Small-tip Fast Recovery (STFR) imaging Using Spectrally Tailored Pulse

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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) [1, 2]. 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. Previous STFR implementations used 2D or 3D pulses spatially tailored to the accumulated phase calculated from a B0 field map. Here we propose to replace the spatially tailored pulse with the spectrally tailored pulse from [3], which can be precomputed to a target frequency range. We show that this "spectral-STFR" sequence has reduced banding artifacts compared to bSSFP.

RF pulse design methods: Figure 1 shows the spin path of the STFR pulse (a) and an example sequence diagram (b), where β (red waveform) and $-\beta$ (blue waveform) correspond to the tip-down and tip-up parts, respectively. In our spectrally tailored design, the tip-down pulse is tailored to a pattern $\boldsymbol{d}(\boldsymbol{\omega}) = \sin\beta \exp(\mathrm{i}\boldsymbol{\omega}\mathrm{T}_{\mathrm{free}}/2)$, where β is the flip angle (uniform for all spins) and $\boldsymbol{\omega}$ is the off-resonance frequency. After readout, the spins should have phase $-\boldsymbol{\omega}\mathrm{T}_{\mathrm{free}}/2$, and a tip-up pulse is tailored to this to bring all the spins back to z-axis. Note that in previous spatial designs [1,2], **d** is a function of position, but here **d** is only a function of off-resonance frequency ($\boldsymbol{\omega}$). We compute the RF waveform by solving: $\boldsymbol{b} = \mathrm{argmin}_{\boldsymbol{b}}\{\frac{1}{2}\|\boldsymbol{d}(\boldsymbol{\omega}) - \boldsymbol{A}\boldsymbol{b}\|_2^2 + \beta\|\boldsymbol{b}\|_2^2\}$, where β is the Tikhonov Regularization parameter, controlling the tradeoff between RF power and excitation accuracy. $\boldsymbol{A}$ is the small tip angle approximation matrix with $a_{ij} = i\gamma M_0 e^{-i\Delta\omega(r_i)(t_j - T)}$. There is no phase encoding term $(-ik(t_j)r_i)$ in $\boldsymbol{A}$ here since all gradients are set to be zero here for spectral selectivity. The final tip-up pulse $-\beta$ is obtained by negating and time-reversing $\boldsymbol{b}$, as in [1, 2].

Experimental methods: A healthy volunteer was imaged with a GE 3.0 T scanner and a birdcage T/R headcoil. We acquired a low resolution 3D B0 map solely to estimate and specify the target off-resonance range. We designed a spectral-STFR sequence (10^{o} flip angle) targeted to -120 to +50 Hz. The pulse lengths are 2 ms for each RF pulse. The integrated total RF power of our spectrally tailored pulse is approximately equal to a 35^{o} degree flip angle sinc pulse. A 3D readout was used with 256x256x65 sampling, 24x24x32cm FOV, and 62.5 KHz receive bandwidth, which results in $\mathrm{T}_{\mathrm{free}}$=4.9 ms and TR= 10ms. We use larger FOV in z than the designed target to eliminate the aliasing effect from untargeted slices, which could be avoided, in practice, using frequency encoding in the z direction [4]. For comparison, bSSFP images are acquired with the same resolution, 20^{o} flip angle, and 7.3 ms TR.

Results: Figure 2 shows the field map, bSSFP image, and STFR image for 10 slices spanning 7 cm. The banding artifacts observed in bSSFP that are within our target frequency range (indicated by the bracket on the colorbar) have been successfully removed in the STFR images. As off-resonance goes beyond the target range, signal drop occurs (e.g., blue arrow), which may due to the phase mismatch [2]. The signal level of spectral-STFR is slightly lower than bSSFP with twice the flip angle, which agrees with our simulations (not shown).

Discussion and Conclusion: We have shown that using a spectrally tailored pulse in unspoiled STFR produces 3D banding free bSSFP-like images over a large frequency range (-120 to 50 Hz) with two short RF pulses (2 ms). Compared with the spatially tailored pulse, the spectrally tailored pulse is easier to implement, and less sensitive to system imperfections (e.g., eddy currents, or mismatch between RF pulse and gradient waveforms), but has higher RF power. In the future, we plan to investigate the relation between the pulse length, RF power, and target frequency range. Also, we will test whether it has the similar steady-state T2* contrast reported in the spatially tailored STFR sequence [5].

