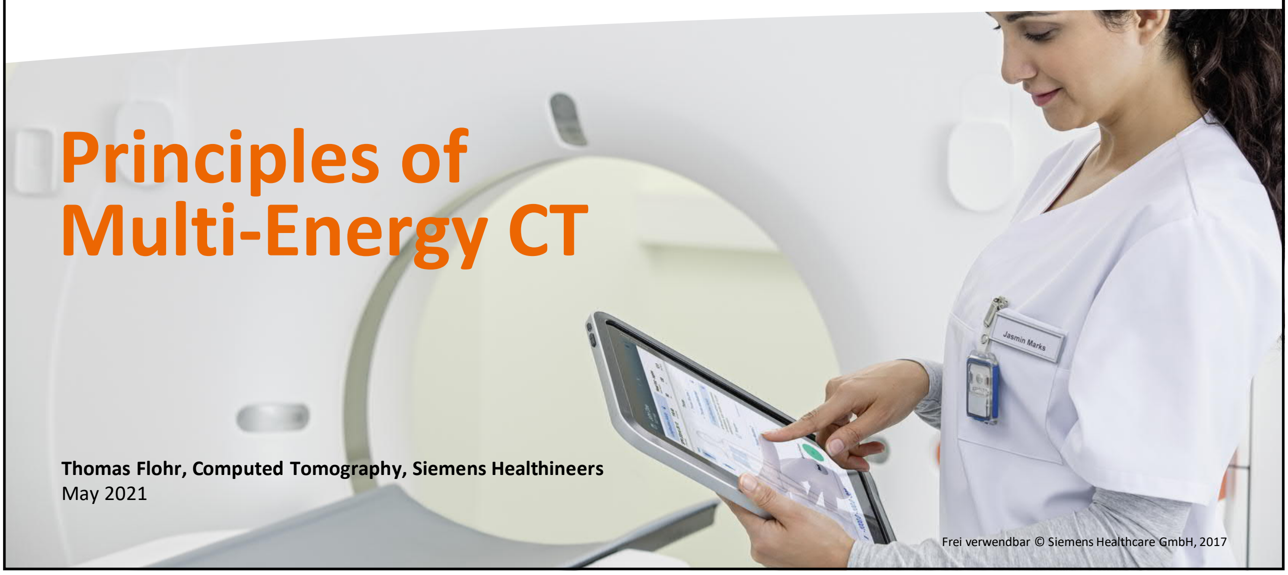
Principles of Multi-Energy CT



Thomas Flohr, Computed Tomography, Siemens Healthineers
May 2021

1

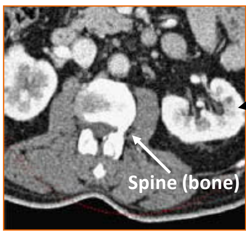
Dependence of x-ray attenuation on Z_{eff}, density and x-ray energy

x-ray attenuation

- x-ray attenuation $\boldsymbol{\mu}$ depends on effective atomic number $\boldsymbol{Z_{eff}}$, density $\boldsymbol{\rho}$ and x-ray energy $\boldsymbol{E}$
- Introducing the mass attenuation coefficient $\left(\frac{\mu}{\rho}\right)(E, Z_{eff})$ we obtain

$$\mu = \rho \cdot \left(\frac{\mu}{\rho}\right)(E, Z_{eff})$$

- Different materials with different mass attenuation coefficients $\left(\frac{\mu}{\rho}\right)(E, Z_{eff})$ can have the same attenuation coefficient $\boldsymbol{\mu}$ in a CT scan depending on the value of the mass density $\boldsymbol{\rho}$!
- Example: Bones and iodine filled vessels in a CT scan with iodinated contrast agent



Kidney with iodinated contrast agent

HC DI CT

2

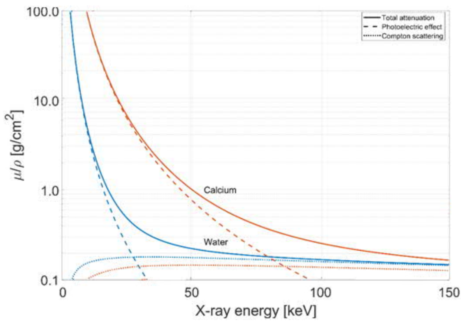
Dependence of x-ray attenuation on Z_{eff}, density and x-ray energy

x-ray attenuation

- Two different absorption mechanisms dominate in the x-ray energy range of CT
  - **Photoelectric effect** $\left(\frac{\mu}{\rho}\right)_p (E,Z) \sim \frac{{Z_{eff}}^4}{E^3}$

    Dominates at low energies
    The more dominant the higher the atomic number $\boldsymbol{Z_{eff}}$
  - **Compton effect** $\left(\frac{\mu}{\rho}\right)_c (E,Z) \sim Z_{eff} \cdot f_{KN}(E)$

    Dominates at high energies
    $f_{KN}(E)$ (Klein-Nishina factor) is almost independent of ***E***



 HC DI CT

3

Dependence of x-ray attenuation on Z_{eff}, density and x-ray energy

x-ray attenuation

- The total mass attenuation coefficient is given by the sum of photoelectric effect and Compton effect

$$\left(\frac{\mu}{\rho}\right)(E, Z_{eff}) = a_p \left(\frac{\mu}{\rho}\right)_p (E, Z_{eff}) + a_c \left(\frac{\mu}{\rho}\right)_c (E, Z_{eff})$$

- The attenuation coefficient is then

$$\mu = \rho \cdot \left[a_p \left(\frac{\mu}{\rho}\right)_p (E, Z_{eff}) + a_c \left(\frac{\mu}{\rho}\right)_c (E, Z_{eff})\right] = \rho \cdot \left[a_p \frac{{Z_{eff}}^4}{E^3} + a_c Z_{eff} \cdot f_{KN}(E)\right]$$

- a_p and a_c are constants for all energies and Z_{eff}'s !

