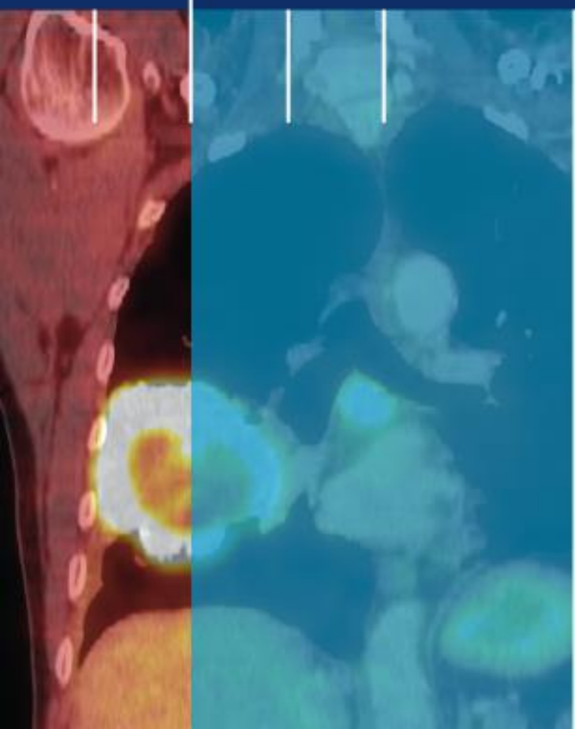
Dual Energy CT:
The next standard imaging modality for radiotherapy?



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Background Dual Energy (CT) imaging
“Not a very new technique”

1973, *British Journal of Radiology*, *46*, 1016–1022

Computerized transverse axial scanning (tomography): Part I. Description of system

G. N. Hounsfield

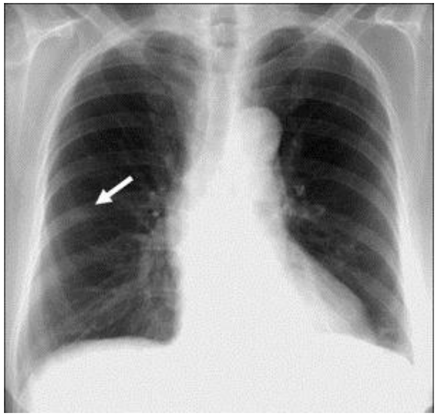
Central Research Laboratories of EMI Limited, Hayes, Middlesex

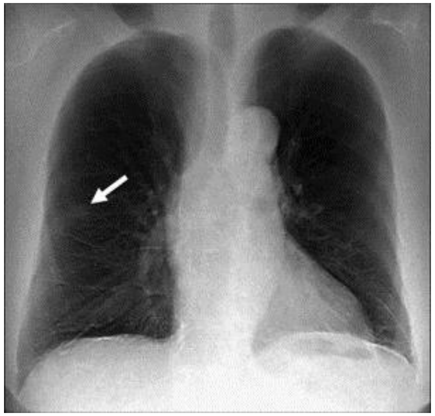
(*Received February, 1973 and in revised form July, 1973*)

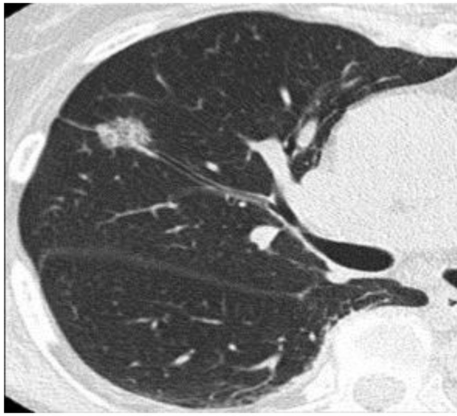
DETERMINATION OF ATOMIC NUMBER OF MATERIAL

It is possible to use the machine for determining approximately the atomic number of the material within the slice. Two pictures are taken of the same slice, one at 100 kV and the other at 140 kV. If the scale of one picture is adjusted so that the values of normal tissue are the same on both pictures, then the picture containing material with a high atomic number will have higher values at the corresponding place on the 100 kV picture. One picture can then be subtracted from the other by the computer so that areas containing high atomic numbers can be enhanced. (In practice a contrast medium, sodium iothalamate containing 420 mg of atomic iodine per millilitre (Conray 420) can be readily detected at a concentration of one part in 1,000 by the machine.) For example, tests carried out to date have shown that iodine ($Z=53$) can be readily distinguished from calcium ($Z=20$). The scope of this technique is under further investigation at present.

Example: Dual Energy x-ray imaging for bone removal

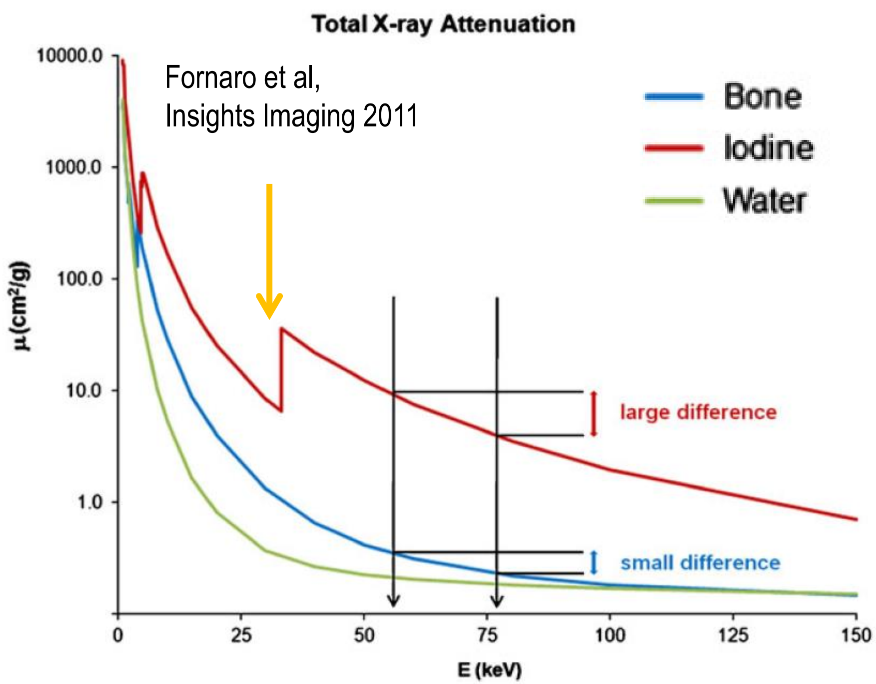






Short physics background
Attenuation of photons in tissues

- Attenuation of photons depends on:
  - Material
    (iodine vs. bone vs. soft tissue)
  - Energy of photons
    (e.g. different kV setting of scanner)
- At diagnostic energies:
  - Compton effect (propertional to ρ_e)
  - Photoelectric effect (propertional to Z)
- Dual Energy approach
  - Two unknowns & two measurements (scans) => solve for different materials



- K-edge of iodine (33 keV)
- Difference in slopes for different tissues/materials

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DECT analysis approaches

Generally two types of analyses/parameterization of μ_{eff}
(for Z_{eff} < 20 and in diagnostic energy range)

- *Electron density (ρ_e) and effective atomic number (Z_{eff}):*

$$\mu_{eff,L} = \rho_{eff}\left[\alpha \frac{Z_{eff}{}^{k}}{E_L{}^{n}} + \beta f_{KN}(E_L)\right],$$

- Basis materials decomposition:

$$\mu_{eff,L} = \rho_{eff}\left[m_1\left(\frac{\mu}{\rho}\right)_{1,L} + (1-m_1)\left(\frac{\mu}{\rho}\right)_{2,L}\right],$$

  - Two materials decomposition
    - one typically chosen as 'water' (e.g. 'Compton' like)
    - one typically chosen as 'iodine' (e.g. 'Photo-electric effect' like)

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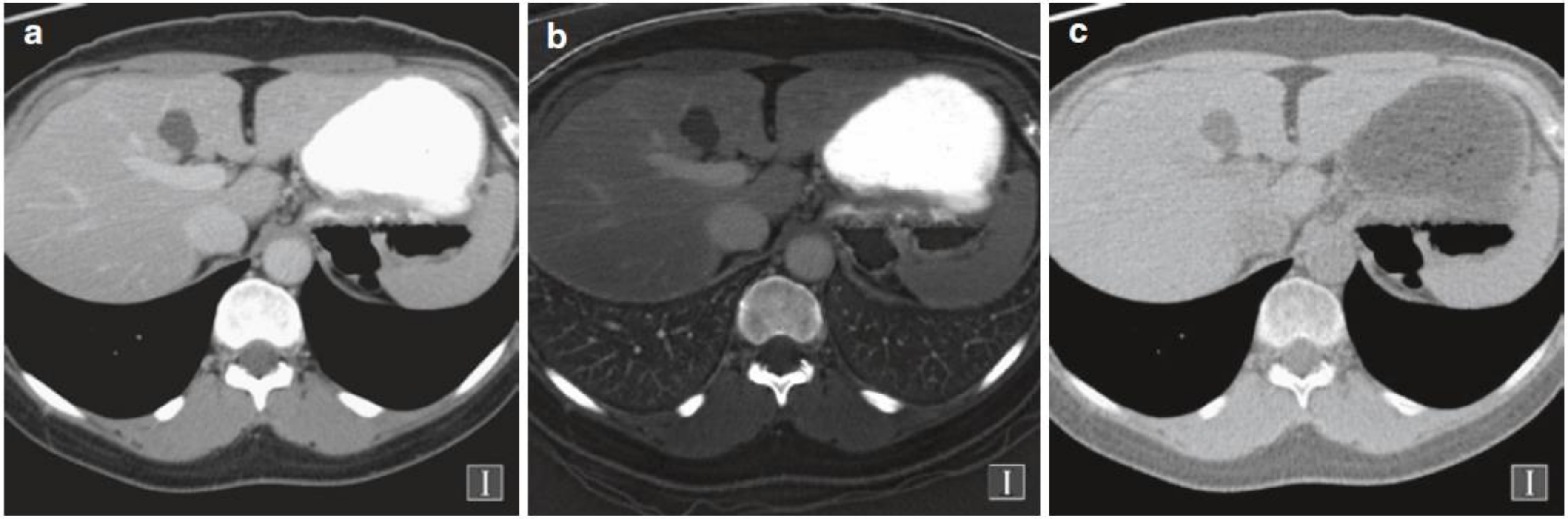
Example of iodine quantification/separation

Dual Energy CT data can be visualized as:

Morphological: Equivalent 120 kVp image (weighted sum) at same dose (not shown)

A) virtual mono energetic images B) contrast material only image, C) Virtual non contrast image (water like)



75keV Monochromatic | MD Iodine | MD Water

T.R.C. Johnson et al. (eds.), *Dual Energy CT in Clinical Practice*, Medical Radiology,
DOI: 10.1007/174_2010_35

Imaging technology for Dual Energy CT

- Several technologies available for DECT imaging
  - Rotate-Rotate DECT
    - Simple approach with two sequential helical CT scans at different kVp
  - Dual Source – Dual Detector approach (Siemens)
  - Rapid kV switching (GE)
  - Dual-layer detector technology (Philips)
  - Single Source – sequential rotations with different kVp (Toshiba)

N.B. Dose burden (ALARA): typically the imaging dose is split over the two energies leading into a imaging dose-neutral approach for most applications.

