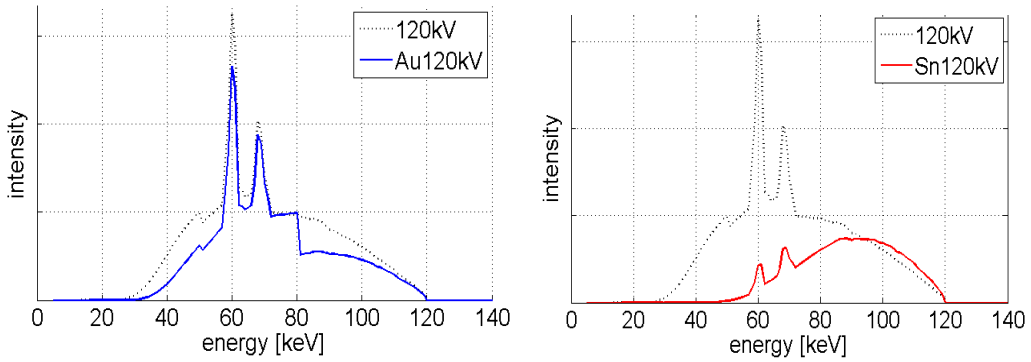
Split filter

Dose neutral:up to 40cm diameter less noise than 120kV

C. Hofmann, B. Schmidt

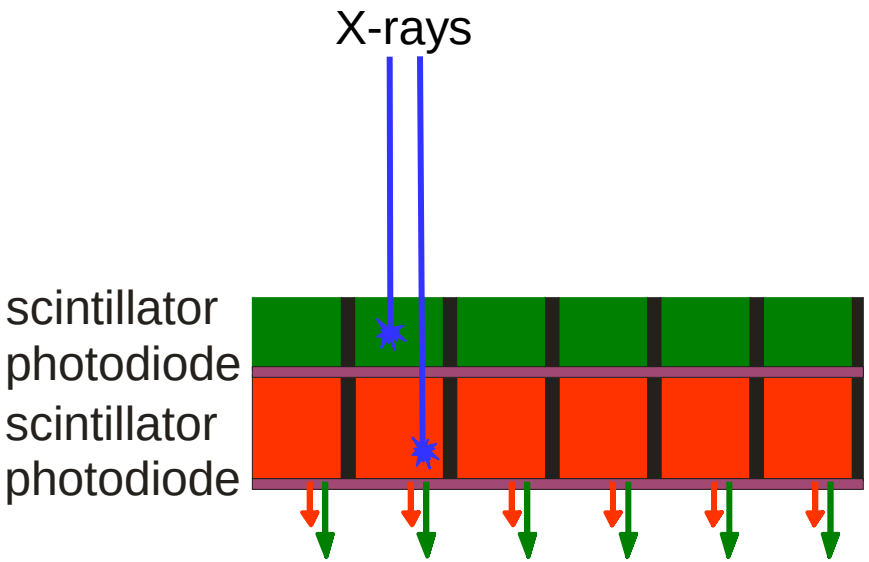
Split Filter : Challenges

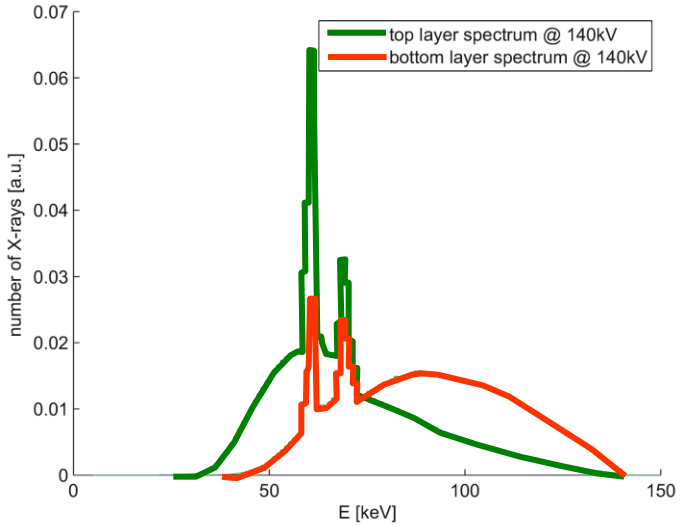
→ Data acquisition not fully simultaneous –potential registration problems
→ Spectral separation not so good – must be compensated with advanced image filters
→ Cross-scattered radiation, in particular for larger patients
→ Spiral mode only
→ pitch factor is limited to 0.5
→ High tube power (2/3 of the dose is absorbed in the filter)