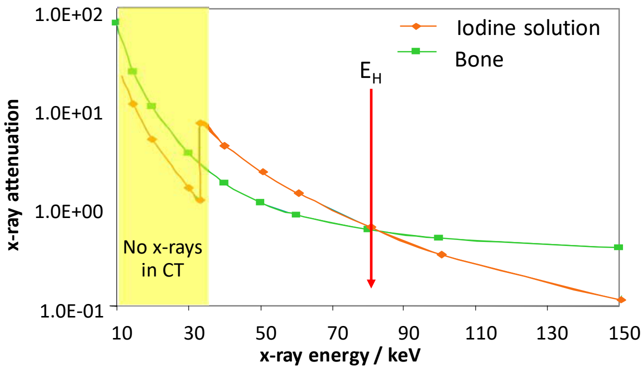
 HC DI CT

4

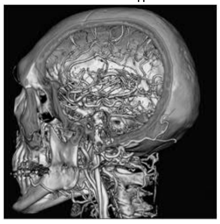
Principle of material separation by CT-scans at two x-ray energies

Why do we need dual energy CT?

- Two different materials with different effective atomic number Z_{eff} and different density ρ can have the same x-ray attenuation at a certain x-ray energy E_H



Scan at E_H



Page 5

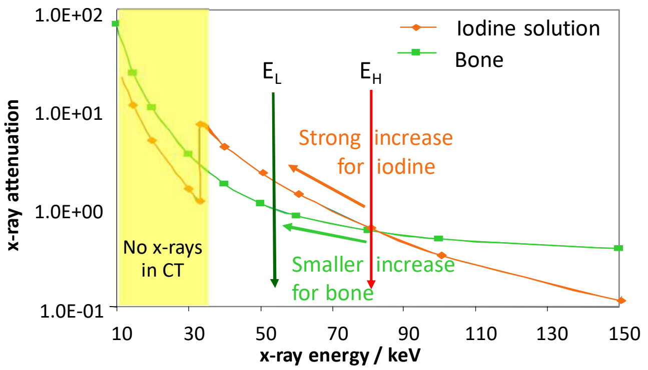
HC DI CT

5

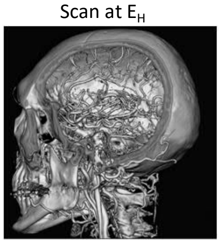
Principle of material separation by CT-scans at two x-ray energies

Why do we need dual energy CT?

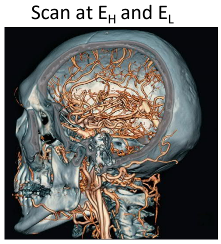
- Two different materials with different effective atomic number Z_{eff} and different density ρ can have the same x-ray attenuation at a certain x-ray energy E_H
- Increase of attenuation for lower x-ray energy depends on Z_{eff}
- **Scan at two energies E_L and E_H: Change of x-ray attenuation from high to low x-ray energy characterizes the material**



Scan at E_H



Scan at E_H and E_L



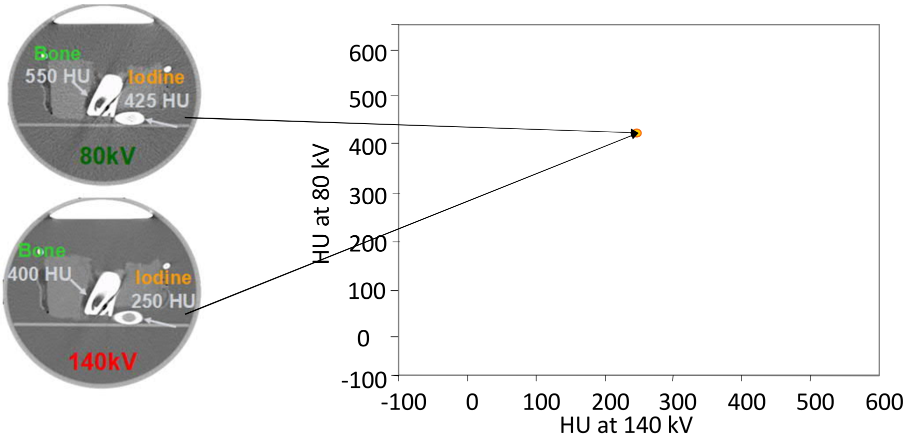
Page 6

6

Basic applications: differentiation of two materials A and B

Mixture of blood + iodine **and** bone + bone marrow **in a phantom experiment, scan at 80kV and at 140kV**

- Iodine: large CT-number difference in scans at two energies
- Bone: smaller CT-number difference in scans at two energies

