Advanced Imaging Techniques
Dual Energy Computed Tomography

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Learning Goals

- introduction to CT imaging
  - basic CT principles -> Physics of Imaging Techniques

- Goals:
  1. How does the technique work?
  2. What kind of images do we receive?
  3. Where is this applied to?

- Slides of the lectures at
  https://www.umm.uni-heidelberg.de/inst/cbtm/ckm/lehre/index.html
References

- Slavic et al, Technology White Paper, GSI Xtream on RevolutionTM CT, 2017
X-Ray Properties: Attenuation

\[ I = I_0 e^{-\int \mu(s,E) ds} \]

\[ S = \int \mu ds = -\ln \left( \frac{I}{I_0} \right) \]

\( E_{\text{max}} = 70, \ldots, 140 \text{keV} \)
Photon Attenuation Effects

Inside a voxel volume...

\[ \mu_i(E, Z) = \rho \frac{n_i}{m_i} \left( \sigma_{\text{p},E}^i(E, Z_i) + \sigma_{\text{Compton}}^i(E, Z_i) \right) \]

Photoelectric effect
Compton effect

![Graphs showing photon energy absorption for different elements](image)

Photoelectric Effect
Photon Attenuation Cross-Section

Cortical Bone

Iodine

20 keV < \( E_v \) < 80 keV

Photon Attenuation Cross-Section

Cortical Bone

Iodine

60 keV < \( E_v \) < 140 keV
Photon Attenuation Ambiguity

\[ \rho = 1 \, \text{g/cm}^3 \]
\[ \rho = 1 \, \text{g/cm}^3 \]
\[ \rho = 0.1 \, \text{g/cm}^3 \]

\( \hat{\mu}_{\text{Bone}} < \hat{\mu}_{\text{Iodine}}^{\rho=0.1} \)
\( \hat{\mu}_{\text{Bone}} \approx \hat{\mu}_{\text{Iodine}}^{\rho=0.3} \)
\( \hat{\mu}_{\text{Bone}} > \hat{\mu}_{\text{Iodine}}^{\rho=0.1} \)

Photon Attenuation Ambiguity
Physics

- Attenuation/radiodensity:
  - Physical density (electron density)
  - Cross-section: Compton + photoelectric

- Measurement is ambiguous:
  - “Dense” Bone vs. “Thin” Iodine

→ Method to resolve: Dual-Energy CT

Dual-Energy CT

- Clinical Requirements:
  - No additional dose
  - Low cost
  - Universality
  - Diagnostic value

- Desired Properties:
  - Little spectral overlap
  - Temporally correlated
  - Good image quality (x2)
DECT: Components

- X-ray tube: Voltage, Current
- Filter/Collimation: Hardening, Filtering
- Bandwidth, Energy, Throughput, Attenuation
- Spectral separation
- Dose
- Image quality
- Efficiency, Resolution
- Spectral sensitivity

DECT: Implementations

- Sequential Scanning
- Rapid Voltage Switching
- Dual Source

- Multi-Layer Detector (not yet implemented clinically)
DECT: Sequential Scanning

Dose
Cost
Spectral overlap
Image quality
Temporal correlation

DECT: Rapid Voltage Switching

Dose
Cost
Spectral overlap
Image quality
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DECT: Rapid Voltage Switching

Slabic et al., 2017

DECT: Rapid Voltage Switching

Slabic et al., 2017

Prof. Dr. Zöllner | Slide 19 | 11/14/2018

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HEIDELBERG UNIVERSITY
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Computer Assisted Clinical Medicine
DECT: Dual Source

Dose (4.5–12.5 mSv)
Cost
Spectral overlap
Image quality
Temporal correlation

Dual Source CT
courtesy: Siemens Medical Solution, Erlangen
### Comparison of Dual Energy CT Imaging Devices

