Dual Energy CT for Density Measurements

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What is in a voxel?
CT number depends on:
• inherent tissue properties (chemical composition, density)
• x-ray spectrum
• administered contrast media
Can we be more specific?

Attenuation coefficients depend on photon energy

use CT measurements at multiple energies for material specificity and improved quantitation.
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)“.


Beam hardening

Accurate for "water-like" materials of any density

Methods:
MLE polynomials are fast:
\( p = a_1L + a_2L^2 + a_3L^3 + \ldots \)

Provides accurate densities if \( Z_{\text{eff}} \) is known and uniform

Single energy CT: “water" beam hardening correction
Single energy CT: “Water” beam hardening correction

Correction fails with materials of very different $Z_{\text{eff}}$

Results in local and distant errors and artifacts

Can we do better?

OUTLINE

- Physical principles of multi-energy x-ray measurements
- Signal processing
- Quantitation opportunities and challenges
- Data acquisition
- Summary
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 \(t_b\)

\[ I_1, I_2 = A \left\{ \ln(I_{01}/I_1) + (\mu_w/\mu_w)(\ln(I_{02}/I_2)) \right\} \]

scale for lost bone signal
subtract water
makes the water contribution at \(E_2\) match that at \(E_1\)

dual energy x-ray absorptiometry (DEXA)

2 energies → 2 materials

material analysis with absorptiometry

• 2 energies → 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
• barring a K-edge:
  any material acts like a combination of pure photoelectric and Compton
  any material can be modeled as a weighted sum of two other materials

**Basis material decomposition**

any material can be represented as a combination of two basis materials:

\[
\begin{align*}
0.04 \text{ M grams of Cu} & \quad + \quad 0.61 \text{ M grams of O} \\
\text{I}_{0} & \quad = \quad I_{0} + M \text{ grams of Ca}
\end{align*}
\]

Indistinguishable at any x-ray energy above their K-edge

Common "basis materials": iodine and water, aluminum and plastic

**Basis material decomposition**

\[
\begin{align*}
\text{I}_{0} & \quad = \quad I_{0} + M \text{ grams of Ca}
\end{align*}
\]

Material parameters:
effective atomic number and electron density
amounts of two basis materials
can be measured using 2 x-ray energies

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Material parameters:
effective atomic number and electron density
amounts of two basis materials
can be measured using 2 x-ray energies
K-edge subtraction

- Very specific material information
  - 2 narrow spectra, or 3 spectra

Dual-energy processing

- Reconstruct images in the normal manner, and combine HU images
  - Easy to implement
- Combine projection data prior to reconstruction
  - Somewhat more difficult
  - Requires aligned projections
  - Enables "exact" beam hardening correction

Dual energy processing

- Monochromatic 55 keV simulation comparable to ~ 80 kVp
- "Water" contrast
- Iodine contrast

Dual energy processing

- Monochromatic simulation comparable to 80/150 kVp
- "Water" contrast
- Iodine contrast
Dual energy processing

Iodine image (water cancelled)

Iodine = a \cdot (\text{Image}_{80} - b \cdot \text{Image}_{140})

- restore reduced iodine signal
- amplify 140 kVp water signal

Water image (iodine cancelled)

Water image = c \cdot (\text{Image}_{80} - d \cdot \text{Image}_{140})

Virtual non-contrast (VNC) image

Applications of Dual Energy CT

80/140kV Mixed Images for regular viewing

Optimal combination ("mixed" image)

Combined image has high SNR

Material cancelled images have increased noise

SNR=37
Noise

\[ \text{Iodine image } = a \times (\text{Image}_{80} - b \times \text{Image}_{140}) \]

\[ \sigma^2 = a^2 \times (\sigma_{80}^2 + b^2 \times \sigma_{140}^2) \]

\text{Noise depends on dose allocation to the 80 kVp and 140 kVp images}

Dose allocation that maximizes iodine SNR:

- 80 kVp dose
- 140 kVp dose
- Same total dose
Dual energy processing

\[ L_L = \ln \left( \frac{I_{0L}}{I_L} \right), \quad L_H = \ln \left( \frac{I_{0H}}{I_H} \right) \]

\[ m_A, m_B = \text{amounts of basis materials} \]