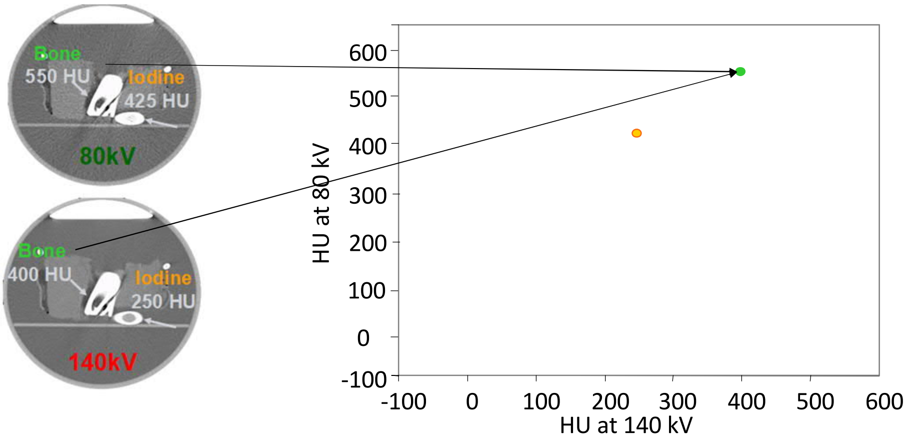


7

Basic applications: differentiation of two materials A and B

Mixture of blood + iodine **and** bone + bone marrow **in a phantom experiment, scan at 80kV and at 140kV**

- Iodine: large CT-number difference in scans at two energies
- Bone: smaller CT-number difference in scans at two energies

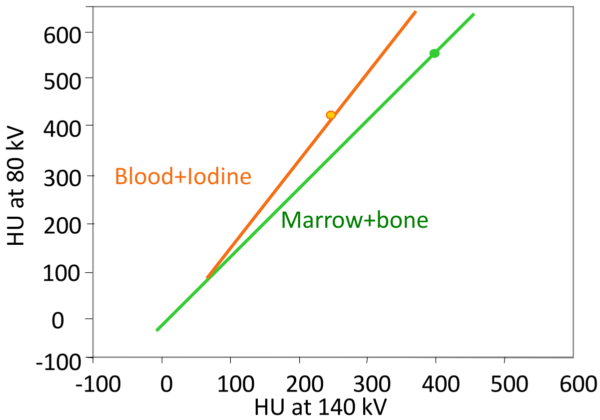


8

Basic applications: differentiation of two materials A and B

Mixture of blood + iodine and bone + bone marrow in a phantom experiment, scan at 80kV and at 140kV

- Iodine: large CT-number difference in scans at two energies
- Bone: smaller CT-number difference in scans at two energies

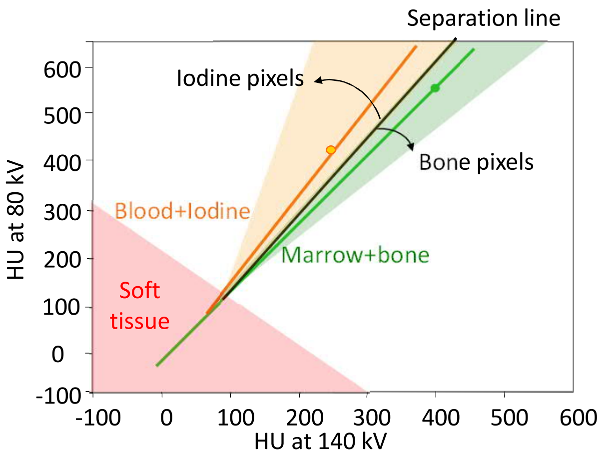


9

Basic applications: differentiation of two materials A and B

Mixture of blood + iodine and bone + bone marrow in a phantom experiment, scan at 80kV and at 140kV

- Iodine: large CT-number difference in scans at two energies
- Bone: smaller CT-number difference in scans at two energies



10

Basic applications: differentiation of two materials A and B

Mixture of blood + iodine and bone + bone marrow in a phantom experiment, scan at 80kV and at 140kV

- Iodine: large CT-number difference in scans at two energies
- Bone: smaller CT-number difference in scans at two energies

CTA

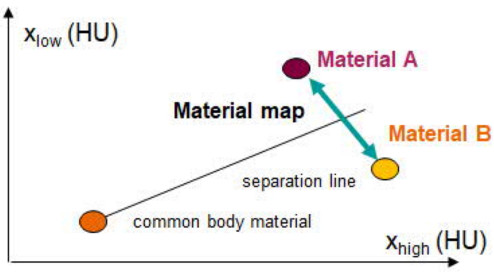
DSA

Dual energy CT
Plaque removal

Courtesy of PUMC, Beijing, China

Basic applications: differentiation of two materials A and B

Differentiation of two materials:
an image pixel is either material A or material B



Clinically relevant applications

- Automatic bone removal (iodine versus calcium)
- Characterization of kidney stones (uric acid versus calcium)
- Characterization of gout (uric acid)

Basic applications: imaging of electron density and effective atomic number

Computation of ρ - and Z_{eff} - images

- The attenuation coefficient is

Known parameters

$$\mu = \rho \cdot \left[a_p \frac{Z_{eff}^{\ 4}}{E^3} + a_c Z_{eff} \cdot f_{KN}(E)\right] = \boxed{\frac{a_p}{E^3}} \cdot \rho\, Z_{eff}^{\ 4} + \boxed{a_c\, f_{KN}(E)} \cdot \rho Z_{eff}$$

