EÖTVÖS LORÁND
UNIVERSITY | BUDAPEST

Image reconstruction in proton computed tomography

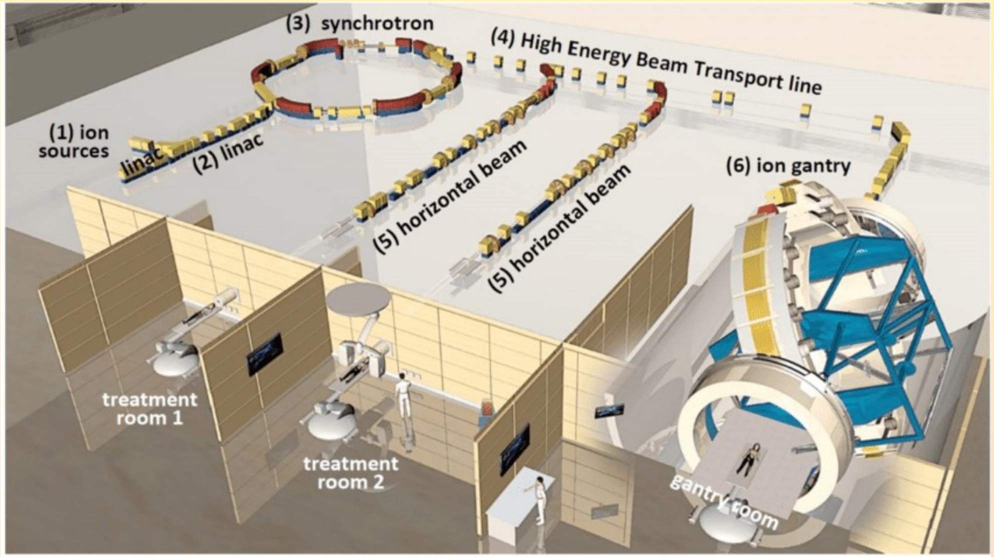
Supervisors:
Gábor Bíró, Ph.D.
Gábor Papp, Ph.D.

HUN-REN Hungarian Research Network
MTA Centre of Excellence

Zsófia Jólesz
23rd Zimányi School, 2023

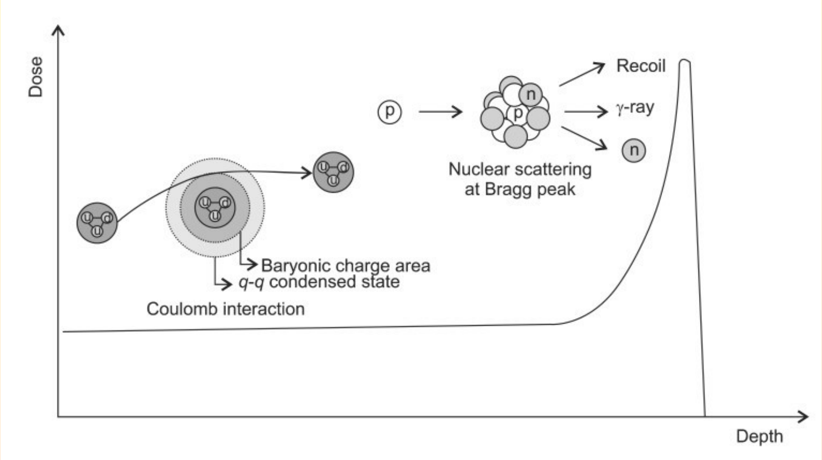
What is proton therapy?

