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

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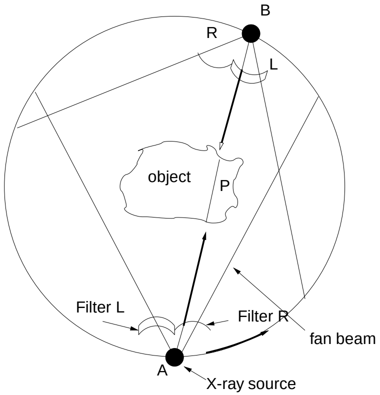
Introduction: DECT

- 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)

Introduction: PWLS Method Using A Single CT Scan

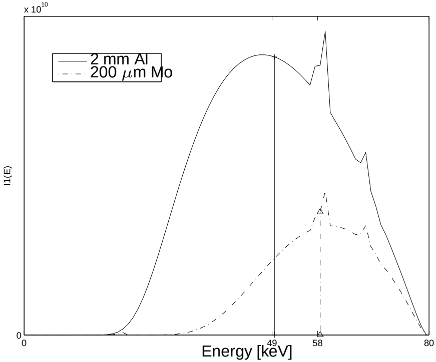
- Propose a penalized weighted least-squares (PWLS) method
    - Edge-preserving regularization
    - Reconstruct two basis materials (*e.g.*, soft tissue and bone)
    - Single energy CT scan acquired with X-ray filters
- Using a split or bow-tie filter
    - Create incident spectra differences among detector channels
    - Require only attachment and alignment of metal filters between the X-ray tube and the patient

Split Filtration



A fan-beam CT scanner with a split filter

[Rutt and Fenster, J. Comp. Assisted Tomo., 1980]

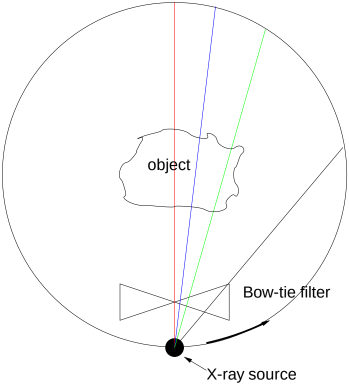


Sample spectra at two half filters

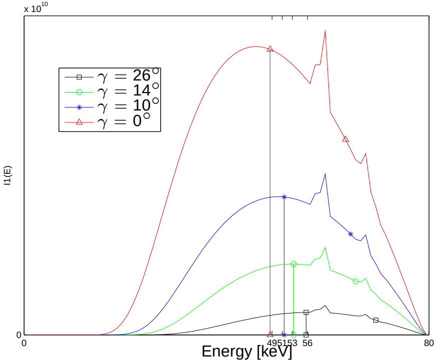
The effective energies are 49 and 58 keV.

[Taschereau *et al.*, PMB, 2010]

Bow-tie Filtration



A fan-beam CT scanner with a bow-tie filter



Sample spectra at four fan angles (γ)

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

Object Model

$$\mu(\vec{x}, \mathcal{E}) = \sum_{l=1}^{2} \sum_{j=1}^{N_\mathrm{p}} \beta_l(\mathcal{E})\, b_j(\vec{x})\, x_{lj}$$

- $\beta_l(\mathcal{E})$: the energy-dependent mass attenuation coefficient of the lth material type (*e.g.*, soft tissue and bone) (known)
- $\{b_j(\vec{x})\}$: spatial basis functions (*e.g.*, pixels)
- x_{lj}: density of the lth material at the jth location (unknown)