Dual Layer Detectors

→ Sandwich-type detector, two layers per channel
→ Detection of lower energy quanta in the top layer
→ Detection of higher energy quanta in the bottom layer





absorbed upper layer spectrum 1 mm ZnSe
absorbed lower layer spectrum 2 mm UFC

Courtesy of Steffen Kappler

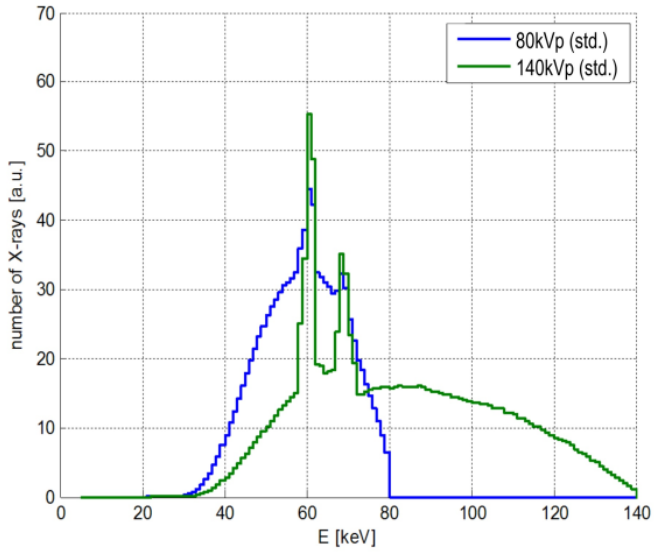
Dual Layer Detectors: Benefits

→ Full field of view
→ No cross-scatter problems
→ Raw-data based evaluation possible
→ Perfect registration due to simultaneous data acquisition
→ No motion artifacts or problems with varying densities of contrast agent
→ Access to dual energy with single-kV scans
→ No low-energy (80kV) dose problems as with kV-switching

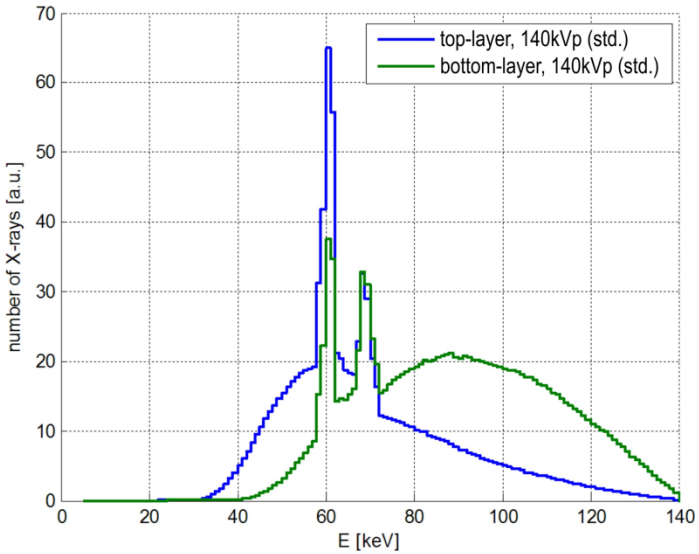
Dual Layer Detectors: Challenges

→ Complex technical realization

→ Reduced dual energy performance compared to dual kV – spectral separation is limited because there is a spectral overlap over the entire spectral range



Dual kV
80 kV / 140 kV



Dual layer overlap over the entire spectral range

(Courtesy S. Kappler, Siemens Healthcare)

When was the Dual Energy Technique of "Rapid kV-Switching" First Realized in a CT Scanner?

20% 1. 1982

20% 2. 1986

20% 3. 1990

20% 4. 1994

20% 5. 1998

When was the Dual Energy Technique of “Rapid kV-Switching” First Realized in a CT Scanner?

1.1982

2.1986

3.1990

4.1994

5.1998

Rapid kV switching has already been implemented in a medical CT scanner in 1986.