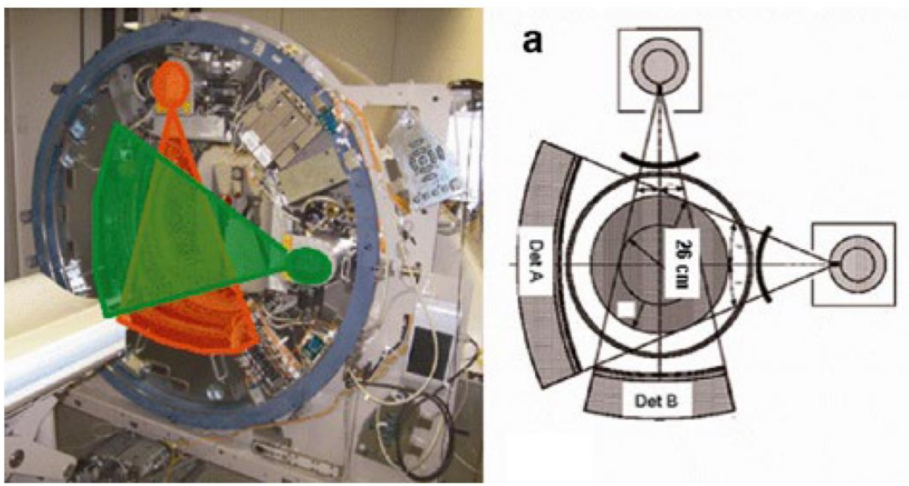
MAASTRO

Current State-of-the-Art CT scanners (two examples)

Dual Source - Dual Detector

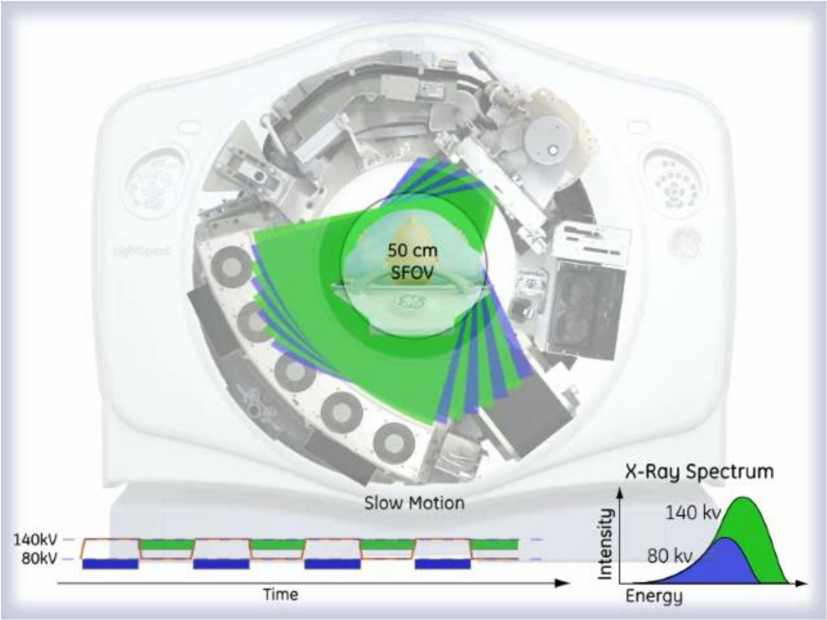
Siemens Definition Force CT

C.N. De Cecco et al. (eds.), *Dual Energy CT in Oncology*,
DOI 10.1007/978-3-319-19563-6_1



Rapid kV switching tube

GE Revolution GSI CT*



* http://www3.gehealthcare.nl/nl-nl/products/categorieen/computer_tomografie/discovery_ct750_freedom/spectral_imaging

Imaging Equipment for Dual Energy CT

Manufacturer and model name	*Technology of DECT acquisition*	*kVp ranges for DECT*
Siemens Definition Force, Definition Flash[1]	Dual Source - Dual Detector	70-150 kVp
GE Revolution GSI[2]	Single Source – Rapid kV switching	80 and 140 kVp
Philips IQon CT[3]	Single Source – Multi-layered detector	120 and 140 kVp
Toshiba Acquilion One Vision[4]	Single Source – Sequential gantry rotations at different kVp	80 and 135 kVp
Siemens Definition Edge[5]	Single Source – Split beam filter at target with single detector ('TwinBeam')	120 kVp (with additional Au and Sn filters to create two spectra)
'Standard CT scanners' **(e.g. Siemens Definition)**	Single Source – two successive spiral scans at different kVp)('rotate-rotate DECT)	Standard available (80-140)

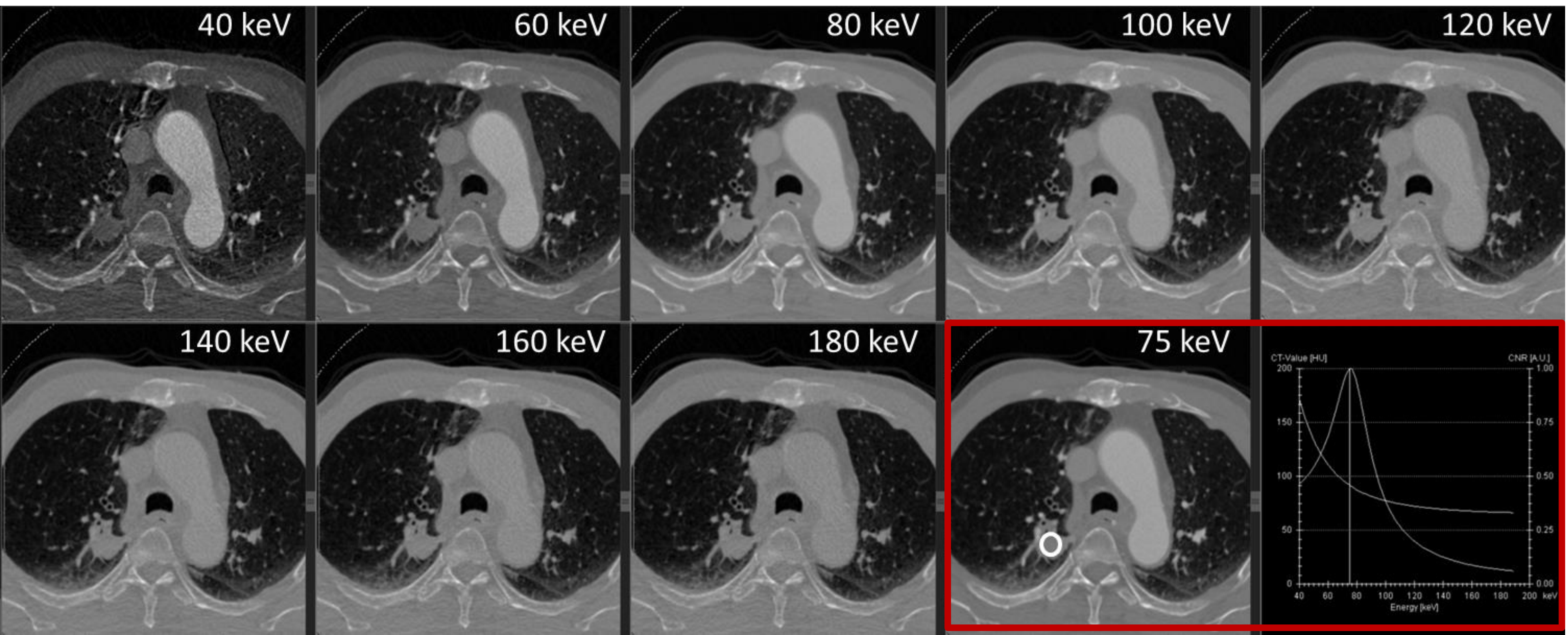
[1] http://www.healthcare.siemens.com/computed-tomography/dual-source-ct/somatom-force/technical-specifications
[2] http://www3.gehealthcare.com/en/products/categories/computed_tomography/revolution_hd
[3] http://www.healthcare.philips.com/main/clinicalspecialities/radiology/solutions/IQon.html
[4] http://www.toshiba-medical.eu/eu/product-solutions/computed-tomography/aquilion-one-vision-edition-overview/
[5] http://www.healthcare.siemens.com/computed-tomography/single-source-ct/somatom-definition-edge/technical-specifications

Applications of DECT imaging for Radiotherapy

- Improved image quality
  - Tumour staging and delineation
  - Tumour characterization: towards functional imaging
  - Normal tissue characterization
  - Metal artifact reduction techniques based on DECT
- Improved dose calculations
  - Brachytherapy
  - External beam therapy - Photons
  - Proton therapy

