Northern Illinois University

Optimizing relaxation parameter for iterative pCT reconstructions

Christina Sarosiek

July 20, 2020

Proton CT

- Proton CT measures the RSP of each voxel directly
- This allows for reduction of beam-specific range margins during treatment planning
- This could lead to a reduction of NTCP on structures close to the CTV

- Single particle tracking
- 1 MHz protons
- 10 x 30 cm field of view
- 6 minute, continuous rotation scans
- 360 million protons
- About 100 million protons after preprocessing

Image Reconstruction

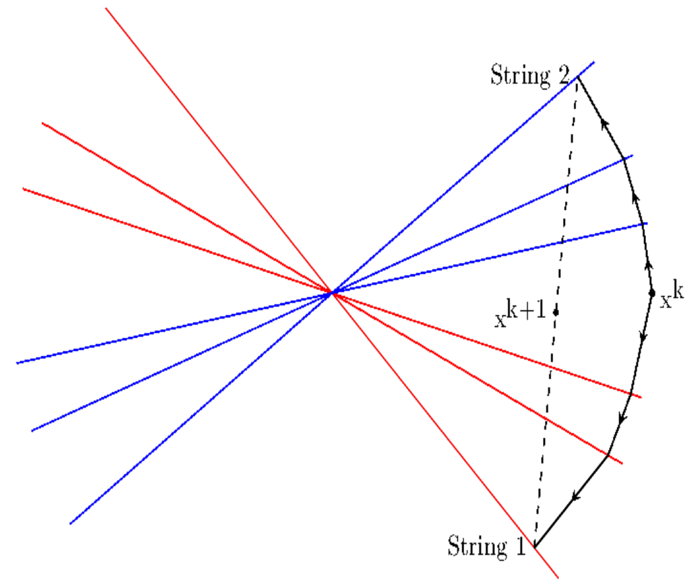
- Most likely path (MLP) algorithm
- Feldkamp, Davis, Kress (FDK) cone beam filtered back projection for initial image reconstruction
- Component Averaged Row Projection (CARP)
  - String average projection (SAP) iterative algorithm
- Total variation superiorization (TVS)
- Reconstruction on cluster with GPUs and CPUs
  - Allows for large amounts of parallelization and faster reconstruction times

pCT Iterative Reconstruction – CARP

- $Ax = b, A = \begin{bmatrix} \square & \square & \square \\ \leftarrow & a^i & \rightarrow \\ \square & \square & \square \\ \square & \square & \square \\ \square & \square & \square \end{bmatrix}, x = \begin{bmatrix} \square \\ \square \\ \square \end{bmatrix}, b = \begin{bmatrix} \square \\ b_i \\ \square \\ \square \\ \square \end{bmatrix}$

$$x^{(k+1)} = \frac{1}{s} \sum_{t=1}^{M} S_t \left(x^{(k)}\right)$$

$$S_t\left(x^{(k)}\right) = x^{(k)} + \lambda \sum_{i} \frac{b_i - \langle a^i, x^{(k)} \rangle}{\|a^i\|^2} a^i$$



a^i = proton path length per voxel

x = RSP in each voxel

b = WEPL per proton track

i = index for proton track

$\frac{1}{s}$ = weighting factor

λ = relaxation parameter

k = iteration number

M = total number of strings= 40

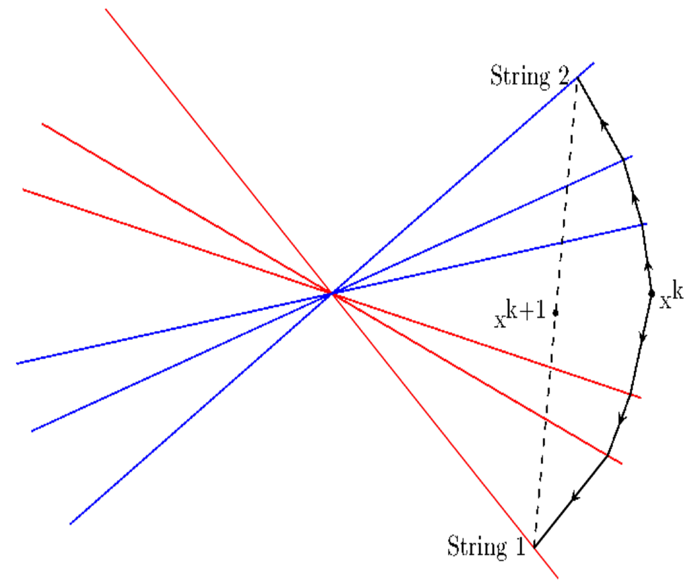
t = String number, {1…40}

pCT Iterative Reconstruction – CARP

- $Ax = b, A = \begin{bmatrix} \square & \square & \square \\ \leftarrow & a^i & \rightarrow \\ \square & \square & \square \\ \square & \square & \square \\ \square & \square & \square \end{bmatrix}, x = \begin{bmatrix} \square \\ \square \\ \square \end{bmatrix}, b = \begin{bmatrix} \square \\ b_i \\ \square \\ \square \\ \square \end{bmatrix}$

