Model-Based Reconstruction for Joint Estimation of T_1, T_2^* and B_0 Inhomogeneity Maps Using Single-Shot Inversion-Recovery Multi-Echo Radial FLASH

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Introduction

Inversion-recovery (IR) Look-Locker and multi-echo gradient-echo are two commonly-used sequences for T_1 mapping, and water-fat, T_2^* imaging, respectively [1-6]. Recently, these two sequences have been combined in one single scan for simultaneous multi-parameter mapping [6-9], providing complementary quantitative information for clinical studies. To obtain robust parameter estimation, most existing approaches usually consist of several steps, e.g., B_0 calibration/estimation, linear image reconstruction, and pixel-wise fitting. As each step utilizes a subset of acquired data, existing approaches may have not made the best use of all available data.

In this work, we propose to jointly estimate T_1, T_2^* and B_0 maps directly from the k-space data acquired from a single-shot IR radial multi-echo FLASH by formulating parameter estimation as a nonlinear inverse problem [10-11]. In this way, all acquired data can be exploited for a joint reconstruction. Furthermore, prior knowledge such as joint sparsity and B_0 smoothness can be applied directly to parameter maps to improve the conditioning of the inverse problem.

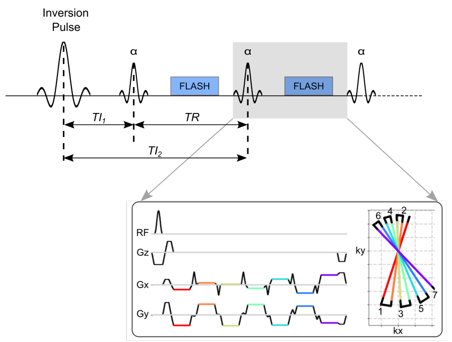

Figure 1: Schematic diagram of the inversion-recovery multi-echo FLASH sequence and its asymmetric radial sampling pattern.

Methods

Sequence Design and Model-based Reconstruction

The IR multi-echo sequence is shown in Fig.1. It starts with a non-selective inversion pulse, followed by a continuous radial multi-echo spoiled gradient-echo (FLASH) using the small golden-angle readout. The signal evolution for this process can be described as:

$$
\begin{aligned}
S_{\mathrm{TI}_n,\mathrm{TE}_m} = \Big[& W_{ss} - (W_{ss} + W_0)\cdot \exp\big(-\mathrm{TI}_n \cdot R_{1,W}^*\big) \\
& + \big(F_{ss} - (F_{ss} \quad + F_0)\cdot \exp\big(-\mathrm{TI}_n \cdot R_{1,F}^*\big)\big)\cdot z_m \Big] \\
& \cdot \exp\big(\mathrm{TE}_m \cdot i2\pi f_{B_0}\big)\cdot \exp\big(-\mathrm{TE}_m \cdot R_2^*\big)\,. \qquad (1)
\end{aligned}
$$

Where $(W_{ss}, W_0, R_{1,W}^*)^T$ are the steady-state signal, the equilibrium-state signal and the effective T_1 relaxation rate for water and $(F_{ss}, F_0, R_{1,F}^*)^T$ represent the corresponding signal components for fat. z_m is the 6-peak fat spectrum, f_{B_0} represents the field inhomogeneity and R_2^* is the T_2^* relaxation rate. TI_n and TE_m denote the n-th inversion time and m-th echo time, respectively. The unknowns optimized for are $\boldsymbol{x} = (W_{ss}, W_0, R_{1,W}^*, F_{ss}, F_0, R_{1,F}^*, f_{B_0}, R_2^*)^T$. Their estimation is formulated as a nonlinear inverse problem:

$$
\boldsymbol{x} = \mathrm{argmin}_{\boldsymbol{x}\in D} \sum_{\mathrm{TI}} \sum_{\mathrm{TE}} \| P\mathcal{F}C \cdot S_{\mathrm{TI}_n,,\mathrm{TE}_m}(x) - Y_{\mathrm{TI}_n,\mathrm{TE}_m} \|_2^2 + R(\boldsymbol{x})\,. \qquad (2)
$$

Here D is a convex set, ensuring non-negativity of all relaxation rates and $R(\boldsymbol{x})$ is a regularization term. We adopt a joint l1-Wavelet sparsity constraints [11] on all parameters of $\boldsymbol{x}$ except f_{B_0}. The latter is regularized with a smoothness enforcing Sobolev penalty [12] also added to the coil sensitivities. The nonlinear inverse problem in Eq.2 is solved with a IRGNM-FISTA [11] using BART [13].