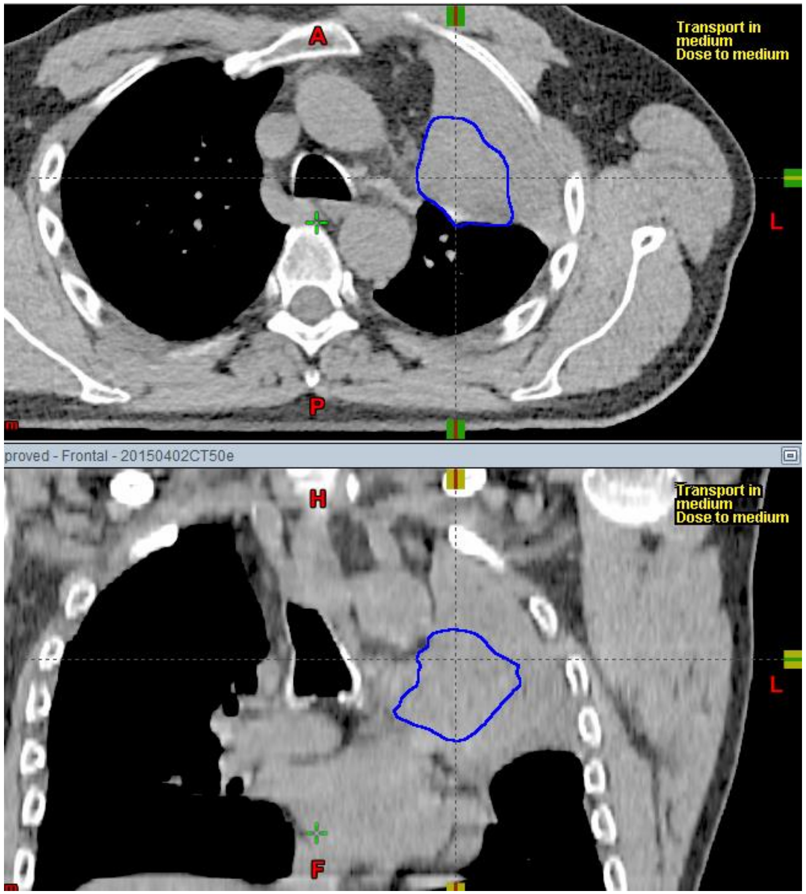
Improved image quality
Mono-energetic reconstructions

- Mono-energetic reconstructions allow to reconstruct the images at any given ‘virtual’ keV setting of a CT scan
- Selection of keV to reach ‘optimal contrast’

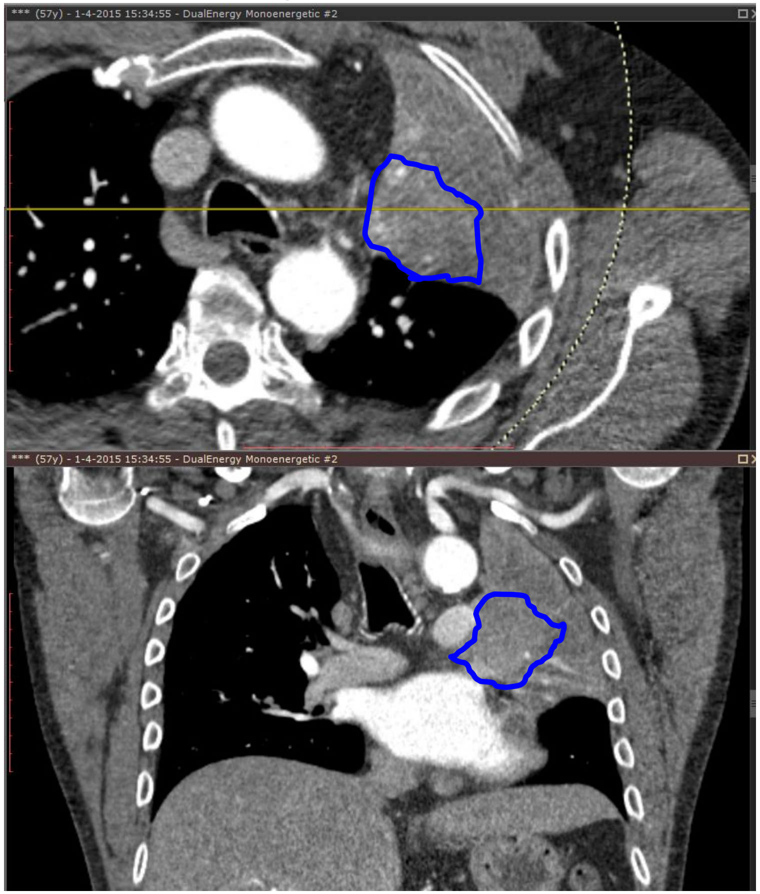


Example of atelectasis
Standard CT vs. Dual Energy CT based mono-energetic CT

Standard planning CT delineation based on FDG-PET/CT



Dual Energy CT based Mono-energetic reconstruction



Tumour staging and delineation
Head and neck primary SCC

More contrast ⟷ Less noise

Linear blend of high and low kVp scan | 40 keV | 60 keV | 80 keV | 100 keV

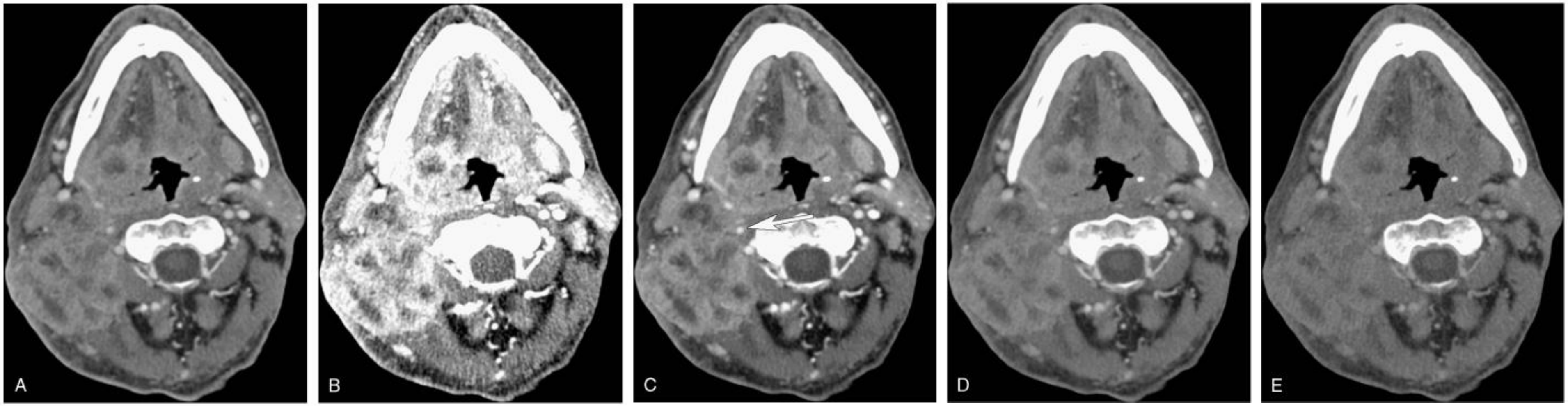


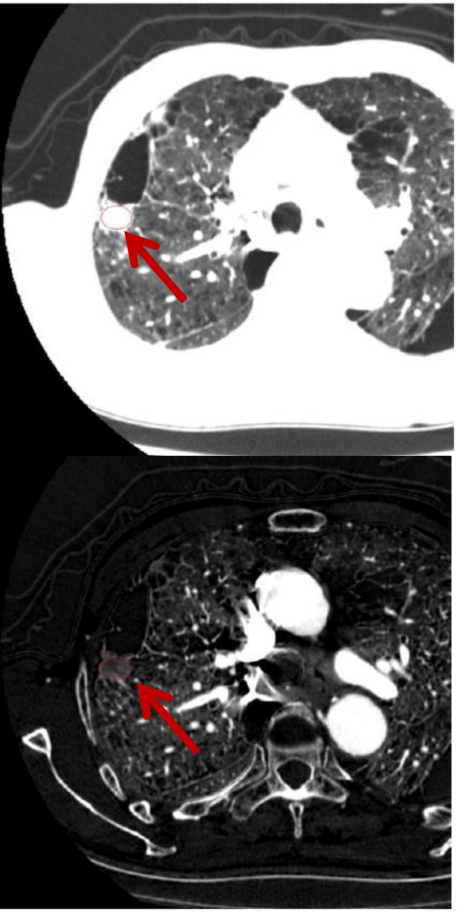
TABLE 2. Results of Subjective Image Analysis

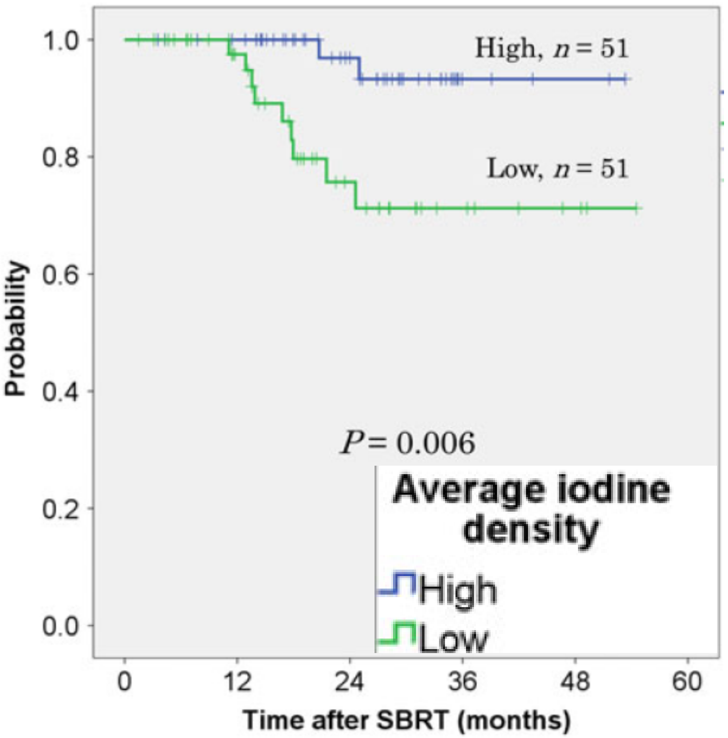
Image Series	Overall Image Quality	Delineation of Lesion	Image Sharpness	Image Noise
M_0.3	3.81 (2–5) [0.394]	3.77 (2–5) [0.451]	3.79 (3–4) [0.585]	4.02 (3–5) [0.518]
40 keV	1.91 (1–3) [0.498]	2.08 (1–4) [0.307]	2.23 (1–4) [0.658]	2.03 (1–3) [0.402]
60 keV	4.22 (3–5) [0.411]	4.35 (3–5) [0.459]	3.81 (3–5) [0.517]	4.12 (3–5) [0.363]
80 keV	3.44 (2–5) [0.381]	2.89 (1–4) [0.301]	3.46 (3–4) [0.279]	4.31 (3–5) [0.728]
100 keV	3.03 (1–4) [0.328]	2.15 (1–4) [0.411]	3.44 (2–5) [0.599]	4.34 (4–5) [0.679]

Data are mean (range) [κ] based on ratings from both observers.