<table>
<thead>
<tr>
<th>Scanner Type</th>
<th>Hardware Description</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual-source dual-energy CT</td>
<td>Two x-ray sources, two detectors</td>
<td>Good spectral separation between high- and low-energy scans; easy to equilibrate dose and noise between high- and low-energy scans by modulating tube currents for each tube; attenuation in Hounsfield units can be measured on virtual unenhanced images</td>
<td>Limited temporal and spatial registration because two separate image datasets are acquired; maximum field of view for dual-energy acquisition is 33 cm; image-domain dual-energy decomposition limits flexibility</td>
</tr>
<tr>
<td>Dual-energy CT with fast kilovoltage switching</td>
<td>Single x-ray source, single detector</td>
<td>Good temporal and spatial registration; projection-space dual-energy decomposition offers greater flexibility, easy quantification of tissue density; 50-cm field of view</td>
<td>Limited spectral separation between high- and low-energy scans; higher noise on images obtained with lower peak voltage (because tube current cannot be modulated at the same time the peak voltage is altered); inability to measure attenuation on virtual unenhanced images</td>
</tr>
<tr>
<td>Multilayered-detector dual-energy CT</td>
<td>Single x-ray source, dual detector layers</td>
<td>Perfect temporal and spatial registration; projection-space dual-energy decomposition can be used</td>
<td>Limited energy separation with substantial spectral overlap</td>
</tr>
</tbody>
</table>

Ravi et al., Radiographics 2012

### Dual-Energy CT

- **Clinical Requirements:**
  - No additional dose
  - Low cost
  - Universality
  - Diagnostic value

- **Desired Properties:**
  - Little spectral overlap
  - Temporally correlated
  - Good image quality (x2)
DECT: Image Processing

- Dual energy CT offers two image informations of the same material
  - allows for material decomposition
  - blended images
  - virtual unenhanced images
  - monocromatic images

- Processing of DE images in
  - projection space
  - image space

DECT: Image Processing in Projection Space

- conventional X-ray source have a broad energy spectrum
- separate the attenuation coefficient into the contributions
  - from photoelectric effect and Compton scattering
- can be approximately modeled using
  - a material’s effective atomic number (Z_{eff})
  - effective mass density (r_{eff})
  - knowledge of the X-ray energy spectra (E)

- Alternative: attenuation coefficient, \( \mu \), can be expressed with sufficient accuracy as a linear combination of the photoelectric and Compton attenuation coefficients

\[
\mu(r, E) = \left( \rho_{\text{PE}}(E) \rho_1(r) + \rho_{\text{CS}}(E) \rho_2(r) \right)
\]
DECT: Image Processing in Projection Space

- DE signal can be written

\[
I_m = \int S_m(E) D(E) \exp \left\{-\left(\frac{\mu}{\rho}\right)_1 (E) \cdot L_1 - \left(\frac{\mu}{\rho}\right)_2 (E) \cdot L_2 \right\} dE
\]

with \( L_1 = \int dl \rho_1 (r) \) and \( L_2 = \int dl \rho_2 (r) \) represent the attenuation density line integrals for the two basis materials.

DECT: Image Based Processing
DECT: Image Based Processing

- simplest way to process dual-energy data
  - Perform a weighted subtraction or addition for the separately reconstructed images at different beam energies (i.e., image blending)
- low-voltage images (typically 80 kV) are multiplied by a weighting factor and subtracted from or added to the high-voltage images (140 kV) to obtain material-specific information
DECT: Image based processing – Types of Images

- **Blended Image**
  - nonmaterial-specific images generated from the dualenergy data to provide images for the purpose of routine diagnostic interpretation

- **Material-Selective Image**
  - differentiation between different atomic elements and therefore chemical compositions

- **Energy-Selective Image**
  - a pseudo monoenergetic image created at any desired energy

Blended Image

- combining the low- and high energy images, mixed images utilize all of the radiation doses delivered by the dual-energy scan
  - better image quality
  - Generating the highest iodine contrast to noise ratio (CNR)
- two types of image blending methods
  - linear and nonlinear
Blended Image

- **Linear blending**
  \[ I = w_L I_L + w_H I_H \]
  with \( w_L + w_H = 1 \).

