Strategies for Improved 3D Small-Tip Fast Recovery (STFR) Imaging

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Introduction: Small tip fast recovery (STFR) imaging has been proposed recently as a potential alternative to balanced steady state free precession (bSSFP). STFR relies on a tailored "tip-up" RF pulse (Fig. 1(a)) to achieve comparable signal level and image contrast as bSSFP, but with reduced banding artifacts [1]. 2D STFR imaging can use fast 2D tailored pulses (e.g., spiral) in combination with RF-spoiling [1], but in many applications such as fMRI it is necessary to do 3D imaging [2]. Designing a 3D RF pulse that accurately tailors the excitation pattern to the local B0 inhomogeneity over the entire imaging volume is a challenging and unsolved problem. Here we propose two complementary strategies for improved 3D STFR imaging: First we show that unbalanced non-RF-spoiled STFR imaging ("G-STFR" [3]) is less sensitive to tip-up pulse error than the corresponding RF-spoiled sequence ("RF-STFR"). Second, we propose to use non-slice-selective tailored pulses for both tip-down and tip-up, and present two alternative RF pulse design algorithms.

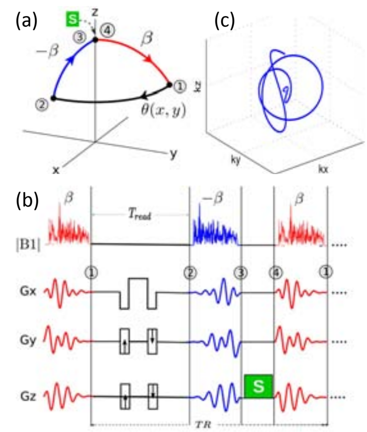

Figure 1. Proposed 3D "G-STFR" pulse sequence. (a) Steady-state spin path. The spin is tipped back to the z-axis by a pulse tailored to the accumulated free precession phase $\theta(x,y) = \omega(x,y)T_{read}$, where T_{read} is the free precession time. (b) 3D STFR diagram. 3D tailored pulses are used for both tip down and tip up. Gradient crusher is used without RF spoiling. (c) Excitation k-space trajectory (SPINS [4]).

RF pulse design methods: The proposed 3D STFR pulse sequence is shown in Fig. 1(b). We propose two different approaches for designing the tip-down (red) and tip-up (blue) tailored excitations.

RF pulse design Method 1 (Separate design): The tip-down pulse is tailored to a uniform magnitude excitation pattern with phase pattern $\theta(x,y)/2$, so that after readout the target phase pattern is $-\theta(x,y)/2$, so the phase variation of the desired pattern for both tailored pulses will be half of the phase variation of a single tailored tip up pulse, which may reduce overall excitation error.

RF pulse design Method 2 (Joint design): We design both the tip-down pulse and the tip-up pulse simultaneously using a joint optimization method. The design requirements are that: after the tip down part, the transverse excitation pattern has to be of uniform magnitude; after the tip-up part, the spin should be tipped back to z–axis so the desired transverse magnetization is 0. In this method, the accumulated phase during free precession is modeled in the system matrix and we only care about the magnitude of the excitation pattern in the RF design. This phase relaxation could potentially improve the design result. To formulate the joint design method, we denote b1 as the tip-down pulse, and b2 as the tip-up pulse. The desired pattern is $[\sin(\beta) \quad 0]^T$, where β is the flip angle of the tip down pulse. In the small tip angle approximation, we express the relation between excitation pattern and RF waveform through the system matrix A with $a_{ij} = i\gamma M_0 e^{-ik(t_j)r_i - i\Delta\omega(r_i)(t_j - T)}$. Let β be the Tikhonov regularization parameter. The joint design becomes the *magnitude least squares* problem: $[b_1\ b_2]^T = \text{argmin}_{b_1,b_2}\{\left\|\begin{bmatrix}\sin(\beta)\\ 0\end{bmatrix} - \left|\begin{bmatrix}A_1 & 0\\ A_2 & A_3\end{bmatrix}\begin{bmatrix}b_1\\ b_2\end{bmatrix}\right|\right\|_2^2 + \beta\|b_1\|_2^2 + \beta\|b_2\|_2^2\}$, which we solve using the method in [5].