Reference: Björn J. Heismann, Bernhard T. Schmidt, Thomas Flohr, “*Spectral CT imaging*”, SPIE Press, PM226, October 2012

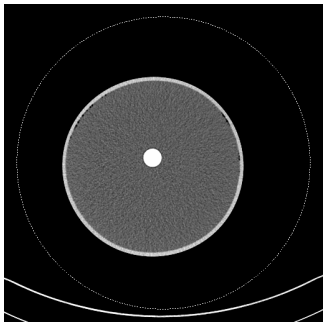
SPECTRAL CT QUALITY

Spectral Separation

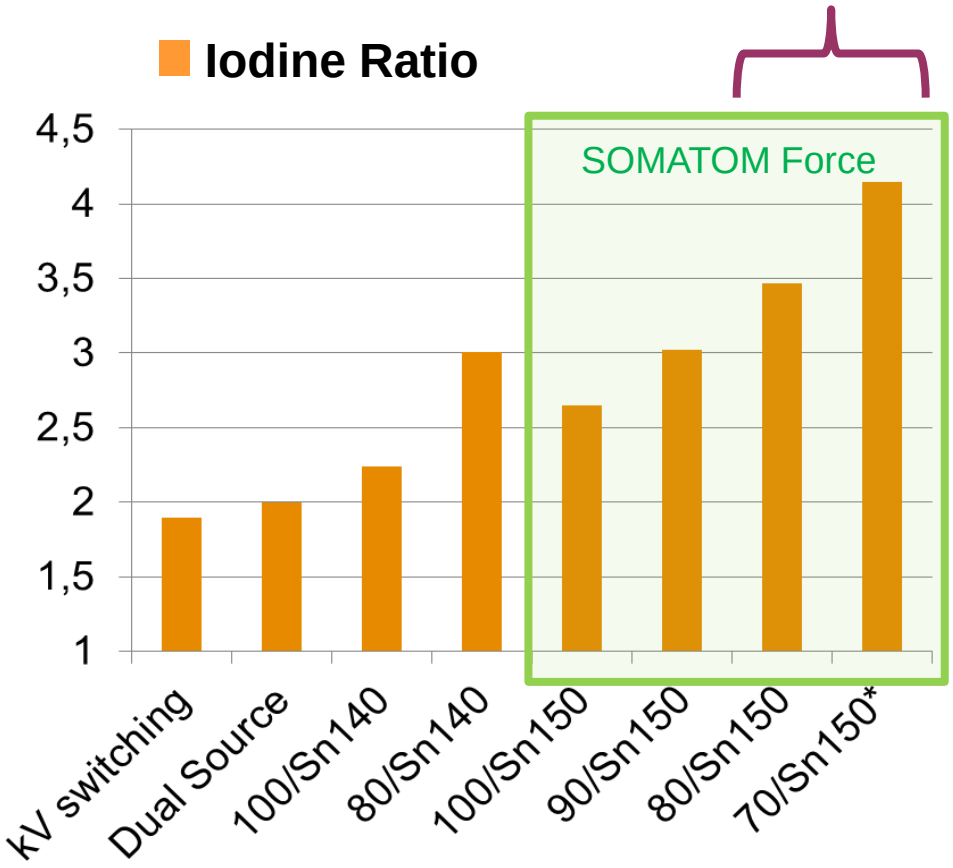
- Very critical for good SNR, separation quality of materials and robustness!