$$x^{(k+1)} = \frac{1}{s} \sum_{t=1}^{M} S_t\left(x^{(k)}\right)$$

$$S_t\left(x^{(k)}\right) = x^{(k)} + \lambda \sum_i \frac{b_i - \langle a^i, x^{(k)} \rangle}{\|a^i\|^2} a^i$$



a^i = proton path length per voxel

x = RSP in each voxel

b = WEPL per proton track

i = index for proton track

$\frac{1}{s}$ = weighting factor

λ = relaxation parameter

k = iteration number

M = total number of strings= 40

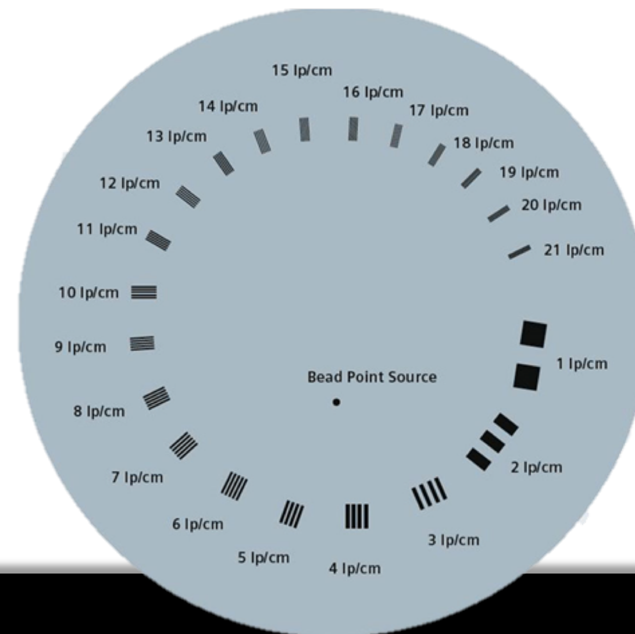
t = String number, {1…40}

Goal

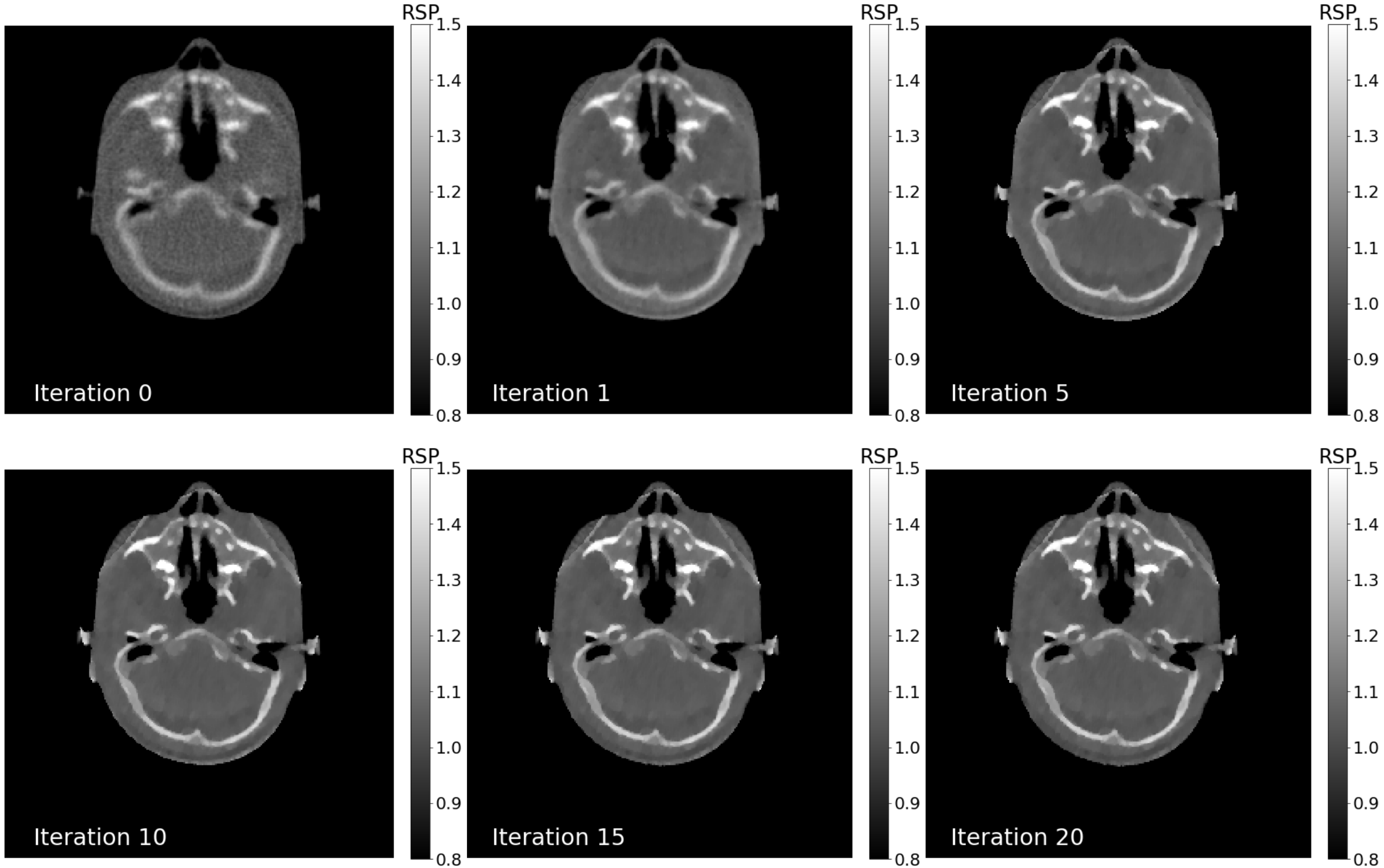