With monochromatic beams, L’s are linear functions of m’s, so

\[ m_A = a_L L_L + a_H L_H, \quad m_B = b_L L_L + b_H L_H \]

With polychromatic beams, functions are nonlinear. Approaches:

1) iterative solutions (e.g., MLE) accurate but slow
2) polynomial approximation

\[ m_A = a_{L_1} L_L + a_{L_1^2} L_L^2 + a_{L_H} L_H + a_{L_L L_H} + \ldots \]

accuracy depends on polynomial order, dynamic range, etc.
Application of monoenergetic images

- Image interpretation
  - High SNR
  - Tissue characterization
- Extrapolation to higher energies
  - MV, SPECT, PET

Beam hardening correction

- If basis material assumption holds (e.g., no K-edge materials),
  - Nonlinear decomposition exactly handles polychromaticity
  - Exact beam hardening correction
  - Projection domain processing is preferred

Monochromatic CT from HDCT projection-based recon

Potential for beam hardening streak-free images

- Image based
  - Water
  - Aluminum
- Projection based
  - Water
  - Aluminum

Discovery CT750 HD

Clinical Value

- Spectral or monochromatic images have a reduced beam hardening effect vs polychromatic reconstructed images
- Beam hardening artifacts can obstruct the accurate interpretation of important brain anatomy
- Notice the visualization improvement of the brain anatomy between the previous images
Posterior Fossa Streak Artifacts are Removed / Lesion Verification

Monochromatic CT from HDCT projection-based recon
Potential for beam hardening streak-free images

Beam hardening correction
If basis material assumption holds (e.g., no K-edge materials),
- nonlinear decomposition exactly handles polychromaticity
- exact beam hardening correction
- projection domain processing is preferred
- starting with image domain data is possible

Dual energy processing
accurate beam hardening built-in
material cancelled images
monoenergetic images

Exact dual energy material decomposition from inconsistent rays (MDIR)

Dual energy CT (DECT) allows exciting images that show the spatial distribution of
the electron density and the atomic number k, two crucial images of two basis material
decomposition, which is a function of the atomic number and electron density. To achieve additional
**Quantitation**

- Decomposition yields local density of basis materials
- Can convert basis materials – i.e., calculate density of any two materials
- Quantifies actual materials only if they match basis materials
- Suppose bases are \(a\) and \(b\), but voxel has \(a\) and \(c\)
  - Truth: \((m_a, m_c)\)
  - Appearance: \((m_a, 0) + (m_a', m_b') = (m_a + m_a', m_b')\)
- (Local) errors resulted if the materials are wrong (e.g., tissue vs. water vs. fat)
- Virtual non-contrast ≠ pre-contrast image

**Scatter**

\[
m_A = a (L_L - (\mu_{BL}/\mu_{BH}) L_R)
\]

\[
w/\text{scatter: } m_A' = m_A - a (\ln(1+\text{SPR}_L) - (\mu_{BL}/\mu_{BH}) \ln(1+\text{SPR}_H))
\]


20 cm water absorber
three known materials

\[
\begin{align*}
\mu_1 &= \mu_{w1}f_w + \mu_{b1}f_b + \mu_{I1}f_I \\
\mu_2 &= \mu_{w2}f_w + \mu_{b2}f_b + \mu_{I2}f_I \\
f_w + f_b + f_I &= 1
\end{align*}
\]

solve for \( f_w, f_b, f_I \)

scatter radiation and other background signals in dual-energy computed tomography material thickness measurements

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(Received 16 December 1997; accepted for publication 12 May 1998)

Both beam hardening and the attenuation of scattered radiation cause nonuniform errors in x-ray computed tomography (CT), leading to artifacts and CT number inaccuracies. Dual-energy measurements can be used to correct beam hardening effects to a high degree of accuracy. However, in the imaging of thick body sections the transmitted intensity of the primary beam is low, making scatter the most significant cause of CT number inaccuracy. Furthermore, the scatter-to-primary ratio is energy dependent, causing a drift in the apparent effective atomic number of the imaging material. We have measured scatter under a variety of conditions on a third-generation CT scanner with dual energy capability in order to determine its effect on the accuracy of quantitative measurements. The efficiency of dual-energy radiation, detector cross-talk, and the levels of energy crossover between the two x-ray beams are important factors affecting the accuracy of quantitative results. The results indicate that for the well collimated system, an accurate correction for scatter can be made based on the detected intensity in projections.