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

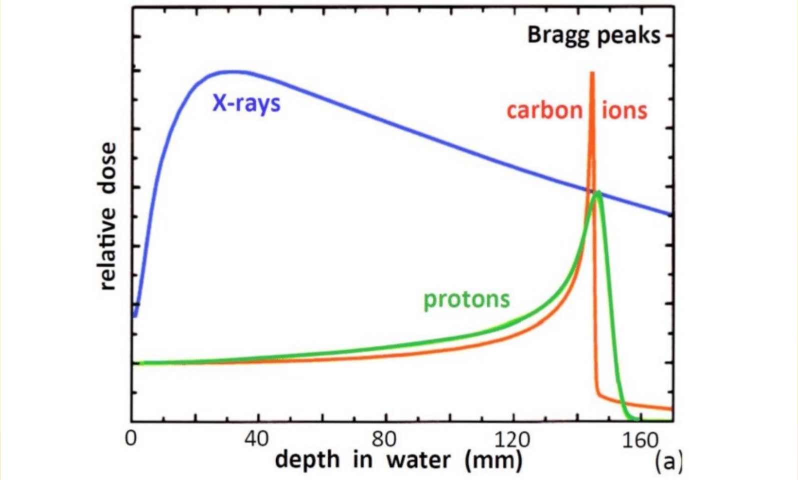


Layout of HIT Centre in Heidelberg [2]

Why is proton therapy so outstanding?

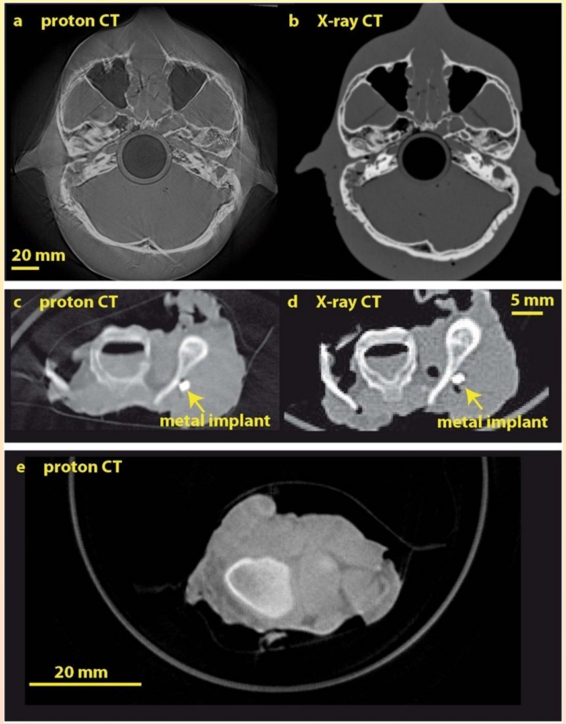


Interactions of protons [3]



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

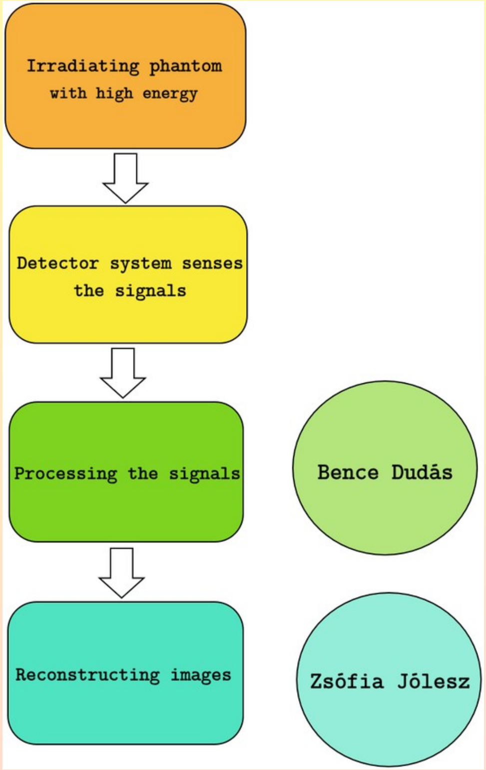


X-ray CT vs. proton CT [8]

