Challenges and Solutions for Quantitative Imaging on Low-Field MR-Guided RT Systems

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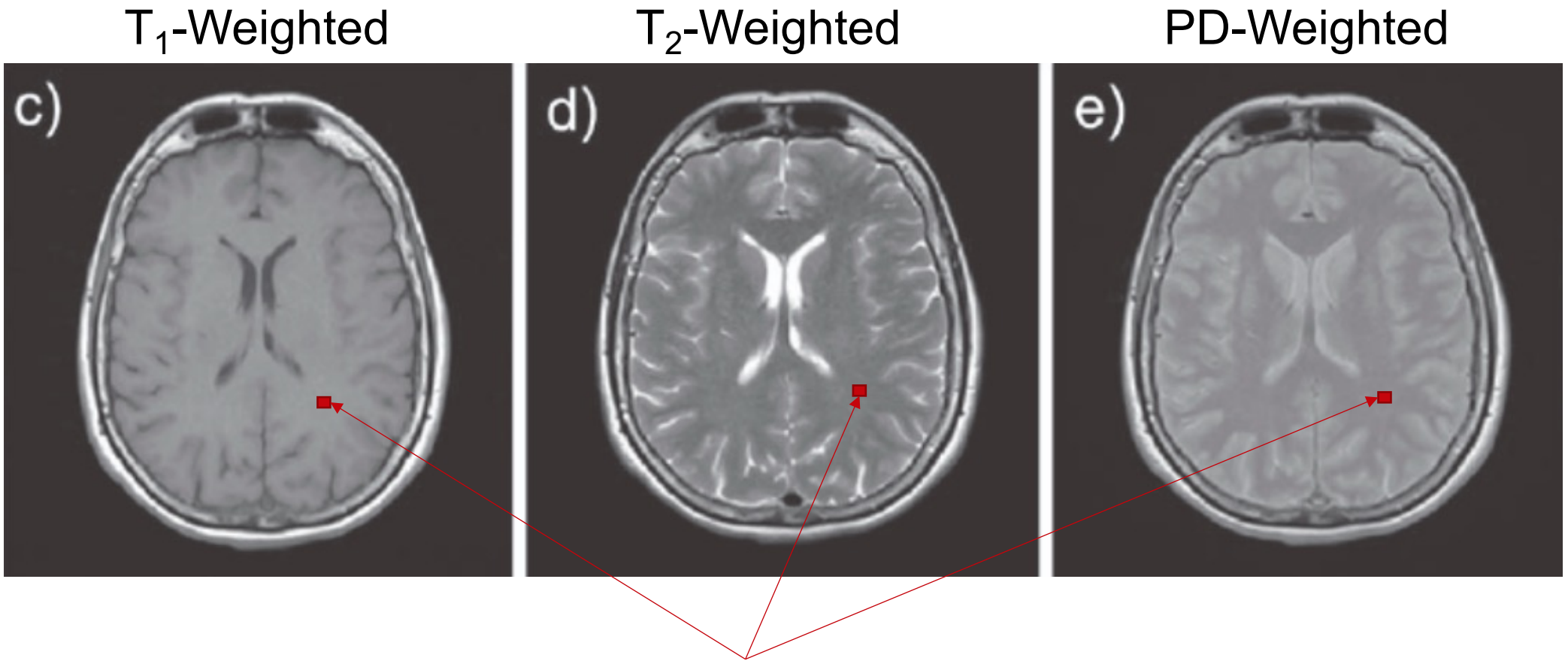
MRI: A Qualitative Imaging Modality

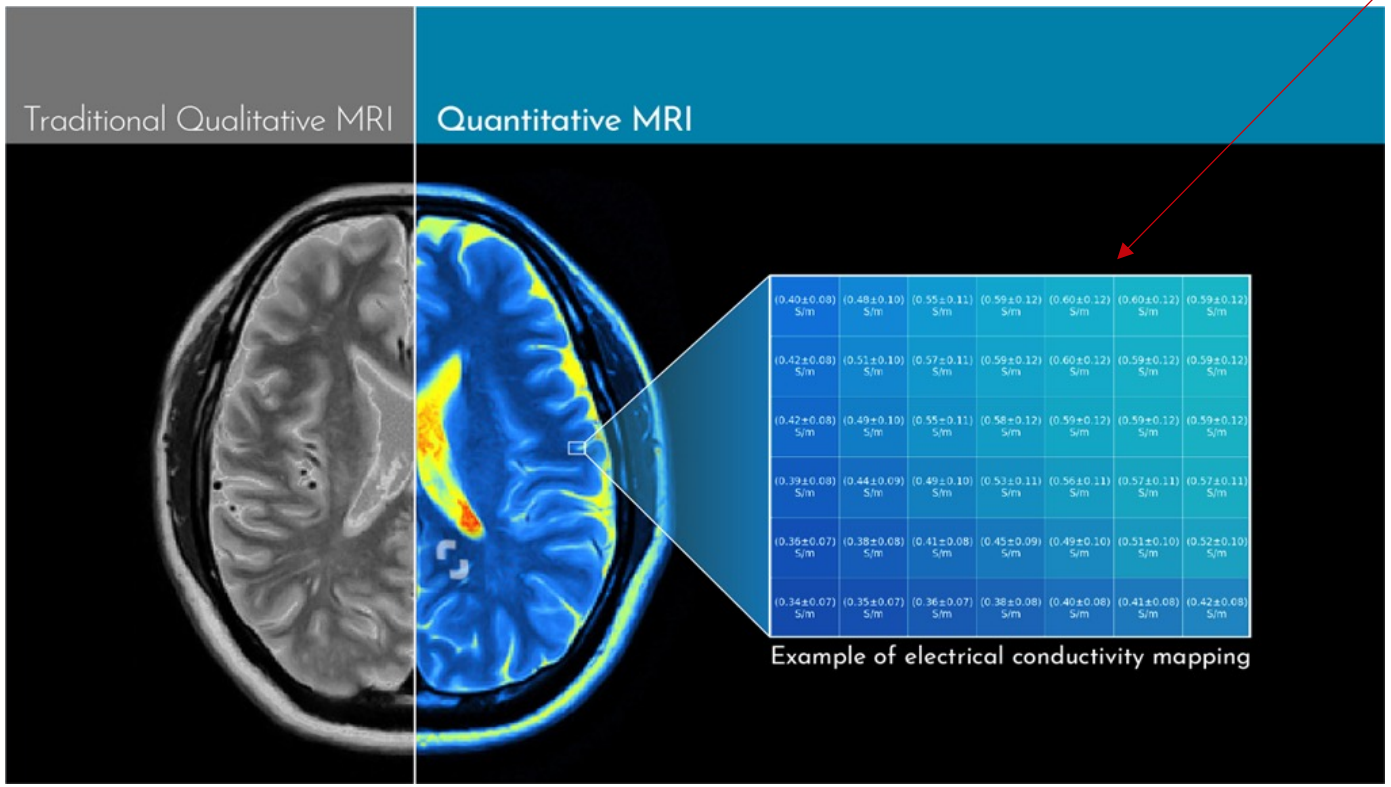


Actual value within each voxel is usually not standardized.

Plewes and Kucharczyk. JMRI 35:1038-1054 (2012).

What is Quantitative MRI?

Real-World Units!!



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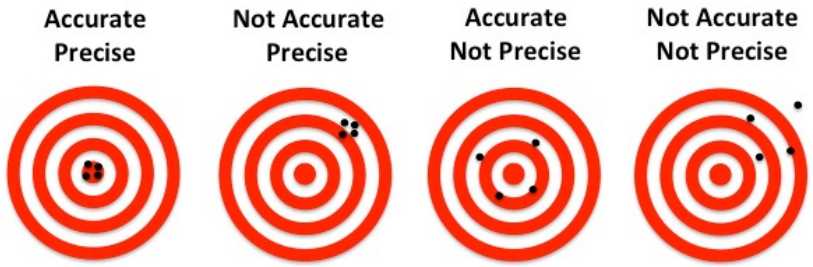
Examples:

- Apparent diffusion coefficient
- Diffusional anisotropy
- Longitudinal relaxation T_1
- Transverse relaxation T_2
- Tissue susceptibility
- Fat fraction
- Flow rates
- Perfusion uptake rates

… The list goes on!

Why Do We Care About Quantitative MRI?

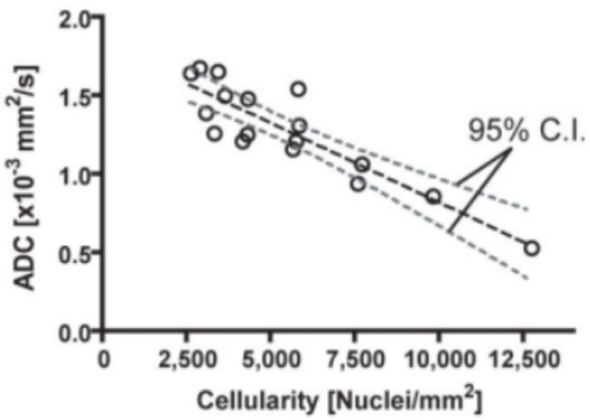
- Use quantitative imaging as a non-invasive biomarker for disease severity or treatment response monitoring.
  - Accurate
  - Precise
  - Repeatable
  - Reproducible



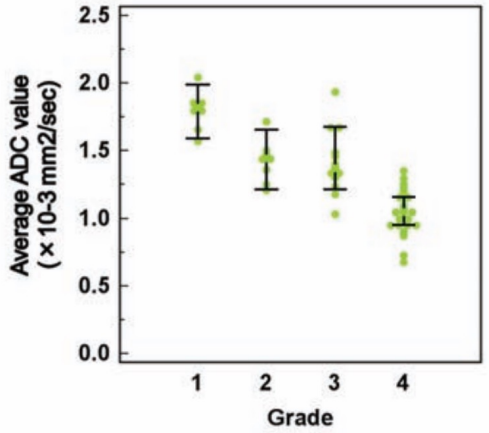
- Many factors can make obtaining precise and accurate qMRI challenging.