Bone mass from single energy CT is inaccurate if fat fraction is unknown

Quantitative Computed Tomography Scanning for Measurement of Bone and Bone Marrow Fat Content: A Comparison of Single- and Dual-Energy Techniques Using a Solid Synthetic Phantom

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We have been continuing interest in the capability of quantitative CT (QCT) to determine the amount of skeletal mineral. Most clinical attention has focused on single-energy techniques, because of the ease of use and precision. 1-5 The accuracy of single-energy CT methods has been
Bone mass from single energy CT is inaccurate if fat fraction is unknown.

DE can be more accurate but is less precise.

Reliable separation requires large $(R_1 - R_2)^2$ where $R = \frac{\mu_{\text{high}}}{\mu_{\text{low}}}$, depends on material and energies.

Works best for one high Z and one lower Z material, and very different x-ray energies.

The choice of photon energies is critical for SNR efficiency, separation robustness, etc.

Implementations include different kVp and/or filtration, layered detector, and photon counting with energy analysis.

Photon counting detectors are promising in the long term but not yet ready for clinical use.
Spectral separation

- Very critical for SNR efficiency, separation robustness, etc.
- Implementations
  - Photon counting with K-edge filter*
  - Photon counting with energy analysis*
  - Different kVp and filtration
  - Different kVp
  - Layered detector

* Assumes good energy response

Dual energy implementations

- Sequential scans at different kVp
  - Motion sensitivity > 50% T_rot
- 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

Contrast material sensitivity - very low concentration CNR

- Optimized single energy CT
  - Advantage: highest CNR
  - Limitation: inhomogeneous background
- Temporal subtraction (post - pre)
  - Advantage: perfect background suppression (w/o motion)
  - Limitation: motion misregistration lower CNR at the same dose
- Rapid dual energy CT
  - Advantage: motion immunity
  - Limitation: Nonuniform Z background?

Summary

- More material specificity than single energy CT (e.g., average material properties, material cancelled images)
- Perfect beam hardening correction (pre-recon)
  - Effective monoenergetic images, more accurate RTP and PET attenuation correction
- Significant challenges but also many opportunities
Thank You

Summary

• virtual pre-contrast image
  perfectly registered and simultaneously acquired
  beware of noise propagation. Separate optimized scans
  probably have lower total dose
• isolate contrast media from calcified plaque
  difficult, especially for small amounts of either
• lower dose?
  not likely, compared to optimized protocols
• molecular imaging?
  I don’t think so

Dose

• Two scans. Do we have to double the dose?
  Depends on the goal
  Start by splitting the dose to both energies

Dose

image quality at given dose
beam energy

higher Z task
thicker object

both spectra of DE system can’t be optimal!
Dose

- Two scans. Do we have to double the dose?
  - Depends on the goal
  - Start by splitting the dose to both energies
- DE not likely to provide the same noise performance as optimized single energy protocols
- penalty, if any, is low

Summary of commercial systems

- Siemens: two sources, different kVp and filtration, image-based processing
- GE: single source with rapid switching, same filter for both kVps, projection-based processing
- Philips: sequential scans at different kVp, same filtration, image-based processing
- Lots of R&D work

Dose comparison

<table>
<thead>
<tr>
<th>Water image</th>
<th>Optimal combination (post contrast image)</th>
<th>DUAL ENERGY 55/80 keV acquisition</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR=37</td>
<td>iodine CNR=10</td>
<td>ideal dose allocation (~1:1)</td>
</tr>
<tr>
<td>pre-contrast dose ~ 0.15D</td>
<td>post-contrast dose ~ 0.79D</td>
<td>total dose = D</td>
</tr>
</tbody>
</table>

CONVENTIONAL 55 keV pre/post contrast scans

| pre-contrast dose ~ 0.13D | post-contrast dose ~ 0.79D | total dose 0.94 D |

Under ideal conditions, DE scan has slightly higher dose

Dose comparison

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<th>Optimal combination (post contrast image)</th>
<th>DUAL ENERGY 55/80 keV acquisition</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR=34</td>
<td>iodine CNR=5.5</td>
<td>poor dose allocation (~1:8)</td>
</tr>
<tr>
<td>pre-contrast dose ~ 0.19D</td>
<td>post-contrast dose ~ 0.23D</td>
<td>total dose 0.36 D</td>
</tr>
</tbody>
</table>