Polyenergetic Measurement Model

$$
\begin{aligned}
\bar{y}_i(\boldsymbol{x}) &= I_i \, \mathrm{e}^{-f_i(\boldsymbol{s}_i(\boldsymbol{x}))} + r_i \quad \text{noisy measurement} \\
f_i(\boldsymbol{s}_i) &\triangleq -\log\left(\frac{1}{I_i}\int I_i(\mathcal{E})\, \mathrm{e}^{-\sum_{l=1}^{2}\beta_l(\mathcal{E})\, s_{il}(\boldsymbol{x})}\, \mathrm{d}\mathcal{E}\right) \\
s_{il}(\boldsymbol{x}) &\triangleq \int_{\mathcal{L}_i} \sum_{j=1}^{N_\mathrm{p}} b_j(\vec{x})\, x_{lj}\, \mathrm{d}\ell \qquad \text{component line integrals} \\
I_i &\triangleq \int I_i(\mathcal{E})\, \mathrm{d}\mathcal{E} \qquad \text{total source intensity}
\end{aligned}
$$

- i indexes rays and $l = 1, 2$ indexes basis materials.
- Incident intensity $I_i(\mathcal{E})$ varies among rays depending on filtration types.

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

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

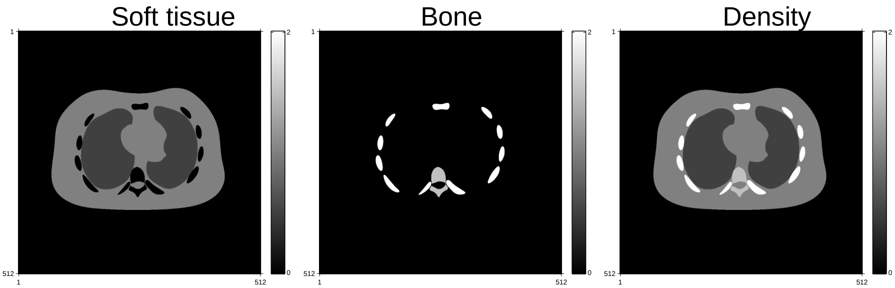
- PWLS reconstruction

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

$$\Psi(\boldsymbol{x}) \triangleq \sum_{i=1}^{N_\mathrm{d}} \frac{1}{2} w_i \left(\hat{f}_i - f_i(\boldsymbol{s}_i(\boldsymbol{x}))\right)^2 + \beta R(\boldsymbol{x})$$

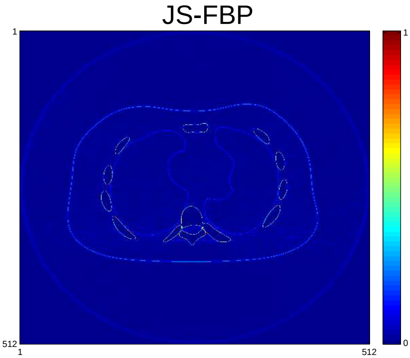
where $w_i = Y_i$ values are statistical weighting factors.

NCAT phantom

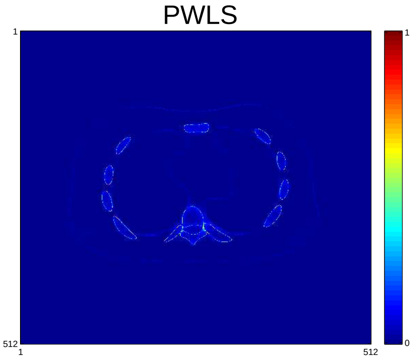


- The units are physical density (g/cm^3)
- NCAT phantom: [Segars Tsui, IEEE TNS, 2002]