qMRI in Cancer

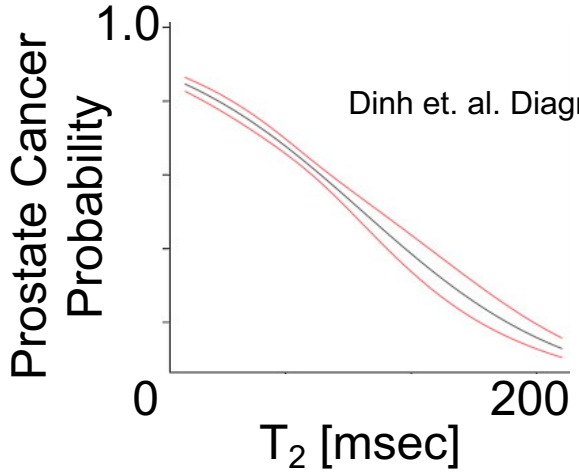
- Apparent diffusion coefficient
- Transverse Relaxation (T_2)
- Longitudinal Relaxation (T_1)



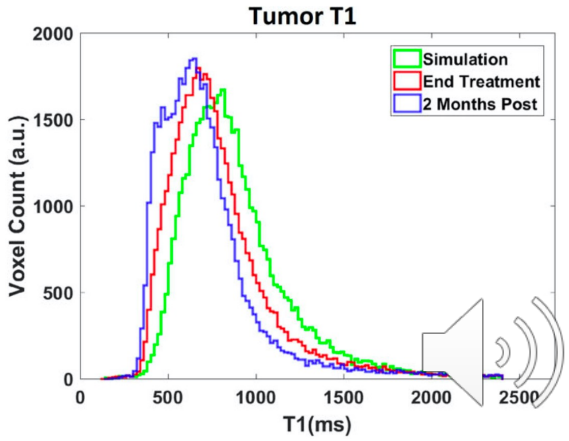
Ellingson et. al. JMRI 31:538-48 (2010)



Murakami et. al. Radiology 251:838-45 (2009)



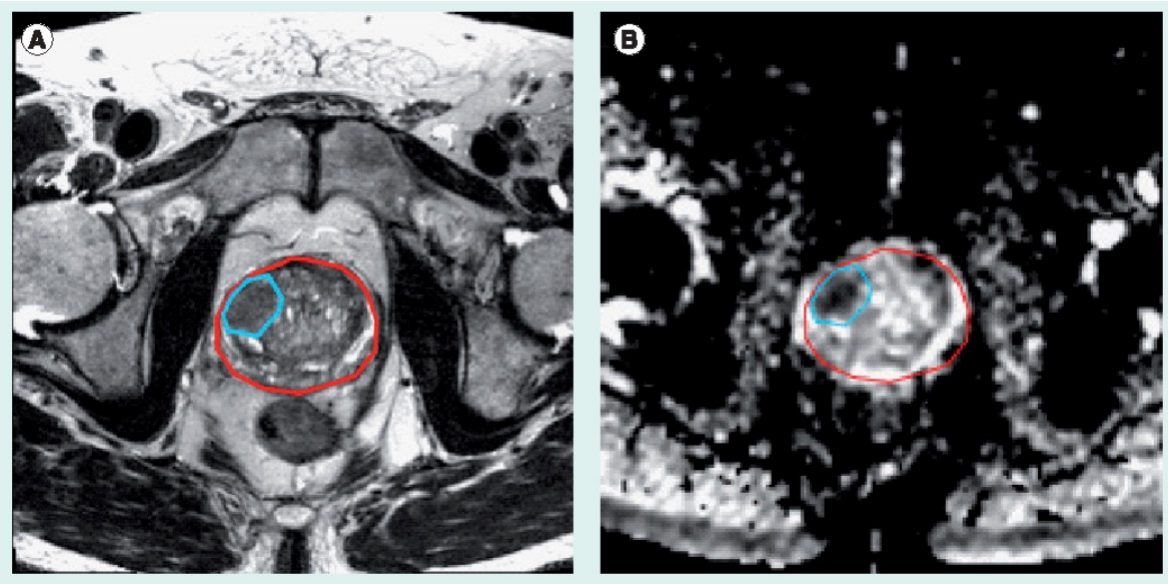
Dinh et. al. Diagnostic and Interventional Imaging (2015)



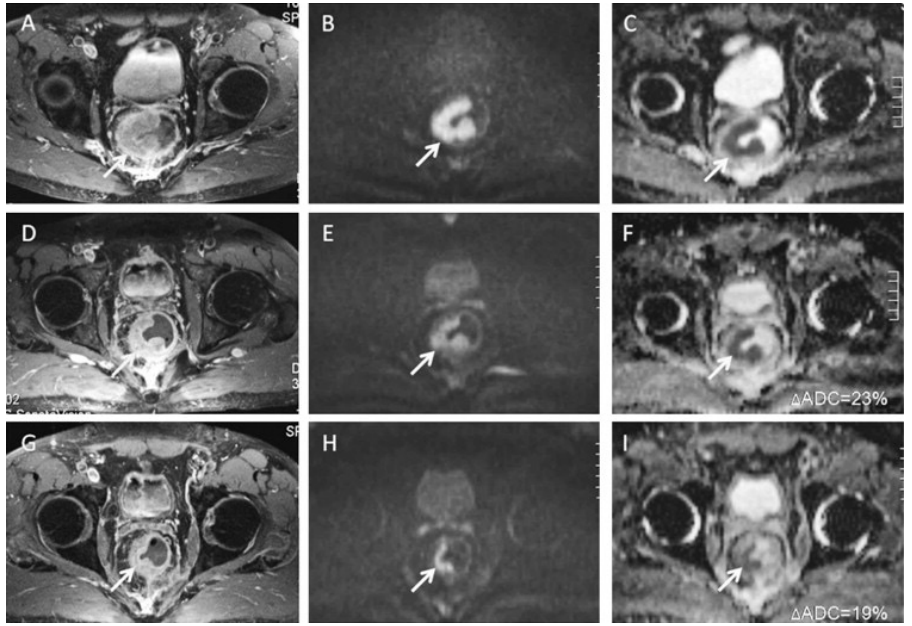
Nejad-Davarani et. al. Medical Physics47: 4064-76 (2020)

qMRI + MR-Guided Radiation Therapy

- MRgRT offers incredible potential to acquire longitudinal functional MRI during the treatment course
- Potential applications to inform clinical decision making



Subvolume targeting[1]

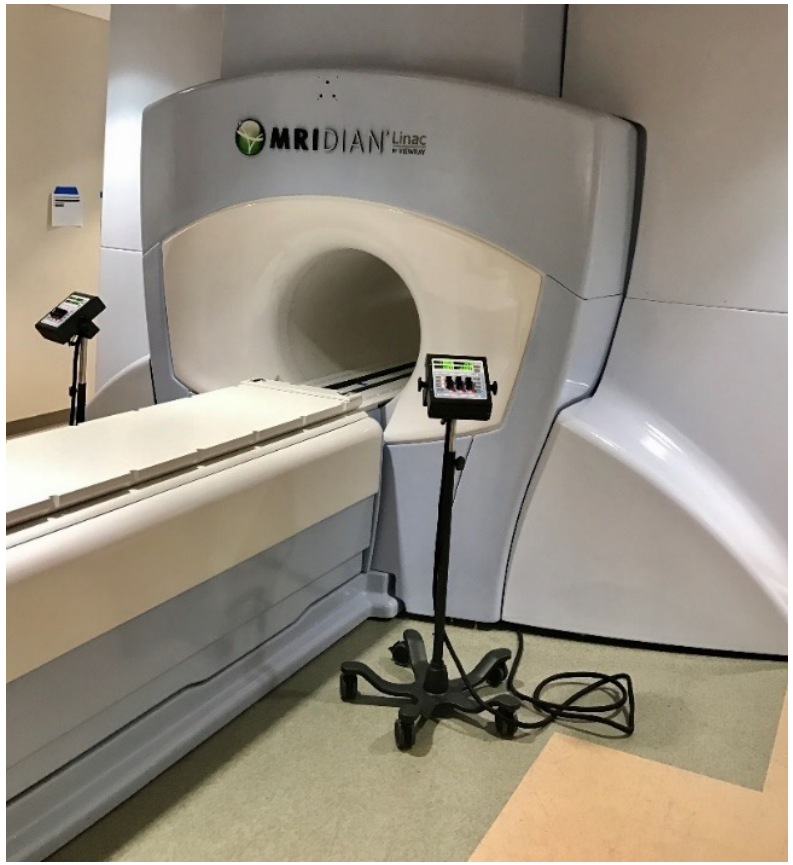


Tumor response assessment[2]