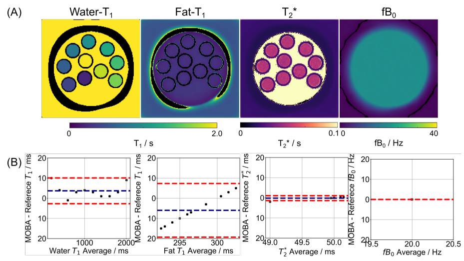

Figure 2: (A) Model-based reconstructed quantitative water-T_1, fat-T_1, T_2^* and $fB0$ maps from a single-shot IR multi-echo radial FLASH acquisition for a simulated phantom. (B) Bland-Altman plots comparing ROI-analyzed mean quantitative values to the ground truth.

Experiments

All MRI studies were conducted on a 3T scanner (Magnetom Skyra, Siemens Healthineers, Erlangen, Germany) with approval of the local ethics committee. The brain study was conducted using a 20-channel head/neck coil. The acquisition parameters were: FOV=192 × 192 mm^2, matrix size=256 × 256, slice thickness = 5 mm, 7 echos with TR=15.6 ms TE_{1-7}=2.36/4.26/6.16/8.06/9.96/11.90/13.80 ms, FA=6°, bandwidth=810 Hz/pixel and 450 excitations in total with 3350 radial acquired spokes. Nice spokes were combined into one k-space frame for fast computation.

Results & Discussion

The proposed model-based reconstruction was first validated for a numerical phantom, which provides ground truth in the presence of noise. Fig.2(A) presents the determined quantitative water T_1, fat T_1, T_2^* and f_{B_0} maps from the model-based reconstruction. Fig.2(B) shows the corresponding Bland-Altman plots comparing quantitative values estimated from ROIs to the known ground truth. The small differences observed in the Bland-Altman plots confirm good accuracy for all parameter maps.

Fig.3 further demonstrates model-based reconstructed brain water T_1, fat T_1, T_2^* and f_{B_0} maps. The steady-state water and fat images (i.e., W_{ss} and F_{ss} in Eq.1) are additionally shown in the second row. Although a reference method need to be performed for a pairwise comparison, visual inspection shows artifact-free quantitative T_1 and T_2^* maps. The quantitative values estimated from ROIs (T_1: white matter: 800±8 ms gray matter: 1388±61 ms; T_2^*: white matter: 46±2 ms gray matter: 61±3 ms) correspond well to the literature values [4,10].

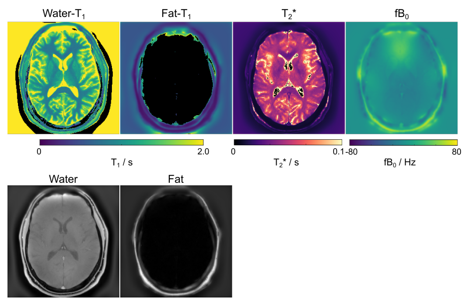

Figure 3: (Top). Model-based reconstructed artifact-free brain water T_1, fat T_1, T_2^* and $fB0$ maps from a single-shot IR multi-echo radial FLASH acquisition. (Bottom). Steady-state water and fat images (i.e., W_{ss} and F_{ss} in Eq.1) from the model-based reconstruction.

Summary

The presented work formulates the joint estimation of T_1, T_2^* and f_{B_0} maps from a single-shot IR multi-echo acquisition as a single nonlinear inverse problem. Initial results on a simulated phantom and a healthy subject demonstrate that high resolution and artifact-free quantitative maps can be reconstructed simultaneously with the proposed method.

References

[1] Look DC*et al.* Rev Sci Instrum 1970;41:250-251. [2] Bernstein M *et al.* Handbook of MRI Pulse Sequences. [3] Hernando D *et al.* Magn Reson Med. 2012; 68: 830?840. [4] Tan Z *et al.* arXiv:2020.02788. [5] Schneider M *et al.* Magn. Reson. Med. 2020; 84:2592-2605. [6] Feng L *et al.* Magn. Reson. Med. 2021; 86:97-114. [7] Cao T.*et al.* Magn. Reson. Med. 2022; 87:1375-1389. [8] Jaubert O *et al.* Magn. Reson. Med. 2020; 84:2625-2635. [9] Lima da Cruz GJ, *et al.* Magn. Reson. Med. 2022;87:2757-2774. [10] Block T*et al.* IEEE Trans Med Imaging 2009;28:1759-1769. [11] Wang X *et al.* Magn Reson Med. 2018;79:730-740. [12] Uecker M *et al.* Magn Reson Med 2008;60:674-682. [13] Blumenthal M *et al.* mrirecon/bart: version 0.8.00. 2022.

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