Analysis and Suppression of Off-slice Excitation in SSFP Imaging

W. Lu[1], B. A. Hargreaves[2]

[1]Electrical Engineering, Stanford University, Stanford, CA, United States, [2]Radiology, Stanford University, Stanford, CA, United States

Introduction: Balanced steady-state free precession (SSFP) is a fast imaging sequence offering good tissue contrast and high signal-to-noise efficiency [1]. It is well studied that SSFP imaging is susceptible to off-resonance effects which result in banding artifacts[2]. However, little attention has been paid to another type of artifact often encountered in SSFP imaging – undesired steady-state excitation outside the selected slice. One simulated example is shown in Figure 1, which displays the transverse magnetization of spins at different spatial positions and off-resonance frequencies. In particular there exists undesired off-slice excitation near 0 off-resonance frequency. In practice such undesired excitation often leads to spurious imaging of objects outside the selected slice or through-slice aliasing. In this work, we analyze the cause of off-slice excitation in an SSFP sequence. The analysis provides useful insight for designing RF pulses to suppress this type of artifact.

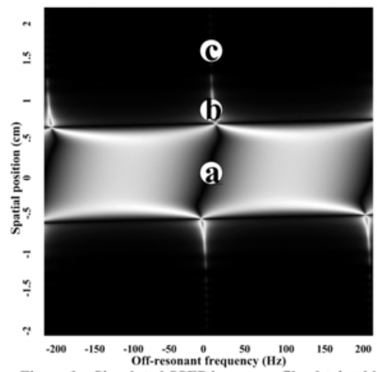

Figure 1: **Simulated SSFP image profile obtained by using a Hamming-windowed SINC RF pulse. The three labels at a, b, and c indicate the spins located at in-slice, just-off-slice, and off-slice positions.**

Theory: Figure 1 is obtained by simulating a SSFP sequence with a fully-refocused slice select gradient waveform and the RF pulse shown in Figure 2(a), which is a Hamming windowed SINC function. We focus on the species with 0 off-resonance frequency but residing at different spatial positions. The spins that are at in-slice, just-off-slice, and off-slice positions are labeled with **a**, **b**, and **c** in Figure 1, respectively. With the initial magnetization in equilibrium, these three spins are excited successively to reach their steady states. The spins reach their steady states due to different mechanisms. Specifically, the spin **a** inside the selected slice undergoes large tip angle and gradually decreases to 0 due to T2 decay and saturation. For the spin **c** the tip angle is so small that the transverse component generated by RF nutation dies out quickly. In contrast to the spin **c**, the tip angle of the spin **b** is large enough to produce undesired excitation in steady state before T2 decay can cause it to relax.

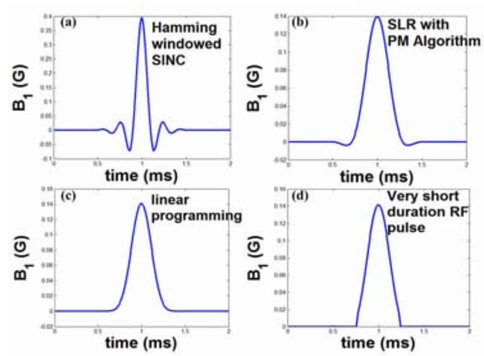

Figure 2: Four RF pulses obtained from (a) Hamming-windowed SINC, (b) SLR with Parks-McClellan algorithm, (c) linear programming and (d) very short duration.

Methods: To suppress off-slice excitation, it is desirable to have a RF pulse which only excites the spins inside the selected slice. Therefore we want a RF pulse with very small stopband ripple compared with standard excitation pulses. In comparison with the Hamming-windowed SINC function shown in Figure 2(a), two other RF pulses were generated by using 1) *Shinnar-Le Roux (SLR) design with Parks-McClellan (PM) algorithm* and 2) *magnitude filter design with linear programming*, respectively. The SLR design [1] with PM algorithm produces optimal equiripple filter in the Chebyeshev sense of minimizing the maximum ripple. On the other hand, it has been shown in [2] that the design of finite-impulse response (FIR) filter with linear phase constraints can be formulated into a linear programming problem. Given the constraints on maximum allowable passband ripple δ_l, passband frequency, stopband frequency, and the filter order n_f, the linear programming is able to produce the FIR filter with minimum possible stopband ripple. With δ_l=10%, n_f=250, and time-bandwidth product TBW=4, the RF pulses obtained from these two approaches are shown in Figure 2(b) and (c), respectively.

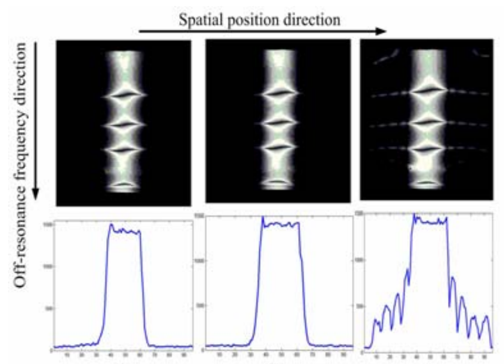

Figure 3: **Scanned phantom images obtained using RF pulses from (a) SLR with PM algorithm and (b) linear programming, and (c) very short duration RF pulse.**

Results and Discussion: Using the RF pulses shown in Figure 2(b,c,d) and TR=2TE=7ms at 1.5T, and a 60º flip angle, 3D SSFP images acquired from a phantom over a 24x24x12 cm3 FOV are shown in Figure 3. In addition, to narrow the slab compared with the phase-encoded FOV, the slice-select gradient was increased accordingly. The off-resonance frequencies were emulated using a local gradient shim of approximately 25 Hz/cm. Below each phantom image is shown the maximum intensity projection along off-resonance frequency direction. As can be seen from the phantom images as well as the excitation profiles, the RF pulses shown in Figure 2(b) and (c) significantly suppress the off-slice excitation shown in the image obtained from the RF pulse shown in Figure 2(d). Although the RF pulses obtained from PM algorithm and linear programming show similar performance in suppressing off-slice excitation in the current work, in future we will further investigate their performance in designing RF pulses with very short duration (in the order of hundreds of μs) and reduced peak RF power.

Conclusion: In this work we have analyzed the cause of undesired off-slice excitation in SSFP imaging and verified this with simulations and experiments. RF pulses for balanced SSFP imaging should be designed with high stop-band suppression in order to avoid off-slice excitations.

References:

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