- Vary relaxation parameter in CARP algorithm and observe changes in image quality metrics
- Observe how the image quality metrics evolve with iteration number
- Image quality metrics:
  - RSP Accuracy
  - Contrast to Noise Ratio (CNR)
    - $CNR = \frac{RSP_A - RSP_B}{\sqrt{(\sigma_A)^2 + (\sigma_B)^2}}$, where σ is the standard deviation in the RSP
  - Spatial resolution / Modulation transfer function (MTF)
    - $MTF(LP) = \frac{(Peak - Valley)_{LP}}{(Peak - Valley)_{LP=1\ cm^{-1}}}$

Phantoms

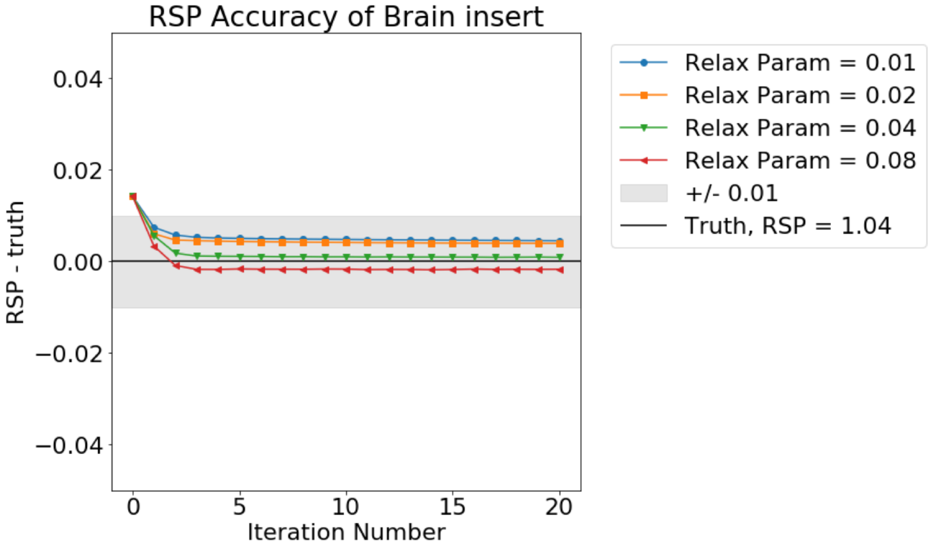
- Custom RSP phantom
- Line pair phantom
- CIRS pediatric head phantom

