Accelerating Multi-Component Relaxometry in Steady State with an Application of Constrained Reconstruction in Parametric Dimension

J. V. Velikina[1], S. A. Hurley[1], A. L. Alexander[1], and A. A. Samsonov[1,2]
[1]Medical Physics, University of Wisconsin - Madison, Madison, WI, United States, [2]Radiology, University of Wisconsin - Madison, Madison, WI, United States

Introduction: Multi-component relaxometry (MCR) [1] is a quantitative MR technique that elucidates tissue microstructure by identifying the relaxation behavior of different tissue compartments. In white matter imaging, the ratio of water signal with shorter T2, which is associated with water trapped between myelin sheath layers, to the total signal, often called myelin water fraction (MWF) can serve as an important non-invasive measure of myelin content. MWF may play an important role in the treatment and management of demyelinating diseases like multiple sclerosis [2]. However, the clinical utility of MCR is compromised by long scan times. CPMG spin echo pulse sequences have been the primary method for MWF mapping with acquisition times on the order of 12 min per slice [1]. The recently introduced MCR in steady state (mcDESPOT) [3] combines short repetition time SPGR (spoiled gradient echo) and bSSFP (balanced steady state in free precession) pulse sequences to generate whole brain 3D MWF maps in under 30 minutes with a 1.5 mm^3 isotropic resolution. However, the imaging time may still be too long for robust clinical imaging in non-cooperative patients, especially in pediatric populations or when higher image resolution is required. In this work, we propose a novel way to accelerate mcDESPOT using advanced reconstruction from incomplete data.

Theory and Methods: In the mcDESPOT method, a complex model with a minimum of 6 free parameters (long and short T1 and T2, MWF, and myelin water residence time) is fit to multiple image volumes acquired at different flip angles (FAs). To ensure an accurate estimation of the parameters from the model, 8-10 image measurements need to be collected for the SPGR sequence and 16-20 measurements for the bSSFP sequence. Recently, an accelerated algorithm for T1 mapping relying on the smooth behavior of SPGR signal dependence on FA was introduced [4]. We note that a similarly smooth dependence on FA values exists for bSSFP signal, making the previous assumptions for SPGR acquisitions also valid for bSSFP. The proposed algorithm applies the 2nd discrete derivative operator in the FA dimension on per-pixel basis, rendering a sparse volume in the combined *x-p* space (*p* denotes the parameter dimension, in this case FA). The obtained sparsity can be exploited by utilizing compressed sensing [5] to reconstruct a parameter-dependent series of image volumes. The images are obtained solving the following optimization problem: $f = \arg\min_f \left(\|Ef - b\|_2^2 + \lambda \left\| \Delta_p^2 f \right\|_{l_1/l_2} \right)$, where f is the underlying signal vector for all FA values, E is encoding matrix for either SPGR or bSSFP sequence, consisting of both Fourier terms and coil sensitivities, b is the measured *k*-space data, λ is regularization parameter providing balance between the data fidelity term and the penalty term utilizing the 2nd discrete derivative in the FA dimension Δ_p^2. In this work, we found that an uneven spacing of FAs better reflects the asymmetric shape of the curves with higher sampling density in the regions of expected higher curvature of the signal. The non-equidistant parameter spacing is reflected in our reconstruction algorithm by taking divided differences in the numerical implementation of the Δ_p^2 operator. We have also noticed that due to discretization of this differential operator, image volumes corresponding to the first and last two sampled values of the parameter (FA) undergo less regularization and, as a result, exhibit more residual undersampling artifacts and higher noise level, which in turn propagate into the subsequently derived parameter maps. To amend the situation, we propose a variable undersampling scheme with lower acceleration factors for the first and last two sampling FAs.

