A Count Rate-Dependent Method for Spectral Distortion Correction in Photon Counting CT

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Aim

- Material decomposition of spectral CT data into contributions of two or more materials
- Rawdata-based material decomposition requires dedicated models to predict the measured counts
- Calibration of spectral response to account for...
  - Spectral distortions: charge sharing, K-escape
  - Count rate-dependent distortions: pulse pileup
Material Decomposition

Cost-function: Log Likelihood

Forward Model

$N_b(l_1, \ldots, M)$

Update

Forward Model

- The detection process of a PCD is described using the bin sensitivity function $S_b(E)$.

\[ N_b(l_1, ..., M) \propto N_0 \int dE \ w(E) \cdot S_b(E) \cdot \exp \left( - \sum_{m=1}^{M} \mu_m(E) \cdot l_m \right) \]

- Total number of x-rays
- X-ray spectrum
- Bin sensitivity
- Interaction with the sample
The detection process of a PCD is described using the bin sensitivity function $S_b(E)$.

$$N_b(l_1,\ldots,l_M) \propto N_0 \int dE \ w(E) \cdot S_b(E) \cdot \exp \left( - \sum_{m=1}^{M} \mu_m(E) \cdot l_m \right)$$
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$$N_b(l_1,\ldots,l_M) \propto N_0 \int dE \ w(E) \cdot S_b(E) \cdot \exp\left(-\sum_{m=1}^{M} \mu_m(E) \cdot l_m\right)$$

Calibration Measurements

• Measure **transmission** through slabs of aluminum and POM

• Adapt forward model such that it reproduces the calibration measurement
Calibration
Reference Methods

• Method 1 by Liu et al. (2015)

\[ N_b(l_1,\ldots,M) \propto N_0 \cdot C_b \left( \int dE \ w(E) \cdot S_b(E) \cdot \exp \left( -\sum_{m=1}^{M} \mu_m(E) \cdot l_m \right) \right) \]

\[ C_b(N) = \frac{\alpha_b + \beta_b \cdot N}{1 + \gamma_b \cdot N} \]

• Method 2 by Sidky et al. (2005)

\[ N_b(l_1,\ldots,M) \propto N_0 \cdot \int dE \ w(E) \cdot S_b(E) \cdot \exp \left( -\sum_{m=1}^{M} \mu_m(E) \cdot l_m \right) \]

\[ = w_b(E) \]


Count Rate-Dependent Spectral Calibration

- Include a multiplicative correction function $P_b(E, N_b)$ to account for spectral distortions and effects depending on the count-rate $N_b$.

$$N_b(l_1, \ldots, M) \propto N_0 \int dE \ w(E) \cdot S_b(E) \cdot P_b(E, N_b) \cdot \exp \left( - \sum_{m=1}^{M} \mu_m(E) \cdot l_m \right)$$

- Model the correction function as a polynomial of order $K$:

$$P_b(E, N_b) = 1 + (E - E_{\text{min}})(E - E_{\text{max}}) \cdot \sum_{k=0}^{K-2} c_{kb}(N_b) E^k$$

where the coefficients depend linearly on the count-rate:

$$c_{kb}(N_b) = c_{kb}^{(0)} + c_{kb}^{(1)} \cdot N_b$$
Count Rate-Dependent Spectral Calibration

\[ w_b(E) = w(E) \cdot S_b(E) \]
Count Rate-Dependent Spectral Calibration

![Graph showing count rate-dependent spectral calibration with energy in keV and count rate values in bins.](image-url)
Count Rate-Dependent Spectral Calibration

- **Count Rate**
- **Dependent**

**Spectral Calibration**

- **Energy / keV**
  - Bin 1
  - Bin 2
  - Bin 3
  - Bin 4

**Energy / keV**

- 10
- 20
- 30
- 40
- 50
- 60
- 70
- 80
- 90
- 100
Simulation Study

- Material decomposition into iodine and water
- Spectrum 80 kV, 6 mm Al prefiltration

a) Distorted bin sensitivity function for decomposition

b) Simulated pulse pileup for paralyzable detector and rectangular shaped pulses


Simulation Study

Ground Truth

With pulse pileup

Ideal  Distorted

Ref. 1 (Liu)

Ref. 2 (Sidky)

Prop. Meth.

C = 0 mg/mL, W = 4 mg/mL
Phantom Measurements

- QRM dual energy phantom DEP-002.
- Reference concentration determined with Siemens Somatom Definition Flash scanner.

**Phantom Measurements**

- Iodine ROI: 21.5 mg/mL
- Water ROI: 0.6 mg/mL

**Diagram**

- Water
- Iodine
- Calcium

**Image**

- QRM-DEP-002 Dual Energy Phantom
- 2 cm scale

**Image Caption**

- Iodine ROI: 21.5 mg/mL
- Water ROI: 0.6 mg/mL
Table-Top Photon Counting CT

Dectris Santis prototype with sample

Rotation stage

X-ray Source

Pixel: 512 x 256
Pixel size: 150 x 150 µm²
Sensor thickness: 1.0 mm CdTe
Phantom Measurements

<table>
<thead>
<tr>
<th></th>
<th>No Calibration</th>
<th>Ref. 1</th>
<th>Ref. 2</th>
<th>Prop. Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iodine</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Water (VNC)</td>
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</tbody>
</table>

- $C = 10 \text{ mg/mL}$, $W = 40 \text{ mg/mL}$
- $C = -500 \text{ HU}$, $W = 2000 \text{ HU}$
Phantom Measurements

Deviation from Reference Scan

- No Calib.: 75.4%
- Ref. 1: 16.7%
- Ref. 2: 6.57%
- Prop. Meth.: 1.86%

C = 10 mg/mL, W = 40 mg/mL
C = -500 HU, W = 2000 HU
Conclusions

• The **count rate-dependent spectral calibration** can accommodate both for spectral distortions and count rate-dependent effects.

• In measurements, **artifacts** in material images were down to noise level.

• Agreement with clinical CT system within 2% for iodine quantification.
Thank You!

The 6th International Conference on Image Formation in X-Ray Computed Tomography

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www.ct-meeting.org

Conference Chair: Marc Kachelriß, German Cancer Research Center (DKFZ), Heidelberg, Germany

This presentation will soon be available at www.dkfz.de/ct.

Job opportunities through DKFZ’s international Fellowship programs (marc.kachelriess@dkfz.de).
Parts of the reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany.
The prototype photon-counting x-ray detectors were provided by Dectris Ltd., Baden, Switzerland.