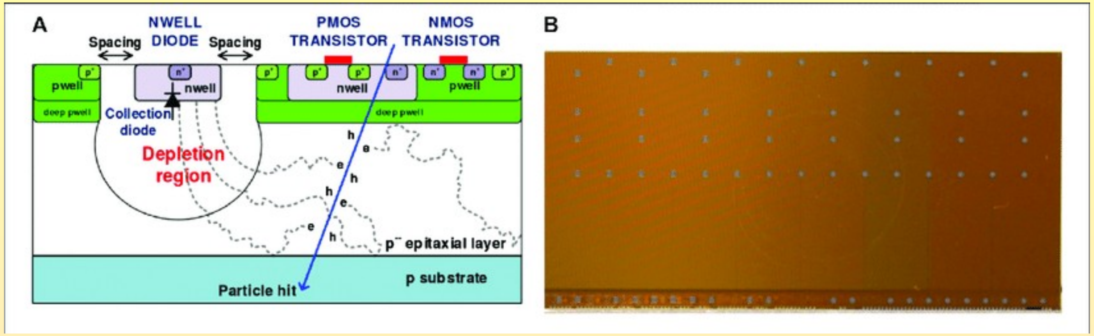
- Today: X-ray CT is used
- We need to know the RSP* of the protons
- Difference between the absorption of photons and the energy loss of protons → conversion is not accurate between Hounsfield units* and RSP [4]
- Solution: we do the imaging with protons! → proton CT