We provide initial validation of the proposed method by applying it to mcDESPOT data collected in a healthy volunteer. Following informed consent, fully sampled datasets were collected for SPGR and bSSFP sequences on a 3.0T GE MR750 (GE Healthcare, Waukesha, WI) with 25 flip angles for each sequence. SPGR acquisition parameters were TR=3.7 ms and FA = 1° - 25° (1° increment). SSFP acquisition parameters were TR=4.5 ms and FA= 1° - 76° (3° increment). SSFP scans were repeated for φ = 0° and 180° phase cycling to remove the effect of SSFP banding artifacts and estimate B0 field [6]. All images were acquired with a 96x96x100 matrix, providing a 2 mm^3 isotropic resolution. An AFI flip angle map was also acquired to correct for the effects of B1 inhomogeneity [7]. Ten FAs were subsequently chosen for both SPGR and bSSFP signals based on the expected shape of these curves. Next, the data acquired for each of the chosen FAs were retrospectively undersampled in the phase encode direction with an acceleration factor R=3 for the first and last two FAs in each sequence and R=5 for the remaining 6 FAs, resulting in the total acceleration factor R=3.95. Three image volume were then reconstructed for each sequence by solving the above problem and by using parallel imaging (SENSE [8]) alone. Parameter maps for short and long T_1 and T_2, MWF, and myelin water residence time were derived from the obtained images with mcDESPOT method and compared to the maps obtained from the fully sampled data.

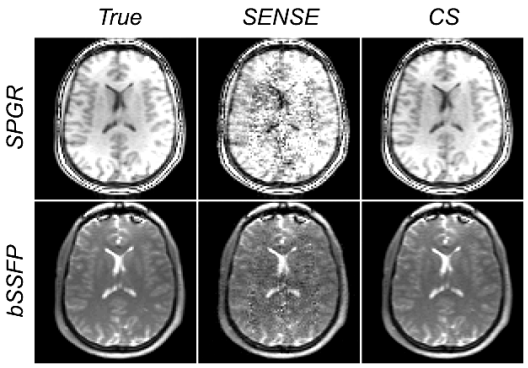

Figure 1. Comparison of representative images for a single FA for SPGR (top) and SSFP (bottom) obtained from (left to right) fully sampled and accelerated data using SENSE and the proposed reconstruction.

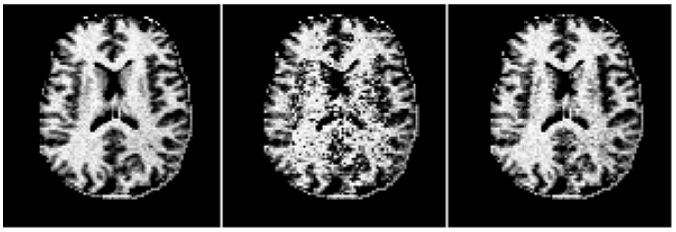

Figure 2. Example MWF maps reconstructed using (from left to right) full data, SENSE, and proposed constrained reconstruction technique.

Results: Figure 1 demonstrates the effect of the proposed reconstruction on quality of mcDESPOT source images. SENSE reconstruction shows increased spatially non-uniform noise due to g-factor. On the contrary, the proposed CS reconstruction significantly regularizes image noise. The effect of noise in the source images on the final MWF maps may be appreciated in Fig. 2. As in Fig. 1, MWF maps reconstructed from SENSE images are contaminated by high and spatially variant noise, while CS MWF is characterized by much more tolerable levels of noise. Similar improvements were observed in the other mcDESPOT parameter maps.

Discussion: In this work, we proposed a CS-based reconstruction to accelerate mcDESPOT. This approach demonstrated utility for both SGPR and bSSFP components of the method enabling a more accurate estimation of MWF maps from accelerated undersampled acquisitions. The proposed reconstruction efficiently suppresses noise amplification and allows tolerating higher reduction factors than possible with parallel MRI alone. The study was done with a uniformly undersampled Cartesian trajectory, while more benefits are expected with mcDESPOT implementations using more randomized sampling patterns. The acceleration may be useful to increase spatial resolution for anatomical targets other than brain and to offset scan time penalties caused by increasing repetition times of SPGR/bSSFP pulse sequences to alleviate on-resonance MT effects [9].

Acknowledgments: We acknowledge financial support of NIH R01NS065034.

References: [1] Mackay A. MRM 1994; 31:673. [2] Vavasour I.M. et al MRM 1998; 40:763. [3] Deoni, S.C, et al MRM 2008;60:496. [4] Velikina ISMRM 2009:350. [5] Candes E, Proc. ICM 2006. [6] Deoni, S.C. Proc ISMRM 2009:4609 [7] Yarnykh V.L. MRM, 2007;57:19. [8] Pruessmann KP et al., MRM 2001;41:638. [9] Bieri O, et al. MRM 2006; 56:1067.