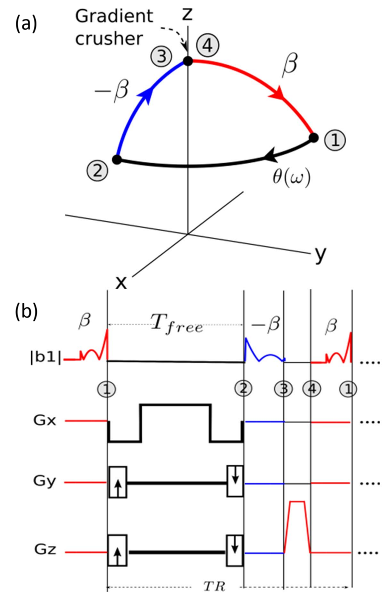

Figure 1. Proposed spectral-STFR pulse sequence. (a) Steady-state spin path. The spin is tipped back to the z-axis by a pulse tailored to the accumulated free precession phase $\theta = \omega\mathrm{T}_{\mathrm{free}}$, where $\mathrm{T}_{\mathrm{free}}$ is the free precession time. (b) pulse diagram. Spectral tailored pulses are used for both tip-down and tip-up. Gradient crusher is used without RF spoiling.

References: [1] Nielsen et al, MRM 2013; [2] Sun et al, MRM 2013; [3] Asslander et al, ISMRM 2013; [4] Malik et al, MRM 2012; [5] Nielsen et al, ISMRM 2013.

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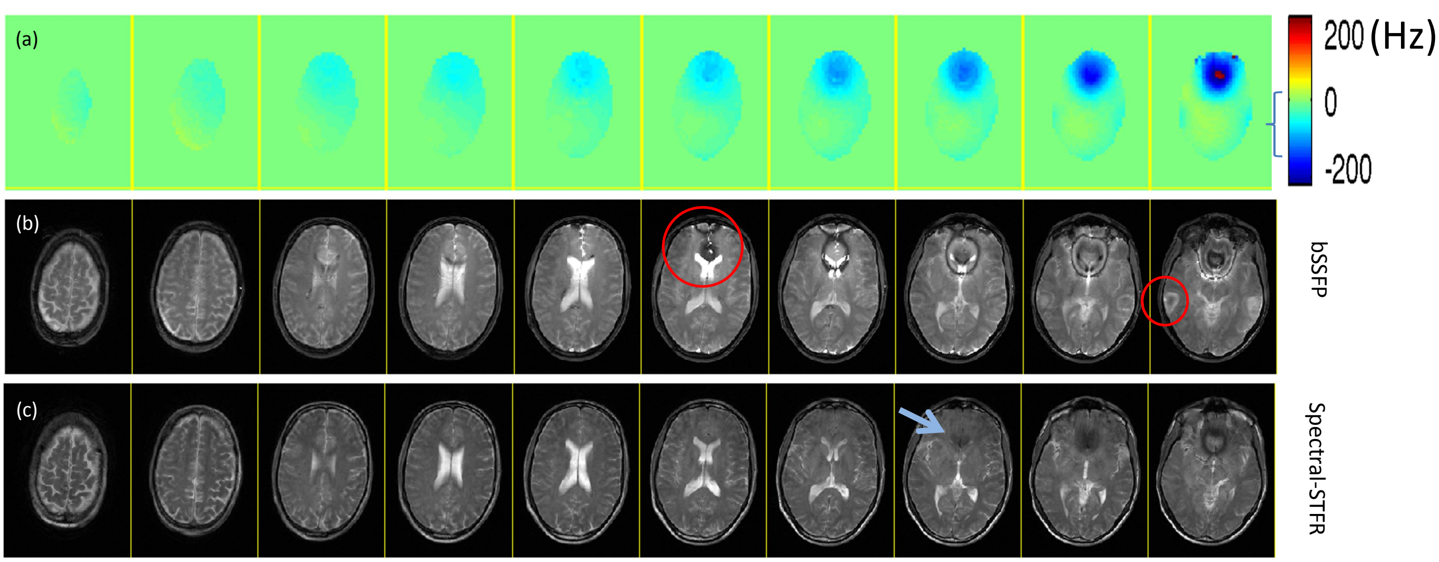

Figure 2. Comparison between the bSSFP image (b) and spectral-STFR image(c). B0 field map is shown in (a). Note the spectral-STFR images have similar image contrast as bSSFP image, with slightly lower signal level. The spectral-STFR successfully removes the banding artifacts (e.g, red circle) within the target frequency range, and signal drop occurs when off-resonance goes beyond the target range (e.g., blue arrow).