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Basic Principles of Dual Energy CT

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Basic Principles of Dual Energy CT

- Physics of Dual Energy CT
- Technical Implementations
- Applications and Trends

following the Learning Objectives stated in the program

Historical Notes on Multi Energy CT

- Multi and Dual Energy (DE) x-ray imaging were hot topics in the 1970s and 1980s including 3-kV k-edge subtraction angiography, computed tomography (DECT), digital subtraction angiography (DEDSA) x-ray absorptiometry (DEXA), and digital radiography (DEDR).
- There was only one DECT product in the past. It was in use at several 100 sites in the 1980s and aimed primarily at densitometry.

The New Horizon: μ(x.y,E) → μ(x,y,z,E,t)

Dual energy methods exploit the differences in the mass attenuation coefficients of different materials as a function of energy.

Two approaches are generally used:

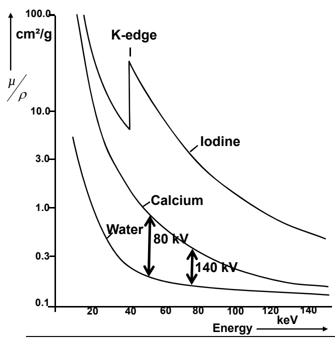
- Energy Subtraction, a weighted subtraction of images taken at two different energies

Dual Energy DSA 1982
Courtesy of C. Mistretta

- Basis Material Decomposition, decomposition of the measured data or images into contributions due to the two so-called "basis materials"

Dual Energy DR 1986
Courtesy of W. Bautz

Mass Attenuation Coefficients as a Function of Energy



Energy	Mass attenuation coefficient		
keV	cm²/g		
	Water	Calcium	Iodine
30	0.371	3.971	8.45
40	0.267	1.804	22.10
60	0.205	0.651	7.55
80	0.183	0.361	3.49
100	0.171	0.254	1.94
150	0.150	0.167	0,71

Principle of Basis Material Decomposition

- The attenuation coefficient μ of any material x can be represented as a linear combination of two linearly independent functions, e.g. the Compton effect and the photoelectric effect.

$$\mu_x(E) = c_1\sigma(E) + c_2\tau(E)$$

- Just the same, attenuation can be assigned to two basis materials, e.g. water and calcium, with sufficiently different atomic numbers *Z*.

$$\mu_x(E) = c_1(\mu/\rho)_1(E) + c_2(\mu/\rho)_2(E)$$

Alvarez RE, Macovski A. Phys Med Biol 1976; 21:733-744

Principle of Basis Material Decomposition

The attenuation for objects of any composition can be reduced to

$$\int \mu(\vec{r},E)\,ds = (\mu/\rho)_1(E)\cdot\delta_1 + (\mu/\rho)_2(E)\cdot\delta_2$$

with the line integrals over the so-called basis material-equivalent area densities

$$\delta_i = \int \rho_i(\vec{r})\,ds$$ **for i = 1,2**

Principle of Basis Material Decomposition

A. Measure attenuation at 2 energies

→ the 2 attenuation values $q_L(E)$ and $q_H(E)$

$$q_H(E) = -\ln \int w_H(E)\cdot e^{-\left(\frac{\mu}{\rho}\right)_1(E)\cdot\int\rho_1(r)\,ds-\left(\frac{\mu}{\rho}\right)_2(E)\cdot\int\rho_2(r)\,ds}\,dE$$

$$q_L(E) = -\ln \int w_L(E)\cdot e^{-\left(\frac{\mu}{\rho}\right)_1(E)\cdot\int\rho_1(r)\,ds-\left(\frac{\mu}{\rho}\right)_2(E)\cdot\int\rho_2(r)\,ds}\,dE$$

B. Solve the system of 2 equations for each ray

→ the 2 unknown basis material values $\delta_i = \int \rho_i(\vec{r})\,ds$

C. Reconstruct 2 basis material density images ρ_1 and ρ_2

Kalender WA et al. Med Phys 1986; 13:334-339

Tissue Parameters derived from Basis Material Density values

Electron Density

$$\rho_e = \left(\frac{Z_1}{A_1}\cdot\rho_1 + \frac{Z_2}{A_2}\cdot\rho_2\right)\cdot N_A$$