Split Filter Results: Soft Tissue |Error|

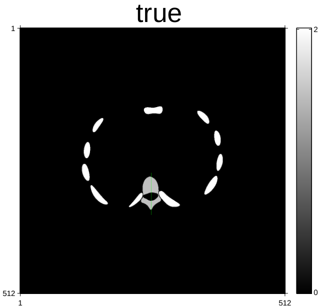


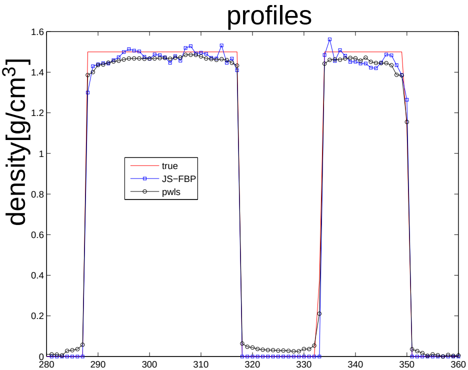
RMS error: 4.0×10^{-2} g/cm^3



RMS error: 3.0×10^{-2} g/cm^3

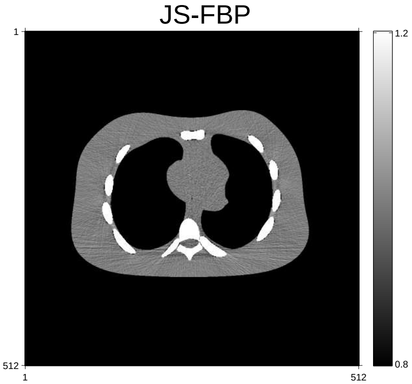
Split Filter Results: Bone



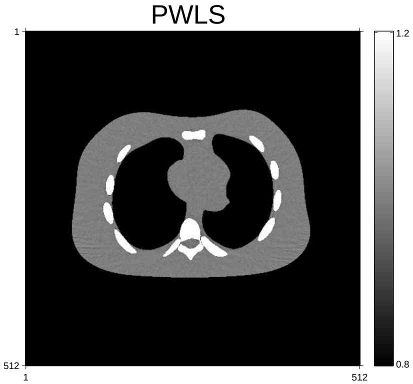


- PWLS produced lower noise, similar edge sharpness.
- PWLS reduced RMS error from 3.4×10^{-2} g/cm^3 to 2.0×10^{-2} g/cm^3.
- PWLS exhibts $\approx$ 0.03g/cm^3 bias.

Split Filter Results: Density



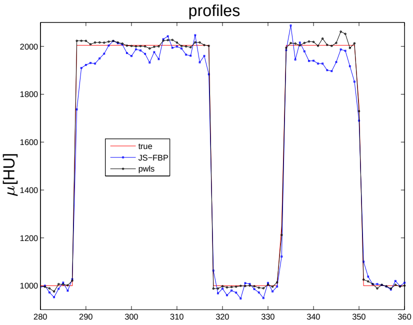
RMS error: 3.2×10^{-2} g/cm^3



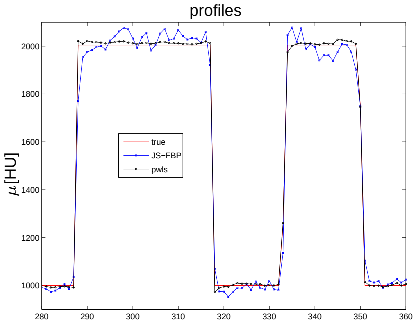
RMS error: 1.2×10^{-2} g/cm^3

- JS-FBP: [Joseph and Spital, J. Comp. Assisted Tomo., 1978]
- PWLS reduced beam-hardening artifacts more effectively

Profiles of Attenuation at 70 KeV



Split



Bow-tie

Split and bow-tie filtration methods had similar results.

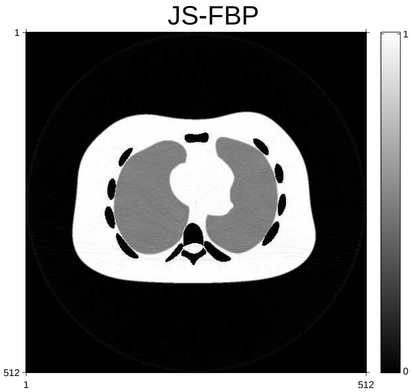
Summary

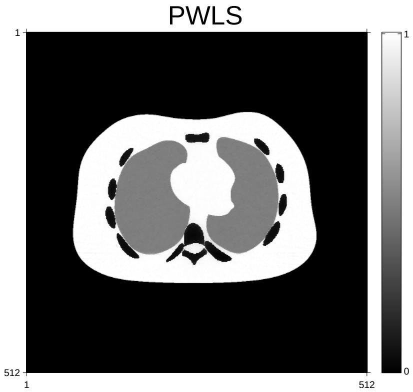
- Statistical PWLS method
  - Two basis materials
  - Single energy CT scan
  - Differential filtration creates spectral differences among rays
- Require only attachment and alignment of metal filters between the X-ray tube and the patient
- Optimizing materials and thickness or filtration type needed