- Assume measurements of μ in CT-images aquired at two different x-ray energies E_L and E_H (for simplification we assume monochromatic x-rays)

$$\mu_L = \frac{a_p}{E_L^{\ 3}} \cdot \rho\, Z_{eff}^{\ 4} + a_c\, f_{KN}(E_L) \cdot \rho Z_{eff}$$

$$\mu_H = \frac{a_p}{E_H^{\ 3}} \cdot \rho\, Z_{eff}^{\ 4} + a_c\, f_{KN}(E_H) \cdot \rho Z_{eff}$$

- We know a_p, a_c and $f_{KN}(E)$ and can solve these two equations for the two unknowns ρ and Z_{eff}

Basic applications: imaging of electron density and effective atomic number

Computation of ρ - and Z_{eff} - images: detection of explosives with baggage scanners

- Explosives are characterized by high density ρ ~ 1.5 g/cm³
  low atomic number Z_{eff} ~ 7 - 8

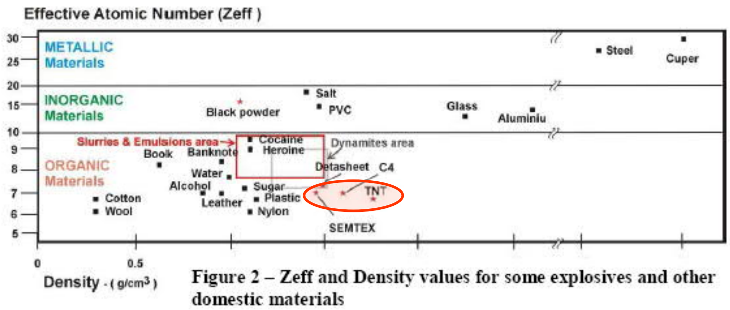


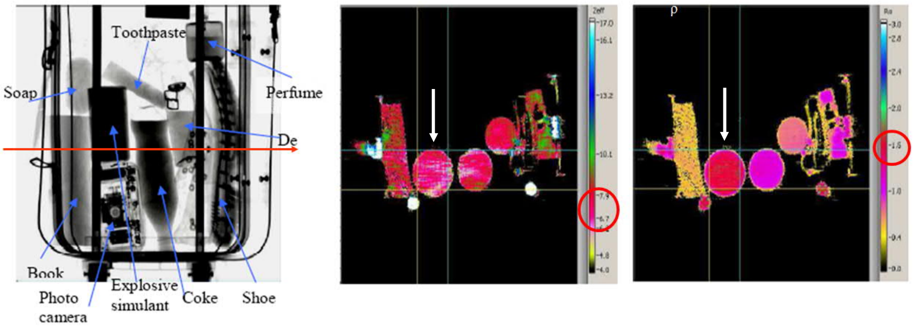
Figure 2 – Zeff and Density values for some explosives and other domestic materials

M. Iovea, High Accuracy X-Ray Dual-Energy Experiments ..for Explosives Detection Techniques in Luggage Control, DIR Symposium Digital Industrial Radiology and Computed Tomography, June 2007, Lyon, France

Basic applications: imaging of electron density and effective atomic number

Computation of ρ - and Z_{eff} - images: detection of explosives with baggage scanners

- Explosives are characterized by high density ρ ~ 1.5 g/cm^3
  low atomic number Z_{eff} ~ 7 - 8



M. Iovea, High Accuracy X-Ray Dual-Energy Experiments ..for Explosives Detection Techniques in Luggage Control, DIR Symposium Digital Industrial Radiology and Computed Tomography, June 2007, Lyon, France

Basic applications: computation of base material images

Two-material decomposition into two base materials A and B of unknown densities ρ_A and ρ_B

- The pure physics representations— photoelectric and Compton effects—do not provide a direct linkage to human anatomy, pathology, or physiology.
- Alternatively, $\left(\frac{\mu}{\rho}\right)$ of any material can be decomposed into a linear combination of $\left(\frac{\mu}{\rho}\right)_A$ and $\left(\frac{\mu}{\rho}\right)_B$ for two base materials A and B, which differ in their photoelectric and Compton characteristics.
- The attenuation coefficient is then

$$\mu(E) = \rho_A \left(\frac{\mu}{\rho}\right)_A (E) + \rho_B \left(\frac{\mu}{\rho}\right)_B (E)$$

- Suitable **base materials A** and **B** are **water** and **calcium**, or **water** and **iodine**

Basic applications: computation of base material images

Two-material decomposition into two base materials A and B of unknown densities ρ_A and ρ_B

- Assume measurements of µ in CT-images aquired at two different x-ray energies E_L and E_H (for simplification we assume monochromatic x-rays)

$$\mu(E_L) = \rho_A \left(\frac{\mu}{\rho}\right)_A (EL) + \rho_B \left(\frac{\mu}{\rho}\right)_B (E_L)$$

$$\mu(E_H) = \rho_A \left(\frac{\mu}{\rho}\right)_A (EH) + \rho_B \left(\frac{\mu}{\rho}\right)_B (E_H)$$

- $\left(\frac{\mu}{\rho}\right)_A$ and $\left(\frac{\mu}{\rho}\right)_B$ are available from tabulated values for all chemical elements indexed by their atomic number.