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

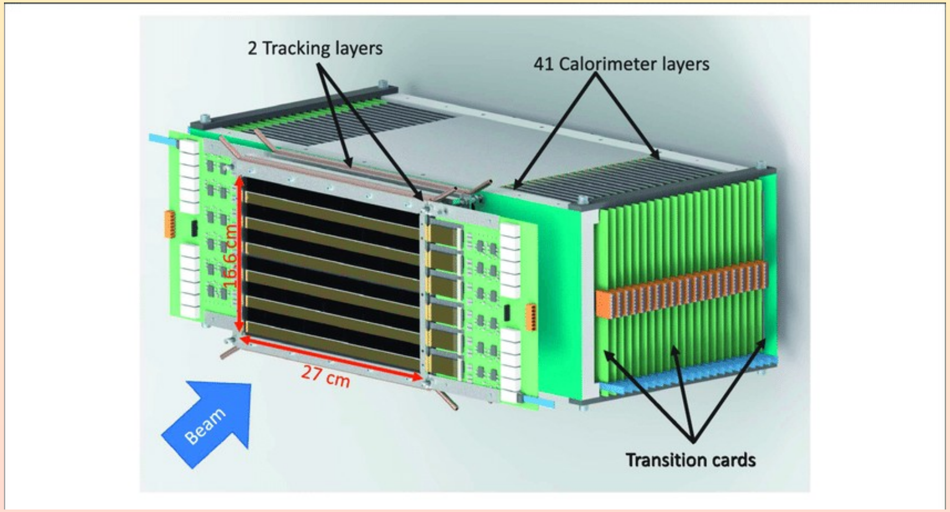
The Bergen pCT Collaboration



- 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

Zsófia Jólesz
23rd Zimányi School, 2023

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

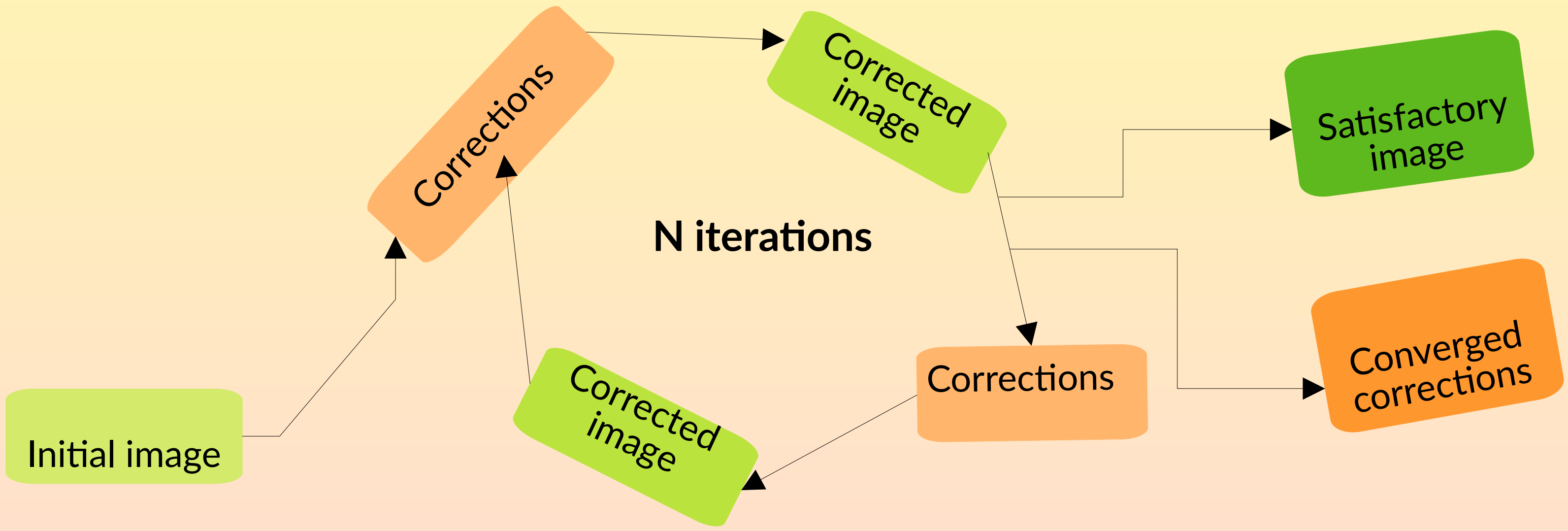
$$\boldsymbol{A} \cdot x = b$$

Matrix that contains interaction coefficients between protons and pixels/voxels

Vector that contains estimated proton RSP values

Vector that contains the known WEPL values of the protons

Iterative methods for image reconstruction



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

Number of iterations

Vector containing WEPL values

Matrix containing interaction coefficients between proton trajectories and voxels

$$x_i^{k+1} = x_i^k \frac{1}{\sum_j A_{i,j}} \sum_j \frac{y_j}{\sum_1 A_{l,j} x_1^k} A_{i,j}$$

Vector containing RSP values

This is very difficult to solve technically (millions of proton trajectories)

- Using GPU
- Using Cuda
- Finding optimization regarding the number of iterations and protons

Development of the framework

Steps of the framework

Generating data with Monte Carlo → Simulations with Geant4 & Gate → Very time-consuming! → Parallelization → Shorter runtime (days → hours)

↓

Adding simulated measurement errors → From correlated Gauss distributions, for every proton's direction & position

↓

3-sigma filtering → Filtering directions and WEPL values of the protons

↓

MLP calculation → Calculating the most likely position of protons going in and coming out of the cylinder around the phantom

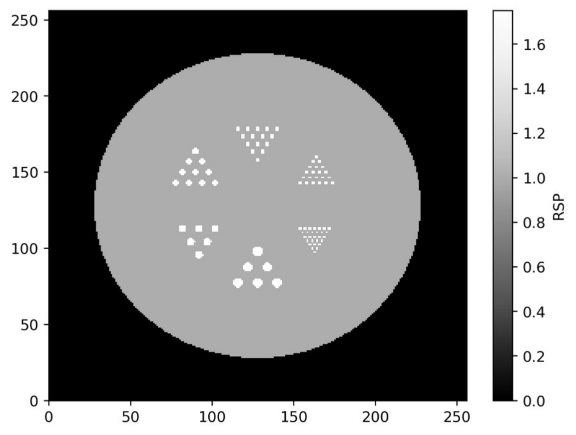
↓

Calculating RSP distribution with Richardson-Lucy → 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

