K-edge subtraction X-ray imaging with a pixellated spectroscopic detector

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Summary

• Hyperspectral imaging
• K-edge subtraction X-ray imaging for mammography
  – Methods
  – Results so far
  – Open problems
  – Perspectives
What is hyperspectral imaging?

- Any imaging technique allowing to retrieve a spectrum of the radiation detected
- Spectral information can be used for
  - Scatter rejection
  - Dual energy techniques
  - Non-conventional techniques (diffraction, fluorescence)
  - Nuclear Medicine
- So far, hyperspectral X-ray imaging methods have been limited due to the limited availability of pixellated spectroscopic detectors
  - Scanning methods are time consuming
- Recent technological developments are making hyperspectral imaging a reality
In the beginning was HPGe...

- HPGe has excellent energy resolution (<0.5 keV @ 60 keV)
- **BUT:**
  - Very expensive
  - Needs cooling → bulky and not suitable for in-field applications
  - Very few examples of position-sensitive devices

- HEXITEC collaboration (EPSRC funded):
  - Collaboration between STFC (Rutherford Appleton Labs), Universities of Manchester, Surrey, Durham, Royal Surrey County Hospital
  - Development of pixellated room temperature spectroscopic detectors (CdTe, CZT)
  - Now in its translational phase
HEXITEC characteristics

- Currently using room temperature/sub-room temperature CdTe sensors
- Current sensors 80x80 pixels, 250 μm pitch, 1 mm thick
  - Tiled arrays of 2 x 2 sensors are under development
- Operated at -500V
K-edge subtraction imaging

- Typically used for angiography/angiogenesis studies
- Two images are acquired with energies above and below the K-edge of a contrast agent
- Combination and subtraction of the two removes the background
- Problems with conventional KES
  - Increased dose (two images!)
  - Image registration (the patient moves between the two images)
- This is removed with a spectroscopic detector:
  - The images above and below the K-edge are obtained by integrating the spectrum in appropriate ranges
Iodine KES with HEXITEC

- Aim: study of angiogenesis around breast tumours
- Different concentrations of Niopam® are used
  - Iodine-based contrast agent
- Iodine K-edge: 33.2 keV
  - Higher energy spectra than in conventional mammography
    W anode, 3 mm Al filtration, 45-50 kVp
- Plus single-photon counting detector
  - Intrinsically low noise
  
  → Significant dose reduction compared to conventional mammography!
The simplest approach: logarithmic subtraction

- The assumption is that the attenuation coefficient of the background materials does not vary strongly on the two sides of the K-edge

→ by subtracting the logarithm of the image below the K-edge from the logarithm of the image above the K-edge the background is removed

\[ S(i,j) = \ln \left( \frac{I^{0}_{\text{high}}}{I^{0}_{\text{high}}(i,j)} \right) - \ln \left( \frac{I^{0}_{\text{low}}}{I^{0}_{\text{low}}(i,j)} \right) \]

\[ = \mu^{I}_{\text{high}} x_{I} + \mu^{bg}_{\text{high}} x_{bg} - \left( \mu^{I}_{\text{low}} x_{I} + \mu^{bg}_{\text{low}} x_{bg} \right) \]

\[ \approx \left( \mu^{I}_{\text{high}} - \mu^{I}_{\text{low}} \right) x_{I} \]

- Problems:
  - Only works if \( \Delta \mu^{bg} \) is negligible across the K-edge
  - Maximum if \( \Delta \mu^{I} \) is maximum

Integration bands must be close to each other

- Poor background removal if wide bands are chosen
Finding the optimum integration ranges

- 3 mm tube filled with undiluted Niopam 150 (150 µg/ml l)
- The optimum integration ranges for the images above and below the K-edge result from a trade-off
  - Wide range → high statistics, BUT low contrast + high structural noise
    - The drop in transmission between the two sides of the K-edge is not fully exploited
  - Narrow range → high contrast, BUT poor statistics/high noise
- Investigated via contrast-to-noise ratio; CNR = (I - Ib)/σ

<table>
<thead>
<tr>
<th>Width (keV)</th>
<th>CNR</th>
</tr>
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<tbody>
<tr>
<td>0.5</td>
<td>48</td>
</tr>
<tr>
<td>1</td>
<td>76</td>
</tr>
<tr>
<td>2</td>
<td>55</td>
</tr>
<tr>
<td>5</td>
<td>32</td>
</tr>
<tr>
<td>10</td>
<td>14</td>
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Complex test objects

- “non uniform background” phantoms to verify the effectiveness of subtraction algorithms
- Images taken with a W-anode tube, 2 mm filtration, 45 kVp, 7µA
  - Entrance dose ~270 µGy

“single layer phantom”
1 cm thick

“multi-layer phantom”
4 cm thick
Initial K-edge studies

- “non uniform background” phantoms to verify the effectiveness of subtraction algorithms
- Images taken with a W-anode tube, 2 mm filtration, 45 kVp, 7µA
  - Entrance dose ~270 µGy

“single layer phantom”
1 cm thick

“multi-layer phantom”
4 cm thick
Results - logarithmic subtraction

“one layer” phantom

Above K-edge

Below K-edge

Subtracted

“multilayer” phantom

Limited background removal:
Outside linear regime
Increasing contrast and improving background subtraction

- When different pixel gain is not taken into account, conservative integration ranges need to be chosen.