Highest Dual Energy ratio

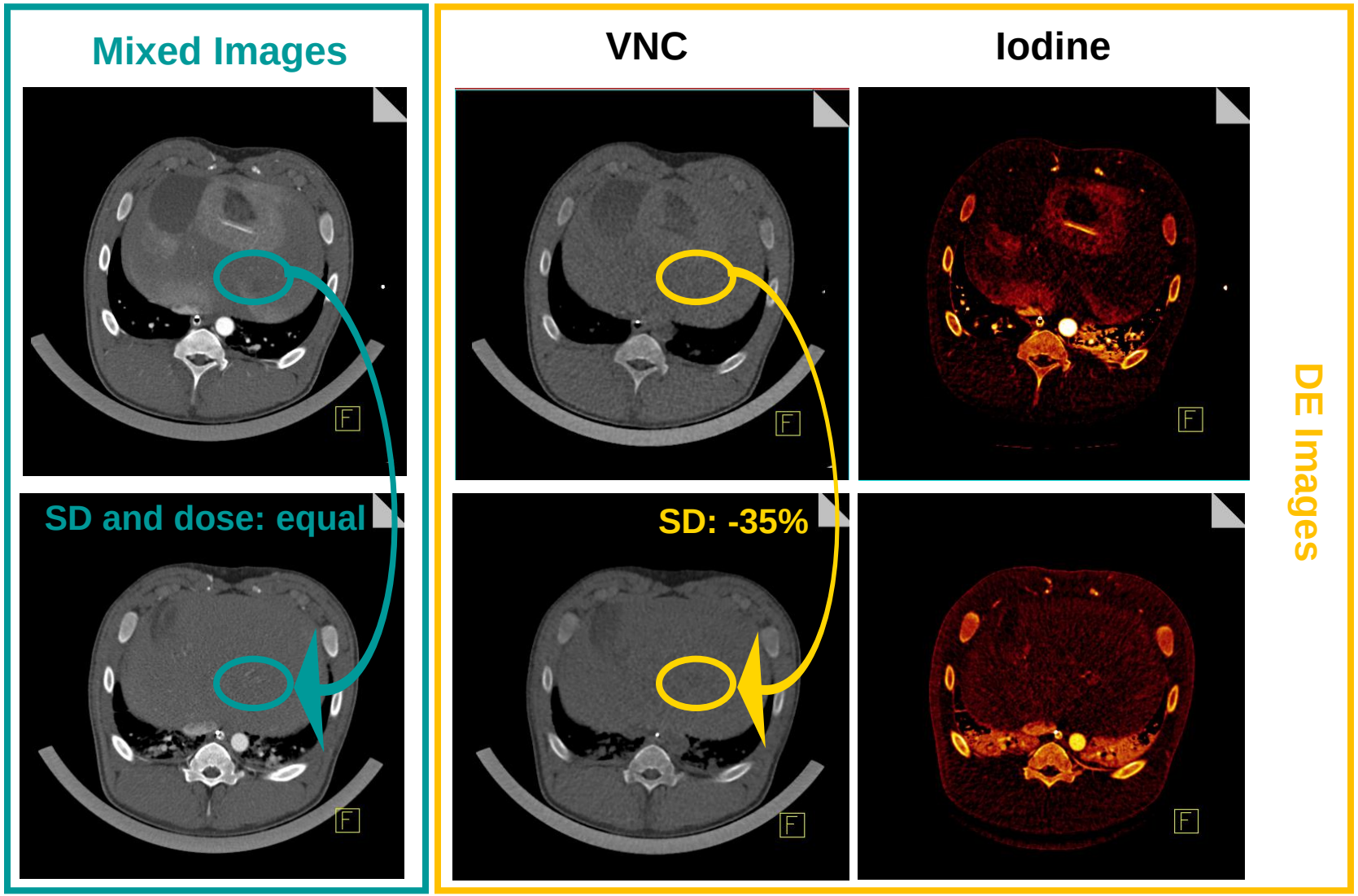
$$ratio = \frac{CTvalue_{lowkV}}{CTvalue_{highkV}}$$



- 15mg/ml Ultravist
- 20ml / 20mm diameter
- 20cm water phantom



Dual Source CT – Spectral Optimization



Importance of Temporal Resolution & Temporal Coherence

Temporal resolution:

- time to collect enough raw data for one image (typically rotation time / 2)
- determines amplitude of motion artifacts

→ temporal resolution as high as possible for good quality!

→ necessary for applications with contrast dynamics and cardiac applications!

Temporal coherence:

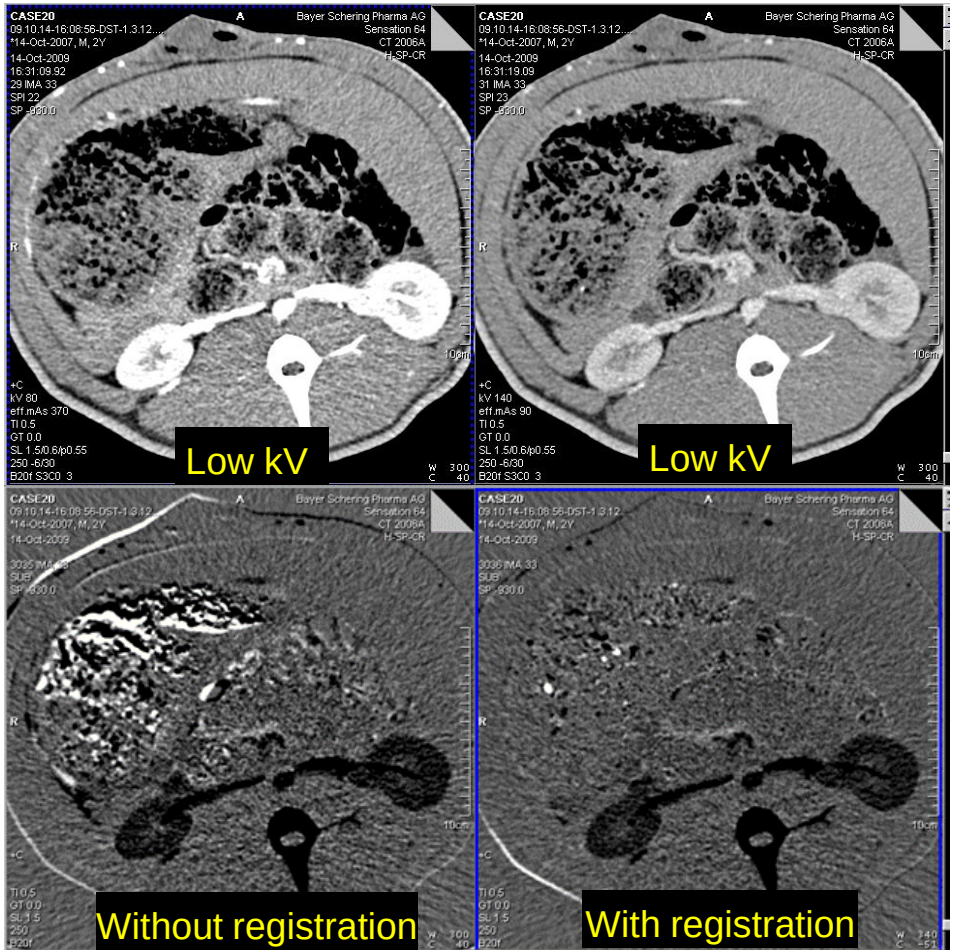
- Differences in the high and low kV images originating from patient motion due to a temporal delay between the high and low kV image acquisitions
- Result: Visibly different low & high kV images

→ temporal coherence as high as possible for good quality!