Discussion

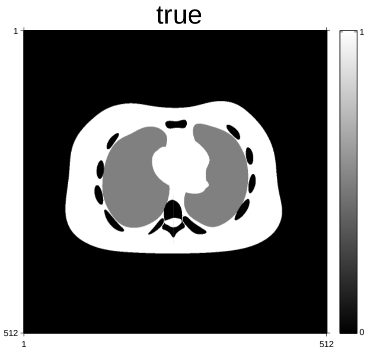
- Inevitable overlap of the filtered spectra
- Practical issues of using filters
  - Precisely align the filters and rotational center
  - Split filters for tilted rays in 3D CT geometries
  - Adjust radiation dose according to X-ray tube voltages
  - Sensitivity to model mismatch: Compton scatter or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

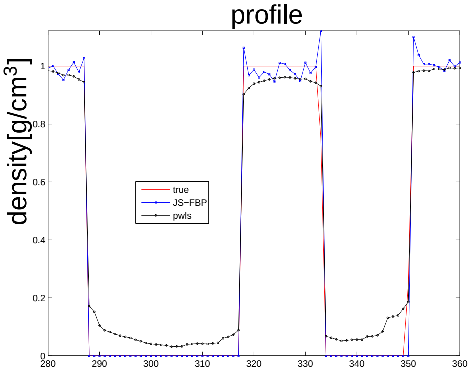
Split Filter Results: Soft Tissue Images





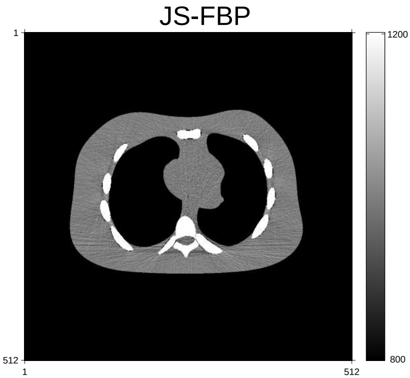
Split Filter Results: Soft Tissue Profiles





- PWLS produced lower noise, similar edge sharpness.
- PWLS exhibts $\approx 0.05\text{g/cm}^3$ bias.

Split Filter Results: Attenuation at 70 KeV



RMS error: 36 HU

RMS error: 8 HU

Bow-tie Filter Results: Density

JS-FBP

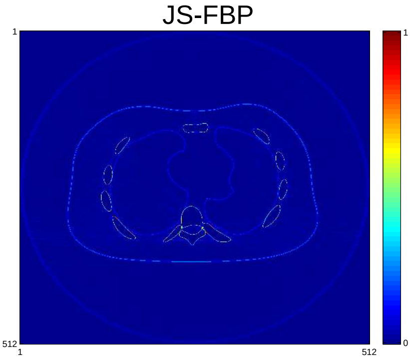
RMS error: 3.0×10^{-2} g/cm^3

PWLS

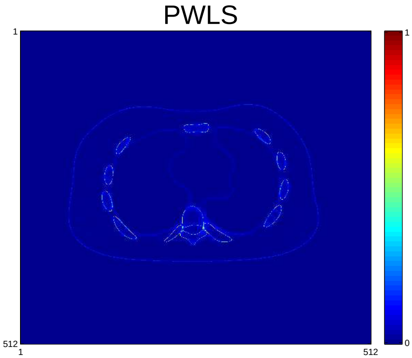
RMS error: 1.2×10^{-2} g/cm^3

- JS-FBP: [Joseph and Spital, J. Comp. Assisted Tomo., 1978]
- PWLS reduced beam-hardening artifacts more effectively

