Improved T_1 and T_2 mapping in 3D-QALAS using temporal subspaces and flip angle optimization enabled by auto-differentiation

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Introduction: T_2 and T_1 estimation improves characterization of various pathologies, but lengthy scan-times preclude widespread application of quantitative MRI (qMRI), so sequences have been developed for efficient 3D acquisitions. For example, 3D-QALAS[1] utilizes an interleaved Look-Locker acquisition with a T_2-preparation pulse for full brain quantification of T_1 and T_2. However, 3D-QALAS applies constant flip angles and reconstructs images at 5 time-points that suffer from blurring due to signal evolution during the lengthy echo-train. Summarized by Figure 1, we propose improving 3D-QALAS by: (1) incorporating subspace-based reconstruction that resolves complete temporal dynamics to eliminate blurring (2) optimizing acquisition flip angles with the Cramer-Rao-Bound (CRB) using simulation compatible with auto-differentiation, (3) and decreasing the number of total acquisitions per repetition time (TR) for reduced scan-time.

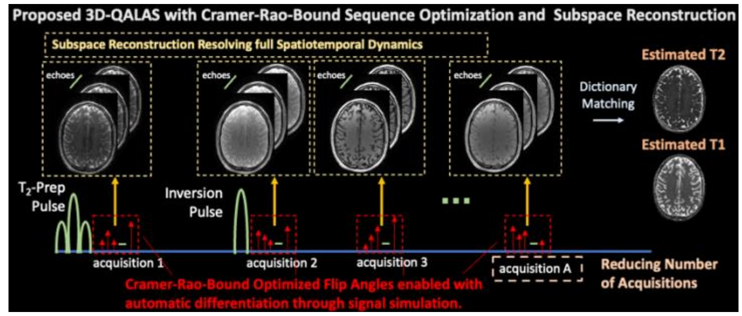

Fig 1: Improving 3D-QALAS with CRB-optimized flip angles, fewer acquisitions, and subspace reconstructions resolving full temporal dynamics for quantitative mapping to produced sharper images with shorter scan-times.

Methods: Subspace Reconstruction: Conventional 3D-QALAS applies T_2-prep and inversion pulses and measures 5 acquisitions which each utilize an echo-train of 4-degree flips. Rather than reconstructing a volume for each of the 5 acquisitions, let E be the number of echoes in one of the A acquisitions in a 3D-QALAS TR (typically $A = 5, E = 120 \rightarrow T = 120 \times 5 = 600\ echoes/TR$), where T is the total number of echoes. We generate a dictionary of signal evolution to compute a low-dimensional linear basis Φ with the SVD, producing a tractable reconstruction problem $argmin_\alpha \|y - A\Phi\alpha\| + R(\alpha)$, where A represents the Fourier, coil, and sampling operators and R regularization. By resolving the spatiotemporal volume with $x = \Phi\alpha$, we aim to estimate sharper quantitative maps utilizing dictionary matching with T echoes[2]. In-vivo experiments in Figure 2 (A) showcase reduced blurring in estimated T_2 maps using subspaces.

CRB Flip Angle Optimization: We optimized flip angles in 3D-QALAS by minimizing CRB in two regimes: (1) optimizing one flip angle per echo-train (2) optimizing all flip angles in every echo-train. We initialized both optimizations with the conventional 4-degree flip angles, utilized representative tissue parameters [T_2=70ms,T_1=700ms,M0=1] and [T_2=80ms,T_1=1300ms,M0=1], and minimized the CRB-based cost function. We implemented an auto-differentiation compatible signal simulation[3] for 3D-QALAS, enabling computation of gradients for CRB based optimization.

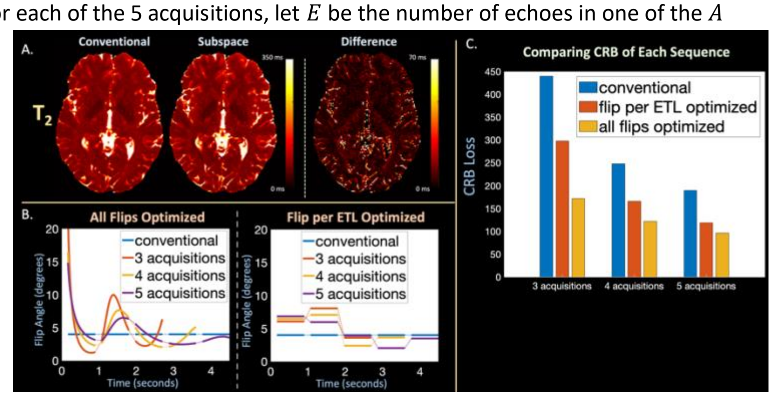

Fig 2: (A) Subspace reconstruction improves sharpness versus conventional reconstruction when estimating T_2. (B) Optimized flip angles and (C) resultant CRB. Sequences with fewer acquisitions either improve or match CRB of the conventional sequence with 5 acquisitions, potentially enabling reduced scan times.