  The United States National Institute of Standards and Technology (NIST) hosts the constantly updated XCOM source at www.nist.gov

- **These two equations can be solved for the two unknown densities ρ_A and ρ_B of the base materials A and B**

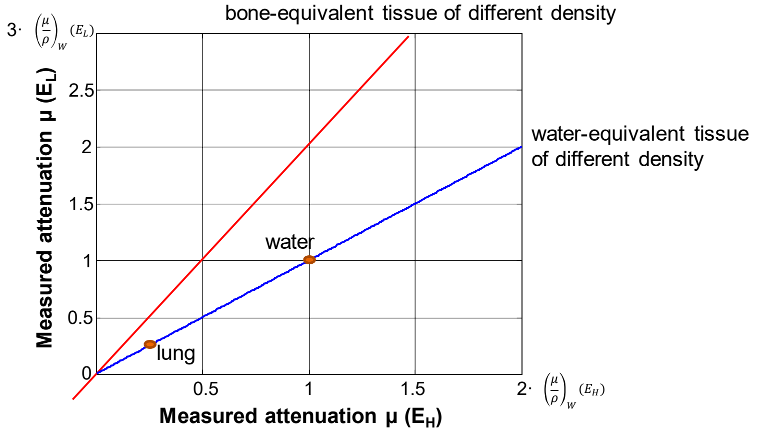
 HC DI CT

17

Basic applications: computation of base material images

Two-material decomposition into two base materials A and B of unknown densities ρ_A and ρ_B

- **Intuitive graphical solution for „image-based two material decomposition", base materials water and bone**



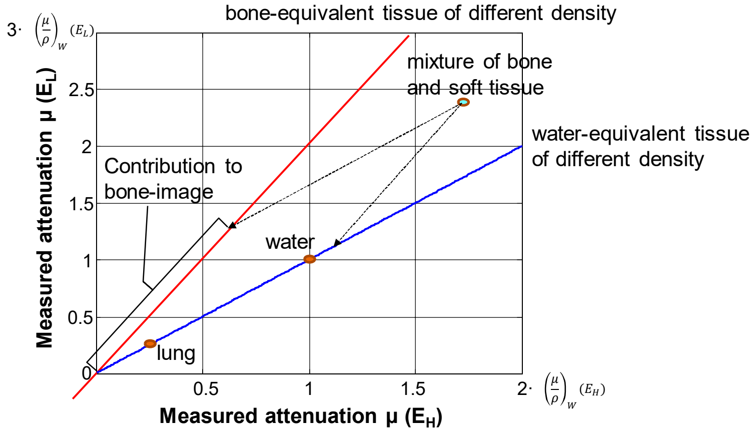
 HC DI CT

18

Basic applications: computation of base material images

Two-material decomposition into two base materials A and B of unknown densities ρ_A and ρ_B

- **Intuitive graphical solution for „image-based two material decomposition", base materials water and bone**



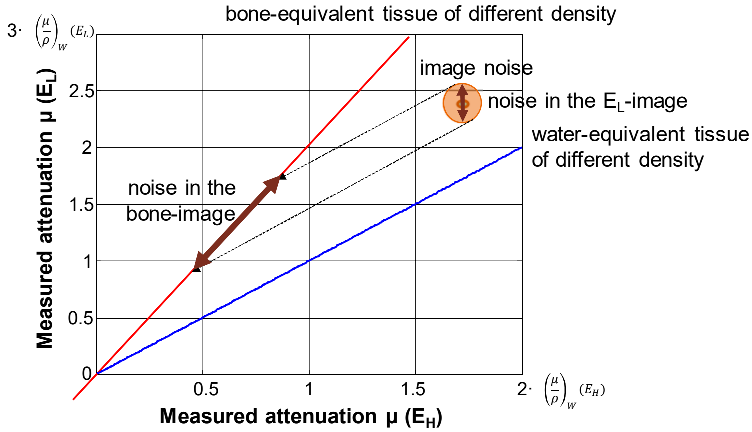
 HC DI CT

19

Basic applications: computation of base material images

Two-material decomposition into two base materials A and B of unknown densities ρ_A and ρ_B

- **Intuitive visualization of noise-amplification in the base material images**



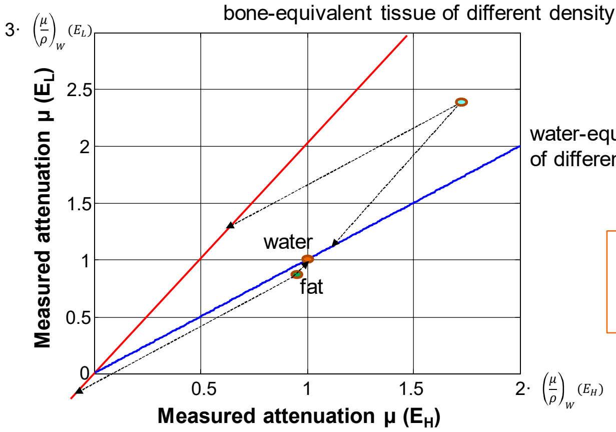
 HC DI CT

20

Basic applications: computation of base material images

Two-material decomposition into two base materials A and B of unknown densities ρ_A and ρ_B

- **What happens to materials outside the bone-water coordinate system?**



Fat shows up with negative density in the bone image!