[1]van der Heide, Imaging Medicine, 2011

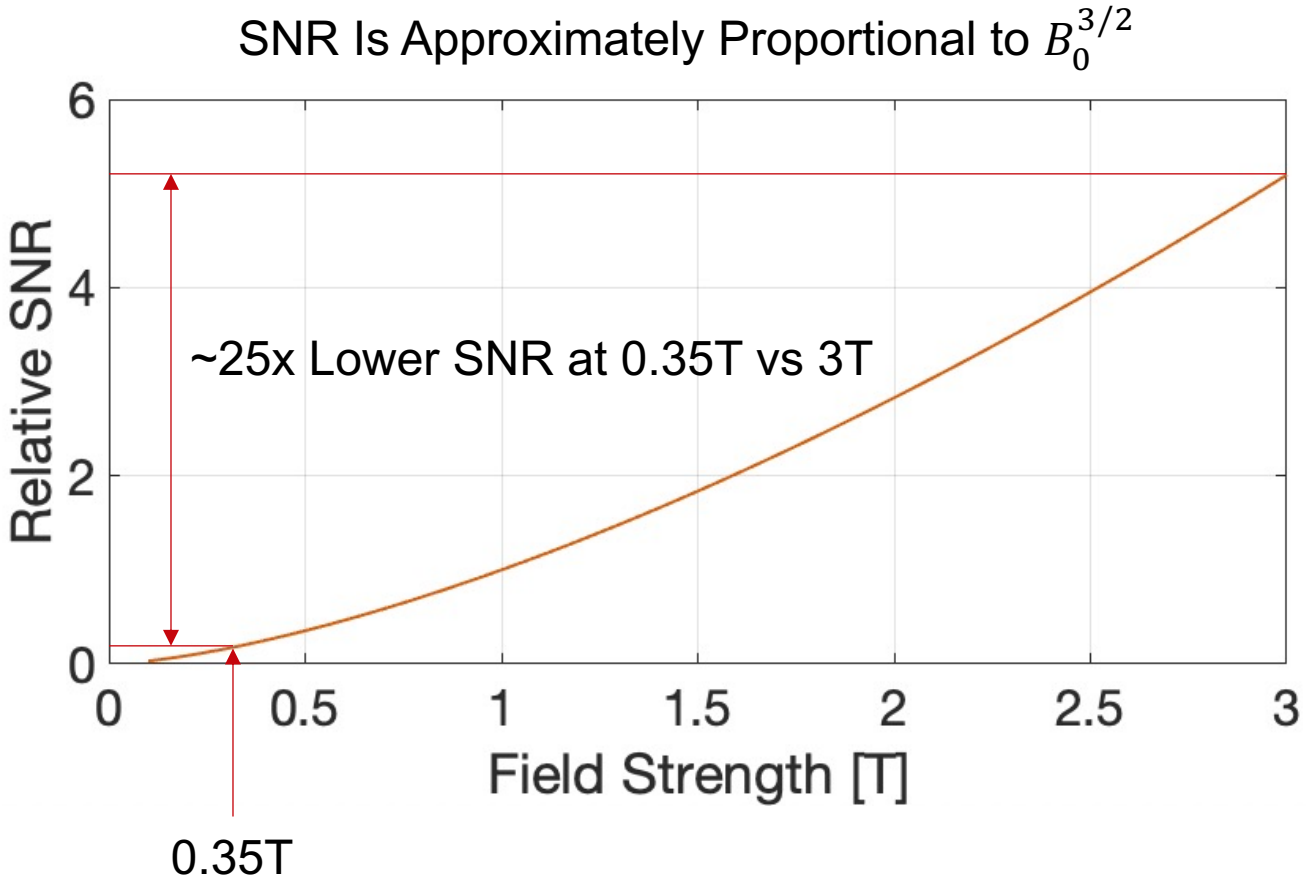
[2]Lambrecht et al., IJROBP, 2012

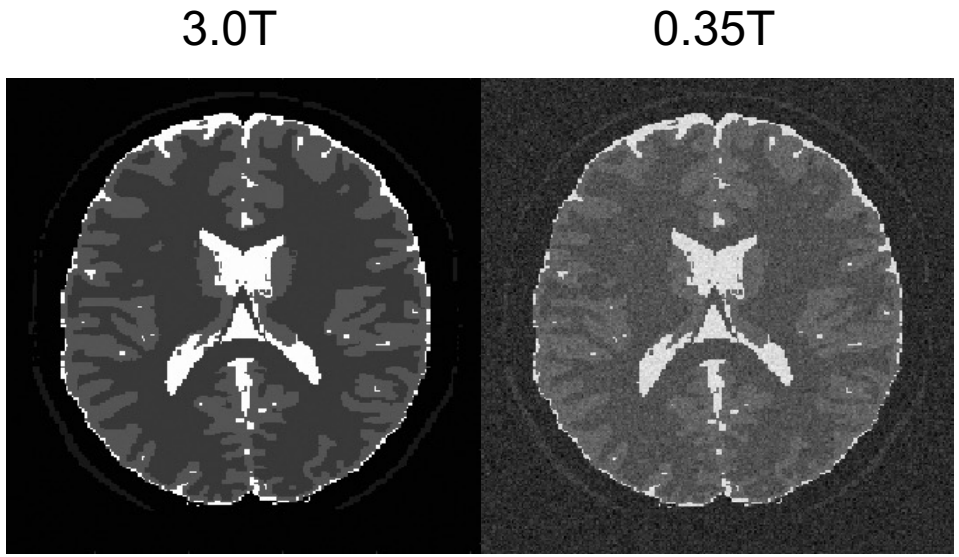
Low-field ViewRay MRIdian MR-Linac



- Split bore 0.35T MR coupled with a 6MV linear accelerator
- Dedicated surface coils for patient imaging

Field Strength and Signal-to-Noise Ratio

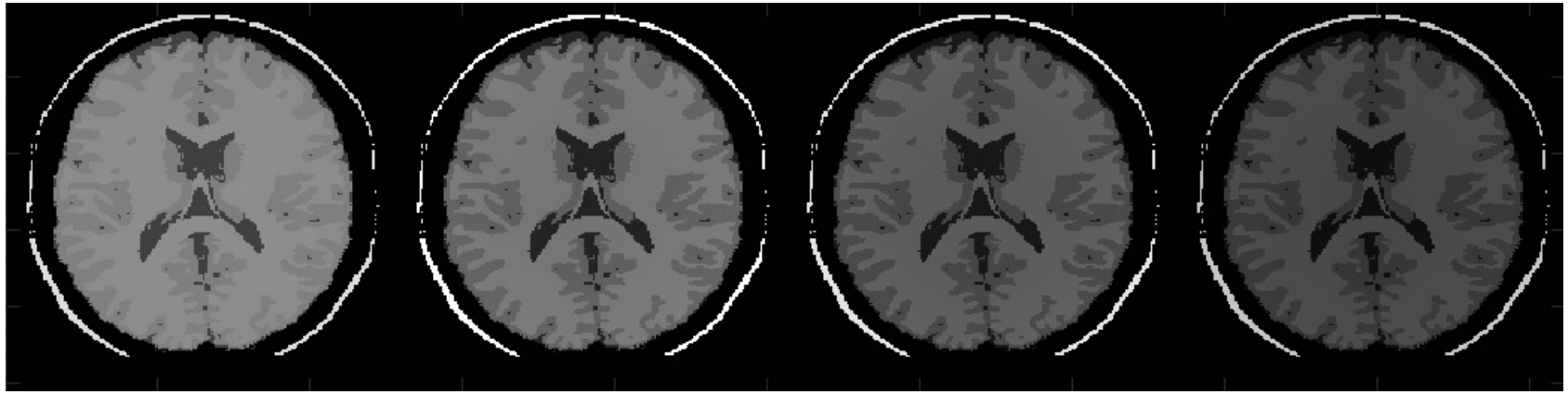


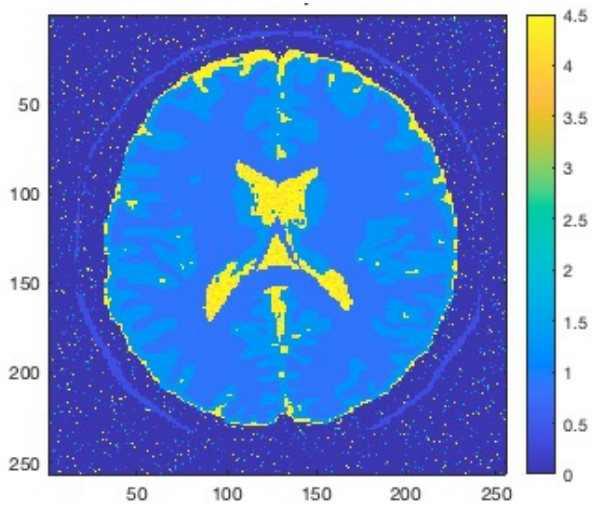


Marques et. al. JMRI 49:1528-42 (2019).

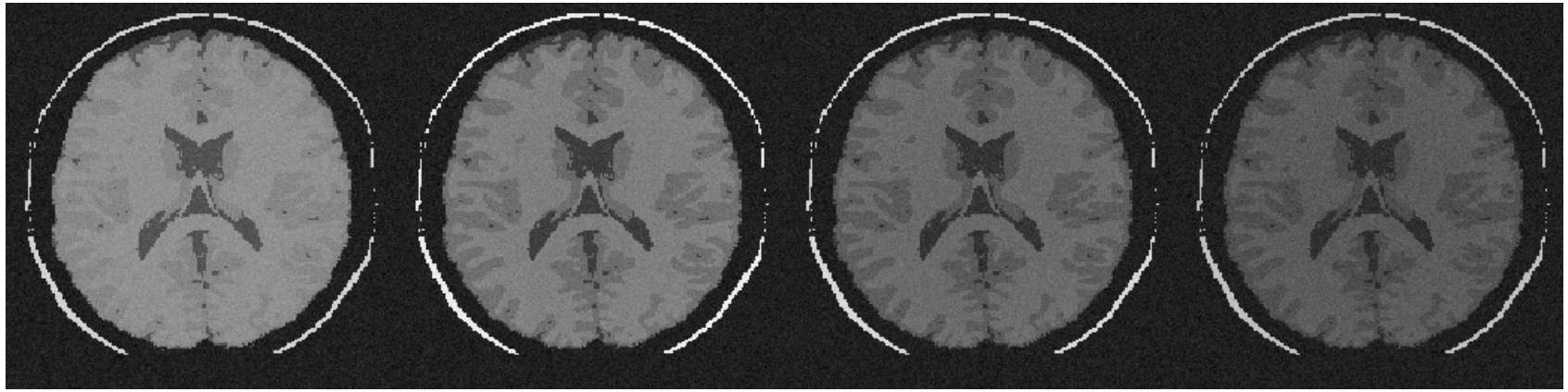
Field Strength and Signal-to-Noise Ratio

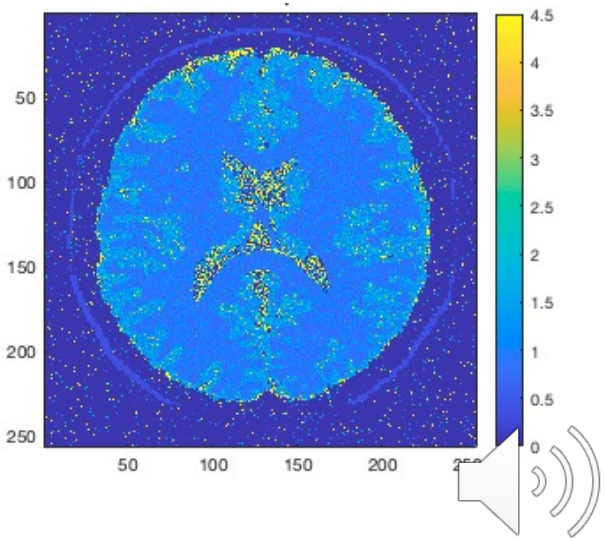
3.0T





0.35T





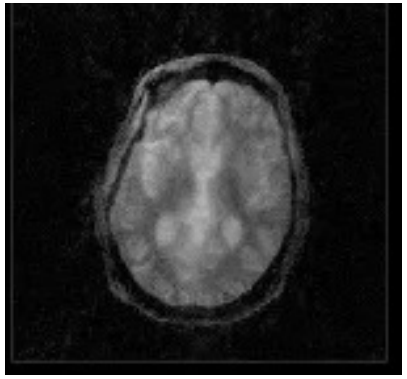
Lankford and Does. Mag. Reson. Med. 79(2):673-682 (2018).