Note:
pdf-version for download
www.imp.uni-erlangen.de

Effective Atomic Number

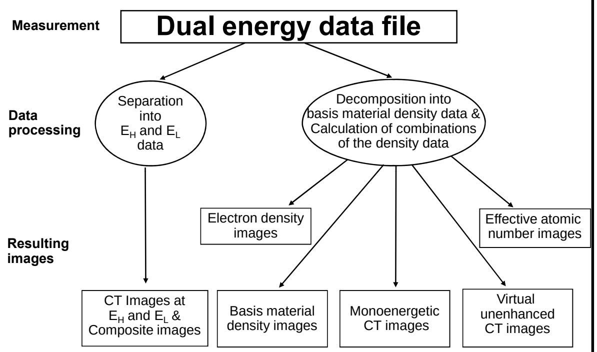
$$Z_{eff} = \left[\left(\frac{Z_1}{A_1}\cdot\rho_1 + \frac{Z_2}{A_2}\cdot\rho_2\right)^{-1}\cdot\left(\frac{Z_1}{A_1}\cdot\rho_1\cdot Z_1^x + \frac{Z_2}{A_2}\cdot\rho_2\cdot Z_2^x\right)\right]^{1/x}$$

Monoenergetic CT values

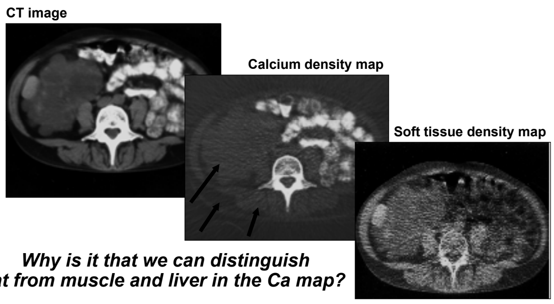
$$\mu(E_0) = (\mu/\rho)_1(E_0)\cdot\rho_1 + (\mu/\rho)_2(E_0)\cdot\rho_2$$

Z_i - atomic number; A_i – mass number; N_A - Avogadro's number

Kalender WA et al. Digit Bilddiagn 1987; 7:66-72



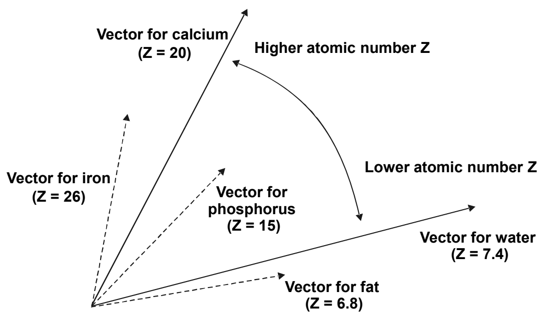
Dual Energy CT
offers information on tissue composition



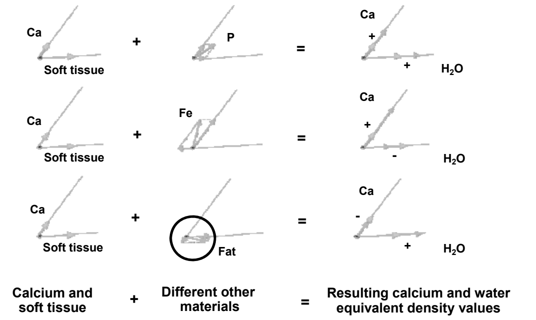
Why is it that we can distinguish fat from muscle and liver in the Ca map?

Kalender WA et al. Radiology 1987; 164:419-423

Representation of arbitrary materials as vectors in the plane of the two basis materials, in this case for calcium and water



Resulting Calcium and Water Equivalent Density Values for Different Materials



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Technical Implementations of DECT

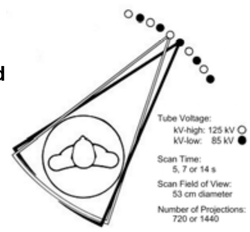
- 1970s: Two separate scans
- 1980s: Rapid kV-switching
- 1990s: Novel detectors
- 2000s: Dual source CT
- 2010s: Spectral CT
- At present
- In the future

Technical Implementations of DECT

- 1970s: Two separate scans
  e.g. xxxham, 1978
- 1980s: Rapid kV-switching

Data at high and low voltage values are obtained during one scan

(product solution: Siemens SOMATOM DR 3; ca. 1984-1989)



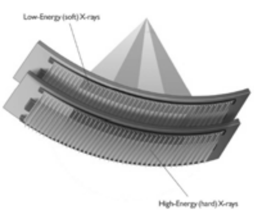
Technical Implementations of DECT

- 1990s: Novel detectors
  experimental work on
  - sandwich detectors
  - energy-discrimination detectors

