Analysis of eddy-current artifacts in interleaved balanced SSFP

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Introduction: Many MRI imaging applications, including interleaved phase-contrast MRI, and magnetization-prepared imaging with center-out k-space ordering, require large and frequent changes in the gradient waveforms from one TR to the next. In SSFP imaging, this is generally problematic, since residual eddy-current fields cause waveform-dependent changes in precession angle, which give rise to an unwanted oscillating steady-state [1]. Waveform "pairing" has been shown to mitigate steady-state signal distortions for spins that are near on-resonance [2], but its performance over the whole 1/TR SSFP bandwidth has not been validated experimentally. We investigate the effect of unequal precession angle on the steady-state magnetization in interleaved SSFP, and propose a strategy for mitigating signal distortions within the entire SSFP bandwidth.

Figure 1: The two different readout waveforms used in the interleaved SSFP phantom experiments.

Methods: Experiments were performed on a GE Signa 3T EXCITE HD system (peak gradient amplitude 40 mT/m; slew rate 150 T/m/s), using a transmit/receive head coil. A spherical water-filled phantom (measured T1/T2 = 200/30 ms) was placed at the scanner iso-center and imaged with an SSFP pulse sequence that interleaved the two different readout waveforms shown in Fig. 1 [3]. The waveforms were switched every N TRs, with N=1 (direct interleaving), 2 (pairing [2]), or 4 ("grouping"). Imaging parameters were: 1x1x3 mm^3 voxel size; TR=8.0 ms; flip angle 60^o; 180^o RF phase cycling every TR; field-of-view = 16x20 cm (for non-interleaved SSFP, and for N=1), 16x40 cm (for N=2), and 16x80 cm (for N=4). Gradient shims were adjusted such that the resonance offset varied approximately linearly across the object along the phase-encode direction.

Simulations were performed in Matlab, using Jaynes' matrix formalism [4]. In our simulations, the two waveforms were associated with two slightly different resonance offset frequencies df1 and df2. The steady-state magnetization was obtained by requiring the magnetization to return to the same value every 2N TRs.

Results: Fig. 2 shows calculated (blue) and measured (red) signal profiles (magnitude only) for resonance offset frequencies in the range (-BW/2,BW/2), where BW = 1/TR is the SSFP bandwidth. Results are shown for both non-interleaved SSFP, and interleaved SSFP with gradients switched every 1, 2, and 4 TRs. For clarity, the waveform ordering is indicated by the sequence of "A" and "B" in each plot (see Fig. 1). Calculations were performed with df2-df1 = 4.0 Hz. Note that Figure 2 plots the magnetization for the first of the 2N echoes. The observed magnetization is in good agreement with theoretical predictions.

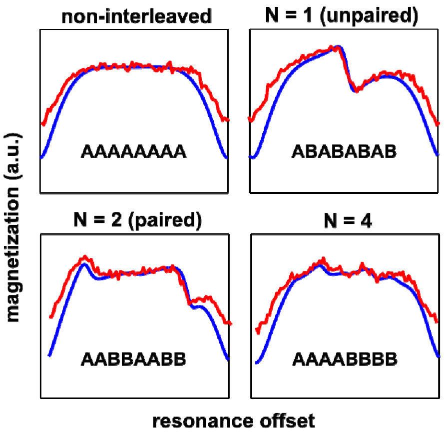

Figure 2: Simulated (blue) and measured (red) magnetization for regular non-interleaved SSFP (top left), and for interleaved SSFP with waveforms executed in groups of 1, 2, or 4.

Apart from the signal magnitude, many imaging applications (e.g. flow imaging) take advantage of the *phase-contrast* (or phase-difference) between two images. Fig. 3 plots the phase-contrast (PC) between echoes 1 and (N+1). Note that there was a small DC offset that was corrected for in each plot. For N=1, the PC value deviates strongly from zero near zero resonance offset. Pairing the waveforms (N=2) removes the artifact from the center of the SSFP band, but substantial steady-state distortions remain near +/- 1/(4TR). In other words, the bandwidth available for imaging is effectively reduced to roughly half the full 1/TR SSFP bandwidth. Increasing N to 4, however, achieves further reductions in phase-contrast distortions.

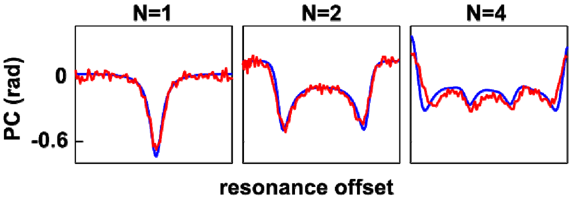

Figure 3: Simulated (blue) and measured (red) phase-contrast between echoes 1 and (N+1), for N = 1, 2, and 4. The amplitude of the steady-state distortions decreases with increasing N.

Fig. 4 shows simulation results for N = 5, 10, and 20, which predicts that both magnitude and PC distortions are mitigated quite effectively as N increases beyond 5.

Discussion: Although grouping the waveforms appears to be a general and simple way to mitigate distortions in interleaved SSFP, it is important to note that for applications such as time-resolved imaging, increasing N inherently reduces the maximum temporal resolution. In particular, the maximum frame rate is 1/(2xNxTR), with an acquisition window of NxTR for each temporal phase. Furthermore, for magnetization-prepared SSFP with centric view-ordering, it is possible that large values of N can cause artifacts related to non-smooth k-space weighting due to signal recovery during image acquisition.

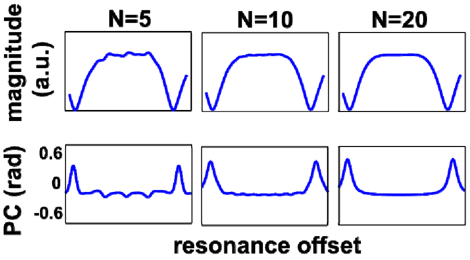

Figure 4: Simulated signal and PC profiles for N=5, 10, and 20. (top row) Magnitude of first echo. (bottom row) Phase-contrast between echoes 1 and (N+1).

Conclusion: Grouping the waveforms is an effective strategy for mitigating steady-state distortions in interleaved SSFP over the full 1/TR bandwidth. The severity of the steady-distortions for a given value of N can be accurately predicted from theory.

References: [1] Scheffler et al, MRM 2006; 55: 598-603, [2] Bieri et al, MRM 2005; 54: 129-137, [3] Nielsen et al, ISMRM2006, p. 879, [4] Jaynes, Phys Rev 1955; 98: 1099-1105