Joint optimization of tip-down and tip-up RF pulses in small-tip (non-spin-echo) fast recovery imaging

J-F. Nielsen[1], D. Yoon[2], N. A. Hollingsworth[3], K. L. Moody[4], M. P. McDougall[3,4], S. M. Wright[3,4], and D. C. Noll[1]
[1]Biomedical Engineering, University of Michigan, Ann Arbor, MI, United States, [2]Electrical Engineering and Computer Science, University of Michigan, [3]Electrical and Computer Engineering, Texas A&M University, [4]Biomedical Engineering, Texas A&M University

Introduction: In "fast-recovery" (FR) or driven-equilibrium steady-state imaging, the magnetization is tipped back toward the longitudinal axis at the end of each repetition interval (TR), with the aim of maximizing the acquired signal. Conventional FR imaging requires one or more 180^o refocusing pulses and hence heavy RF deposition (see e.g. [1]). With the use of parallel RF transmission and 3D RF pulse design, it may be possible to replace the conventional 90^o–180^o–90^o pulse train with a tip-down pulse α_+ followed by a tip-up pulse α_- (Fig. 1). The idea is to use α_+ to "pre-phase" the spins according to the local off-resonance and sequence TR, and to design α_- such that all spins are brought back toward the longitudinal axis [2,3]. The potential advantages of small-tip FR (ST-FR) imaging are high signal and balanced SSFP-like image contrast with moderate RF deposition and absence of SSFP banding artifacts, and opportunities for novel contrast mechanisms. The primary challenge in ST-FR imaging is to design fast RF pulses that accurately tailor the spatial excitation and recovery (tip-up) profiles to the local B0 inhomogeneity. We present a simple and effective approach for jointly optimizing α_+ and α_- such that the residual (unwanted) transverse magnetization after the tip-up pulse α_- is minimized.

Methods: Slice-selective excitation (tip-down) and recovery (tip-up) pulses with 2D in-plane phase variation were designed using a small-tip (Fourier) approach based on a fast-kz (or echo-volumar/spoke) excitation k-space trajectory [4,5]. α_+ and α_- were designed iteratively: At iteration i, $\alpha_+(i)$ was designed using the predicted excitation pattern of the time-reverse of $\alpha_-(i-1)$ as the target pattern, and subsequently the time-reverse of $\alpha_-(i+1)$ was designed using the predicted excitation pattern of $\alpha_+(i)$, and so on. Note that each tip-up pulse $\alpha_-(i)$ was created by first designing an intermediate tip-down pulse α^* using the negative of the measured B0 map. The recovery pulse $\alpha_-(i)$ was then obtained by "undoing" the excitation created by α^*, i.e. by traversing the excitation k-space pattern for α^* in reverse. Importantly, $\alpha_-(i)$ is in general not simply the negative of a tip-down pulse.

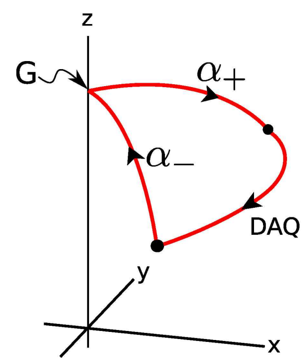

Figure 1: Small-tip fast-recovery imaging principle. The tip-down pulse α_+ "pre-phases" the spins according to the local off-resonance frequency. Data is acquired in the usual way during the free precession segment (DAQ). At the end of TR, the tip-up, or "recovery", pulse α_- tips the spins back toward the longitudinal axis, and residual transverse magnetization is removed with a gradient or RF spoiler G.

Validation experiments were performed with a custom parallel transmit system (Fig. 2) based on current-source amplifiers [6], integrated with a GE 3T scanner with body coil signal reception. The tip-down/excitation pulse α_+ consisted of a single sinc pulse (i.e. a fast-kz pulse train of length 1), as did the tip-up/recovery pulse α_-. The residual transverse magnetization in a uniform ball phantom following the tip-up pulse was imaged with a spin warp (GRE) sequence (TE/TR = 4/200 msec; 64x64 matrix size). For comparison, we also designed a tip-down/up pair by designing the tip-down pulse independently of the tip-up pulse (and vice-versa), using a uniform-magnitude target excitation pattern corresponding to the measured B0 map. For reference, a uniform excitation pulse was also simulated and played out on the scanner.