CONVENTIONAL 55 keV pre/post contrast scans

| pre-contrast dose ~ 0.19D | post-contrast dose ~ 0.23D | total dose 0.36 D |

Under non-ideal conditions, DE scan has much higher dose
Applications of Dual Energy CT

Another image based application: characterization of kidney stones

- Uric acid stones can be differentiated from other renal calculi

Principle of Dual Energy CT – Image Based Evaluation

Each material is characterized by its “Dual Energy Index”:

\[ \text{DEI} = \frac{x_{80} - x_{140}}{x_{80} + x_{140}} \]

- Bone
- Liver
- Lung
- Soft Tissue
- Skin
- Proteins
- Fat
- Gall Fluid

Dual energy CT can measure chemical composition!

Image Based Methods

- Modified 2-material decomposition: Separation of two materials
  - Assume mixture of blood + iodine (unknown density)
  - bone marrow + bone (unknown density)

- Automatic bone removal without user interaction
  - Clinical benefits in complicated anatomical situations:
    - Base of the skull
    - Carotid arteries
    - Vertebral arteries
    - Peripheral runoffs

- Additional postprocessing to improve classification at low HU numbers

Image Based Methods

- Modified 2-material decomposition: Separation of bone and iodine

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**Principle of Dual Energy CT**

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

Different mean energies of the X-ray quanta

**Dual kVp, dual filtration**

- switched filtration improves separation
- different mA helps apportion dose

---

**noise in processed images**

- low energy
- high energy
- material 1: high, correlated noise
- material 2

- usually high noise
- can be low noise

material cancelled images
equivalent monoenergetic images
SOMATOM Definition Flash

S1: 80 kV  S2: 140 kV + SPS

S1: 80 kV  S2: 140 kV

S1: 80 kV  S2: 140 kV + SPS

Dual Source Challenge: Inconsistent scans

Moving Objects

Moving Phantom Simulation

Dual Source system

**Layered detector**

- simultaneous dual energy sensing
- relatively poor spectral separation

---

**Dose efficiency**

3 component decomposition, each technique optimized

<table>
<thead>
<tr>
<th>Technique</th>
<th>kVp</th>
<th>Filtration</th>
<th>Relative exposure</th>
<th>Relative std dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single kV</td>
<td>70</td>
<td>3.0 mm Al</td>
<td>13</td>
<td>24.1</td>
</tr>
<tr>
<td>Two kV</td>
<td>180</td>
<td>0.5 mm Cu</td>
<td>18</td>
<td>36.2</td>
</tr>
<tr>
<td>Two-crystal</td>
<td>180</td>
<td>0.5 mm Sn</td>
<td>51</td>
<td></td>
</tr>
</tbody>
</table>

4x overall difference in dose efficiency

*Dalcz et al., Med Phys 5, 418-25, 1979*
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

Stored counts of all energy windows, for each reading time period

Direct conversion material

Electronics

Pixelated electrodes

Photon energy

Photon Counting Spectral CT – Detector Principle

(CZT crystal: Cadmium Zinc Telluride)

Photon Counting Prototype*
Early results
- Two systems in Philips Research labs
- Research system installed at Washington University-Saint Louis in Nov. 2008

Photon Counting Prototype* Works-in-Progress: Pending commercial availability and regulatory clearance

Dual energy implementations
- Sequential scans at different kVp
  motion sensitivity > 50% T_rot
  Helical?
- Two sources at ~90° on the same gantry

SYNGO Dual Energy
- Principle of Dual Energy

SOMATOM Definition
SOMATOM Definition Flash

Two X-ray tubes, one at 80 kVp, second at 140
Image Based Methods

- Calculate material specific images: 2 materials of unknown density
  - Noise amplification in the material specific images!

Image noise $\sigma$

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

But what material is it?

Even more confusing if $T$ is unknown

Three known materials

Dual energy CT

Can calculate both iodine and bone.
Requires known mixing properties and consistent water density

\[ \text{Kelcz et al: Med Phys 6, 418-25, 1979.} \]