Reduction of Flow Artifacts in Balanced SSFP Imaging Using S5FP

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Introduction: Balanced SSFP (bSSFP, true FISP, FIESTA, balanced FFE) is a popular sequence for cardiac imaging because it provides a high SNR that is practically independent of the sequence TR. Magnetization is recycled from one TR to the next, rather than simply being crushed or spoiled at the end of each TR, thereby preserving phase coherences in the magnetization over the T_1 and T_2 relaxation timescales. While beneficial for well-behaved magnetization, such longevity can be a problem for out-of-control magnetization. Flowing spins are a particularly significant source of artifacts that often corrupt bSSFP images. The S^5FP sequence, originally proposed for fat-suppression in real-time bSSFP imaging [1], provides balanced SSFP-like contrast for on-resonance spins, but destroys magnetization depending on the phase of the magnetization at TE = TR/2. Here we demonstrate that S^5FP [1] is an effective, robust and efficient method to suppress flow artifacts in bSSFP.

Theory: During balanced SSFP imaging, magnetization is partitioned into phase-opposed bands according to resonance frequency and TR. When (e.g. blood) magnetization in the steady-state of one spectral band moves into a region in an adjacent, phase-opposed band, it exhibits transient behavior over the following several hundred TRs as it converges to the new phase-opposed steady-state (Figure 2). During this transition, this magnetization yields highly oscillatory signals that are a significant source of flow artifacts in bSSFP [2].

The S^5FP sequence employs short trains of (approximately) 8-64 gradient-balanced TRs. Between trains, isochromats in the on-resonance spectral band are z-stored and the usual bSSFP signal levels are retained, whereas off-resonance spectral bands (phased-opposed at TE) are suppressed by gradient crushing and RF spoiling (Figure 1). S^5FP provides several features that assist with bSSFP flow-artifact suppression. Blood flowing into off-resonance spectral bands is automatically suppressed by the S^5FP mechanism. Conversely, blood flowing into on-resonance bands was previously suppressed; hence, it does not contribute large signals with spurious phase fluctuations. Furthermore, blood flowing out of the slice is suppressed by the gradient crushing between S^5FP trains. More generally, flow artifacts occur when long-term phase-coherences are maintained. In S^5FP, by breaking the SSFP-train, z-storing, gradient crushing, RF spoiling and subsequently re-exciting the magnetization, the phase-memory is destroyed. Thus, even the phases of moving spins that remain within the on-resonance band are reset on a regular basis.

Methods: MR imaging was performed using a 1.5T Siemens Espree scanner (Siemens Medical Solutions, Erlangen, Germany). Two sequences were developed to support S^5FP imaging: (1) a real-time, interactive sequence was modified to permit interactive switching between standard bSSFP and S^5FP, and (2) an ECG gated, segmented (CINE) sequence. Imaging with informed consent was performed under the NHLBI IRB. Cardiac images of human volunteers were obtained at various scan-plane orientations using the two sequences operating in both standard bSSFP and S^5FP modes to provide comparison of flow artifacts.

Results: Typical examples of real-time, cardiac images obtained with standard bSSFP and S^5FP (parameters: flip=45°, TR=3.44ms, FOV=300×225mm^2, slice=6mm, AQ matrix=160×90 and 22 TRs per S^5FP train) are shown in Figure 3. Cine images obtained using bSSFP and S^5FP (parameters: flip=45°, TR=4.2mm, FOV=340×340mm^2 slice=8mm, AQ matrix=192×192, 7 lines/segment) from a near candy cane aortic arch scan plane orientation are shown in Figure 4. In both cases, flow artifacts are significantly reduced in the S^5FP images.

Discussion and Conclusions: S^5FP works particularly well with continuous, real-time imaging methods employing sliding window (view-shared) or accelerated imaging methods such as UNFOLD and TSENSE. In applications such as MR guided interventions, where the scan-plane is controlled interactively and external devices may be introduced that disrupt the local field homogeneity it is not generally possible to employ regionally localized shim optimization to reduce bSSFP flow artifacts. Generally, shorter trains provide better flow artifact suppression but reduce sequence efficiency. In practice we have found that trains comprising around 24 TRs to be a suitable trade off. Since the time required for storing, crushing and re-starting the sequence between the S5FP trains is minimal (typically 1-2 TRs), the sequence is approximately retains 95% of the efficiency of standard bSSFP and potential issues with interrupting the SSFP steady state are minimized. S^5FP efficiently suppresses bSSFP flow artifacts.

References:

[1] J. A. Derbyshire et al. Magn. Reson. Med. 54:918-928, 2005

[2] Markl et al, Magn. Reson. Med. 50:892:2003

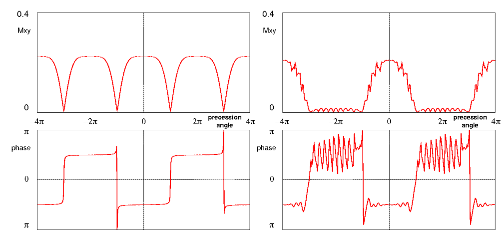

Figure 1: Spectral response for bSSFP and S^5FP

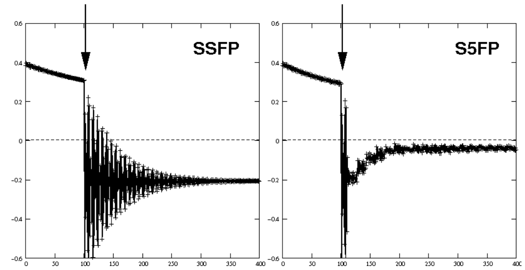

Figure 2: bSSFP and S^5FP transient responses. Initially fully relaxed magnetization in the on-resonance band is catalyzed (a/2-TR/2) and then transitions towards steady-state under bSSFP conditions. At the arrow, the resonance frequency is suddenly changed by (1/TR)Hz into an adjacent off-resonance band. The SSFP signal exhibits severe oscillatory behavior, which is suppressed by S^5FP.

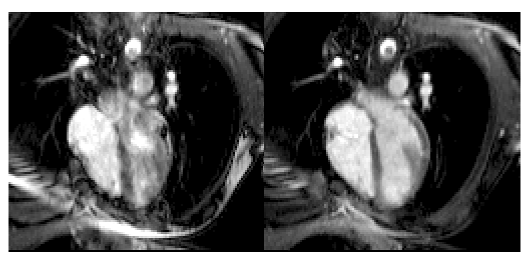

Figure 3: SSFP and S^5FP real-time images compared

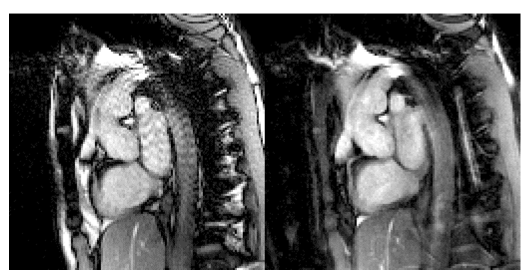

Figure 4: Comparison of SSFP and S^5FP cine images