Image reconstruction in proton computed tomography

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What is proton therapy?

• Cancer treatment: surgery, chemotherapy, radiotherapy, immunotherapy
• Radiotherapy: uses ionizing particles
• What kind of particles?
  ➔ Photons
  ➔ Protons
  ➔ Heavy ions

Layout of HIT Centre in Heidelberg [2]
Why is proton therapy so outstanding?

Interactions of protons [3]

Comparison of depth dose profiles of high-energy photon (X-rays, in blue), protons (green), and carbon ions (red) beams [2]
Problems with imaging and the solution

- Today: X-ray CT is used
- We need to know the RSP* of the protons
- Difference between the absorption of photons and the energy loss of protons → conversion is not accurate between Hounsfield units* and RSP [4]
- Solution: we do the imaging with protons! → proton CT

*X-Relative Stopping Power
*Quantitative measurement of radio density used in CT imaging, calculated of the baseline linear absorption of the X-ray beam

X-ray CT vs. proton CT [8]
The Bergen pCT Collaboration

- Based at University of Bergen
- Goal: to build a proton CT system, based on high-energy particle detectors used in CERN and other collaborations
- Detector system is based on ALPIDE chip (originally developed for the ALICE experiment in CERN)

Cross-sectional view (A) and photograph (B) of the ALPIDE chip

The Bergen pCT system
Image reconstruction techniques

2 main types

- Based on integral transformations → Radon, Inverse Radon
  - Easy, but not accurate and cannot be used with proton CT

- Iterative reconstruction techniques
  - Model the problem as a linear equation system
    \[ A \cdot x = b \]
    - Vector that contains interaction coefficients between protons and pixels/voxels
    - Matrix that contains estimated proton RSP values
    - Vector that contains the known WEPL values of the protons

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Iterative methods for image reconstruction

N iterations

Initial image

Corrected image

Satisfactory image

Converged corrections

Corrections

Corrected image

Corrections
The Richardson-Lucy algorithm

- Statistical iterative algorithm
- Maximum Likelihood - Expectation Maximization (ML-EM)
- Originally used in optics [5], [6], [7]
- Input data from Monte Carlo
- MLP Calculation
- Calculating RSP distribution

\[ x_{i}^{k+1} = \frac{1}{\sum_{j} A_{i,j}} \sum_{j} y_{j} A_{i,j} x_{1}^{k} \]

This is very difficult to solve technically (millions of proton trajectories)
- Using GPU
- Using Cuda
- Finding optimization regarding the number of iterations and protons

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Steps of the framework

1. Generating data with Monte Carlo
2. Adding simulated measurement errors
3. 3-sigma filtering
4. MLP calculation
5. Calculating RSP distribution with Richardson-Lucy
6. Simulations with Geant4 & Gate
7. From correlated Gauss distributions, for every proton's direction & position
8. Filtering directions and WEPL values of the protons
9. Calculating the most likely position of protons going in and coming out of the cylinder around the phantom

Parallelization

C++ code accelerated with GPU (using CUDA): Hadamard ratios are calculated for every trajectory in the GPU kernels (Wigner WSCLAB)

Shorter runtime (days → hours)
Evaluating the algorithm

Derenzo phantom

- 200 mm diameter water cylinder with 6 sectors of 1.5-6 mm diameter aluminium rods
- Used for measuring spatial resolution

CTP404 phantom

- 150 mm diameter epoxy cylinder with 8 different material inserts with 12.2 mm diameter
- Used for measuring reconstruction accuracy for RSP
Results

The original (left) and the reconstructed (right) Derenzo phantom

<table>
<thead>
<tr>
<th></th>
<th>X axis</th>
<th>Y axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>0.78</td>
<td>0.78</td>
</tr>
<tr>
<td>Reconstructed</td>
<td>0.71</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Valley-to-peak intensity ratios

MTF\(_{10\%}\) values

\[
MTF_{10\%} = \frac{2}{\pi} \cdot \sqrt{-\ln 0.1 \cdot \ln 2} \cdot \frac{1}{\text{FWHM}}
\]

One slice of the original (left) and reconstructed (right) Derenzo phantom and the intensities projected onto the x, y axis

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The difference between the real and reconstructed RSP values of the different materials

<table>
<thead>
<tr>
<th>Material</th>
<th>RSP (original phantom)</th>
<th>RSP (reconstructed phantom)</th>
<th>Relative difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.000</td>
<td>5.324*10^{-4}</td>
<td>5.324*10^{-4}</td>
</tr>
<tr>
<td>Teflon</td>
<td>1.833</td>
<td>1.749</td>
<td>0.046</td>
</tr>
<tr>
<td>Delrin</td>
<td>1.363</td>
<td>1.289</td>
<td>0.054</td>
</tr>
<tr>
<td>PMMA</td>
<td>1.179</td>
<td>1.124</td>
<td>0.047</td>
</tr>
<tr>
<td>Air</td>
<td>0.000</td>
<td>5.324*10^{-4}</td>
<td>5.324*10^{-4}</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>1.048</td>
<td>0.987</td>
<td>0.058</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>1.003</td>
<td>0.919</td>
<td>0.084</td>
</tr>
<tr>
<td>PMP</td>
<td>0.866</td>
<td>0.813</td>
<td>0.061</td>
</tr>
</tbody>
</table>
Results

Difference between the original and the reconstructed images

10th iteration

100th iteration

200th iteration

300th iteration
Results

- **Absolute Error**: number of pixels that differ
- **Peak Absolute Error**: the largest absolute difference between any two corresponding pixels
- **Mean Absolute Error**: the average absolute difference between corresponding pixels
- **Mean Squared Error**: the average squared difference between corresponding pixels
- **Root Mean Squared Error**: square root of the above
Summary

- I have optimized a framework that utilises the Richardson-Lucy algorithm for pCT image reconstruction
  - More compact framework, more user-friendly
  - Significantly shorter runtime (days → hours)
- Tested the framework on two phantoms
  - Good spatial resolution and reconstruction accuracy
- Accuracy converges with the number of iterations
- Runtime should be even shorter for clinical usage (~minutes)

Future plans

- Development of the framework → realistic phantom (Shepp-Logan)?
- Implementing Machine Learning for MLP calculation?
- Clinically usable form
Thank you for your attention!

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References