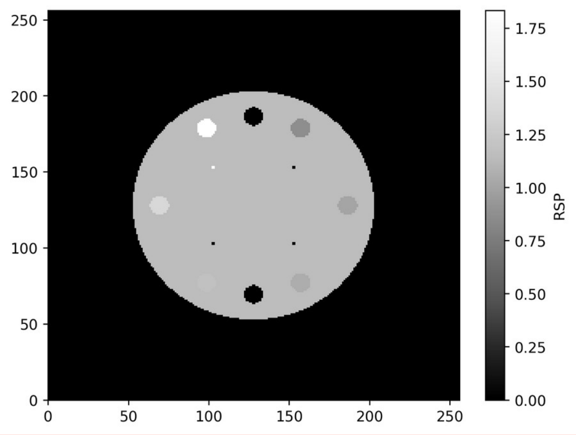
Derenzo phantom

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

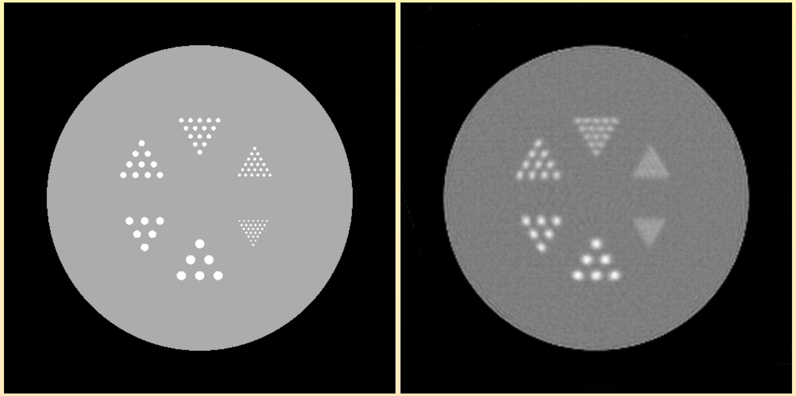


CTP404 phantom

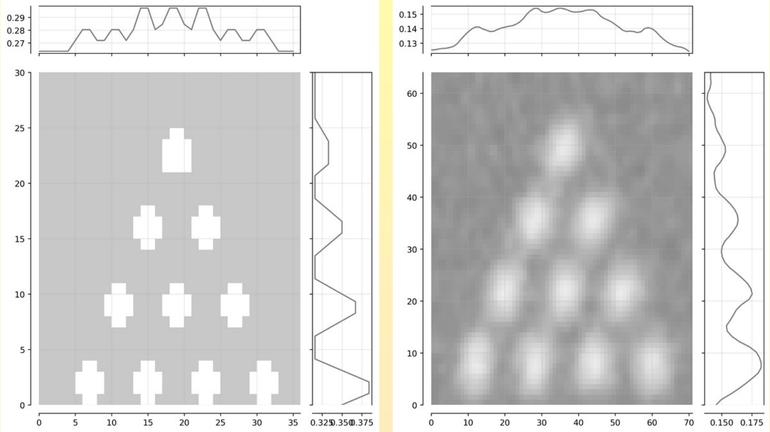
- 150 mm diameter epoxy cylinder with 8 different material inserts with 12.2 mm diameter
- Used for measuring reconstruction accuracy for RSP



Results



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



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

	X axis	Y axis
Original	0.78	0.78
Reconstructed	0.71	0.69

Valley-to-peak intensity ratios

	$MTF_{10\%}$
Original	1.69
Reconstructed	0.95

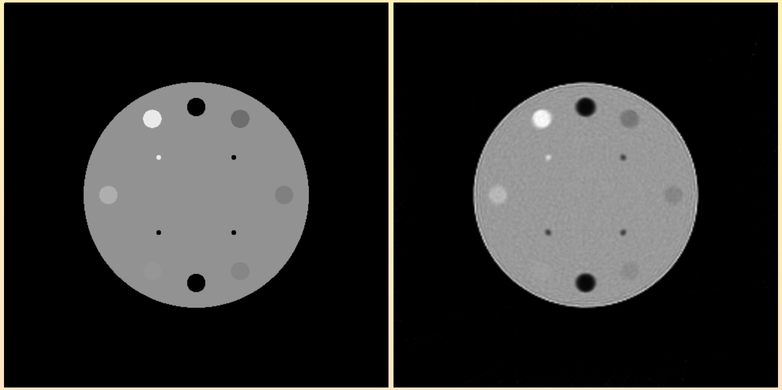
$MTF_{10\%}$ values
(x and y values are averaged)