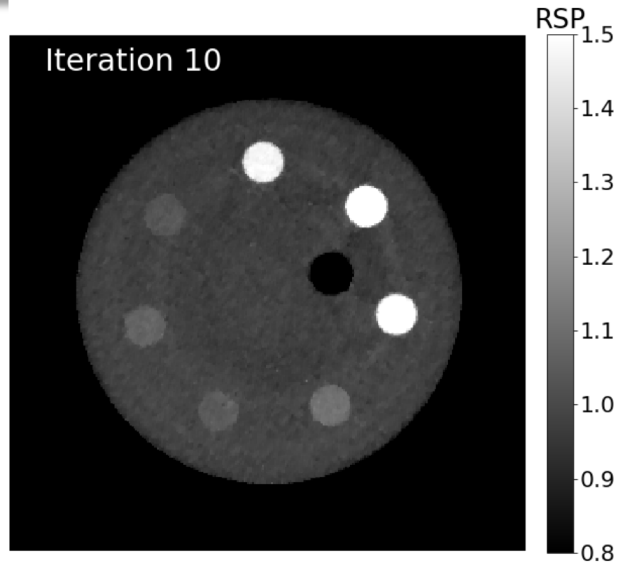


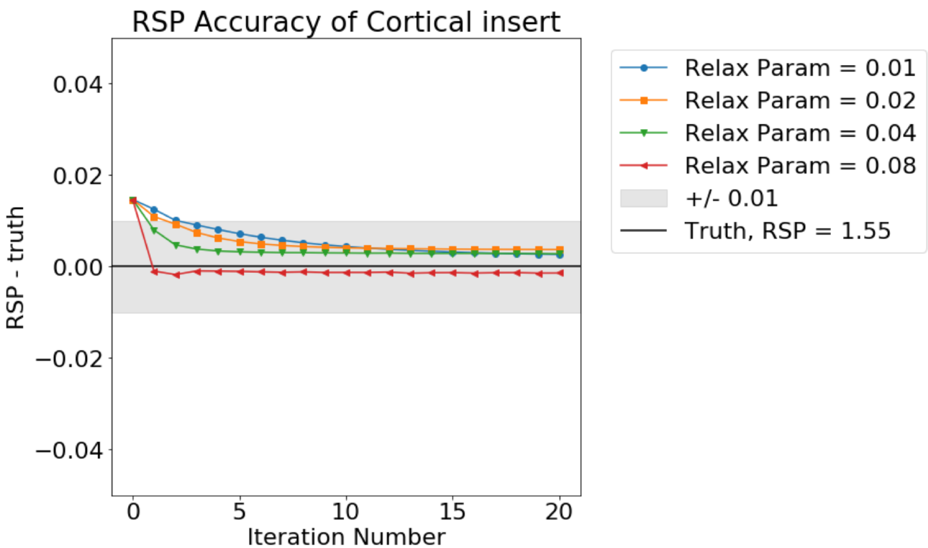
Reconstruction per iteration

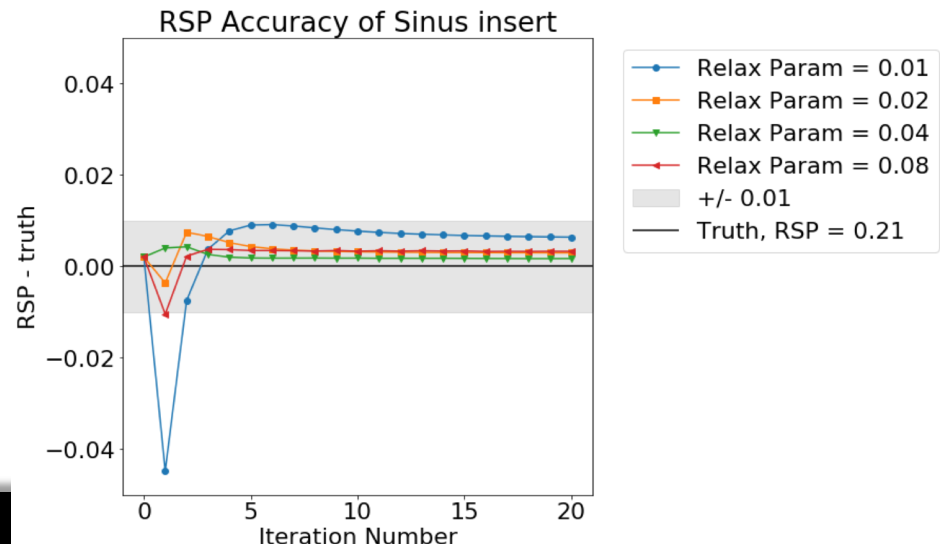


RSP Accuracy using custom RSP phantom (CIRS tissue substitutes)