Wichmann et al, Inv Radiol 2014

Tumour characterization
Functional imaging?

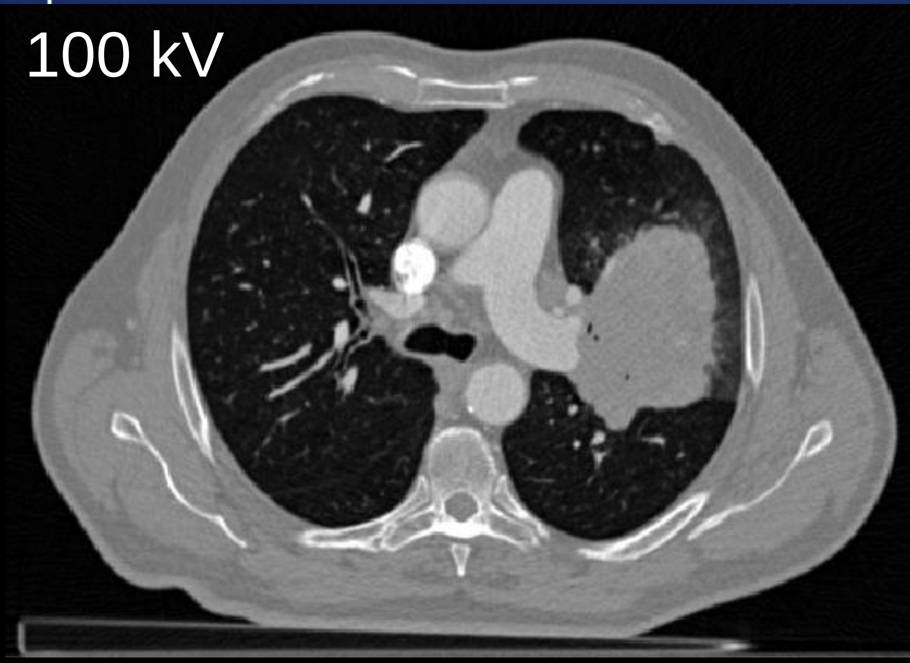


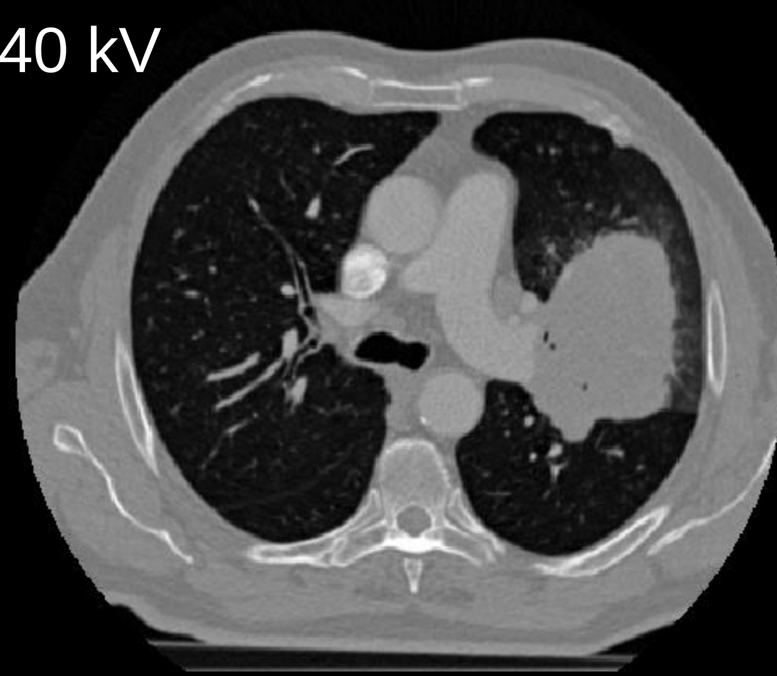


- Lung SBRT – 102 lesions
- Local control related to iodine uptake levels
- Low iodine uptake might indicate low blood flow and increased hypoxia levels → worse outcome
- Needs further investigation and validation

Aoki et al, J Rad Res 2016

Normal tissue characterization
'Functional Imaging of lung parenchym perfusion'



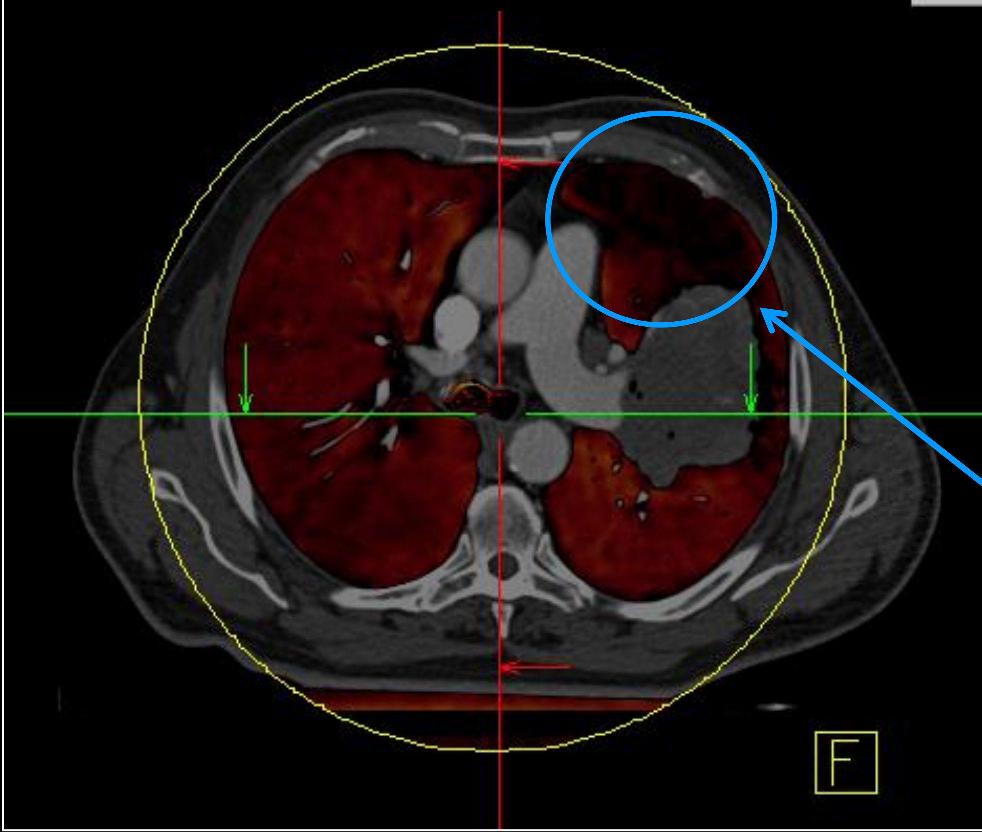


Van Elmpt et al, MAASTRO

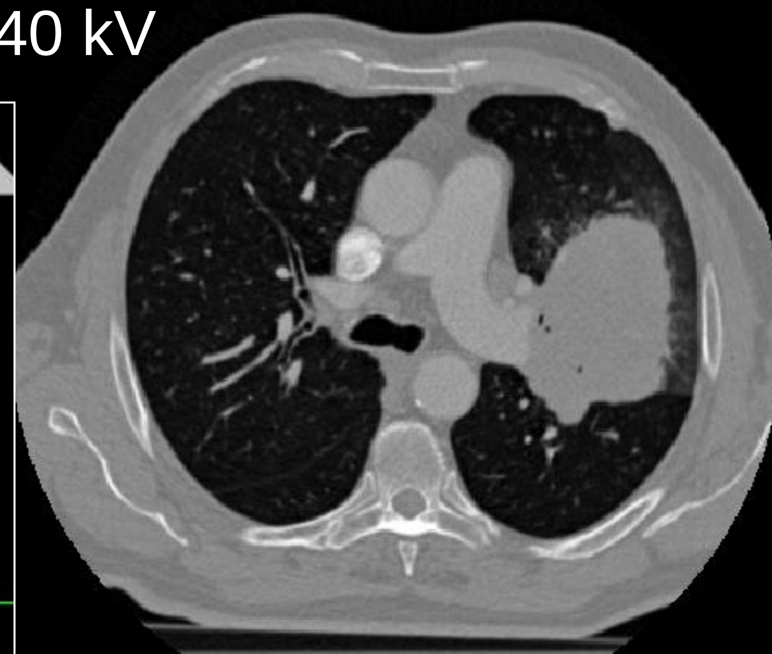
Normal tissue characterization
'Functional Imaging of lung parenchym perfusion'

100 kV

Iodine overlay (color)



140 kV

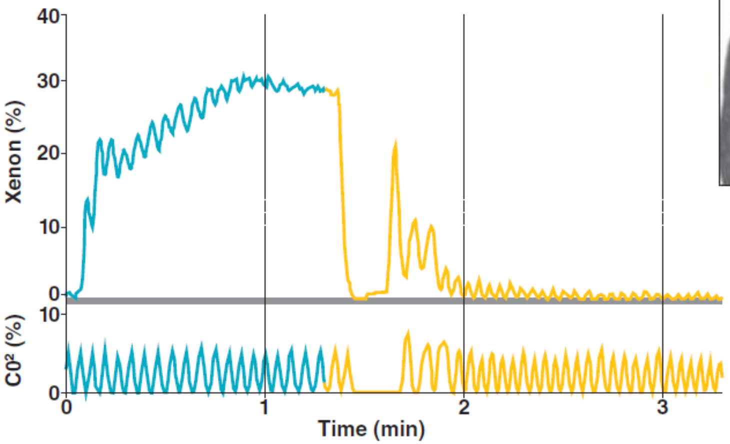


Perfusion defect in the normal lung tissue around the tumour:
- Permanently damaged ?
- Function again after reduction of tumour size?