Reducing Acquisitions: We designed optimized sequences with A={5,4,3} acquisitions by removing acquisitions from the end of the TR, thus speeding up the scan.

Experiments: We implemented the optimized-per-echo-train 3D-QALAS sequence on the scanner and acquired data using the conventional and optimized sequence on the Mini System Phantom, Model #136 (CaliberMRI, Boulder, CO, USA) and a human subject (under IRB approval) with 3 and 5 acquisitions (1x1x1mm^3 resolution, R=2). We compared quantitative maps estimated with subspace reconstructions (rank = 3) and dictionary matching.

Results: Optimized Sequences: Figure 2 (B) plots optimized flip angles and (C) resultant CRB in comparison to the conventional sequence when applying subspace reconstruction for quantitative estimation. Optimization either reduces CRB or matches conventional 5 acquisition CRB with fewer acquisitions, potentially enabling reduced scan-time.

Phantom and In-vivo: Figure 3 (A) and (B) displays estimated maps from phantom and in-vivo data where the per-ETL-flip-angle-optimized sequence with A=3,5 acquisitions matches constant flip angles.

Discussion and Conclusions: Future work will implement the all-flip-angle-optimized sequence to address the T_1-bias in the prospective experiments. Combining subspace reconstruction with auto-differentiation enabled flip-angle optimization yields improved 3D-QALAS sequences with 1.75-fold reduction in scan-time.

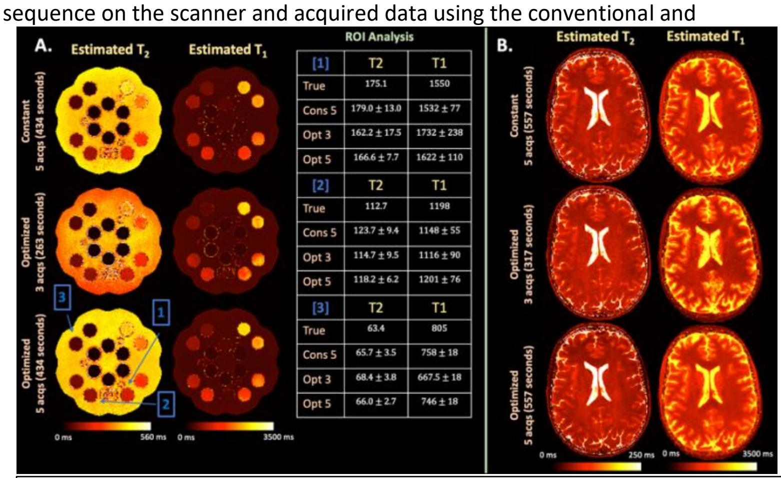

Fig 3: Estimated T_1 and T_2 maps with subspace reconstruction from phantom and in-vivo data using the conventional sequence with 5 acquisitions and constant flip angles, and per-ETL-optimized sequence with 3 and 5 acquisitions. (A) In the phantom, the optimized and conventional sequence with 5 acquisitions achieve similar performance, while the optimized sequence with 3 acquisitions roughly matches T_2 performance with a slight reduction in T_1 performance while reducing scan-time. (B) All three sequences yield comparable quantitative maps in-vivo.

References: [1] Kvernby, S. *et al. J. Cardiovasc. Magn. Reson.* **16**, 102 (2014). [2] Tamir, J. I. *et al. Magn. Reson. Med.* **77**, 180–195 (2017). [3] Lee, P. K. *et al. Magn. Reson. Med.* **82**, 1438–1451 (2019).

Acknowledgments: NIH R01 EB032708, R01HD100009, R01 EB028797, U01 EB025162, P41 EB030006, U01 EB026996, R03EB031175, R01EB032378, 5T32EB1680