$$\mathrm{MTF}_{10\%} = \frac{2}{\pi} \cdot \sqrt{-\ln 0.1 \cdot \ln 2} \cdot \frac{1}{\mathrm{FWHM}}$$

Results

Material	RSP (original phantom)	RSP (reconstructed phantom)	Relative difference
Air	0.000	$5.324*10^{-4}$	$5.324*10^{-4}$
Teflon	1.833	1.749	0.046
Delrin	1.363	1.289	0.054
PMMA	1.179	1.124	0.047
Air	0.000	$5.324*10^{-4}$	$5.324*10^{-4}$
Polystyrene	1.048	0.987	0.058
Polyethylene	1.003	0.919	0.084
PMP	0.866	0.813	0.061

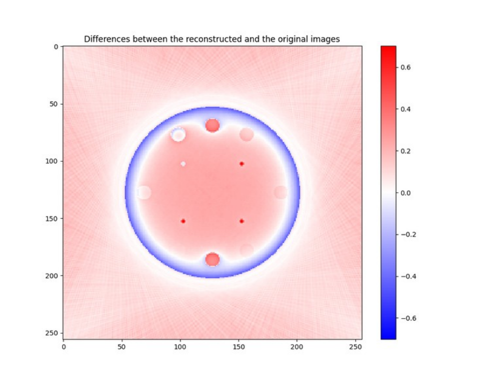
The difference between the real and reconstructed RSP values of the different materials



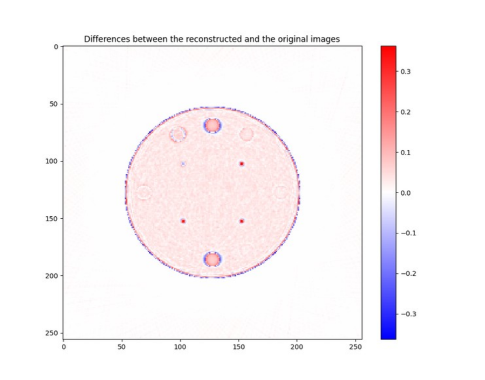
The original (left) and the reconstructed (right) CTP404 phantom

Results

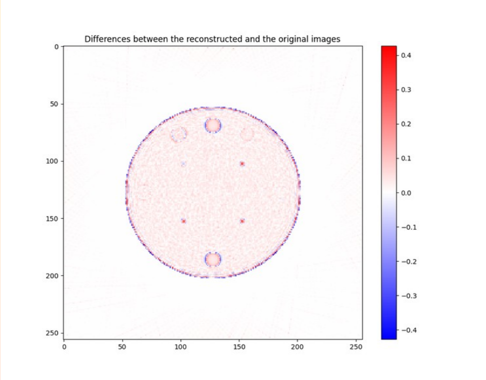
Difference between the original and the reconstructed images