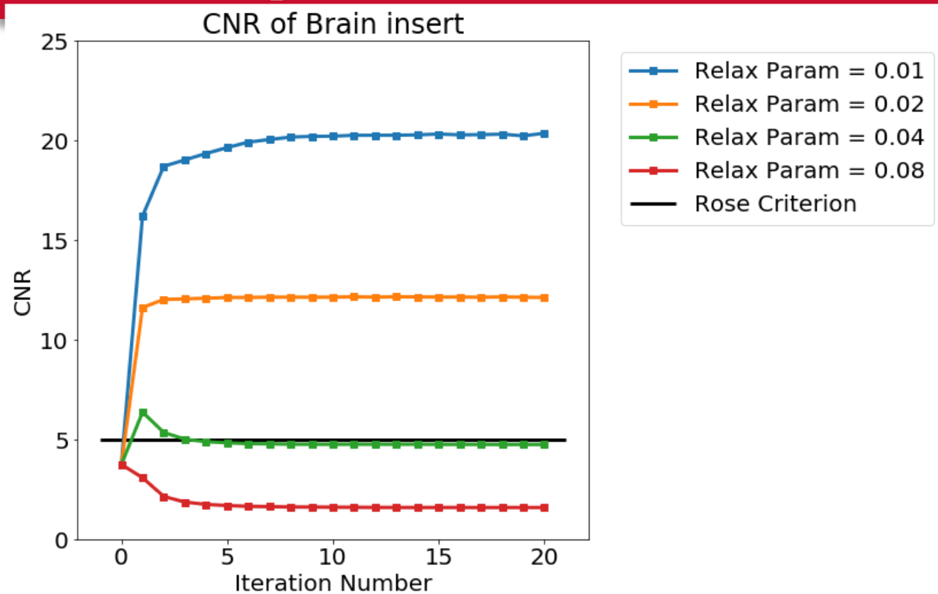


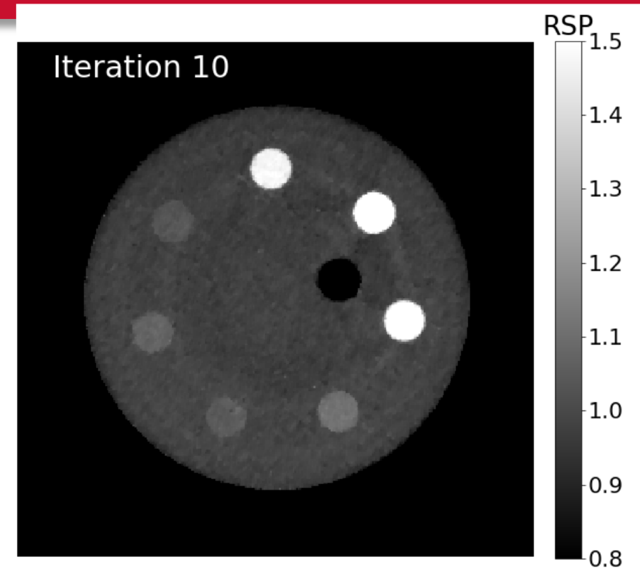


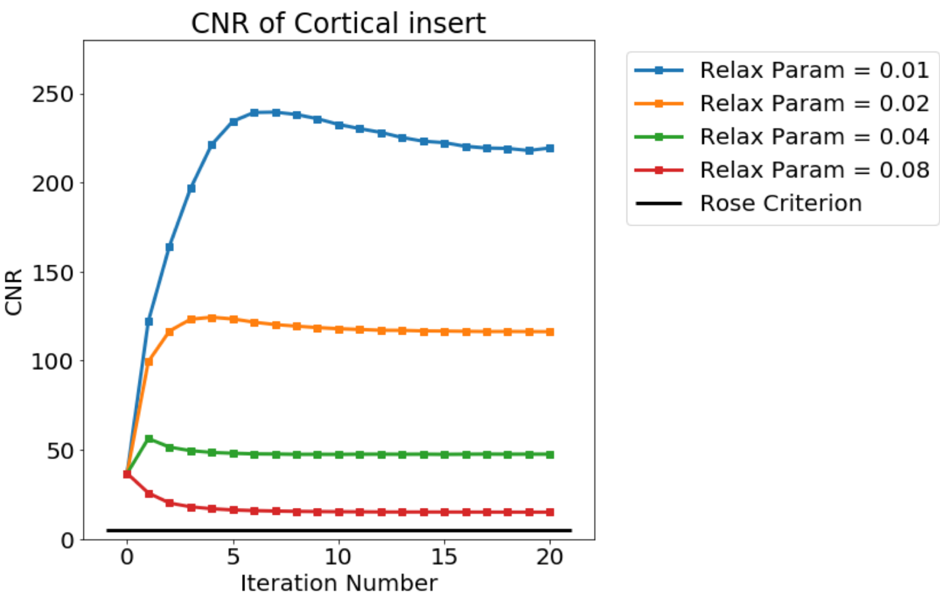


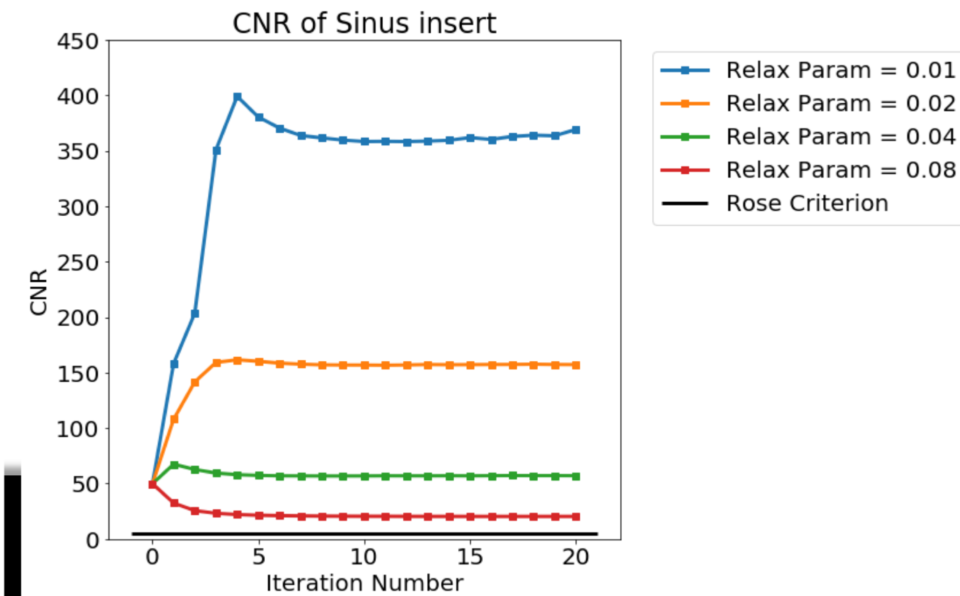


Contrast-to-Noise Ratio (CNR) using custom RSP phantom



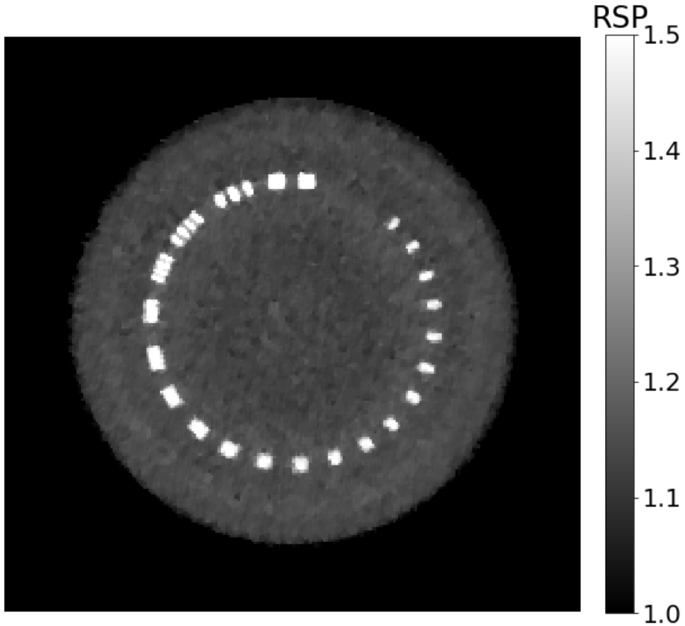


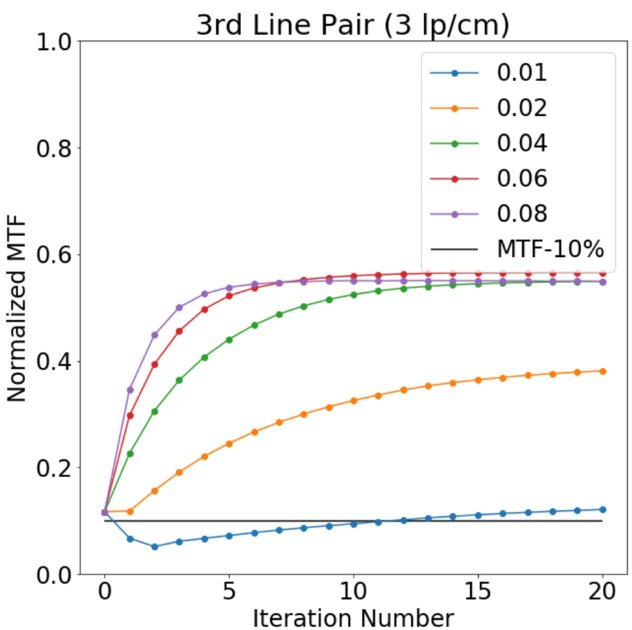


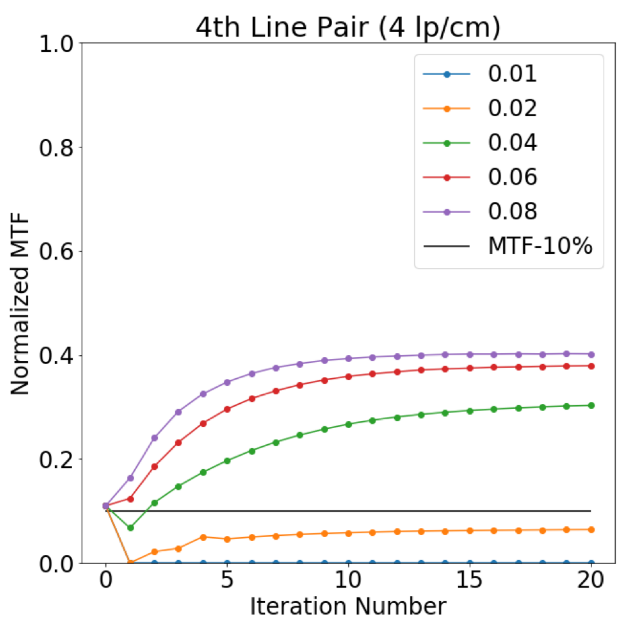