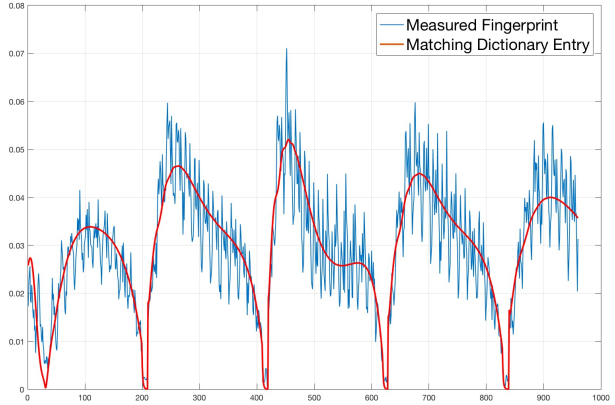
Tradeoffs for Low-Field qMRI

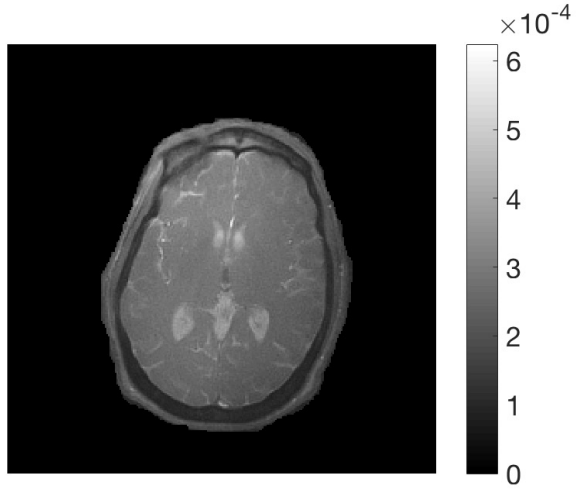
- Increase the number of averages to improve SNR
  - Scan time increases linearly with number of averages
- Decrease sampling bandwidth to increase SNR
  - More prone to chemical shift artifacts and geometric distortions
- Decrease image resolution
  - Number of averages can be reduced when voxels are larger[1]
- Increase number of acquired qMRI contrasts
  - One method that takes this approach to the extreme is MR fingerprinting.

Marques et. al. JMRI 49:1528-42 (2019).

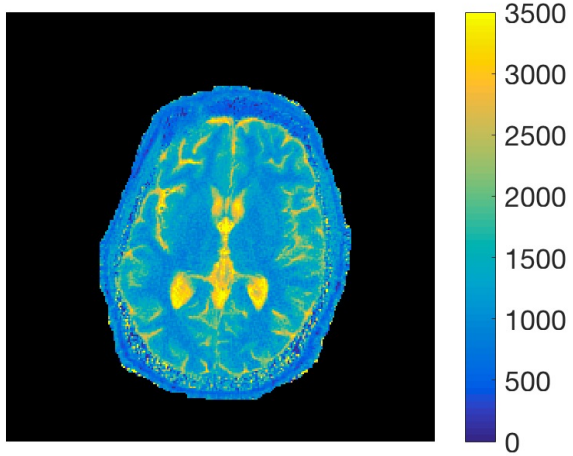
MR Fingerprinting for Efficient T_1/T_2 Mapping



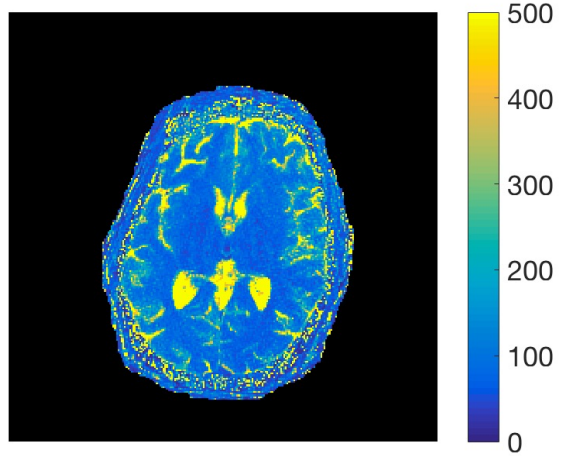




Proton Density



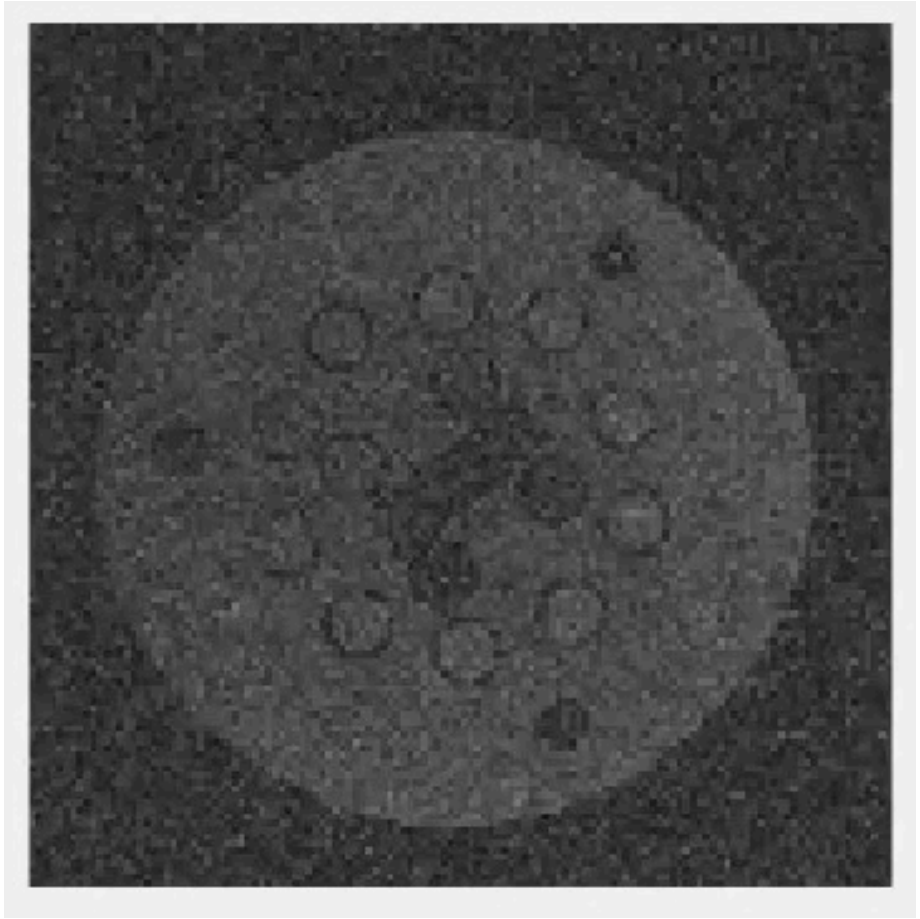
T_1

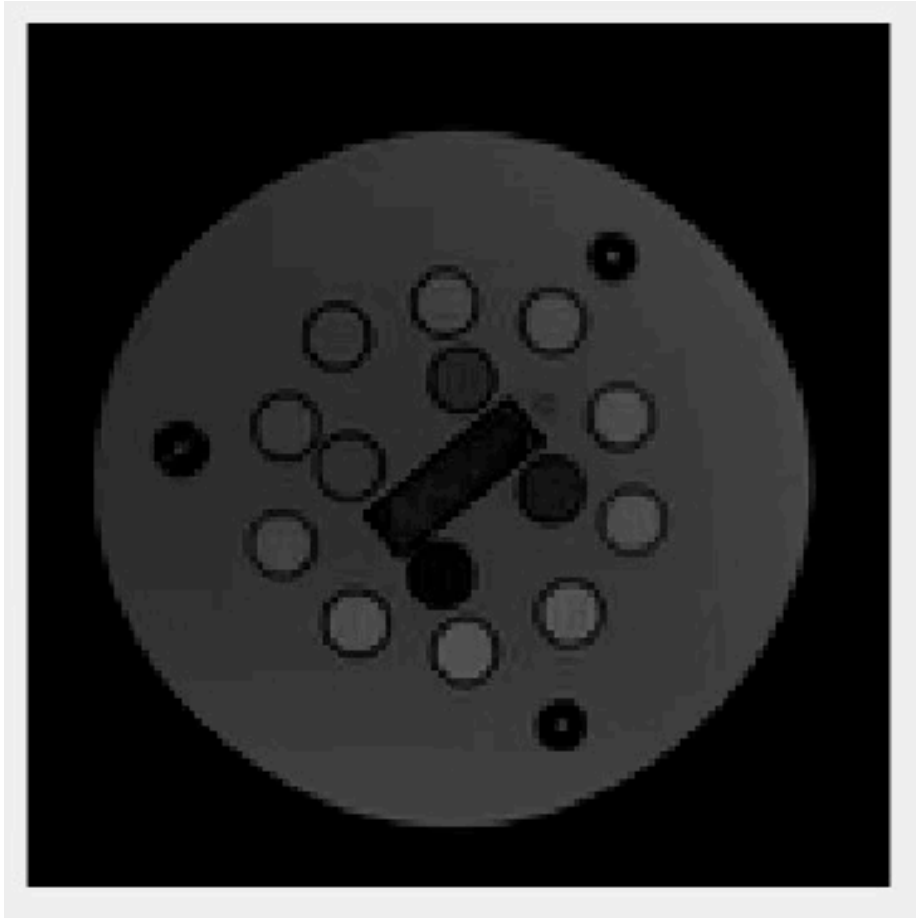


T_2

Ma et. al. Nature (2013)

Adapting MR Fingerprinting for Low Field

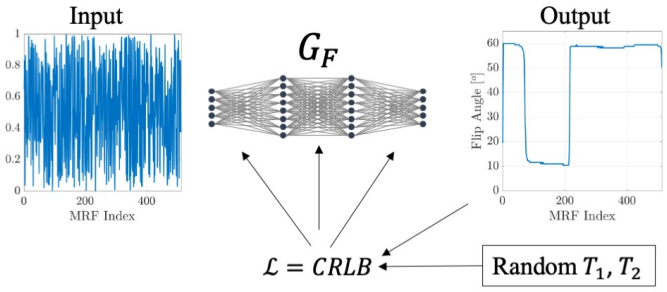


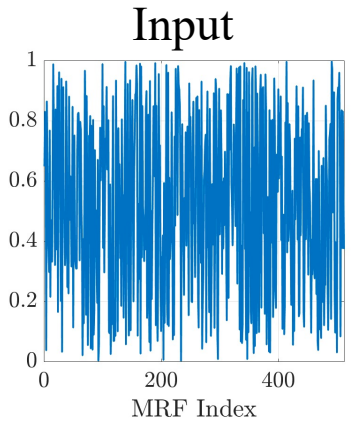


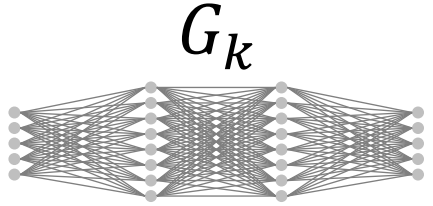
Takeaway: For high dimensional qMRI at low field, using subspace constrained reconstructions is crucial.