To assess the performance of the proposed joint RF pulse design in the brain, we simulated the residual signal based on observed magnitude and B0 maps in a healthy volunteer. RF pulses were designed using observed transmit sensitivity maps for the 8-channel transmit array in Fig. 2.

Results: Figure 3 shows experimental parallel transmission results. We observe good agreement between Bloch simulations and observations, both for a uniform excitation pulse and the dual tip-down/up pulses. Joint RF pulse design greatly reduces the residual signal. Figure 4 shows brain simulation results. Again, joint RF pulse design suppresses residual transverse signal compared to an independent (non-joint) design.

Discussion and Conclusions: Joint design of tip-down and tip-up pulses can greatly reduce the residual magnetization after the recovery (tip-up) pulse. We hypothesize that the proposed RF pulse design approach will minimize the signal loss in steady-state small-tip fast-recovery/driven-equilibrium imaging, allowing rapid imaging with bSSFP-like signal contrast and GRE-like robustness to B0 inhomogeneity. A potential drawback of the proposed approach is that the magnitude of the excitation (tip-down) pattern is not explicity controlled, which may lead to increased image non-uniformity.

References: [1] Hargreaves et al, MRM 42:695-703 (1999); [2] Heilman et al, ISMRM 2009, p251; [3] Nielsen et al, ISMRM 2010, p77; [4] Zhang et al, MRM 57:842-847 (2007); [5] Yoon et al, ISMRM 2009, p2595; [6] Kurpad et al, Magn Reson Engineering (Conc. Magn. Reson. B), 29:75-83 (2006).

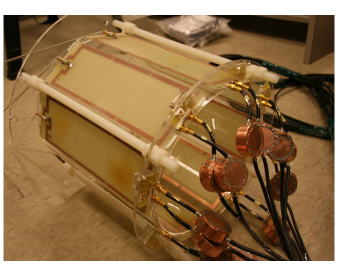

Figure 2: Parallel transmit head array used for validation experiments. This array was driven by RF current source amplifiers that produce a high degree of isolation between transmit elements.

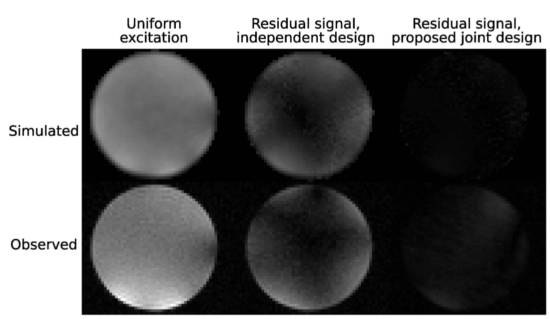

Figure 3: Parallel transmit validation experiments. Simulated (top row) and observed (bottom row) transverse magnetization following 4-channel RF transmission. When the tip-down and tip-up pulses are designed independently (see text), significant transverse signal remains after the tip-up pulse (middle column). Joint tip-down and tip-up RF pulse design produces minimal residual magnetization after the tip-up pulse (right column).

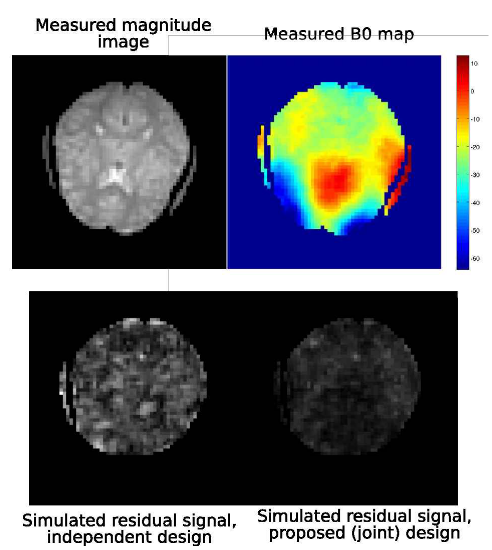

Figure 4: Simulation results based on observed magnitude (a) and B0 maps (b) in a volunteer. Joint tip-down/up design (d) produces less residual transverse magnetization than a corresponding independent design (c). RF pulses were designed for a 16 msec DAQ time, using 6 spokes for α_+ and 6 spokes for α_-.