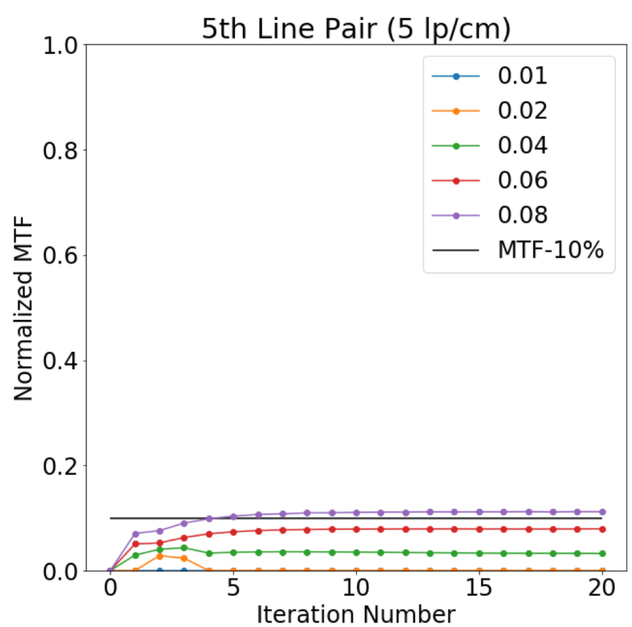
Spatial Resolution

$$MTF(LP) = \frac{(Peak\ - Valley)_{LP}}{(Peak\ - Valley)_{LP=1\ cm^{-1}}}$$

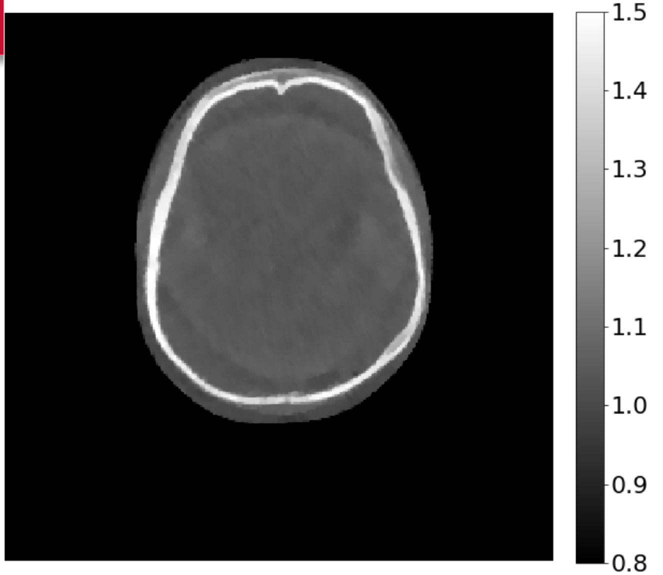


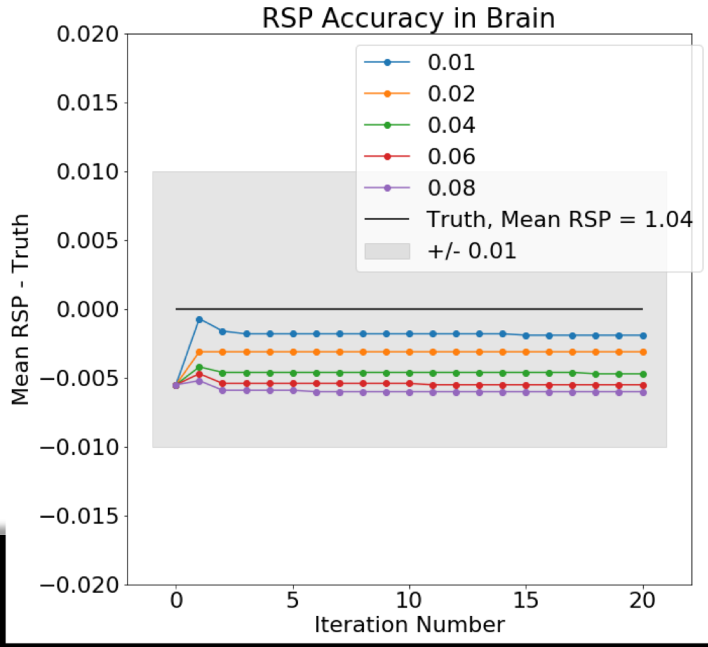


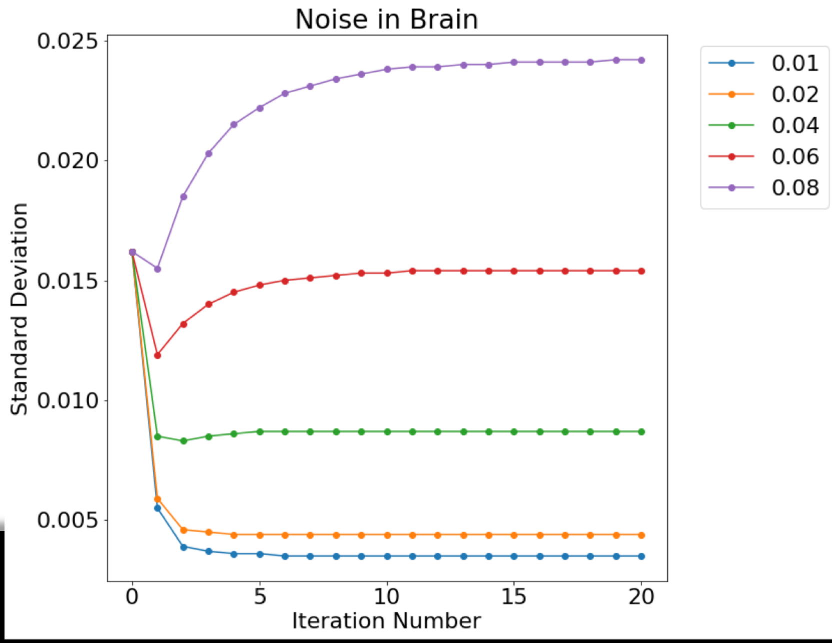




Pediatric Head Phantom - Brain







Conclusions

- Within the range of relaxation parameters tested, the RSP accuracy is +/- 0.01 for all CIRS materials and is not sensitive to relaxation parameter.
- CNR was measured to be 20 for Brain, 250 for Cortical Bone, and 400 for Sinus in the custom RSP phantom with $\lambda = 0.01$
- Spatial resolution of 5 lp/cm was measured for the line pair phantom with $\lambda = 0.08$
- There is a tradeoff between noise and spatial resolution.
  - Lower relaxation parameter shows lower noise, higher CNR
  - Higher relaxation parameter shows better spatial resolution

Future work

- Expand relaxation parameter range
- Repeat with DROP
- Repeat with half the total number of proton histories
- Suggestions?

Acknowledgements

- George Coutrakon
- Caesar Ordoñez
- Nick Karonis
- Reinhard Schulte
- Robert Johnson