Bow-tie Filter Results: Soft Tissue |Error|

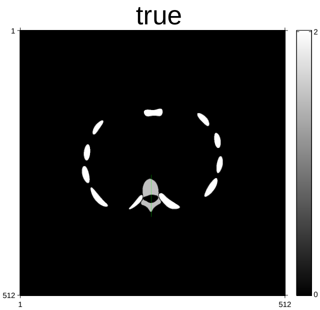


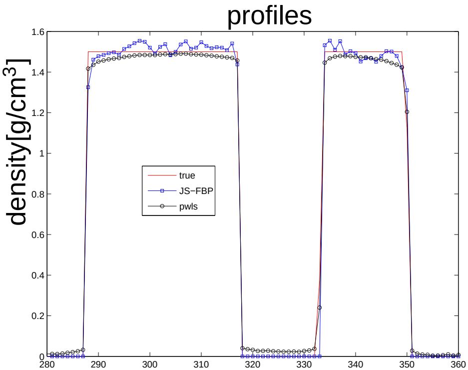
RMS error: 4.0×10^{-2} g/cm^3



RMS error: 3.0×10^{-2} g/cm^3

Bow-tie Filter Results: Bone





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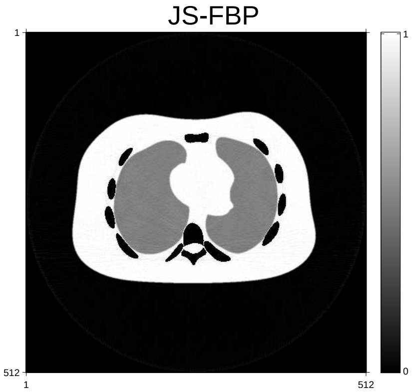
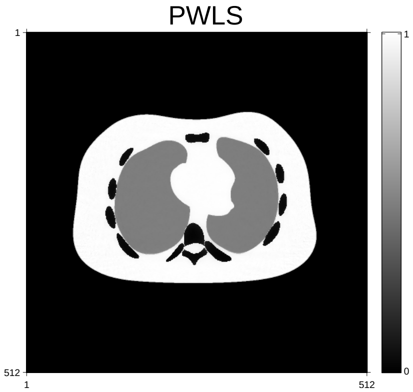
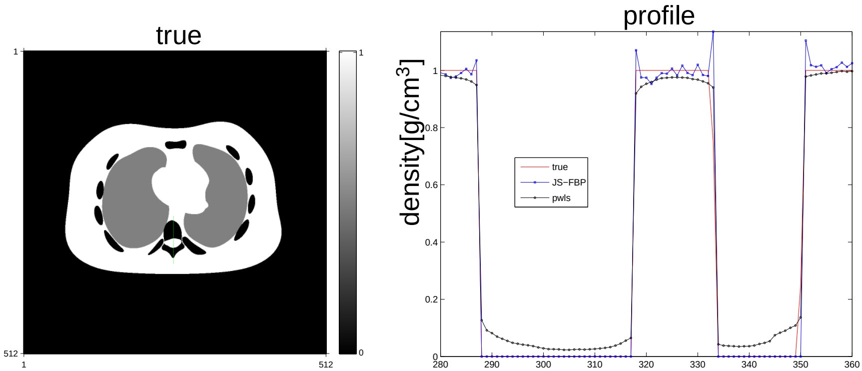
Bow-tie Filter Results: Soft Tissue Images





Bow-tie Filter Results: Soft Tissue Profiles



- PWLS produced lower noise, similar edge sharpness.
- PWLS exhibts $\approx 0.05\text{g/cm}^3$ bias.

Bow-tie Filter Results: Attenuation at 70 KeV

JS-FBP

RMS error: 34 HU

PWLS

RMS error: 9 HU