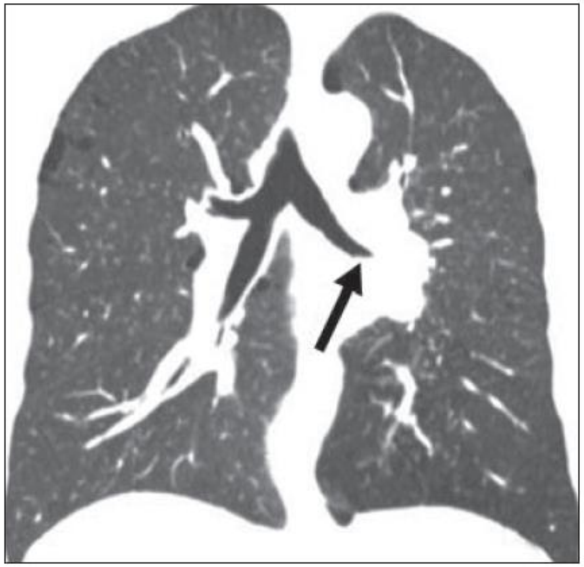
Van Elmpt et al, MAASTRO

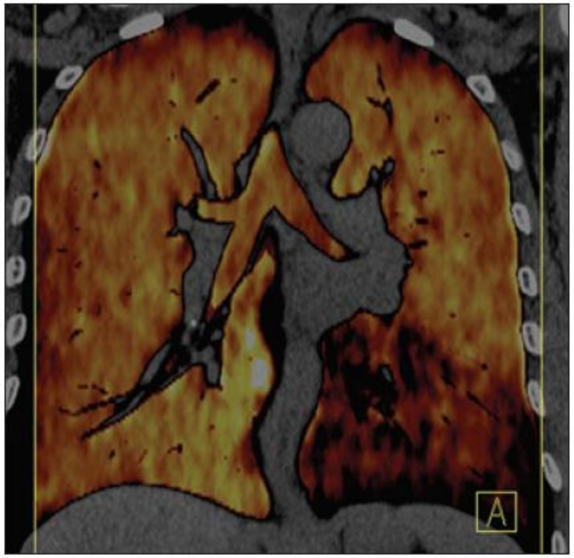
Normal tissue characterization
'Functional Imaging of lung ventilation'

Step 1: Breath Xenon (or Krypton) as exogenous contrast agent



Step 2: DECT scan to quantify ventilation (Xenon concentration) in lungs

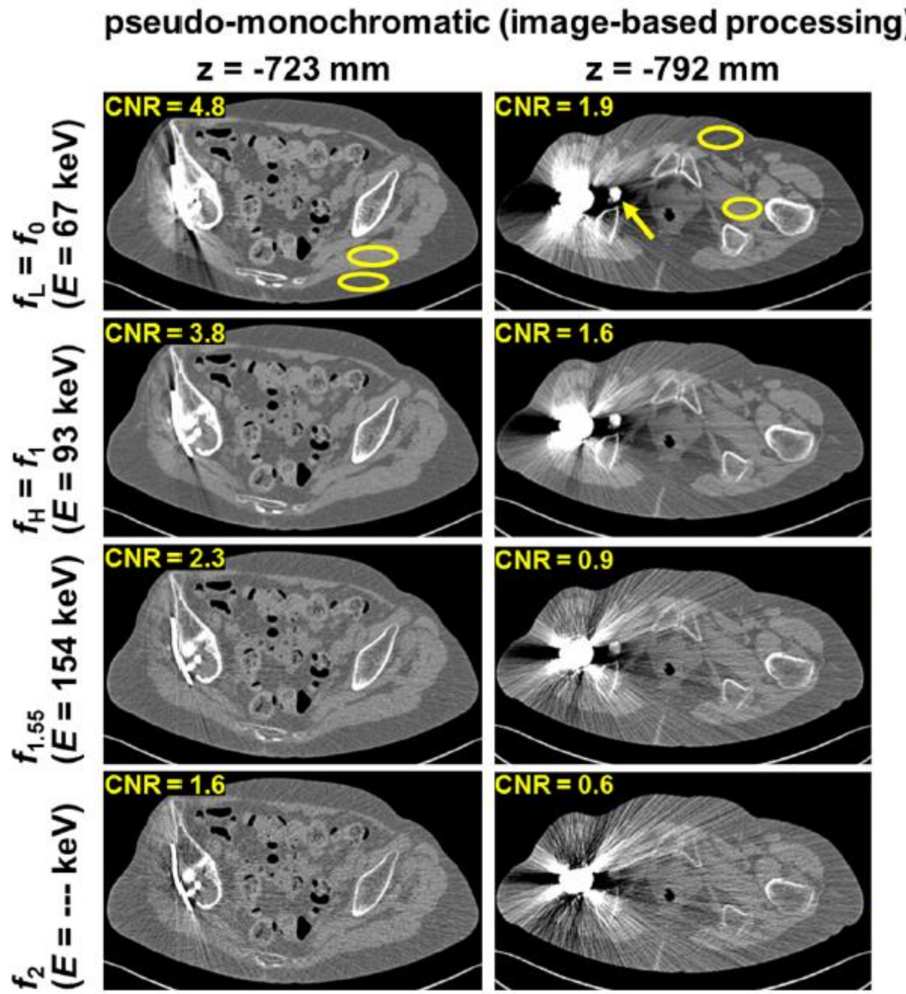




Kong et al, AJR 2014

Improved image quality
Metal artifact reduction

- Using the mono-energetic CT reconstructions allow artifact reduction at high keV
- Severe artifacts cannot be recovered → raw data based metal artifact reduction techniques are then necessary



Kuchenbecker et al, MedPhys 2015

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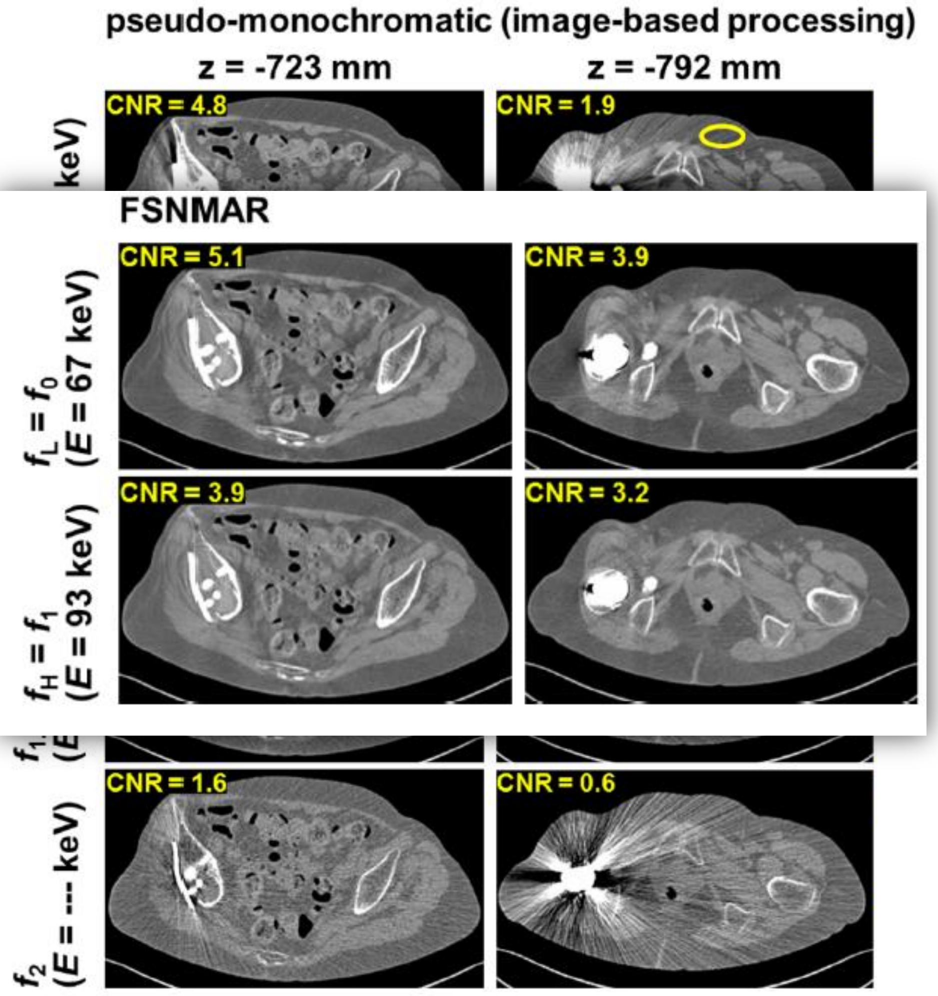

Kuchenbecker et al, MedPhys 2015

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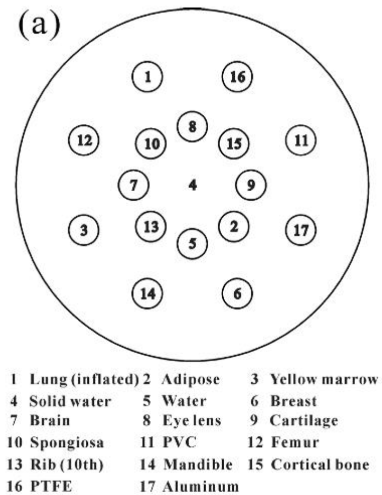
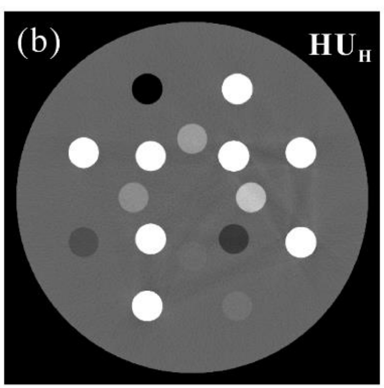
- Improved image quality
  - Tumour staging and delineation
  - Tumour characterization: towards functional imaging
  - Normal tissue characterization
  - Metal artifact reduction techniques based on DECT