→ needed for all DE applications

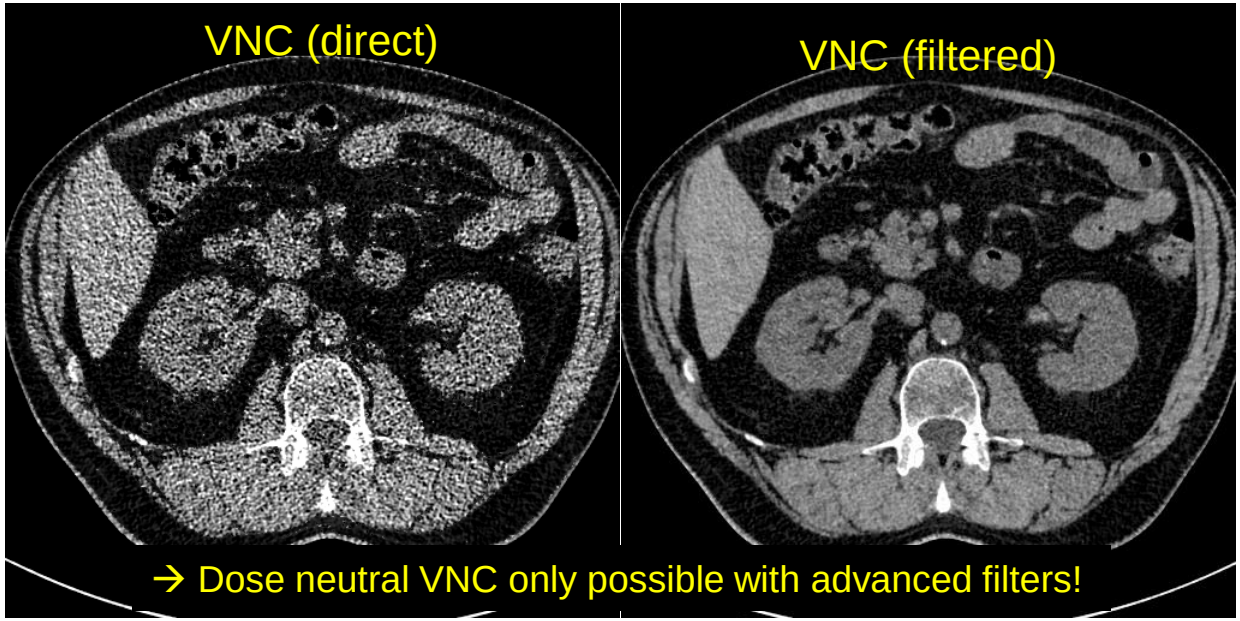
Importance of Temporal Coherence

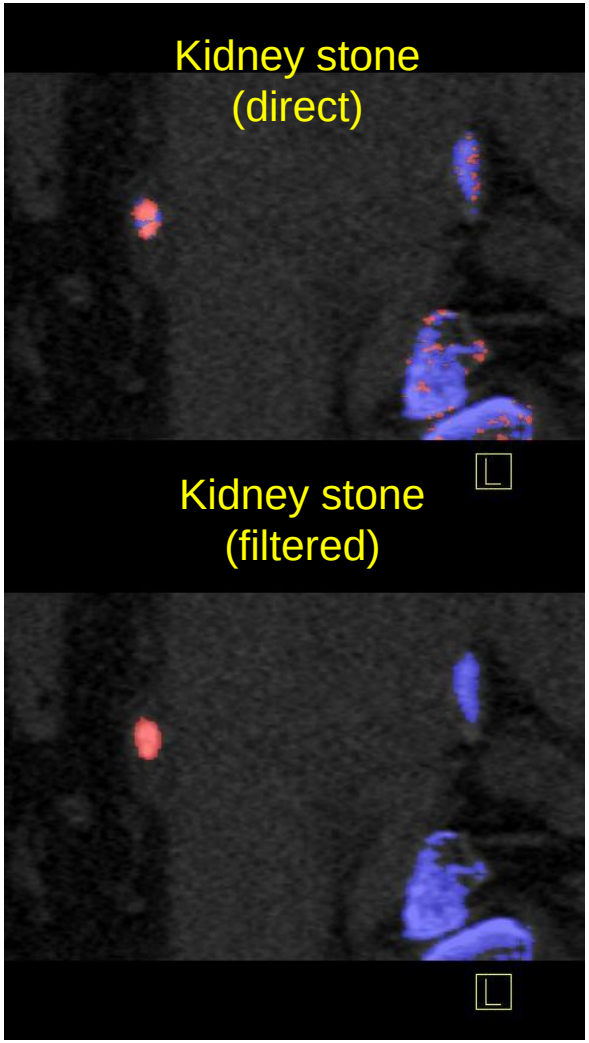
- Visibly different low & high kV images (breathing motion / incomplete breathold, bowel movement)



Technique	Temporal Coherence	Temporal Resolution
Dual Spiral	Low	High
Slow kV Switching	Medium	High
Fast kV Switching	Very high	Low
Dual Source	High	High
Split Filter	Medium	High
Sandwich Detector	Very high	High
Quantum Counter	Very High	High

The Importance of Noise Reduction





Active field of research; achieve good result quality at single energy dose:

- iterative reconstruction
- non-linear image filters

For a Dual Source System, Which of the following tube voltage combinations results in the best Dual Energy performance (DE ratio)?

20%	1. 80 / 140 kV
20%	2. 100 / Sn140 kV
20%	3. 80 / Sn150 kV
20%	4. 90 / Sn150 kV
20%	5. 100 / Sn150 kV

For a Dual Source System, Which of the following tube voltage combinations results in the best Dual Energy performance (DE ratio)?

