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 Horizons: \( \mu(x,y,E) \rightarrow \mu(x,y,z,E,t) \)

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

Principle of Basis Material Decomposition
• The attenuation coefficient \( \mu \) 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 \( Z \).

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

**Principle of Basis Material Decomposition**

The attenuation for objects of any composition can be reduced to

\[ I_p(E) = \left( \mu_i(\mu_i E) - \mu_0(\mu_i E) \right) A_i \]

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

\[ A_i = \int \rho_i(E) \, dz \]

for \( i = 1, 2 \)

**Tissue Parameters derived from Basis Material Density values**

Electron Density

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

Effective Atomic Number

\[ Z_{\text{eff}} = \left( \frac{Z_1 \cdot Z_1 + Z_2 \cdot Z_2}{A_1 + A_2} \right) = \left( \frac{Z_1 \cdot A_2 + Z_2 \cdot A_1}{A_1 + A_2} \right)^{1/2} \]

Monoenergetic CT values

\[ \rho_\text{mono}(E) = \left( \frac{\mu_\text{mono}(E)}{\mu_\text{mono}(E_0)} \right) \cdot \rho_1 + \left( \frac{\mu_\text{mono}(E)}{\mu_\text{mono}(E_0)} \right) \cdot \rho_2 \]

**Dual Energy CT offers information on tissue composition**

CT image

Calcium density map

Soft tissue density map

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

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

- Vector for calcium (\( Z = 20 \))
- Higher atomic number Z
- Vector for iron (\( Z = 26 \))
- Vector for phosphorus (\( Z = 15 \))
- Vector for water (\( Z = 7.4 \))
- Vector for fat (\( Z = 6.8 \))
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**Resulting Calcium and Water Equivalent Density Values for Different Materials**

\[
\begin{align*}
\text{Soft tissue: } & \text{Ca} + \text{P} = \text{Ca} + \text{H}_2\text{O} \\
\text{Soft tissue: } & \text{Ca} + \text{Fe} = \text{Ca} + \text{H}_2\text{O} \\
\text{Soft tissue: } & \text{Ca} + \text{Fat} = \text{Ca} + \text{H}_2\text{O}
\end{align*}
\]

Calcium and soft tissue + Different other materials = Resulting calcium and water equivalent density values

**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

**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

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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 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 cartilage, tendons, ligaments
6. Evaluation of lung perfusion defects
7. Heart perfusion blood volume
8. Uric acid crystal visualization
9. Lung vessel embolization
10. Brain hemorrhage differentiation
Dual Energy Functional Imaging vs. SPECT

Iodine concentration in the myocardium depicting perfusion deficit

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.

Thank you for your attention!

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Image: Courtesy of T. Johnson, Munich, Germany