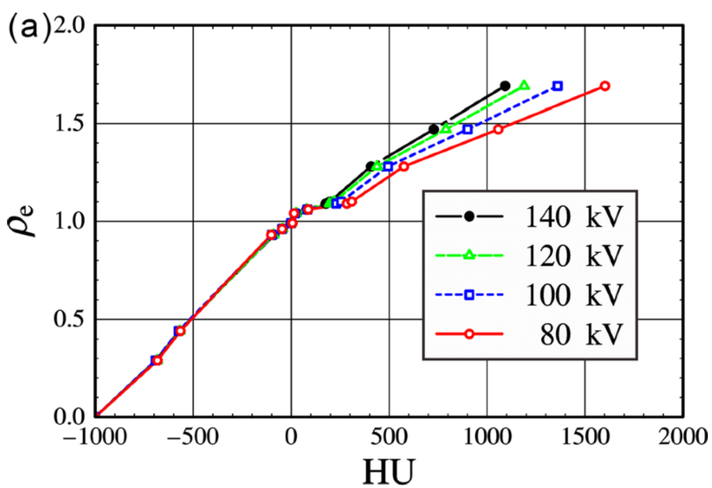
- Improved dose calculations
  - Brachytherapy
  - External beam therapy - Photons
  - Proton therapy

Conversion of HU to electron density (Single Energy CT)





$$\mathrm{HU} = 1000\left(\frac{\bar{\mu}_{meas}}{\bar{\mu}_{water}} - 1\right)$$

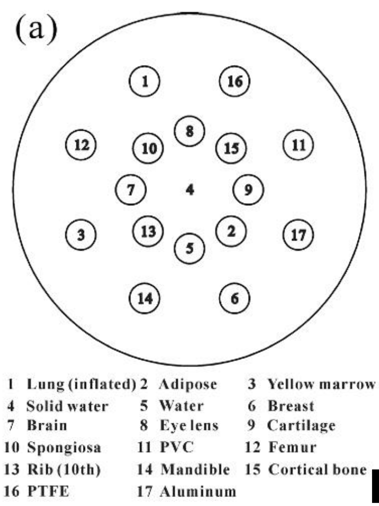


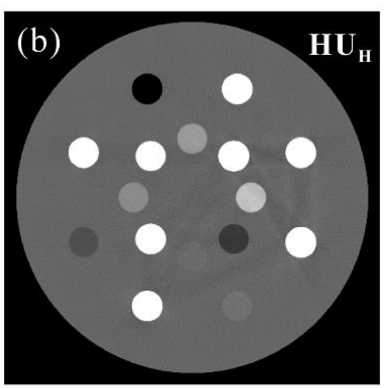
Calibration curve to electron density

Electron density (ρ_e) = f(HU)
→ from a calibration (look-up table)

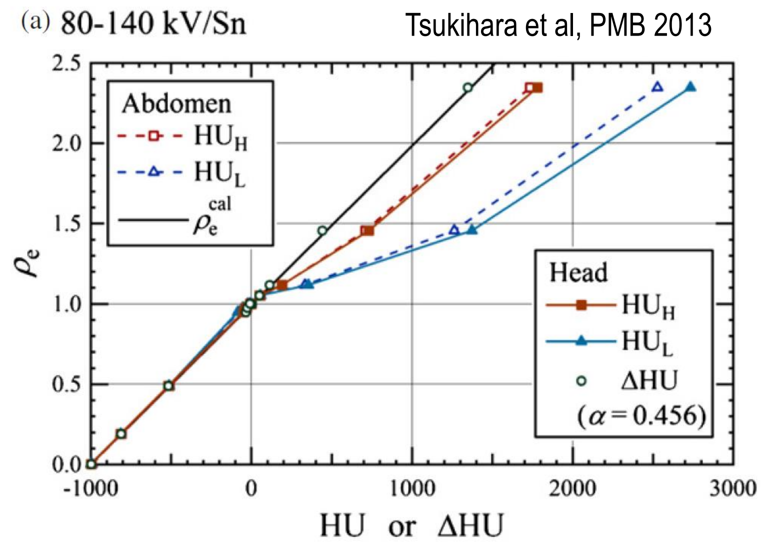
No information on atomic composition (Z_{eff}) possible

Conversion of HU to electron density **& atomic number** (Dual Energy CT)

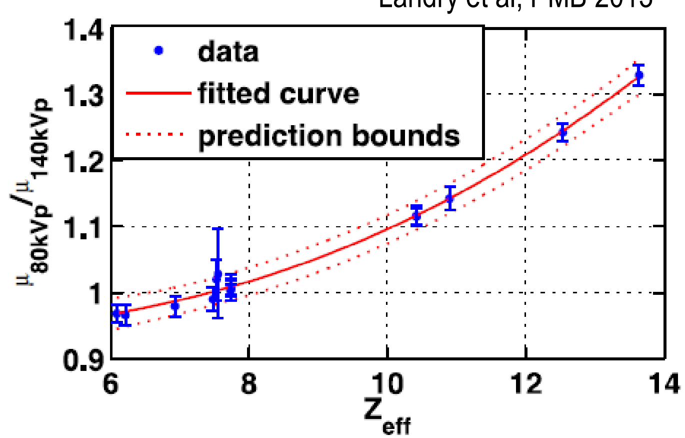




Tsukihara et al, PMB 2013



Landry et al, PMB 2013



Electron density (ρ_e):

$$\rho_e = a\frac{[(1+\alpha)HU_H - \alpha HU_L]}{1000} + b$$

&

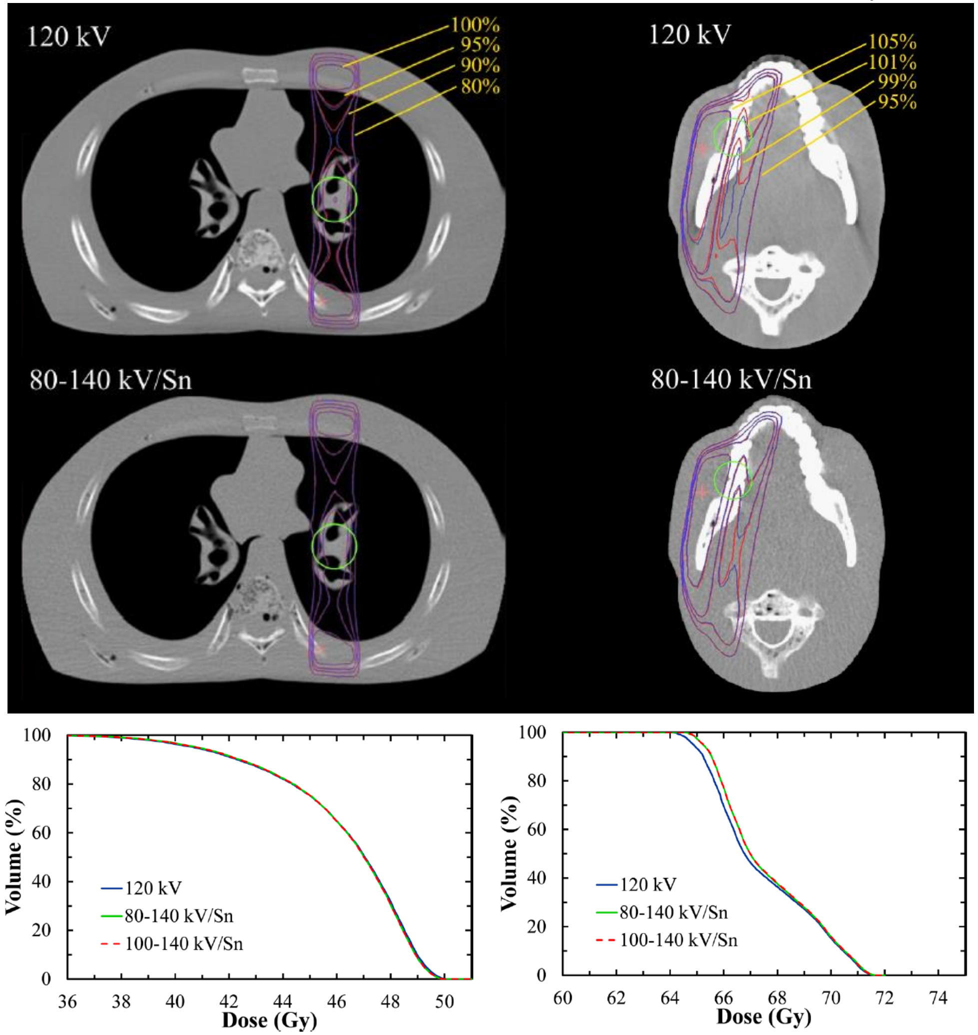
Atomic number (Z_{eff}) :

$$\frac{HU_L/1000+1}{HU_H/1000+1} = \frac{1+AZ_{eff}^{m-1}}{B+CZ_{eff}^{m-1}}$$

Clinical situations dose calculations
External Photon Beams (6-18MV)

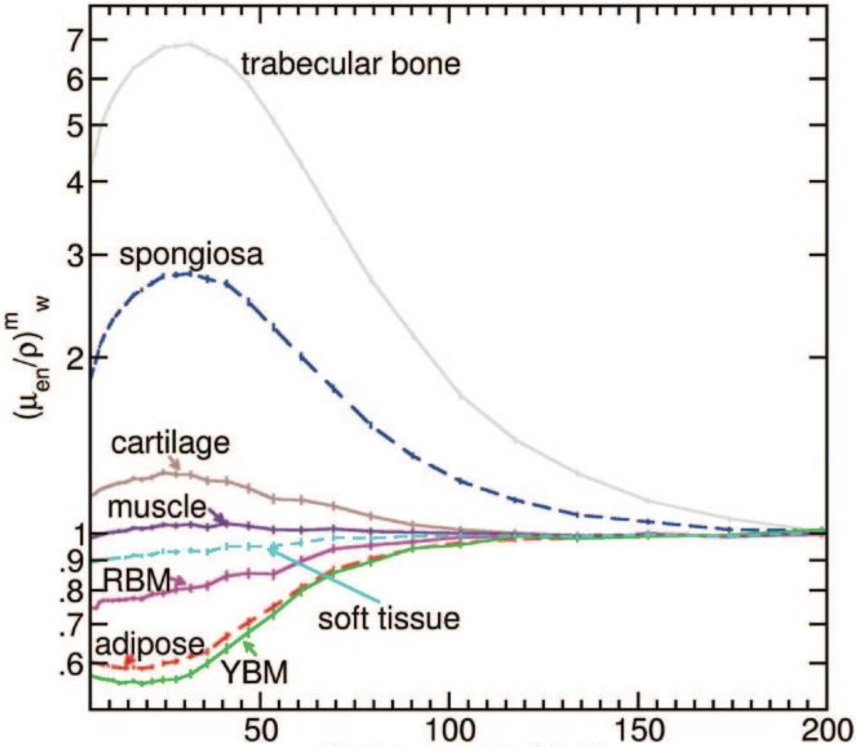
Tsukihara et al, Med Phys 2015

- CT images form the basis of dose calculations
  - Presence of heterogeneities (lungs, bones) are taken already into account with single energy CT
  - Electron density used to calculate radiological properties at the treatment beam's energy 6-10 MV is typically sufficient