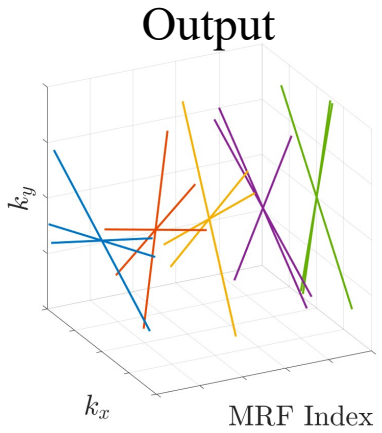
Adapting MR Fingerprinting for Low Field

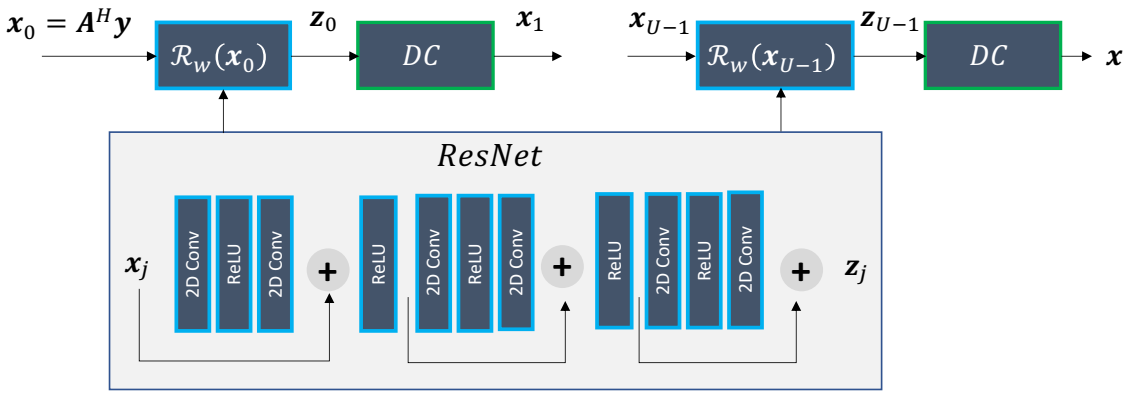
- An end-to-end optimization of the MRF acquisition and reconstruction pipeline improves quantitative T1 and T2 estimates.









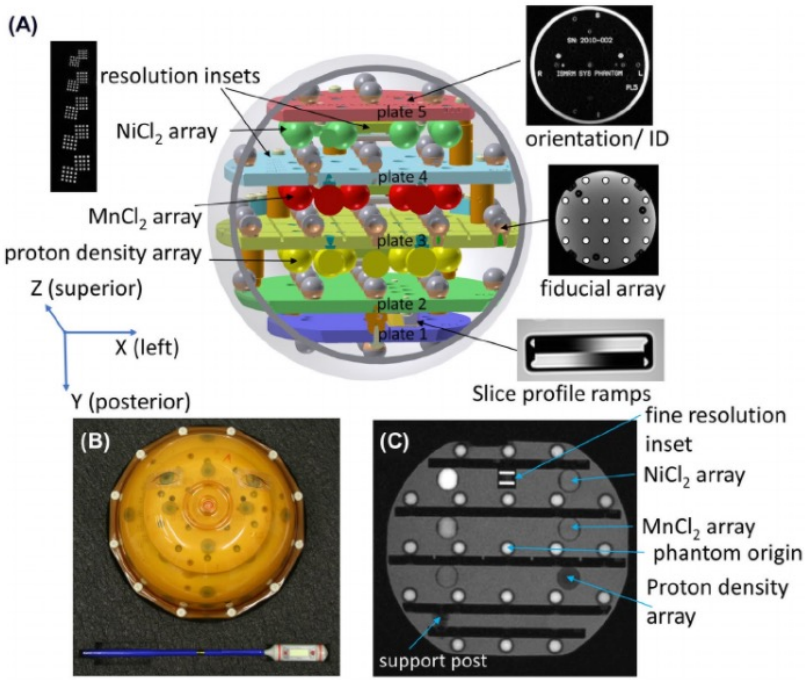


MRF Implementation on 0.35T System

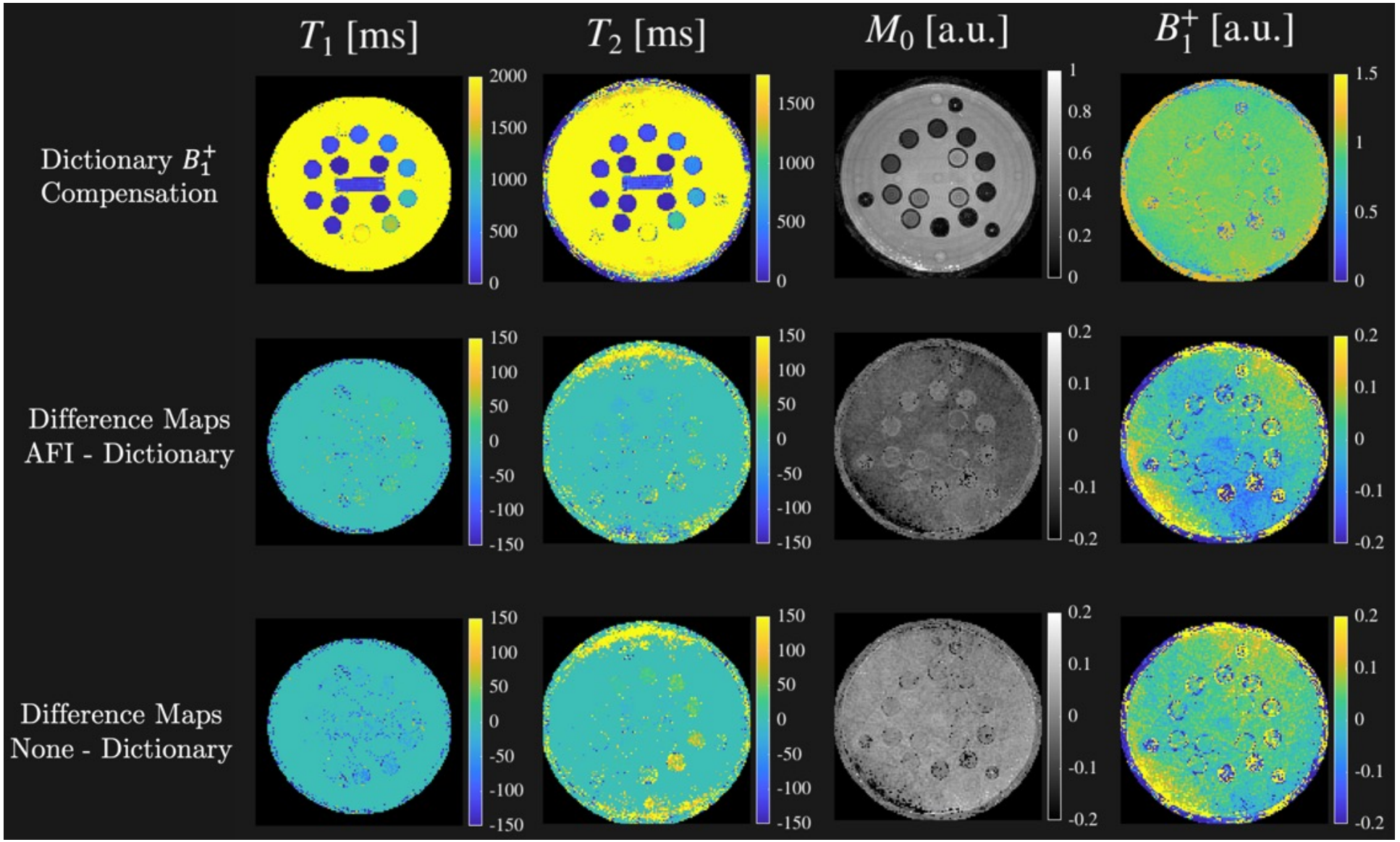
- Slab-selective 3D acquisition to improve SNR
- Radial k-space coverage
  - Lower performance gradient coils (18 mT/m, 180 T/m/s) would make spiral imaging challenging
- Slice-by-slice low rank reconstruction
- Matching with dictionary including T_1, T_2, and B_1