- Increasing the blending ratio more toward the 80 kV image
  - Iodine contrast enhancement but more noise

- Increase towards high energy image
  - higher CNR and less noise

- Optimal settings for best settings exist

Blended Image

- **Non linear blending**
  - combine images by various weighting functions
  - e.g. modified sigmoidal blending
Material Decomposition / material selective image

- DE CT offers decomposition into two materials
- total mass attenuation coefficient of an object containing two constituent elements is the weighted summation of the two element's mass attenuation coefficients
- assume the dual-energy measurements are made with two monochromatic X-ray beams of high energy $E_H$ and low energy $E_L$

$$\mu_{\text{eff},L} = \rho_{\text{eff}} \left[ m_1 \left( \frac{\mu}{\rho} \right)_{1L} + (1 - m_1) \left( \frac{\mu}{\rho} \right)_{2L} \right],$$
$$\mu_{\text{eff},H} = \rho_{\text{eff}} \left[ m_1 \left( \frac{\mu}{\rho} \right)_{1H} + (1 - m_1) \left( \frac{\mu}{\rho} \right)_{2H} \right].$$
DECT: Image Based Processing

- effective linear attenuation coefficients $\mu_{\text{eff}}$ can be obtained from the dual-energy CT image data:
  $$\mu_{\text{eff}, L \text{ or } H} = \left( \frac{\text{CT Number}_{L \text{ or } H}}{1000} + 1 \right) \cdot \mu_{\text{water}, L \text{ or } H}$$

- perform chemical identification (i.e., material decomposition) based on previous equations using the reconstructed dual-energy images
  $$\mu_{\text{eff}, L} = \rho_{\text{eff}} \left[ m_1 \left( \frac{\mu}{\rho} \right)_L + (1 - m_1) \left( \frac{\mu}{\rho} \right)_{\text{H}, L} \right]$$
  $$\mu_{\text{eff}, H} = \rho_{\text{eff}} \left[ m_1 \left( \frac{\mu}{\rho} \right)_{\text{H}, L} + (1 - m_1) \left( \frac{\mu}{\rho} \right)_{\text{H}, H} \right]$$

DECT: Two Material Decomposition

![Diagram showing density at 80 kVp (HU) compared to density at 140 kVp (HU)]
DECT: Three “Material” Decomposition

- DECT can quantify 2 mass fraction → 2 independent measurements
- for 3 materials and 2 spectral measurements one need additional condition
- assume sum of volumes of the 3 materials is equivalent to the mass of the mixture
  \[ f_1 + f_2 + f_3 = 1 \]
- therefore effective density \( \rho_{eff} \)
  \[ \rho_{eff} = f_1 \rho_1 + f_2 \rho_2 + (1 - f_1 - f_2) \rho_3 \]
  \[ \mu_m = m_1 \mu_1 + m_2 \mu_2 + m_3 \mu_3 = \frac{1}{\rho_{eff}} (f_1 \rho_1 \mu_1 + f_2 \rho_2 \mu_2 + f_3 \rho_3 \mu_3) \]
Application - Angiogram Bone-Removal

Two material decomposition

+ 

Contrast material map

Application - Pulmonary Perfusion

Contrast Agent Map (Iodine based)
Application - Gout Diagnosis

calcium pyrophosphate crystal
uric acid

Virtual noncontrast- enhanced Images

Axial CE DE scan, mixed images shows subcapsular menatoma (*) and low attenuation lesions (arrow)
Virtual noncontrast-enhanced Images

Iodine overlay demonstrate iodine within one lesion indicating a metastasis, the other a hematoma

Atherosclerotic Plaque Removal
Dual-Energy CT Summary

- Two spectrally separated (simultaneous) CTs
- Exploits:
  - Lower E: Photo-effect regime
  - Higher E: Compton effect regime
- High-Z Material differentiation
- Multiple Applications in Radiology

Outlook/Honorable Mentions

- DECT for artifact reduction (beam hardening)
- Quantitative Use: Electron Density
- Other Technologies:
  - Multi-Layer Detector
  - Quantum detector → Multi-energy CT