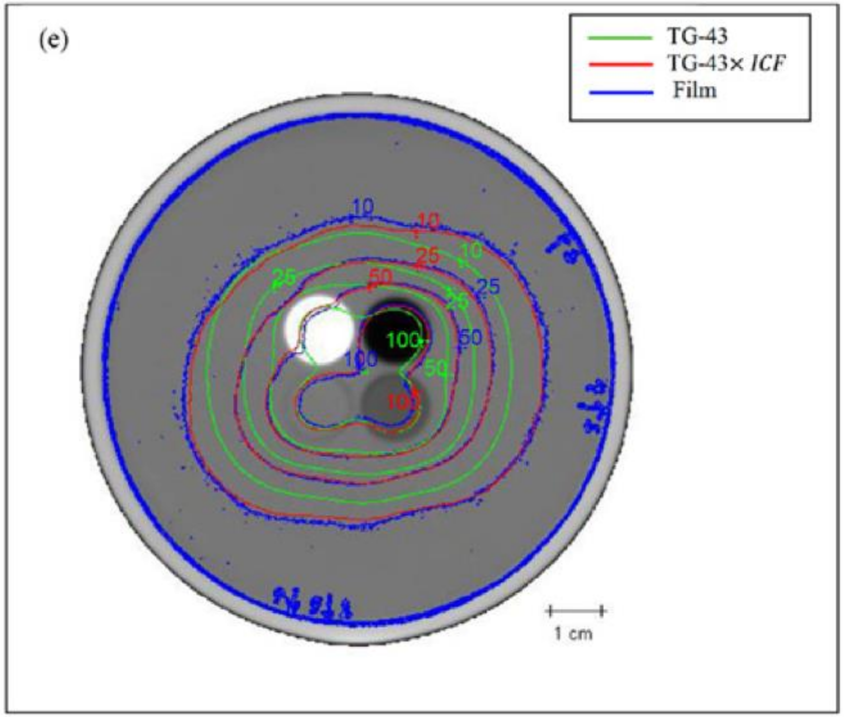
Improved dose calculations
Brachytherapy

Attenuation has large tissue dependence < 100 keV



Beaulieu et al. Report of the Task Group 186 Med Phys 2012

Experimental verification of Dual Energy CT based dose calculation

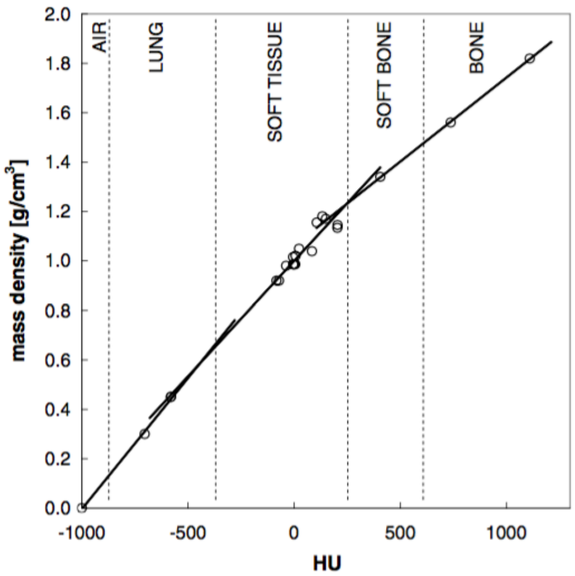


Mashouf et al. Phys Med Biol (2014)

Improved dose calculation **proton therapy**
Single Energy CT based Stopping Power Ratio

Bethe-Bloch formula

$$\mathrm{SPR} = \frac{\varrho_{\mathrm{e,medium}}}{\varrho_{\mathrm{e,water}}} \cdot \frac{\ln\left(\frac{2m_e c^2\beta^2}{(I_{\mathrm{medium}}/\mathrm{eV})(1-\beta^2)}\right) - \beta^2}{\ln\left(\frac{2m_e c^2\beta^2}{(I_{\mathrm{water}}/\mathrm{eV})(1-\beta^2)}\right) - \beta^2}$$



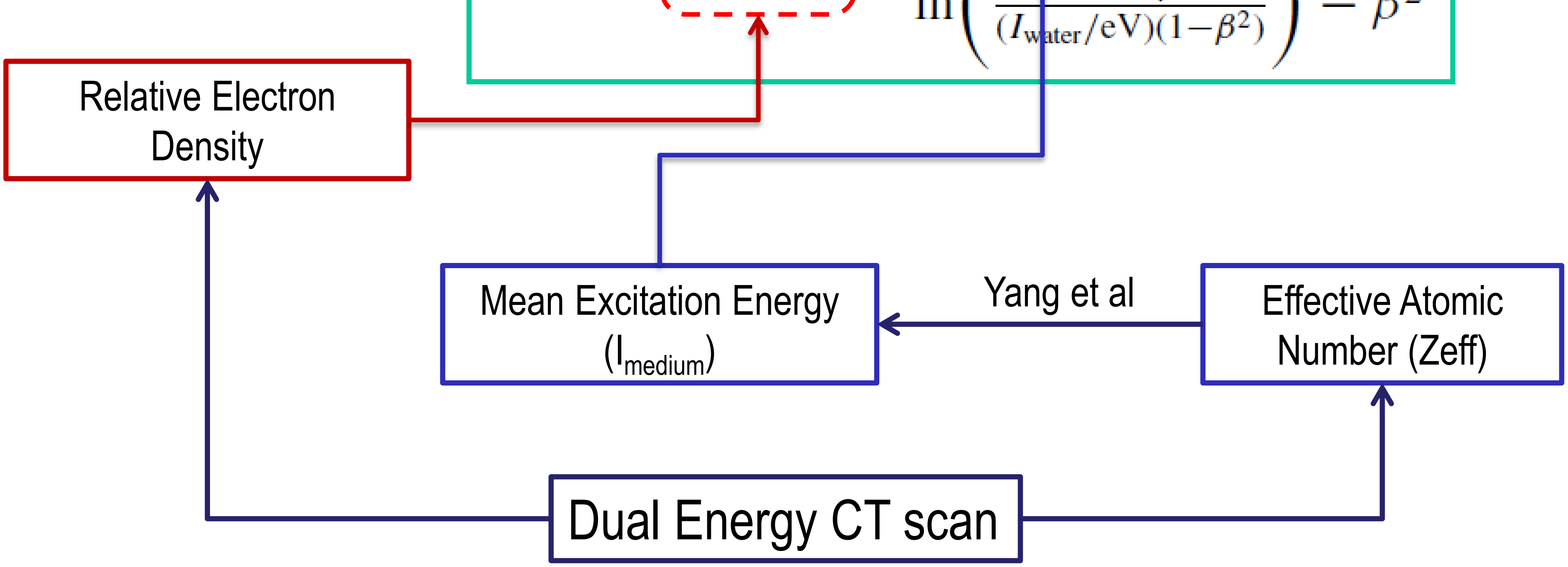
Slide adapted from: Verhaegen & de Almeida, MAASTRO.

- Calibration curve (look up table) using tissue equivalent materials to obtain densities and ionization pot.
- Choices to be made:
  - how many linear segments should be used?
  - which tissue-equivalent materials are suitable for calibration?
  - where should the boundaries between tissue types be set?

DECT based estimation of Stopping Power Ratio (SPR)

