Two-Material Decomposition From a Single CT Scan Using Statistical Image Reconstruction

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Introduction: DECT

- Motivation: Provide information about material composition for
  - Radiotherapy, dose calculation and anatomy segmentation
  - PET/CT, attenuation correction
  - Virtual nonenhanced images

- Popular methods: Dual-energy CT (DECT)

- Disadvantage: Require two scans or specialized scanners (e.g.,
  fast kVp-switching, dual source-detector CT)
Propose a penalized weighted least-squares (PWLS) method
  - Edge-preserving regularization
  - Reconstruct two basis materials (e.g., soft tissue and bone)
  - Single energy CT scan acquired with X-ray filters

Using a split or bow-tie filter
  - Create incident spectra differences among detector channels
  - Require only attachment and alignment of metal filters between the X-ray tube and the patient
A fan-beam CT scanner with a split filter

Sample spectra at two half filters

The effective energies are 49 and 58 keV.

[Rutt and Fenster, J. Comp. Assisted Tomo., 1980]  [Taschereau et al., PMB, 2010]
A fan-beam CT scanner with a bow-tie filter

Sample spectra at four fan angles ($\gamma$)

The effective energies are 49, 51, 53 and 56 keV.
Object Model

\[ \mu(\vec{x}, \mathcal{E}) = \sum_{l=1}^{2} \sum_{j=1}^{N_p} \beta_l(\mathcal{E}) \ b_j(\vec{x}) \ x_{lj} \]

- \( \beta_l(\mathcal{E}) \): the energy-dependent mass attenuation coefficient of the \( l \)th material type (\( e.g., \) soft tissue and bone) (\textit{known})
- \( \{ b_j(\vec{x}) \} \): spatial basis functions (\( e.g., \) pixels)
- \( x_{lj} \): density of the \( l \)th material at the \( j \)th location (\textit{unknown})
Polyenergetic Measurement Model

\[ \bar{y}_i(x) = l_i e^{-f(s_i(x))} + r_i \quad \text{noisy measurement} \]

\[ f_i(s_i) \triangleq - \log \left( \frac{1}{l_i} \int l_i(\mathcal{E}) e^{-\sum_{l=1}^{2} \beta(\mathcal{E}) s_{il}(x)} d\mathcal{E} \right) \]

\[ s_{il}(x) \triangleq \int_{\mathcal{L}_i} \sum_{j=1}^{N_p} b_j(\vec{x}) x_{lj} d\ell \quad \text{component line integrals} \]

\[ l_i \triangleq \int l_i(\mathcal{E}) d\mathcal{E} \quad \text{total source intensity} \]

- \( i \) indexes rays and \( l = 1, 2 \) indexes basis materials.
- Incident intensity \( l_i(\mathcal{E}) \) varies among rays depending on filtration types.
Penalized Weighted Least-Squares (PWLS) Reconstruction

- Logarithm sinogram estimates $\hat{f}_i$

$$\hat{f}_i \triangleq -\log\left(\frac{Y_i - r_i}{l_i}\right)$$

- PWLS reconstruction

$$\hat{x} = \arg \min_{x \succeq 0} \psi(x)$$

$$\psi(x) \triangleq \sum_{i=1}^{N_d} \frac{1}{2} w_i \left(\hat{f}_i - f_i(s_i(x))\right)^2 + \beta R(x)$$

where $w_i = Y_i$ values are statistical weighting factors.
The units are physical density (g/cm$^3$)

NCAT phantom: [Segars Tsui, IEEE TNS, 2002]
Split Filter Results: Soft Tissue | Error |

RMS error: $4.0 \times 10^{-2}$ g/cm$^3$  
RMS error: $3.0 \times 10^{-2}$ g/cm$^3$
PWLS produced lower noise, similar edge sharpness.

PWLS reduced RMS error from $3.4 \times 10^{-2}$ g/cm$^3$ to $2.0 \times 10^{-2}$ g/cm$^3$.

PWLS exhibits $\approx 0.03$ g/cm$^3$ bias.
JS-FBP: [Joseph and Spital, J. Comp. Assisted Tomo., 1978]

PWLS reduced beam-hardening artifacts more effectively
Profiles and bow-tie filtration methods had similar results.
Summary

- **Statistical PWLS method**
  - Two basis materials
  - Single energy CT scan
  - Differential filtration creates spectral differences among rays

- Require only attachment and alignment of metal filters between the X-ray tube and the patient

- Optimizing materials and thickness or filtration type needed
Discussion

- Inevitable overlap of the filtered spectra
- Practical issues of using filters
  - Precisely align the filters and rotational center
  - Split filters for tilted rays in 3D CT geometries
  - Adjust radiation dose according to X-ray tube voltages
  - Sensitivity to model mismatch: Compton scatter or imperfect spectral models
- Investigate choosing regularizers and optimizing their parameters
- Extend to three material reconstruction using dual-energy CT
Split Filter Results: Soft Tissue Images

JS-FBP

PWLS

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PWLS produced lower noise, similar edge sharpness.
PWLS exhibits $\approx 0.05\text{g/cm}^3$ bias.
Split Filter Results: Attenuation at 70 KeV

JS-FBP

RWLS

RMS error: 36 HU

RMS error: 8 HU
Bow-tie Filter Results: Density

RMS error: \(3.0 \times 10^{-2}\) g/cm\(^3\)  
RMS error: \(1.2 \times 10^{-2}\) g/cm\(^3\)

- **JS-FBP**: [Joseph and Spital, J. Comp. Assisted Tomo., 1978]
- **PWLS** reduced beam-hardening artifacts more effectively
Bow-tie Filter Results: Soft Tissue

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<th>JS-FBP</th>
<th>PWLS</th>
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Bow-tie Filter Results: Soft Tissue Images

JS-FBP

PWLS
**Bow-tie Filter Results: Soft Tissue Profiles**

- PWLS produced lower noise, similar edge sharpness.
- PWLS exhibits $\approx 0.05\text{g/cm}^3$ bias.
Bow-tie Filter Results: Attenuation at 70 KeV

JS-FBP

PWLS

RMS error: 34 HU

RMS error: 9 HU