 HC DI CT

Basic applications: computation of base material images

Two-material decomposition into two base materials A and B of unknown densities ρ_A and ρ_B

- **Material decomposition can be performed in the image space (as shown) and in the raw-data space**
- Using base materials A and B, and assuming the object only consists of a mixture of the two base materials, the measured line integrals L can be expressed as a linear combination

$$\mathrm{L}(E_L) = \rho_A\, d_A \cdot \left(\frac{\mu}{\rho}\right)_A (EL) + \rho_B d_B \cdot \left(\frac{\mu}{\rho}\right)_B (E_L)$$

$$\mathrm{L}(E_H) = \rho_A\, d_A \cdot \left(\frac{\mu}{\rho}\right)_A (EH) + \rho_B d_B \cdot \left(\frac{\mu}{\rho}\right)_B (E_H)$$

d_A and d_B are the path lengths of the two base materials along the x-ray

- **These two equations can be solved for $\rho_A d_A$ and $\rho_B d_B$ to generate material specific raw-data**

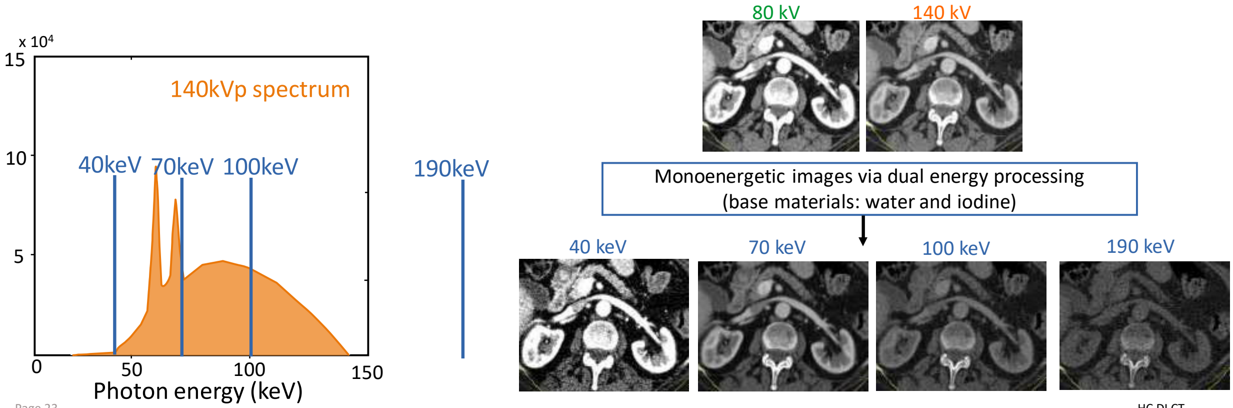
$\mathrm{L}_A(E) = \rho_A\, d_A \cdot \left(\frac{\mu}{\rho}\right)_A (E)$ **and** $\mathrm{L}_B(E) = \rho_B\, d_B \cdot \left(\frac{\mu}{\rho}\right)_B (E)$ **to reconstruct material-specific images**

 HC DI CT

Basic applications: computation of virtual monoenergetic images

Images at user-selectable "virtual" energies, e. g. in the range from 40 keV to 190 keV

- Derived from a **two-material decomposition into water and iodine images**
- Iodine and water images are **scaled to represent the attenuation of iodine and water at the selected keV** and added
- keV-dependency of other materials (e. g. Ca) may not be correct



 HC DI CT

23

Computation of three-material images with a boundary condition

Three-material decomposition into three materials with known densities ρ, but unknown volume fractions

- Three materials can only be differentiated by assuming an additional boundary condition, e. g. volume conservation, to solve two equations with three unknowns
- With f_A, f_B, and f_C as the volume fractions of materials A, B, and C, volume conservation implies $f_A + f_B + f_C = 1$

- The attenuation coefficient of the mixture is then

$$\mu(E) = f_A \rho_A \left(\frac{\mu}{\rho}\right)_A (E) + f_B \rho_B \left(\frac{\mu}{\rho}\right)_B (E) + (1 - f_A - f_B) \rho_C \left(\frac{\mu}{\rho}\right)_C (E)$$

- **Different from two-material composition into two base materials with unknown densities, we now assume base materials with known densities and can solve for the volume fractions** f_A, f_B, and $f_C = 1 - f_A - f_B$

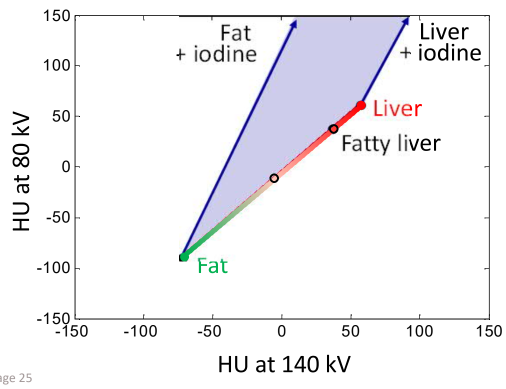
 HC DI CT

24

Computation of three-material images with a boundary condition

Special, but relevant case: two materials with known density and unknown volume fractions f_A and $f_B = 1 - f_A$ plus one material of unknown density ρ with very high absorption coefficient and negligible volume fraction (e. g. iodine)