Validation Methods

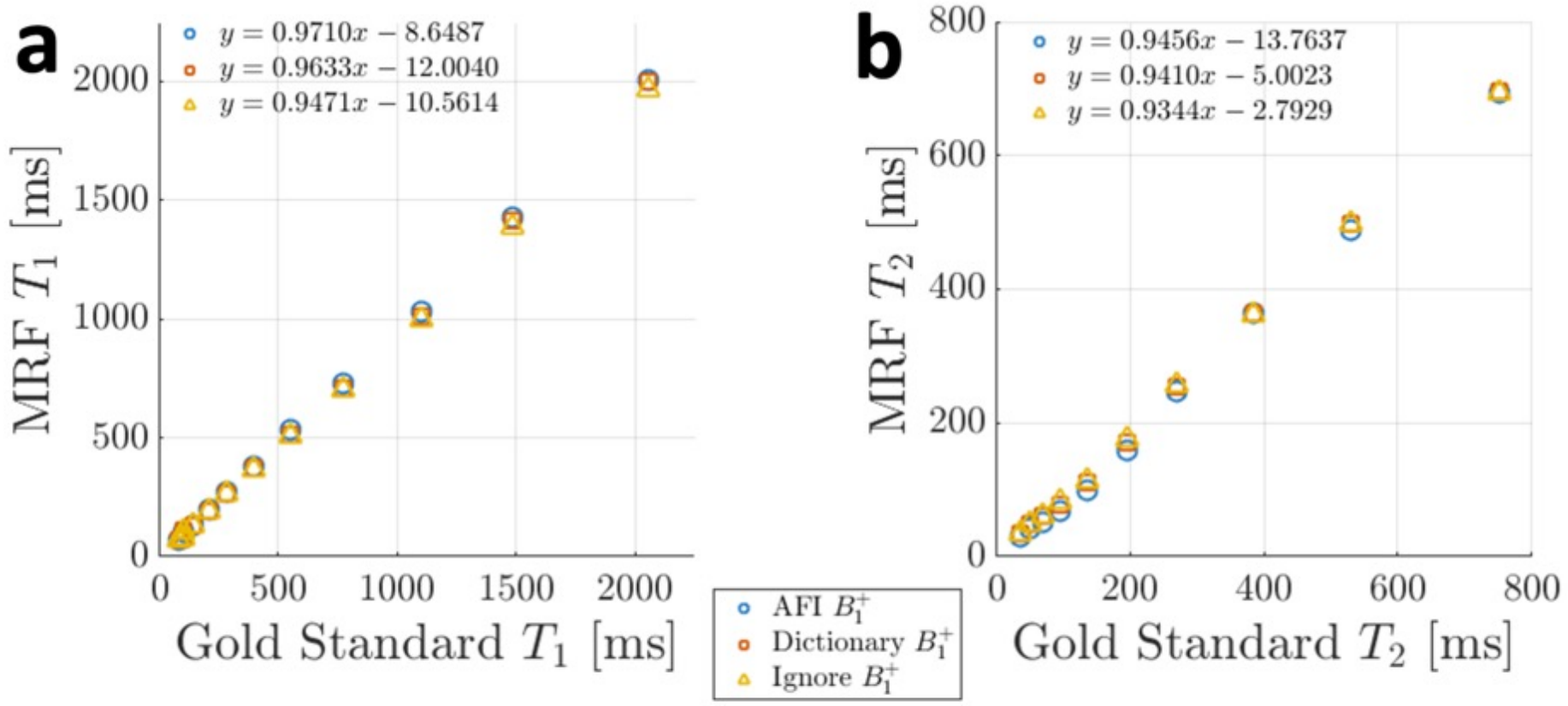
- NIST/ISMRM system phantom
- Compare T_1 and T_2 times from MRF with gold standard single spin echo
  - With externally measured B_1 map
  - With dictionary-mapped B_1 map
  - While ignoring B_1
- Impact of scan time
  - Varied number of k-space spokes acquired per frame
- Repeatability assessment from 3 measurements over 10 hours
- Reproducibility assessment in 3 scanners from 2 institutions