- The problem is removed by interpolating the spectra for all calibrated pixels so that peaks/K-edges coincide.
Results – optimised calibration

- The procedure allows the choice of integration bands closer to the physical K-edge of contrast agent
  - Higher intrinsic contrast
  - Lower noise due to improved background removal

<table>
<thead>
<tr>
<th>Width (keV)</th>
<th>CNR – uncorr</th>
<th>CNR – corr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>31</td>
<td>54</td>
</tr>
<tr>
<td>2</td>
<td>26</td>
<td>41</td>
</tr>
<tr>
<td>3</td>
<td>31</td>
<td>36</td>
</tr>
</tbody>
</table>

![Graph showing intensity vs pixel comparison between uncorrected and corrected data.](image-url)
“Dual energy algorithm” (Lehmann 1981)

- Any image pixel is seen as a vector
- The vector is projected onto a basis \{iodine component, water component\} and the two projections are retrieved separately, giving rise to a “iodine equivalent” image and a “water equivalent” image

\[
\begin{align*}
\ln\left(\frac{I_0}{I}\right)_{low} &= \left(\frac{\mu}{\rho}\right)_{low}^I \cdot \left(\rho x\right)_{low} + \left(\frac{\mu}{\rho}\right)_{low}^{water} \cdot \left(\rho x\right)_{water} \\
\ln\left(\frac{I_0}{I}\right)_{high} &= \left(\frac{\mu}{\rho}\right)_{high}^I \cdot \left(\rho x\right)_{high} + \left(\frac{\mu}{\rho}\right)_{high}^{water} \cdot \left(\rho x\right)_{water}
\end{align*}
\]

- Allows quantitative information (\(\mu x\))
- No pre-assumptions on the position and width of integration bands
  - Proved much more effective than log-subtraction on conventional KES
Results – Dual energy algorithm (2 keV)

• Background removal is improved!
• Increased CNR (more uniform background)

Log subtracted

Iodine projection

Water projection
Dual energy optimisation

- "Breast equivalent" test object (Perspex spheres + oil)
- 50 kVp, 3 mm Al (mean energy 33 keV)
- 2 µA, 9 min acquisitions → entrance air dose 75 µGy
Dual energy optimisation - II

- CNR reaches a maximum at wider band than with log subtraction
  - Better background removal → lower structural noise
Iodine vs water

- Unlike with the log-subtraction algorithm, contrast increases when increasing the bandwidth (but structural noise increases, too)
What is going on?

- The two base vectors are no longer orthogonal.
- A more accurate treatment will involve changing the system of linear equations for dual energy into a system of integrals.
Open problems - calibration

- The energy calibration of an 80x80 array must be done automatically.
- Typically, the user selects a range for peak search using the spectrum averaged on all pixels.
- This may cause a problem with pixels with gain significantly off-average → speckles.
Comparison with conventional imaging

- Pairs of spectra were chosen with average energies below and above the K-edge of iodine, respectively
- CNR was calculated to identify the optimum pair of spectra
  - Low: W anode, 45 kVp, 250 µm Tin filter
  - High: W anode, 50 kVp, 12.5 mm Al filter

<table>
<thead>
<tr>
<th>Tube Ø (mm)</th>
<th>CNR – HEXITEC</th>
<th>CNR – conventional</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>55</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>68</td>
<td>62</td>
</tr>
</tbody>
</table>

Entrance dose
Conventional 1.2 mGy
HEXITEC 75 µGy
A large test object

- Mean glandular dose 0.5 mGy
  (in conventional mammography 1.5 mGy/image)
Very low dose – MGD 1.5 µGy

Full spectrum

Low

High

Iodine

Water

www.surrey.ac.uk
Conclusions

• A pixellated spectroscopic CdTe detector has proven effective in one-shot K-edge subtraction imaging around the Iodine K-edge
  – Dose 15 times lower than conventional imaging with comparable image quality
  – The optimum energy band to be integrated results from a trade-off between signal and noise (statistical and structural)

• Open problems:
  – Limited linearity (to be addressed with a systematic study on pulse shaping parameters)
  – Pixel gain spread

• Future work
  – Improving spatial resolution (sub-pixel) with charge-sharing algorithms
  – Design of a “dynamic” test object for uptake-washout measurements
  – New contrast agents
    Gold nanoparticles?
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