Example of a sandwich detector

It provides attenuation values for two different mean energies

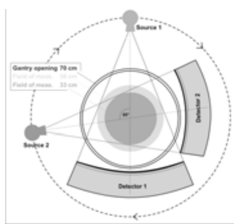
Source of figure: Philips Healthcare



Technical Implementations of DECT

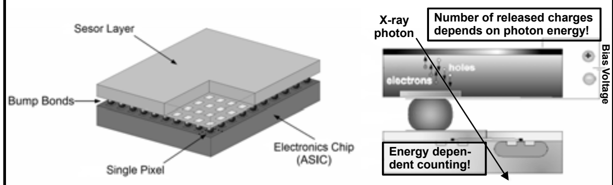
- 2000s: Dual source CT
  obtain data at high and low voltage values simultaneously in a single scan with the possibility to choose two different current and filtration values

Sketch of a dual-source CT setup (Siemens Definition Flash)



Technical Implementations of DECT

- **2010s: Spectral CT**
  obtain data for multiple energy intervals during a single scan by using an energy-discriminating detector



(Courtesy of ECAP, Physikalisches Institut, Friedrich Alexander University, Erlangen)

Technical Implementations of DECT

- 1970s: Two separate scans
- 1980s: Rapid kV-switching
- 1990s: Novel detectors
- 2000s: Dual source CT
- 2010s: Spectral CT
- At present: All of the above

GE	rapid kV-switching
Philips	Novel detectors (work in progress)
Siemens	Dual source CT
Toshiba	Two separate scans

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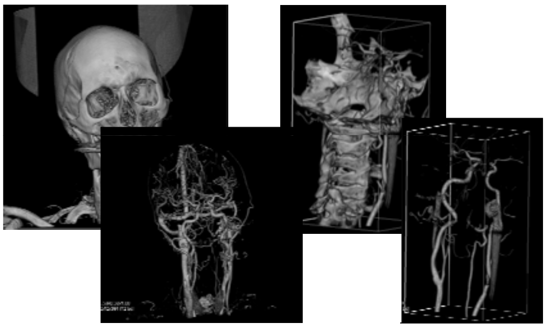
Dual Energy CT Applications

approved by the FDA 2007

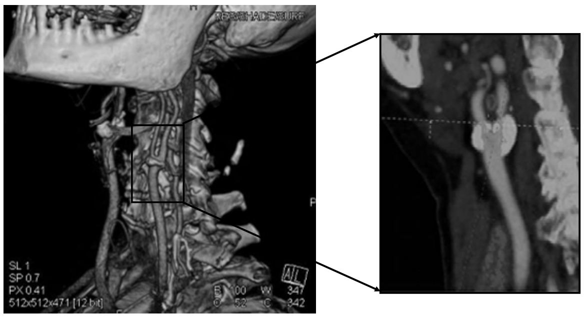
1. Direct subtraction of bone
2. Differentiation between plaque and contrast agent
3. Virtual unenhanced abdominal organ imaging
4. Kidney stone characterization
5. Visualization of cartillage, tendons, ligaments
6. Evaluation of lung perfusion defects
7. Heart perfusion blood volume
8. Uric acid crystal visualization
9. Lung vessel emblisation
10. Brain hemorrhage differentiation

Dual Energy CT: 1. Direct Bone Removal



Courtesy of C. Becker, Munich, Germany

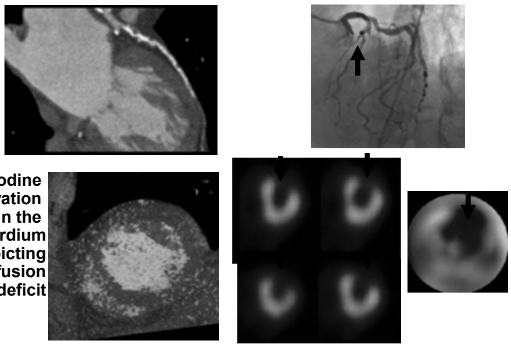
Dual Energy CT: 2. Differentiation between hard plaques and contrast



Courtesy of F.Civaia, Centre Cardiothoracique de Monaco

Dual Energy Functional Imaging vs. SPECT

Iodine concentration in the myocardium depicting perfusion deficit



Courtesy of J. Schoepf, Charleston, SC, USA (Circulation, in press)

Summary

- Dual Energy CT is based on two measurements at different energies and provides additional tissue parameters, but not spectroscopic features.
- There are four technical implementations at present; dual source CT and novel detector designs appear most promising.
- The number of applications is still increasing. Dose statements will depend on the parameters and the application. Virtual non-contrast imaging may allow for dose reduction.

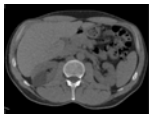


Image: Courtesy of T. Johnson, Munich, Germany