MRF Accuracy on Low Field MR-Linacs

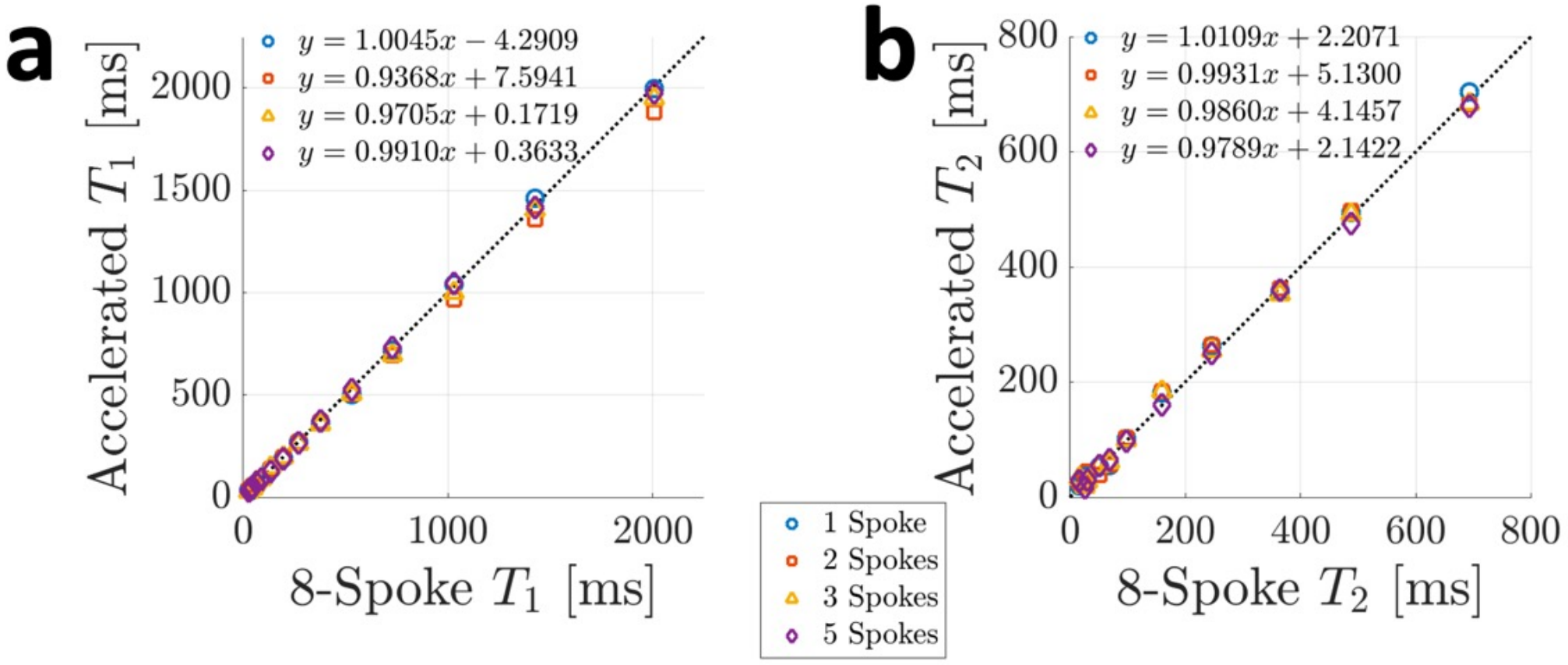


MRF Accuracy on Low Field MR-Linacs

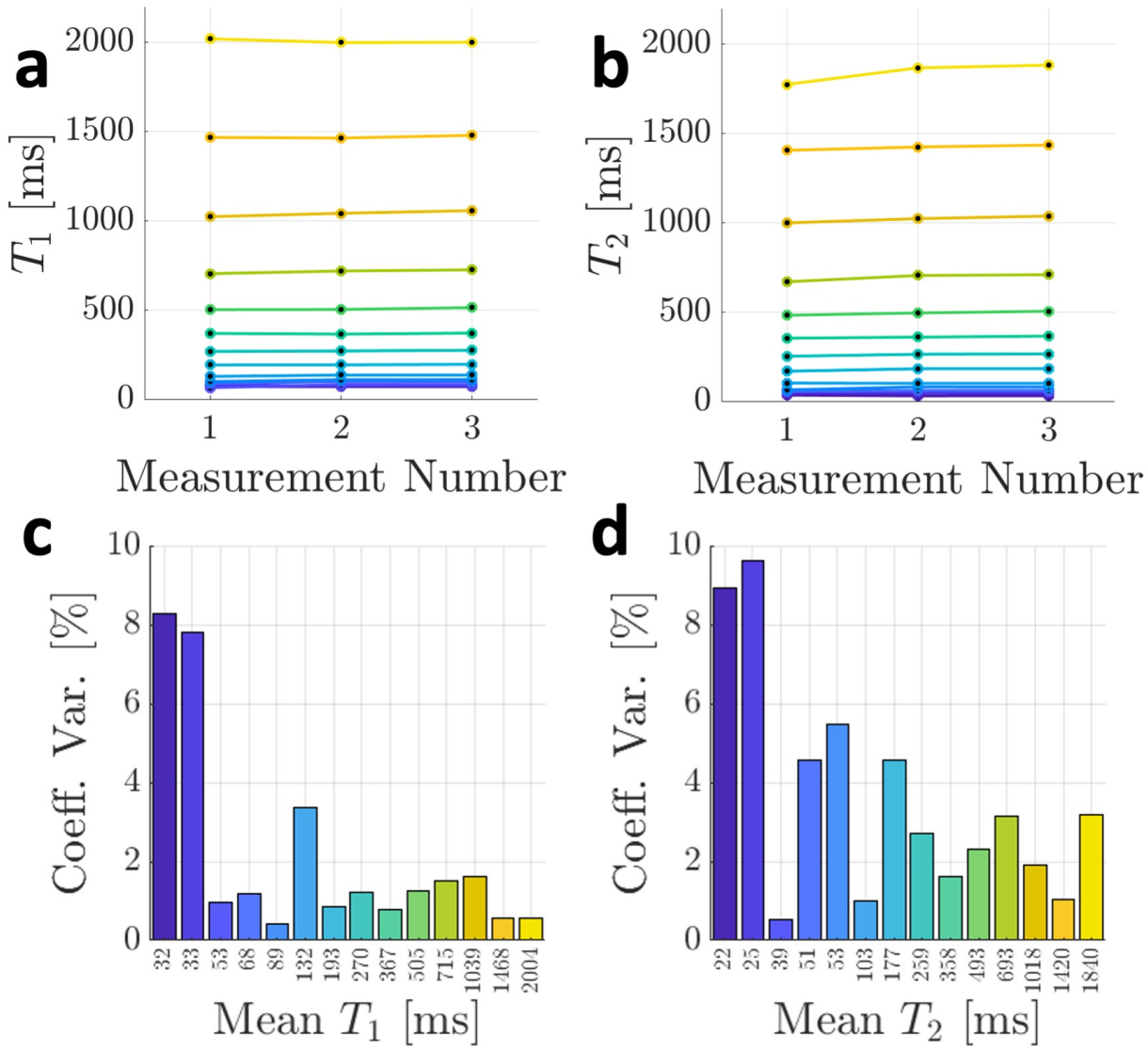


Average error of 6% for T_1 and 10% for T_2

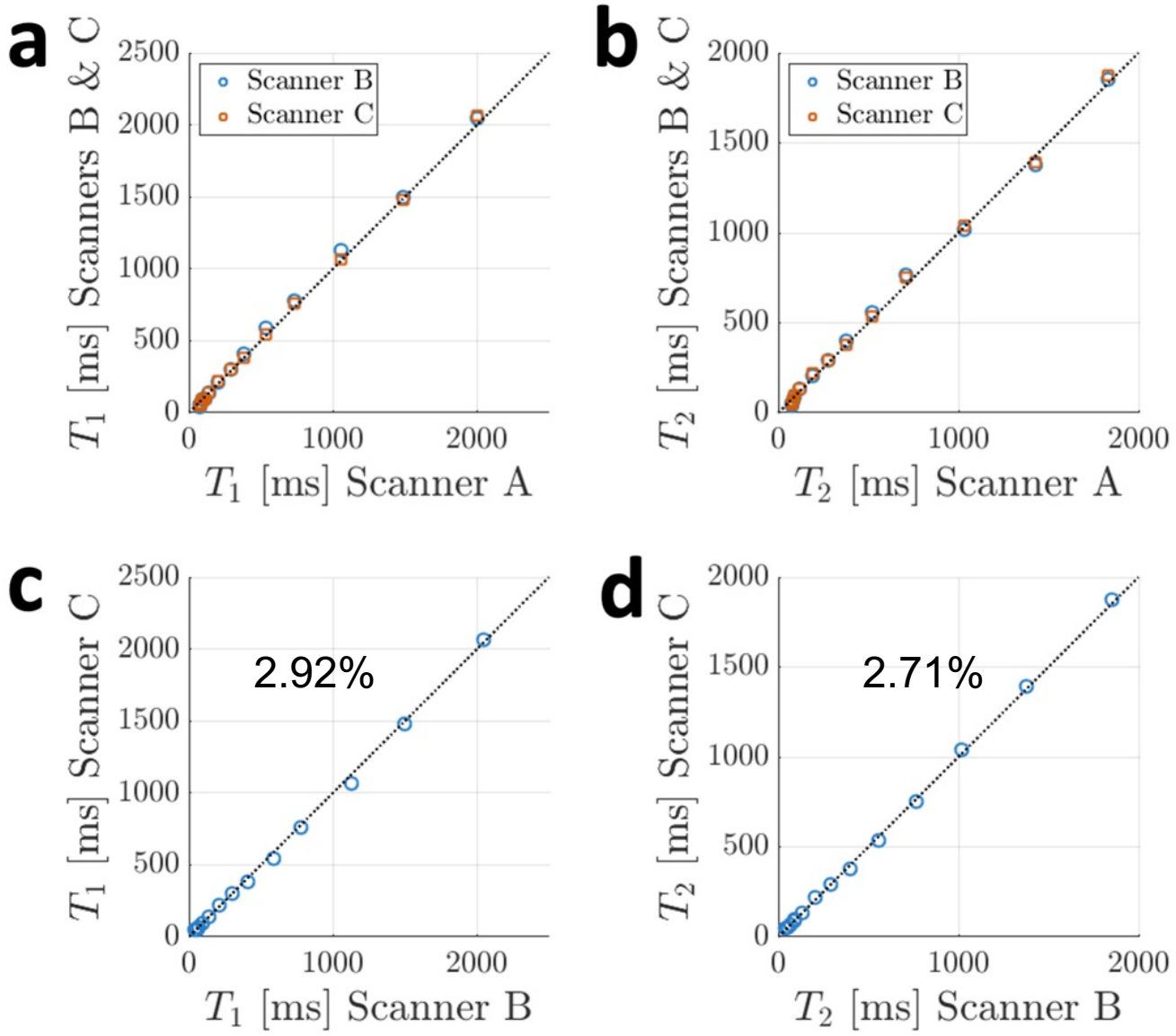
Rapid MRF on Low-Field MR-Linacs



Repeatability of MRF at Low-Field



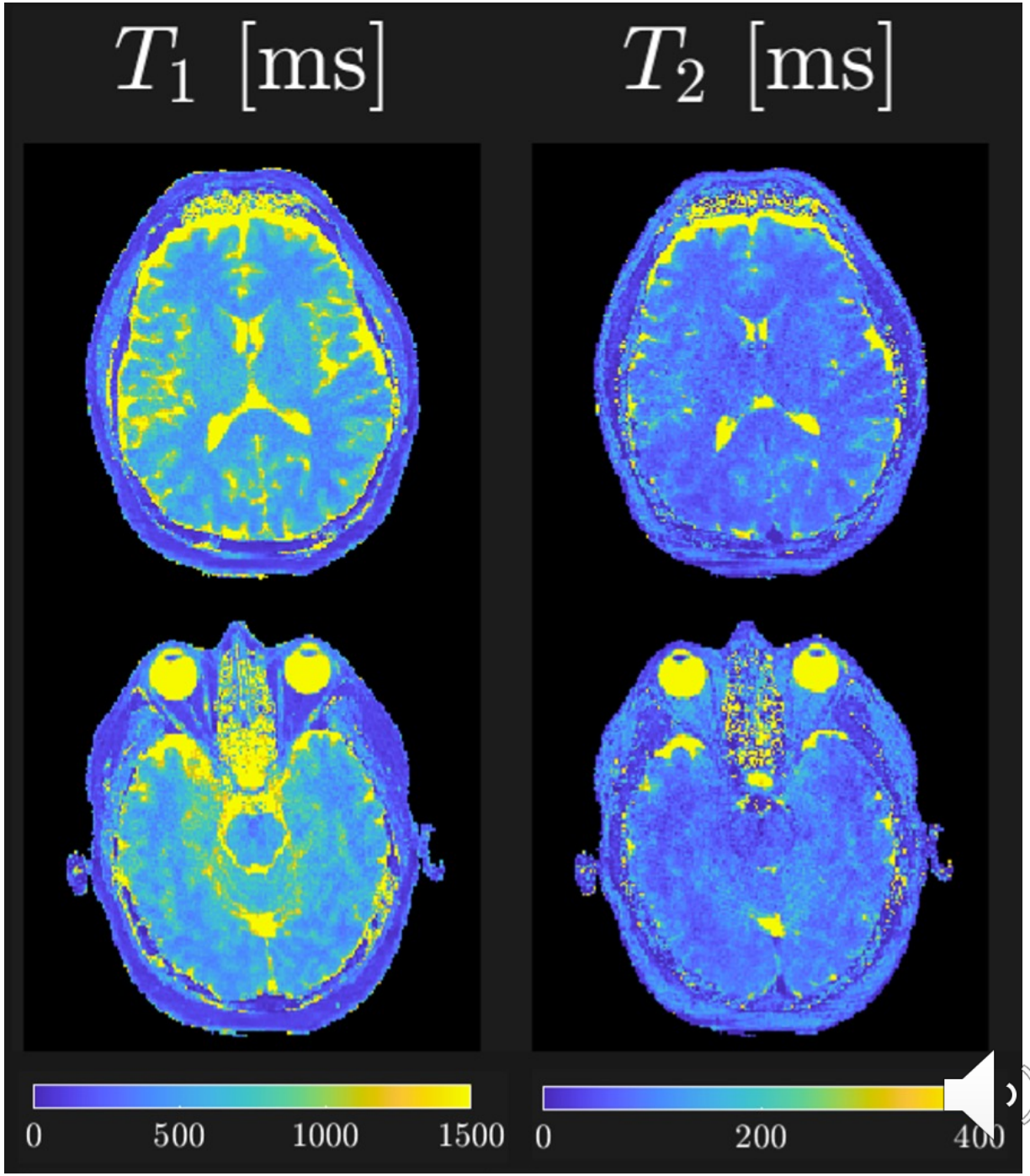
Reproducibility of MRF on Low-Field MR-Linacs