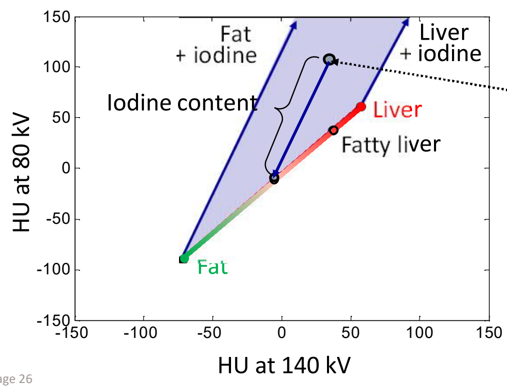
- **Differentiation and quantification of fat, liver and iodine**

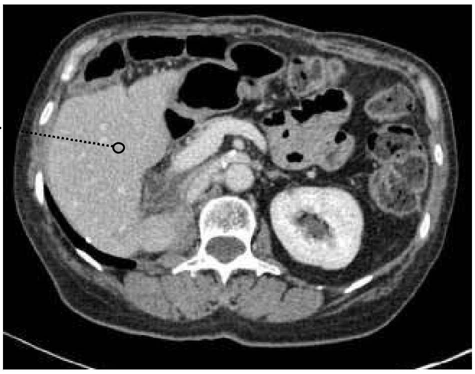


Computation of three-material images with a boundary condition

Special, but relevant case: two materials with known density and unknown volume fractions f_A and $f_B = 1 - f_A$ plus one material of unknown density ρ with very high absorption coefficient and negligible volume fraction (e. g. iodine)

- **Differentiation and quantification of fat, liver and iodine**

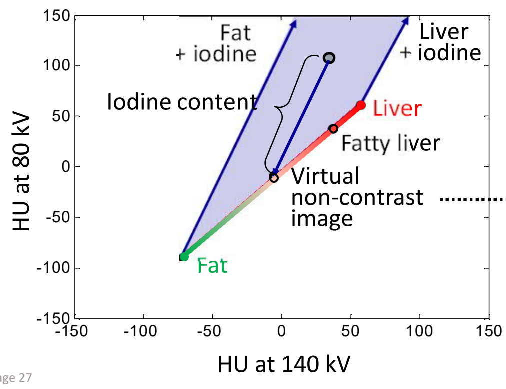




Computation of three-material images with a boundary condition

Special, but relevant case: two materials with known density and unknown volume fractions f_A and $f_B = 1 - f_A$ plus one material of unknown density ρ with very high absorption coefficient and negligible volume fraction (e. g. iodine)

- **Differentiation and quantification of fat, liver and iodine**

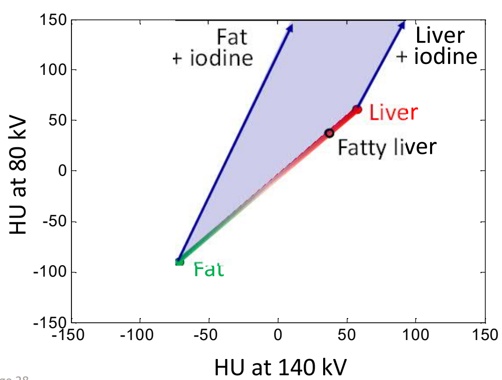


HC DI CT

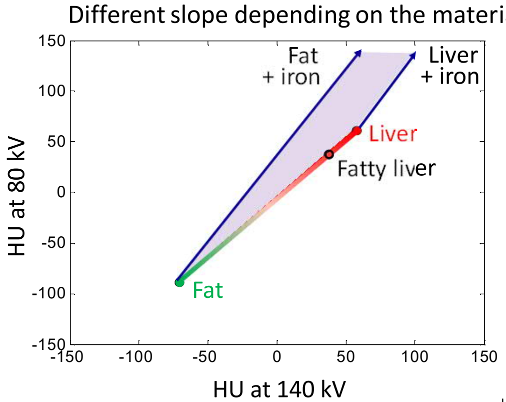
Computation of three-material images with a boundary condition

The modified three-material decomposition can be extended to other materials as well:

- **Differentiation and quantification of fat, liver and ~~iodine~~ iron**



Different slope depending on the material!

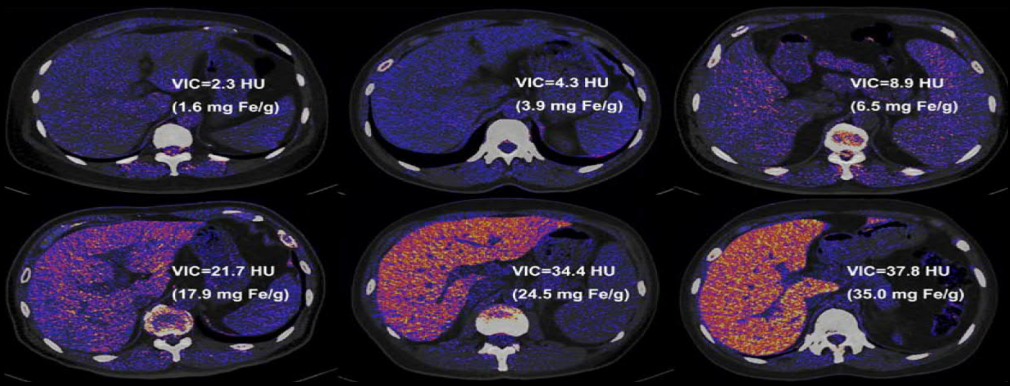


HC DI CT

Computation of three-material images with a boundary condition

Assessment of iron concentration in the liver; quantification in mg/cm³ by DE DSCT