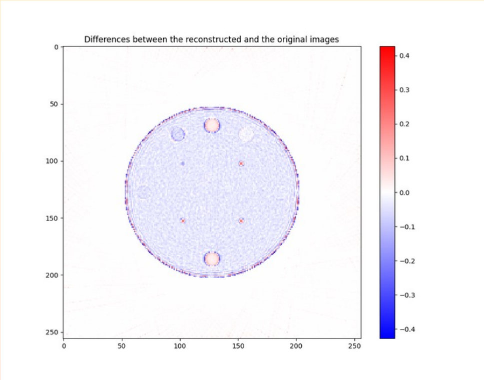
10th iteration



100th iteration

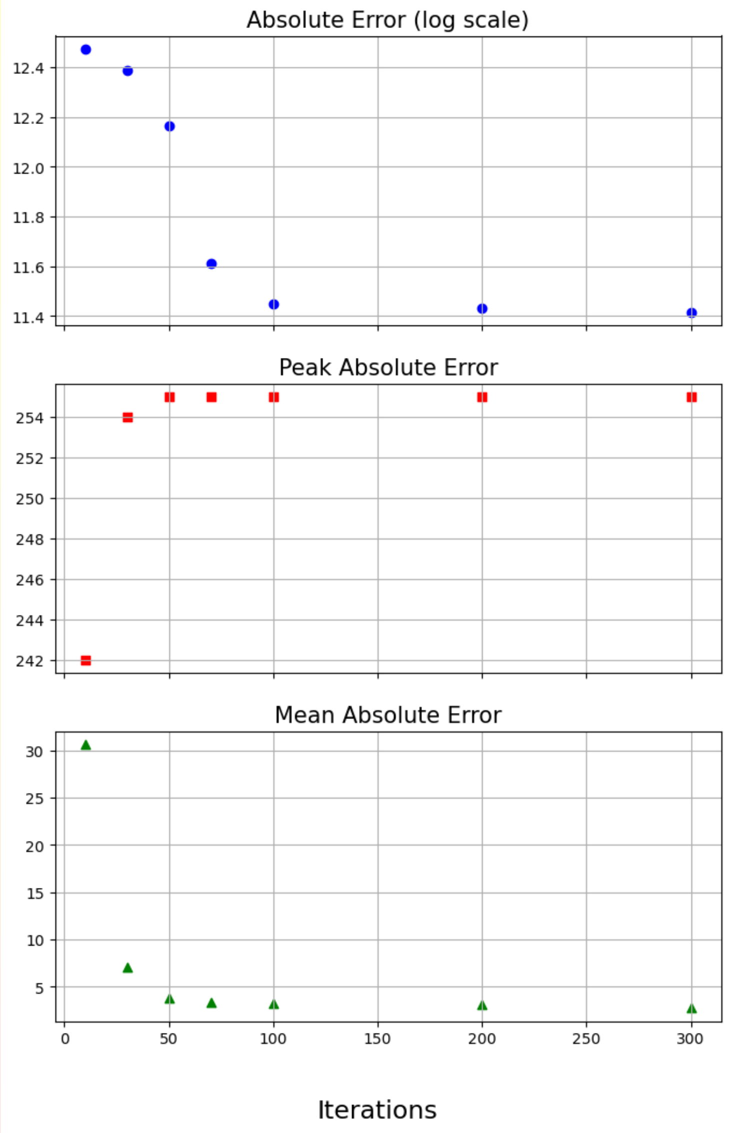


200th iteration

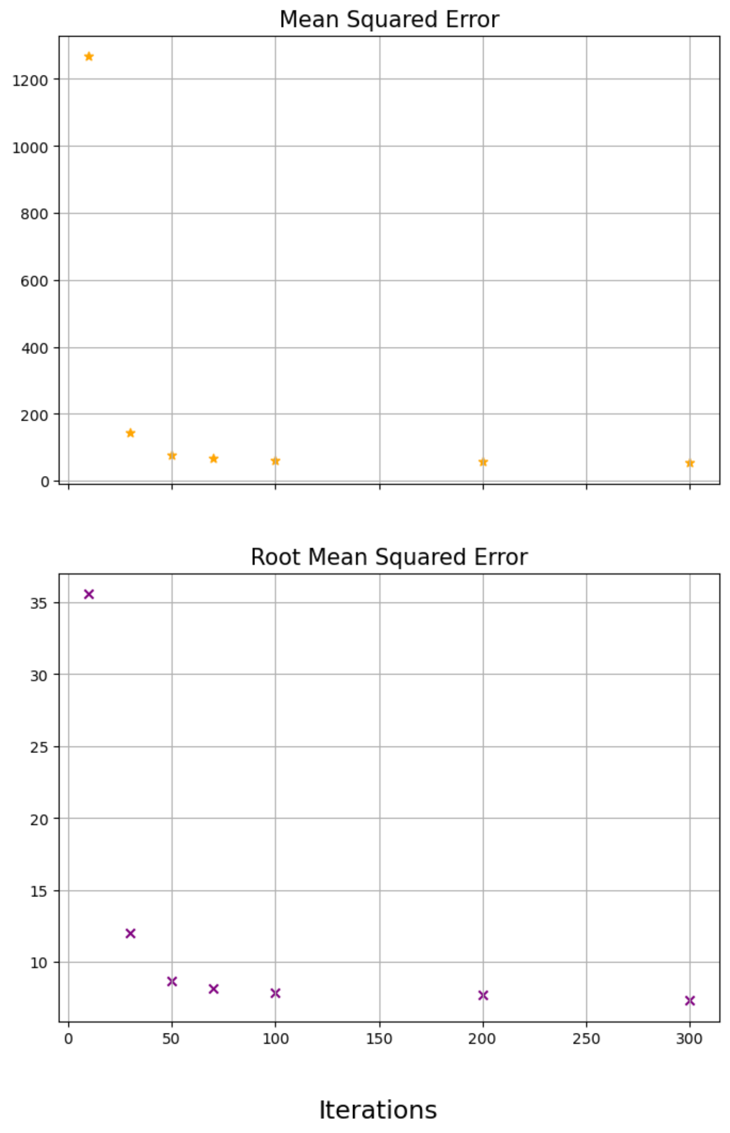


300th iteration

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

Shepp-Logan phantom

Thank you for your attention!

My research was supported by the Hungarian National Research, Development and
Innovation Office (NKFIH) grants under the contract numbers OTKA K135515.

References

[1] Simon Deycmar, Erica Faccin, Tamara Kazimova, Philip Knobel, Irma Telarovic, Fabienne Tschanz, Verena Waller, Rona Winkler, Carmen Yong, Dario Zingariello, and Martin Pruschy. The relative biological effectiveness of proton irradiation in dependence of dna damage repair. The British Journal of Radiology, 93:20190494, 11 2019.

[2] Ugo Amaldi, Manjit Dosanjh, Jacques Balosso, Jens Overgaard, and Brita Sørensen. A facility for tumour therapy and biomedical research in south-eastern europe. 09 2019.

[3] Seo Hyun Park and Jin Oh Kang. Basics of particle therapy i: physics. Radiation oncology Journal, 29(3):135, 2011.

[4] Caesar E Ordoñez, Nicholas T Karonis, Kirk L Duffin, John R Winans, Ethan A DeJongh, Don F DeJongh, George Coutrakon, Nicole F Myers, Mark Pankuch, and James S Welsh. Fast in situ image reconstruction for proton radiography. Journal of radiation oncology, 8:185–198, 2019.

[5] Leon B Lucy. An iterative technique for the rectification of observed distributions. Astronomical Journal, Vol. 79, p. 745 (1974), 79:745, 1974.

[6] William Hadley Richardson. Bayesian-based iterative method of image restoration. JoSA, 62(1):55–59, 1972.

[7] Ákos Sudár and Gergely Gábor Barnaföldi. Proton Computed Tomography Based on Richardson-Lucy Algorithm. ArXiv:2212.00126, 2022.

[8] Prall, Matthias & Durante, Marco & Berger, Thomas & Przybyla, Bartos & Graeff, Christian & Lang, P & Latessa, C & Shestov, Lev & Simoniello, Palma & Danly, C & Mariam, Fesseha & Merrill, Frank & Nedrow, P & Wilde, Carl & Varentsov, D. (2016). High-energy proton imaging for biomedical applications. Scientific Reports. 6. 10.1038/srep27651.