Flow Independent Angiography at 3.0T with Dual-Acquisition Balanced SSFP and Multi-Echo IDEAL

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Introduction: Balanced SSFP imaging provides high signal, with good angiographic contrast and is well suited to 3D imaging [1]. The use of balanced SSFP has been limited, especially at field strengths of 3.0T and higher, by the signal variation due to off-resonance effects [2]. Although a short repetition time (TR) reduces this sensitivity, this places a limit on spatial resolution and maximum flip angle (due to RF power absorption constraints), as well as reducing the acquisition efficiency. For static tissue, the use of multiple, phase-cycled acquisitions allows a longer repetition time with reduced signal variations [3]. Here we apply IDEAL fat/water separation [4] to the signal sum from phase-cycled multi-echo balanced SSFP [5] to achieve excellent high-resolution angiographic contrast.

Theory: Balanced SSFP uses rapidly repeating RF pulses to produce a high-signal steady state with T2/T1 contrast. The signal at TE=TR/2 is refocused to an echo [6], with alternating signal polarity. If the RF and receiver phase (ϕ) alternate by π, the signal shifts by 0.5/TR and the phase changes by $\pi/2$ [3]. Figure 1 shows that these two signals resemble $\cos(fTR)$ and $i \times \sin(fTR)$, where f is frequency, and their sum is approximately a complex exponential, as with a gradient-echo signal [7]. Any deviation of TE from TR/2 in both echoes simply adds a linear phase to this exponential. This suggests application of the IDEAL (Iterative Decomposition of water and fat with Echo Asymmetry and Least squares estimation) water/fat separation technique [4], which corrects for slowly varying phase while providing robust water/fat separation. Furthermore, a fly-back multi-echo balanced SSFP sequence (Figure 2) acquires three echoes within a single TR [5], so that only two acquisitions are required, reducing scan time while improving SNR efficiency.

Methods and Results: Using a 3.0T GE Excite scanner (40 mT/m gradients with 150 mT/m/ms slew rates) and a quadrature transmit/receive extremity coil (GE Healthcare), images were acquired in four healthy volunteers with and without phase cycling using TR = 12 ms, $TE_{1,2,3}$ = 2.4, 5.4, 8.4 ms, 125 kHz receive bandwidth, 60º flip angle, 384x144x140 matrix, 32x12x12 cm^3 FOV for a total scan time of 8 min. Phase cycled images were added, and IDEAL fat/water separation was performed on each slice using a robust 3D field map correction.

Figure 3 shows the water image after IDEAL separation from (a) a single RF phase and (b) the sum of signals from two RF phase cycles. The sum of phase-cycled images removes the dark signal band, and also results in correct fat/water separation. The residual bright spot in Fig. 3(b) is a cyst. Figure 3(c) shows a coronal maximum-intensity projection in another subject, with excellent depiction of the arterial structure and suppression of veins.

Discussion: Balanced SSFP is challenging at 3.0T, due to high sensitivity to off-resonance effects. However, excellent arterial-venous separation of balanced SSFP at 3.0T with extended repetition time has been shown previously [8,9]. Further work will optimize the flip angle and slab profile to compensate for B1 variation to achieve more uniform contrast in images, and use dual leg coils as they become available. The use of a robust 3D field map correction was necessary due to the longer-than-normal "$8\pi/3$" echo spacing used with IDEAL.

Conclusion: Dual-acquisition multi-echo balanced SSFP with IDEAL fat/water separation is a promising technique for flow independent, non-contrast-enhanced angiography. At higher field strengths, this technique *simultaneously* reduces the sensitivity to field variations while allowing moderate flip angles, fat/water separation, and high contrast between arteries and veins.

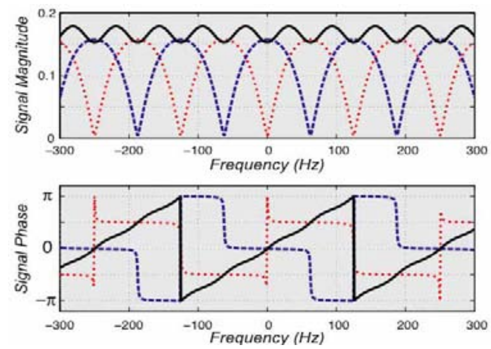

***Figure 1:** Magnitude (top) and phase (bottom) of balanced SSFP signal for constant RF phase (red, dotted), alternating RF phase (blue, dashed) and the signal sum (black, solid), which has relatively constant magnitude and smoothly-varying phase.*

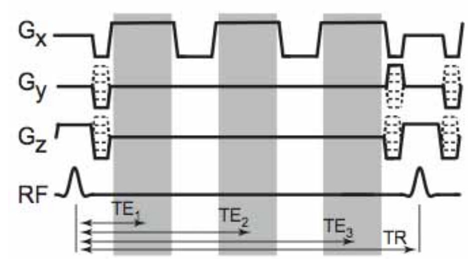

***Figure 2:** Multi-echo balanced SSFP pulse sequence with high SNR efficiency due to a significant acquisition-time fraction (gray).*

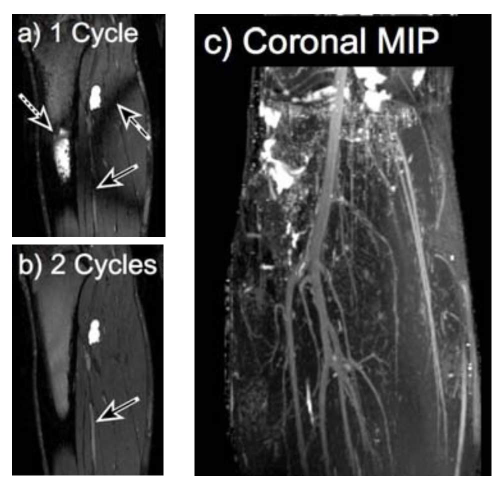

***Figure 3:** Single SSFP cycle (a) image showing dark bands (dashed arrow) fat/water swap (dotted arrow) and vessel signal loss (solid arrow) compared with the dual-acquisition image (b). Coronal MIP (c) in another subject shows excellent arterial-venous vessel contrast.*

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