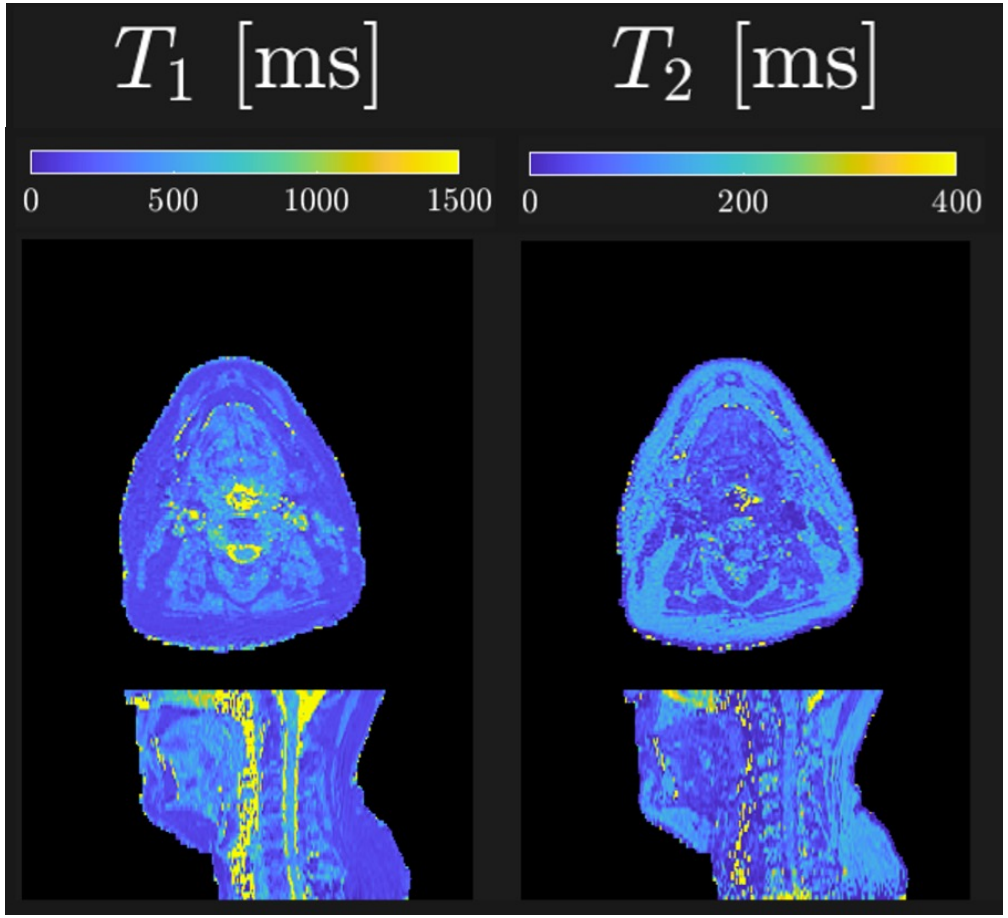
Feasibility of *In Vivo* MRF at 0.35T

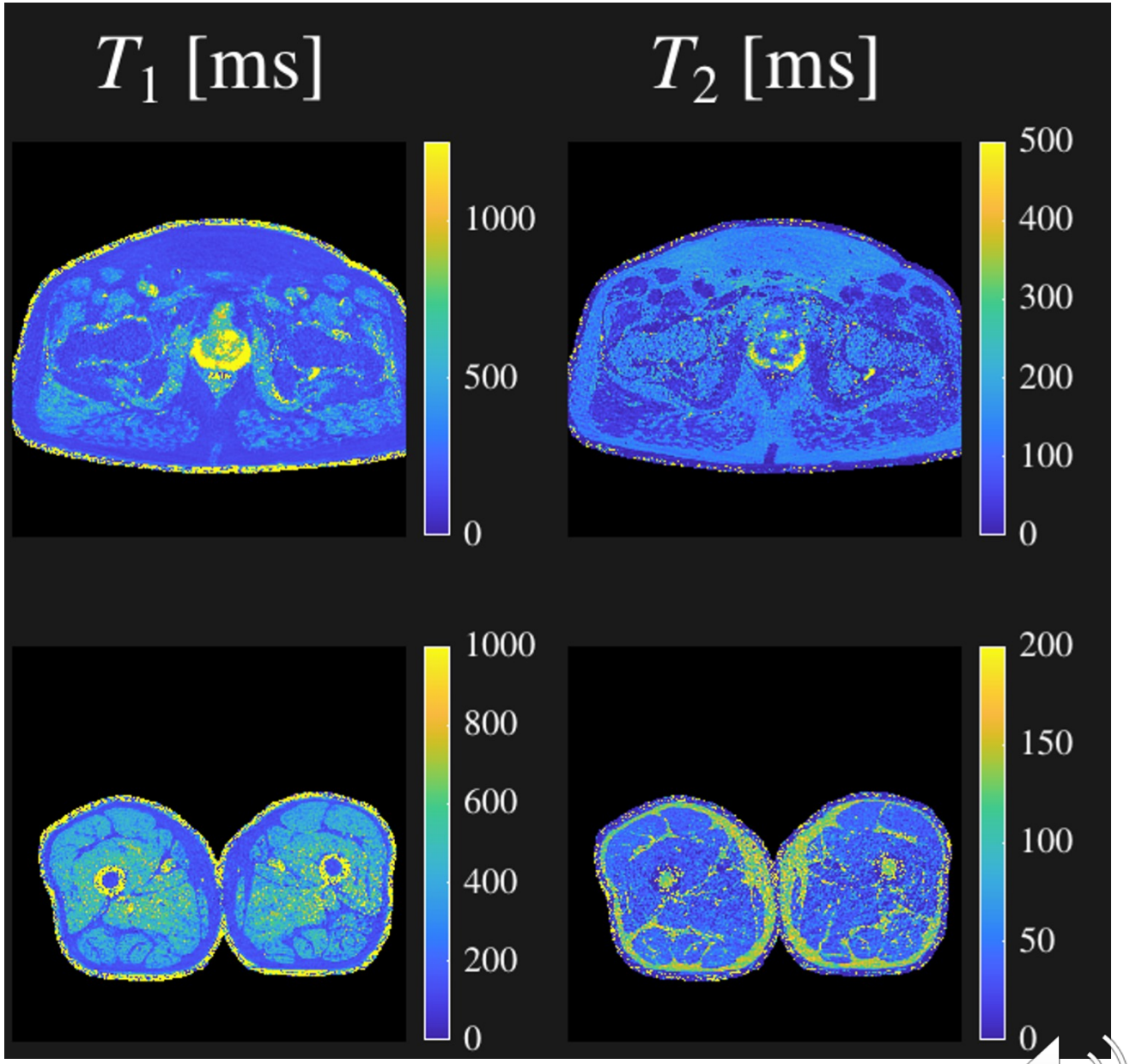
- Volunteer studies were performed in:
  - Brain
  - Head/Neck
  - Prostate
  - Thigh
- 6-minute 3D MRF protocol
  - 256x256x32 imaging matrix
  - 25% slice oversampling to reduce aliasing artifacts along the slice direction

Brain MRF at 0.35T



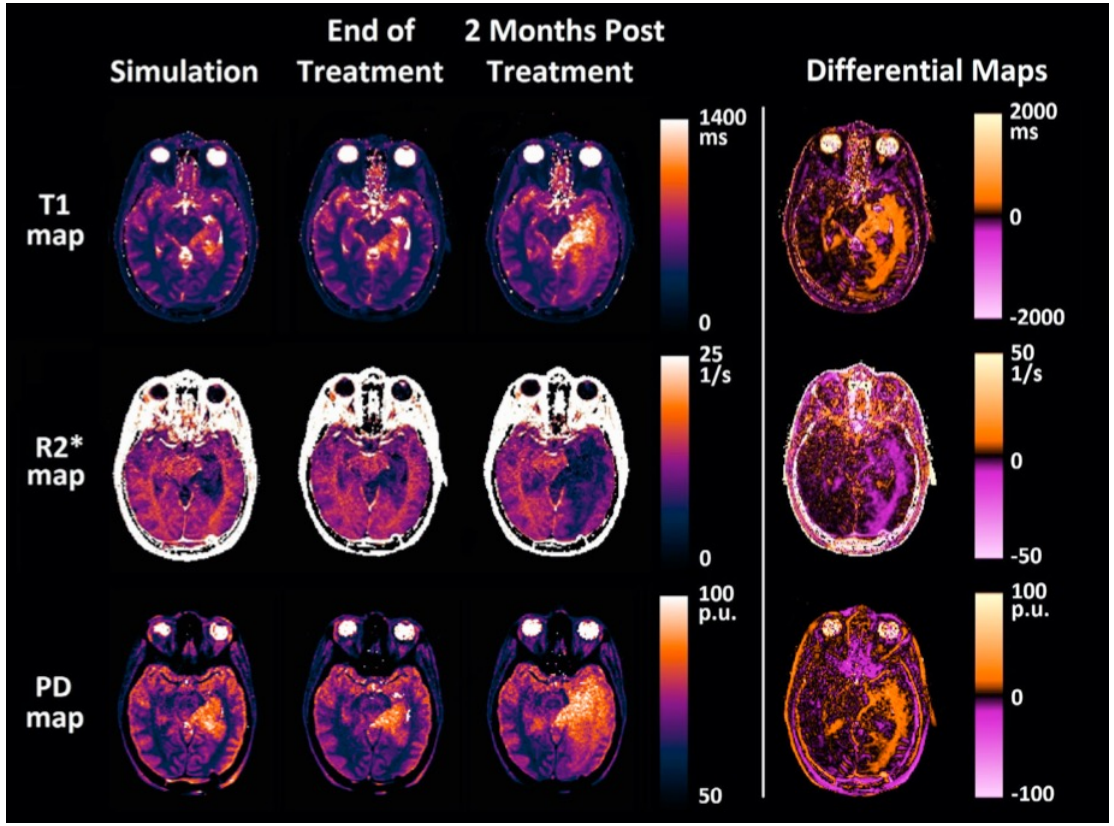
In Vivo MRF at 0.35T



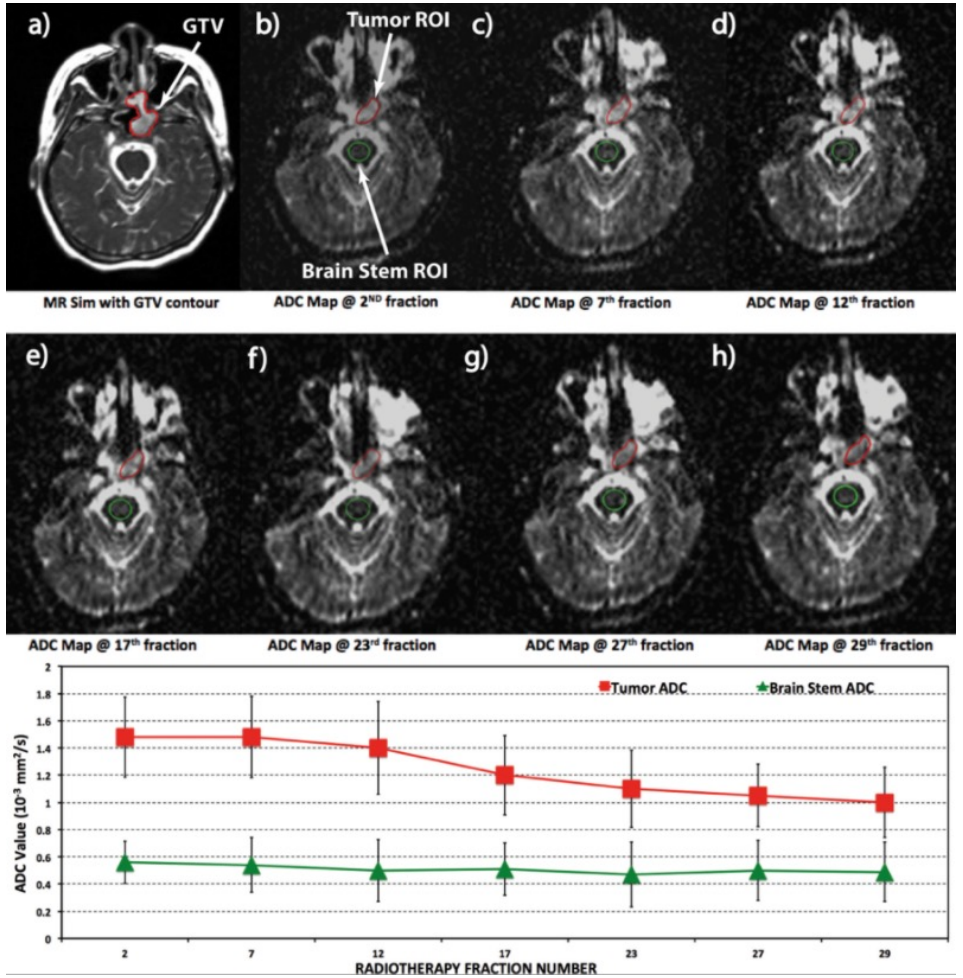


Uses for MRF on Low-Field MRgRT Systems

- Multi-parametric quantitative MRI for longitudinal treatment response monitoring



Nejad-Davarani et. al. Medical Physics (2020)



Yang et. al. Medical Physics (2016)

Quantitative MRI at Low-Field Summary

- Quantitative imaging at low-field is very challenging
- Tailored solutions help to ensure its success:
  - 3D acquisitions with multiple averages to improve SNR
  - Acquiring many contrast time points to improve robustness of fitting the qMRI model to the acquired data
  - Using constrained reconstructions for high-dimensional qMRI (e.g. MR fingerprinting)
- Carefully designed qMRI experiments will allow for applications in sub-volume targeting and longitudinal treatment response monitoring.

Acknowledgements

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