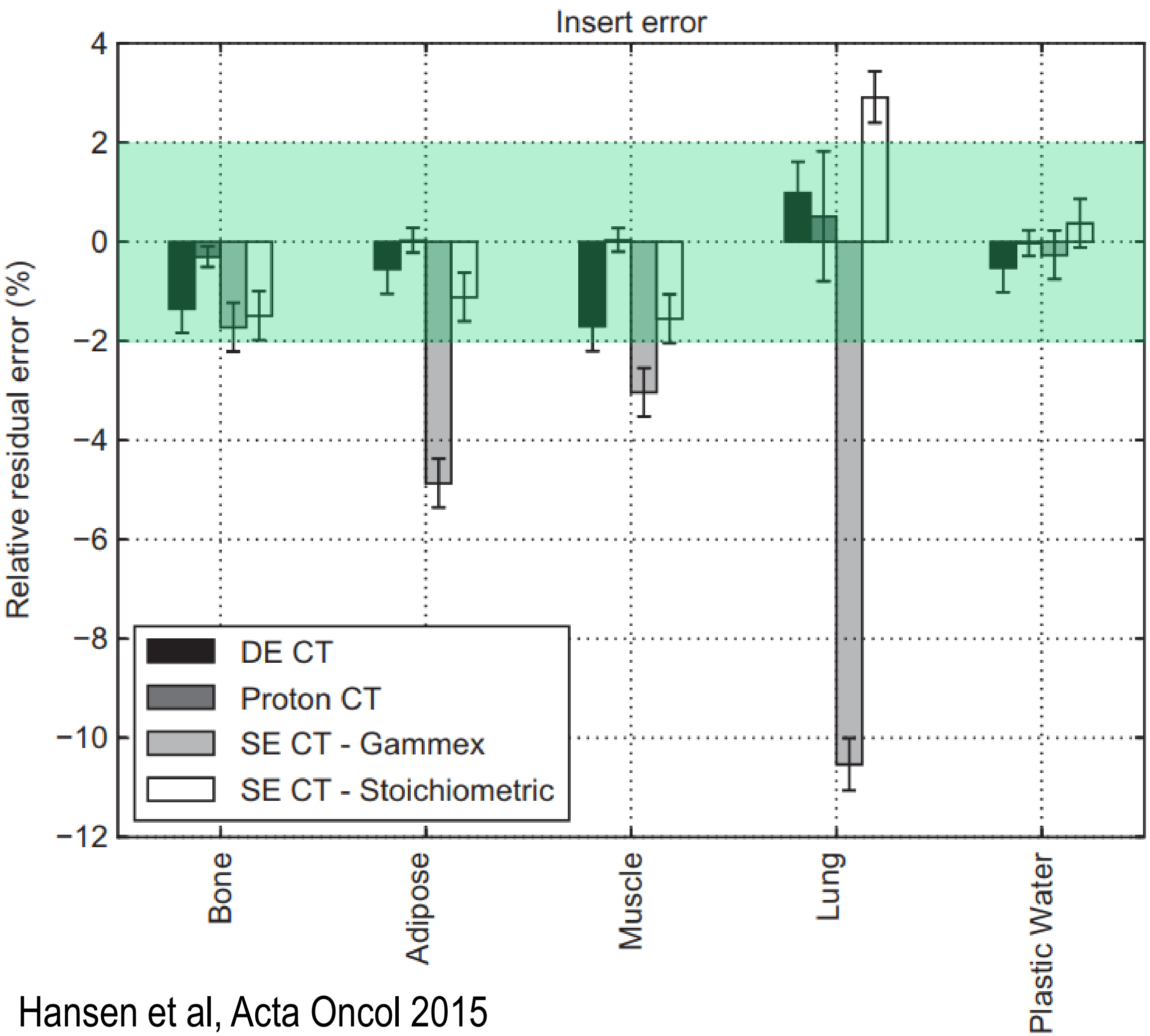
Bethe-Bloch formula

$$\mathrm{SPR} = \frac{\varrho_{\mathrm{e,medium}}}{\varrho_{\mathrm{e,water}}} \cdot \frac{\ln\left(\frac{2m_e c^2\beta^2}{(I_{\mathrm{medium}}/\mathrm{eV})(1-\beta^2)}\right) - \beta^2}{\ln\left(\frac{2m_e c^2\beta^2}{(I_{\mathrm{water}}/\mathrm{eV})(1-\beta^2)}\right) - \beta^2}$$



Slide adapted from: Verhaegen & de Almeida, MAASTRO.

Comparison different approaches for SPR estimation
Single Energy vs. Dual Energy vs. proton CT

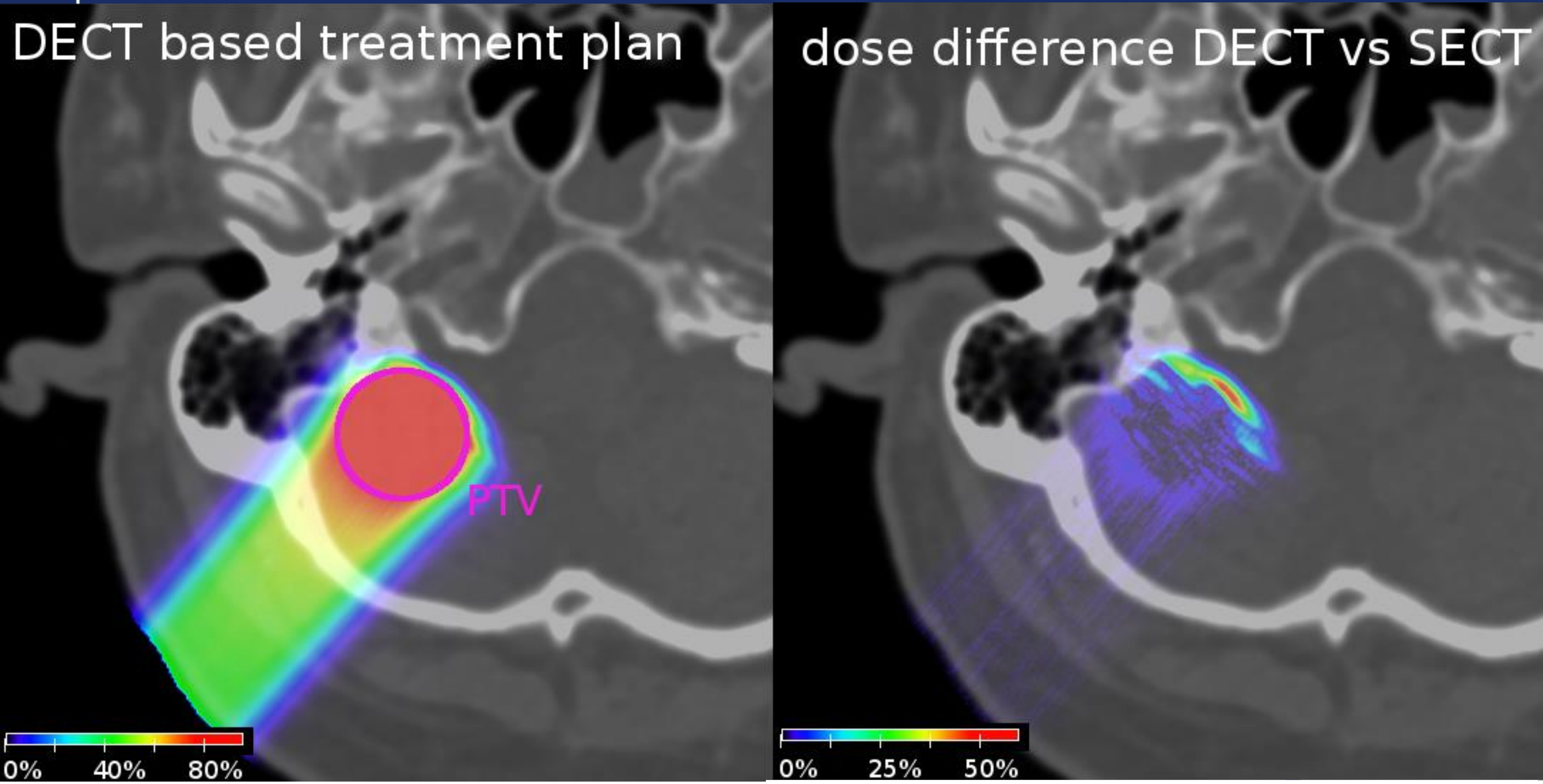


Conversion of SECT into stopping power results in ~3-4% range uncertainty

Dual Energy CT allows for a reduction in this uncertainty
→ smaller safety margins

Hansen et al, Acta Oncol 2015

Difference Single Energy CT vs. Dual Energy CT
Proton therapy plan

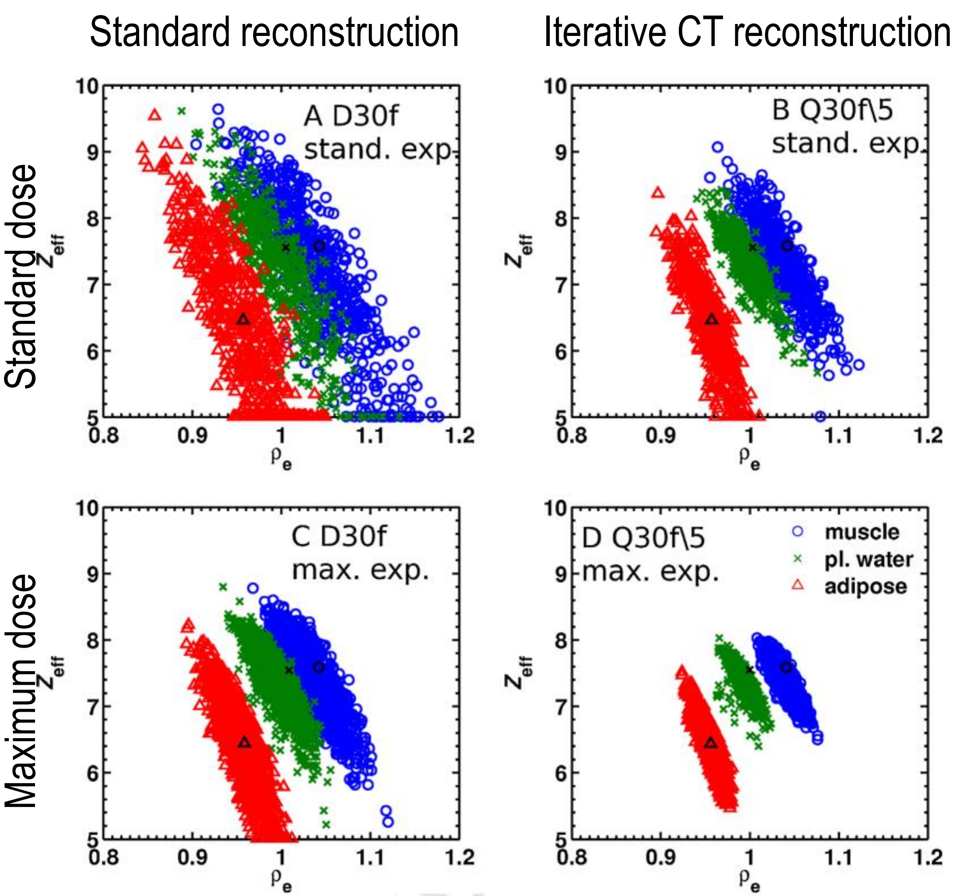


Courtesy: Guillaume Landry, LMU

Hudobivnik et al. Med Phys 2016

Remark: Uncertainties of DECT imaging

- Electron density images are relatively robust
  - $\rho_e = a \frac{[(1+\alpha)HU_H - \alpha HU_L]}{1000} + b$
- Z images can be noisy
  - proportional to ratio:
    $$\frac{HU_L/1000+1}{HU_H/1000+1} = \frac{1+AZ_{eff}^{m-1}}{B+CZ_{eff}^{m-1}}$$
  - noise can mask benefit of extra dimension
  - difficult to separate soft tissues



- Iterative CT reconstruction and increased dose (mAs) reduce uncertainties.

Landry et al. Z Med Phys 2016

Conclusion & Future perspectives for Dual Energy CT for RT

- Improved dose calculations
  - Photons probably no huge benefit, although if DECT is available it simplifies the procedure for electron density estimation
  - For brachytherapy (material classification) and proton therapy (better SPR estimation) improvements are expected; need to be quantified
- Improved imaging
  - Mono-energetic reconstructions allow optimal contrast for visualisation and specific Dual Energy CT protocols for RT need to be developed and optimized

  → subjective image quality improvements need to be quantified for reduction in delineation uncertainty (margins!)
  - 'Functional imaging': quantification/monitoring perfusion of tumor and normal tissue → still in development phase

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  - Bart Reymen
  - Karen Zegers
  - Aniek Even
  - Isabel de Almeida
  - Prof. Frank Verhaegen
  - Prof. Philippe Lambin
  - Prof. Dirk De Ruysscher

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  - Marco Das
  - Prof. Joachim Wildberger
- LMU (Munich)
  - Guillaume Landry

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