Experimental methods: A healthy volunteer was imaged with a GE 3.0 T scanner and a birdcage T/R headcoil. A 3D B0 map was acquired with SPGR with different TE. We then acquired 3 different STFR images (20^o flip angle): *(1) "Separate RF-STFR":* Separate RF design, and RF spoiling. *(2) "Separate G-STFR":* Separate RF design, and RF spoiling. *(3) "Joint G-STFR":* Joint design, and no RF spoiling (constant RF phase). The SPINS [4] excitation k-space trajectory was used for all tailored pulses (Fig.1(c)). The RF waveform is designed using small-tip method [6]. The pulse lengths are 1.7ms for each RF pulse. The design is targeted to a 3cm thick slab of brain. A 3D readout was used with 256x256x49 sampling, 24x24x24cm FOV, and 62.5KHz receive bandwidth, which results in a 10ms TR. We use larger FOV in z than the designed target to eliminate the aliasing effect from untargeted slices, which could be avoided using frequency encoding in the z direction in practice [4]. For comparison, 180^o phase-cycled bSSFP images are acquired with the same resolution, 40^o flip angle, and 7.6ms TR.

Results: Figure 2 compares 3 different STFR images with bSSFP for a single slice, and Joint G-STFR produces the best result. Figure 3 compares 180^o phase-cycled bSSFP (top) with Joint G-STFR (bottom) in 5 slices spanning 4 cm range in z. The Joint G-STFR image has similar contrast and signal level as bSSFP but with reduced banding.

Discussion and Conclusion: We have shown that combining G-STFR with joint tailored pulse design can produce 3D banding free bSSFP-like images over a 3D region-of-interest (24x24x3 cm^3) using a single RF transmission channel and short (1.7ms) tip-down and tip-up pulses. We plan to implement our method using parallel transmission in the future, which we expect to substantially improve the tailored excitation accuracy.

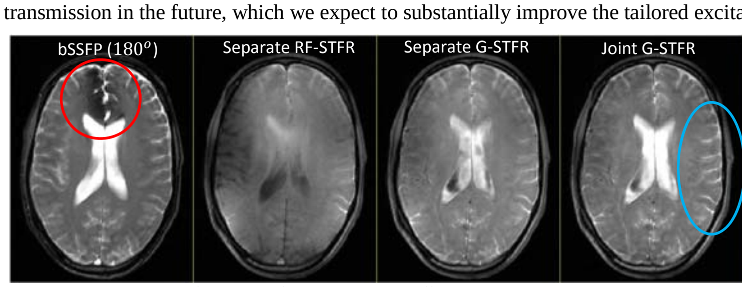

Figure 2: Comparison of bSSFP (left) with the three different STFR images, in one slice. The bSSFP image has banding artifact in front (red circle). G-STFR is less sensitive to excitation error than RF-STFR. Separate and Joint design have similar results, but joint design produces better match with bSSFP (e.g., blue circle).

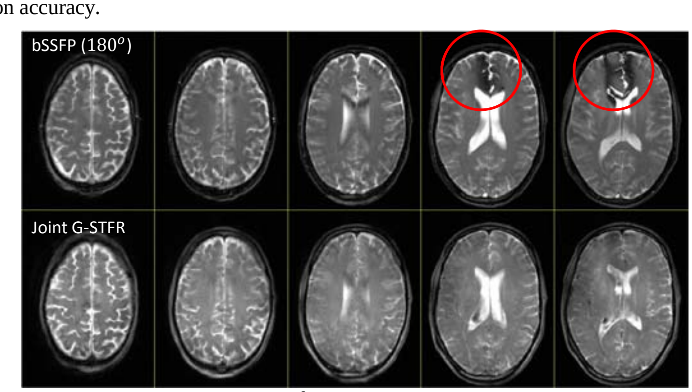

Figure 3:. Top row: bSSFP with 180^ophase-cycling; Bottom row: Joint G-STFR images. We obtain banding free bSSFP-like image over a wide range (4cm) using a single transmission coil in one acquisition.

Reference: [1] Nielsen et al, MRM 2012; [2] Lee et al, MRM 2008; [3] Sun et al, ISMRM 2012; [4] Malik et al, MRM 2011; [5] Setsompop et al, MRM2008; [6] Yip et al, MRM 2005.

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