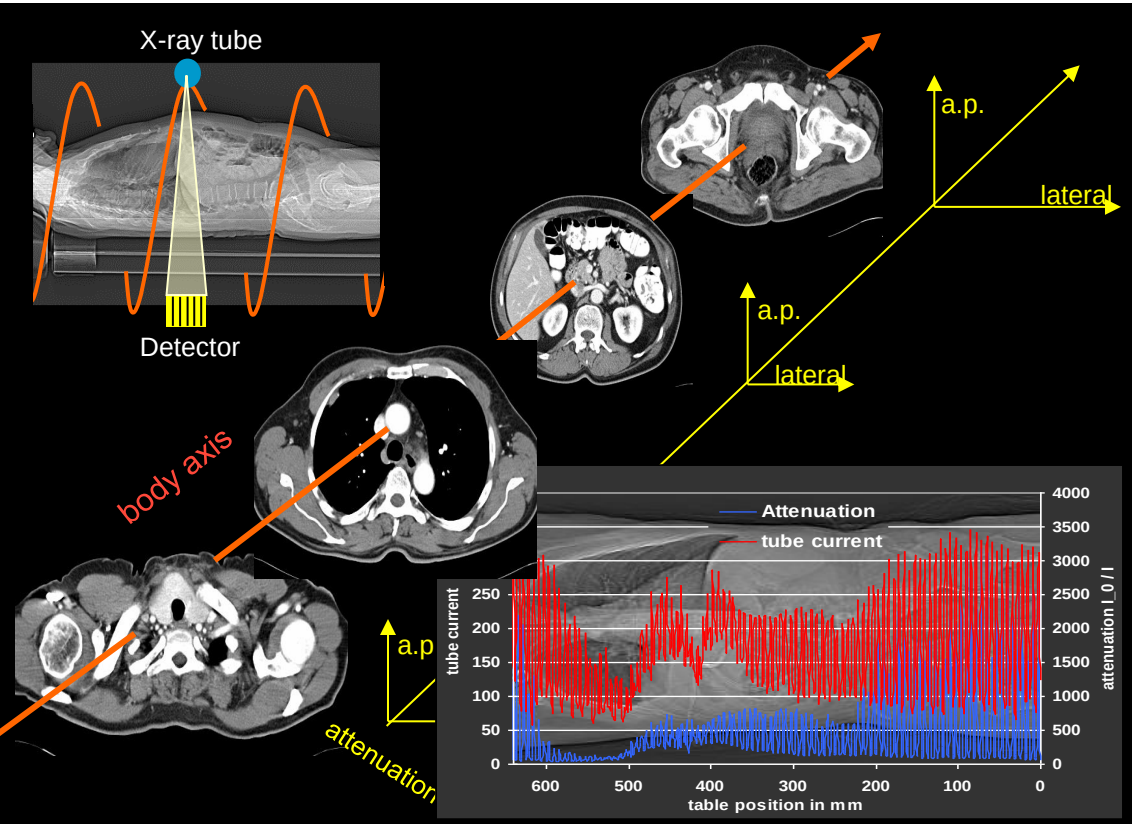
1. 80 / 140 kV
2. 100 / Sn140 kV
3. 80 / Sn150 kV
4. 90 / Sn150 kV
5. 100 / Sn150 kV

Dual Energy ratio increases with decreasing voltages of the low kV beam and with increasing voltages of the high kV beam, and they increase when prefiltration (e.g. tin) is added to the high kV beam.

Reference: Bernhard Krauss, Katharine L. Grant, Bernhard T. Schmidt and Thomas G. Flohr, " *The importance of spectral separation, an assessment of dual energy spectral separation for quantitative ability and dose efficiency*", Investigative Radiology, 50(2), February 2015.

WHAT ABOUT THE DOSE?

Dose Efficiency: Tube Current Modulation?



Technique	Tube Current Modulation
Dual Spiral	Yes
Slow kV Switching	Yes
Fast kV Switching	Problematic
Dual Source	Yes
Split Filter	Yes
Sandwich Detector	Yes
Quantum Counter	Research topic

Not available for all DE techniques!!!