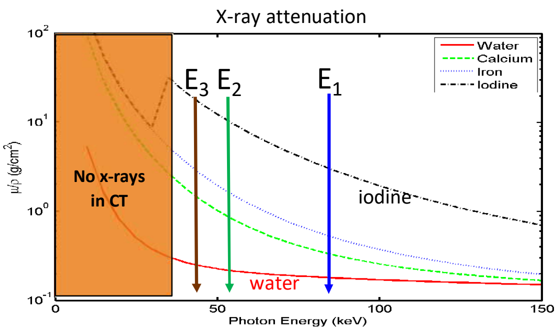
- Iron map and virtual non-iron image by decomposition into iron, fat and liver



Courtesy of Xian Fu Luo, Ruijin Hospital, China

29

Is there a need for data acquisition with more than energies?



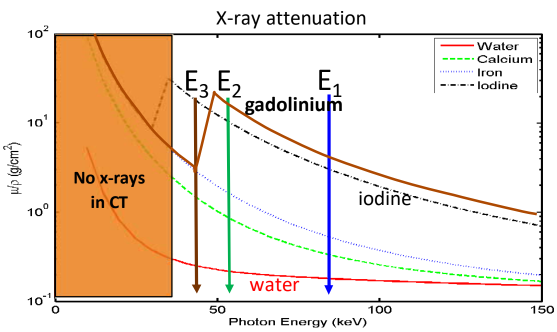
N energies = N materials?

- No! Only two basic interaction mechanisms in the relevant x-ray energy range of CT (40 – 150 keV)!

Page 30 HC DI CT

30

Is there a need for data acquisition with more than energies?



N energies = N materials?

- No! Only two basic interaction mechanisms in the relevant x-ray energy range of CT (40 – 150 keV)!

How to differentiate 3 (or more) materials?

- **K-edge needed!**
- Measurement at 3 (or more) energies
  → Base materials e. g. water and iodine + **material with a k-edge** in the relevant CT energy range, e. g. gadolinium (K-edge 50.2 keV**)**

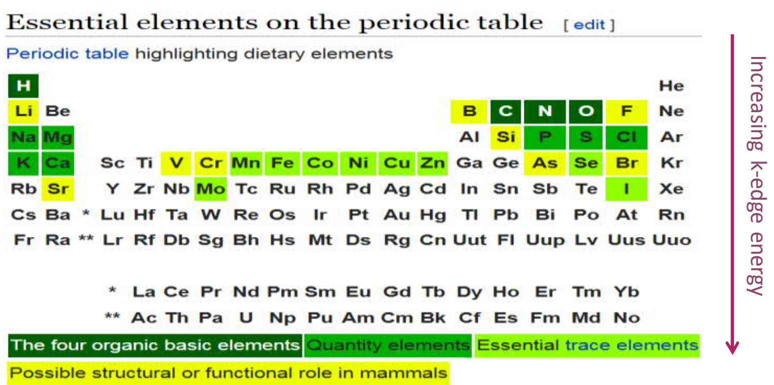
$$\mu(x,E) = a_{photo}(x)\frac{1}{E^3} + a_{compton}(x) f_{KN}(E) + a_{K-edge}(x) f_{K-edge}(E)$$

Photon-counting detectors can provide CT data at more than 2 energies!

Page 31 HC DI CT

31

Is there a need for data acquisition with more than energies?



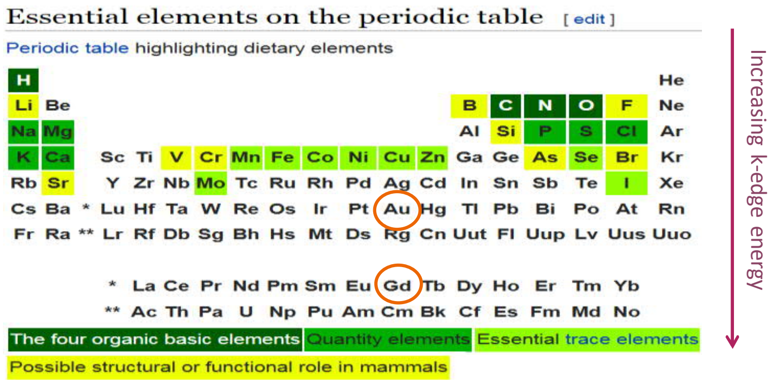
- Elements naturally found in the human body have k-edges below the relevant x-ray energies in CT (40 – 150 keV**)**
- This includes iodine in contrast enhanced scans (k-edge 33.2 keV)

→ Only two energy levels are needed for spectral CT in clinical routine

Page 32 https://en.wikipedia.org/wiki/Composition_of_the_human_body HC DI CT

32

Is there a need for data acquisition with more than energies?



- Relevant elements with higher k-edge: Gd 50.2 keV, Au 80.7 keV
- Only used in experimental applications, e. g. Au-nanoparticles

→ **Measurements at three or more energies may identify additional element with a k-edge → photon counting CT**

Page 33 https://en.wikipedia.org/wiki/Composition_of_the_human_body HC DI CT

33

SIEMENS Healthineers

Thank you!

34