Multi-Energy CT: Current status and recent innovations

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Multi-Energy CT: Current status and recent innovations
Basic concepts & current implementations
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Data and image analysis methods
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Clinical applications
Cynthia McCollough
Future directions
Taly Gilat Schmidt
Panel Discussion

Multi-Energy CT: Basic concepts & current implementations

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Motivation

Lower density or lower atomic number?

Motivation

Is the HU increase due to underlying tissue property or contrast agent?
Motivation

Can we separate iodine and calcium, or reduce blooming?

Attenuation coefficients depend on photon energy

use CT measurements at multiple energies to add material specificity

Motivation

“Two pictures are taken of the same slice, one at 100 kV and the other at 140 kV...so that areas of high atomic numbers can be enhanced... Tests carried out to date have shown that iodine (Z=53) can be readily differentiated from calcium (Z=20).”

OUTLINE

- Physical principles of multi-energy x-ray measurements
- Implementations
  - achieving spectral selectivity
  - obtaining multi-energy measurements
- Summary

attenuation and material identification

\[ I = I_0 e^{-\mu T} \]
\[ \mu T = \ln(I_0 / I) \]

measures product of \( \mu \) & \( T \)
not very material specific

unknown thickness two known materials

\[ I_1 = I_{01} e^{-(\mu_{w}t_w + \mu_{b}t_b)} \]
\[ I_2 = I_{02} e^{-(\mu_{w}t_w + \mu_{b}t_b)} \]
solve for \( t_w \) and/or \( t_b \)
**dual energy x-ray absorptiometry (DEXA)**

2 energies \(\Rightarrow\) 2 materials

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**material analysis with absorptiometry**

- 2 energies \(\Rightarrow\) 2 materials
- can we generalize this? N energies for N materials?
- limitation: two strong interaction mechanisms
  Compton scattering and photoelectric absorption
  Barring a K-edge in the spectrum, the energy dependence of each is the same for all elements!!

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**basis material decomposition:**

- Attenuation of any material is \(\sim\) a weighted sum of photoelectric and Compton functions
- Any material can be modeled as a weighted sum of two other materials (basis materials)
Basis material decomposition

\[ \text{.04 M grams of Cu} \]
\[ \text{.61 M grams of O} \]

\[ \text{Indistinguishable at any x-ray energy above their K-edge} \]

Common “basis functions”:
- iodine and water, aluminum and plastic
- photoelectric and Compton

Applications of Dual Energy CT

80/140kV Mixed Images for regular viewing
material analysis with absorptiometry

- 1 energy, constant thickness ⇒ 2 known materials
  (constant thickness is a constraint)
- 2 energies, unknown thickness ⇒ 2 known materials
- N energies, unknown thickness ⇒ still only 2 known materials
  (only 2 independent functions)
- 2 energies, constant thickness ⇒ 3 known materials
  (constant thickness (CT voxel) is a constraint)
**K-edges**

Very specific material information

**Noise**

Iodine data ~ $a \cdot \text{Data}_{\text{low}} - b \cdot \text{Data}_{\text{high}}$

$\sigma^2 = a^2 \sigma_{\text{low}}^2 + b^2 \sigma_{\text{high}}^2$

depends on:
- specific energies
- allocation of dose to the two measurements

**Noise depends on dose allocation**

with 80/140 kVp dose allocation that maximizes iodine SNR

↓ 80 kVp dose, ↑140 kVp dose same total dose
Spectral separation and control

- very critical for SNR efficiency, separation robustness, etc.
- implementations
different kVp and/or filtration
detectors with energy discrimination

Principle of Dual Energy CT

Data acquisition with different X-ray spectra: 80 kV / 140 kV

Different mean energies of the X-ray quanta

SOMATOM Definition Flash

S_{1}: 80 kV  
S_{2}: 140 kV  
+ SPS

SPS: Selective Photon Shield
**Dual kVp, dual filtration**

- switched filtration improves separation
- different mA helps apportion dose


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**NanoPanel Prism**

Perfect alignment
Simultaneous alignment in time and space

Top scintillator:
- Effective atomic number small but does not sacrifice light output
- Thickness optimized for energy separation and low-energy image noise

Bottom scintillator absorbs 99.5% of high-energy spectrum

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**Layered detector**

- relatively poorer spectral separation
- simultaneous dual energy sensing

Absorbed single X-ray photon

High Voltage Counter 3
Counter 2
Counter 1
Counter 4

Charge pulse

Pulse height proportional to x-ray photon energy

Discriminating thresholds

Storing counts of all energy windows for each imaging time period

Spectral separation

Separation and control of the spectra is important
reduced noise
improved material characterization
improved dose efficiency

Achieved by
choice of kVp (and mAs allocation)
use of filtration
performance of energy discriminating detectors

Spectral separation implementations

- ideal photon counting with K-edge filter
- ideal photon counting with energy analysis
- different kVp and filtration
- different kVp
- layered detector

better spectral separation and dose efficiency
Data acquisition implementations

• Sequential scans at different kVp
  motion sensitivity > scan time
• Two sources at ~90° on the same gantry

Two X-ray tubes, 1st: 80 or 100 kVp, 2nd: 140 kVp

Dual Source Challenge: Inconsistent scans
Data acquisition implementations

- Sequential scans at different kVp
  motion sensitivity > scan time
- Two sources at ~90° on the same gantry
  some motion sensitivity (~ 25% T_{rot})
- Switching kVp within a single scan\(^1,2\)


Rapid kVp switching
Dual energy CT

- Requires fast generator and detectors
- Dose allocation controlled by dwell time
- Difficult to switch filters

Data acquisition implementations

- Sequential scans at different kVp
  motion sensitivity > scan time
- Two sources at 90° on the same gantry
  some motion sensitivity (~ 25% T_{rot})
- Switching kVp within a single scan
- Energy discriminating detectors
  layered detector, photon counting
<table>
<thead>
<tr>
<th>Summary of commercial systems</th>
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<tbody>
<tr>
<td>• Siemens: two sources, different kVp (80 or 100 /140) and filtration, direct control of mA</td>
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<tr>
<td>• GE: single source with rapid switching, same filter for both kVps, control mAs by dwell time</td>
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<tr>
<td>• Philips: dual-layer detector, usual kVp mAs control</td>
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<tr>
<td>• Lots of R&amp;D work, especially on photon counting detectors</td>
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