C. Hofmann, B. Schmidt

Dual Source DE – Fit for Clinical Routine: No Compromise in Dose

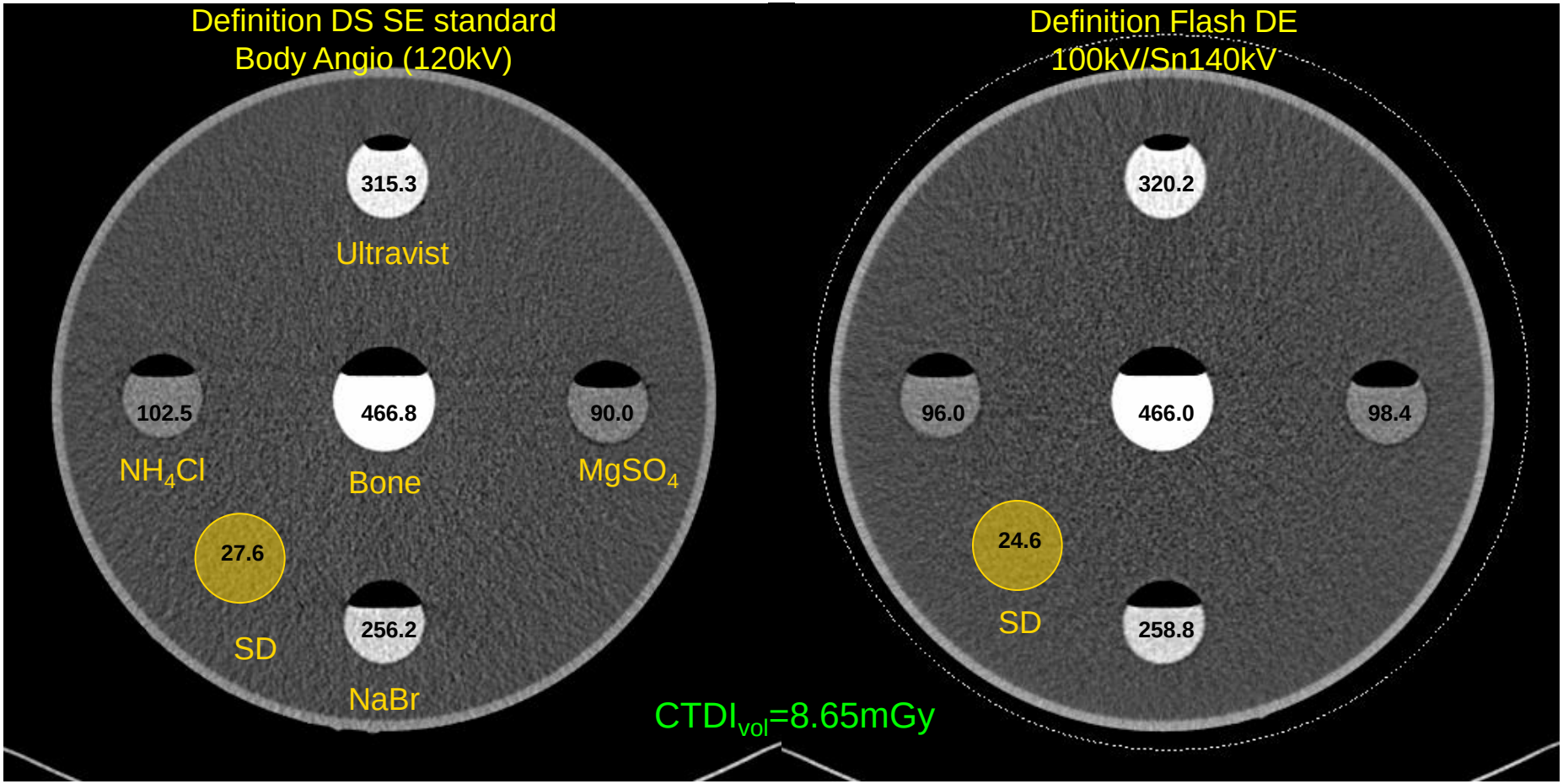
“Dual energy CT of the chest: how about the dose?”

Invest Radiol. 2010 Jun;45(6):347-53.

RESULTS:

- The effective dose measured with thermoluminescent detectors was 2.61, 2.69, and 2.70 mSv, respectively, for the 140/80 kVp, the Sn140 /100 kVp, and the standard 120 kVp scans.
- Image noise measured in the average images of the phantom scans was 11.0, 10.7, and 9.9 HU ($P > 0.05$).
- The CNR of iodine with optimized image blending was 33.4 at 140/80 kVp, 30.7 at 140Sn/100 kVp and 14.6 at 120 kVp.

Comparison Definition DS SE / Flash DE (DE composition 0.6)



Noise & Contrast & Dose equivalent to single energy on Definition DS (for FAST body bone removal protocol)

More Dose or Less Dose?

- same total dose = half dose per spectrum

Body Region	Dual Energy (mGy)	Single Energy (mGy)
Abdomen (Kidney)	16.3	14.2
Abdomen (Liver)	17.8	14.2
Thorax (LungPBV)	7.3	7.4
Carotid Angio (Bone Removal)	8.0	8.1
Body Angio (Bone Removal)	9.2	8.1
Extremity-Hand (Gout)	8.8	6.7

*** CTDIvol for default scan protocols on SOMATOM Definition Flash**

- mixed image has similar image noise & contrast as single energy image
- Dual Energy analysis does not need more dose
- may save dose by omitting scans

THANK YOU FOR YOUR ATTENTION