Off-resonance banding maps with low flip angle balanced steady-state free precession

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Introduction: Balanced steady-state free precession (bSSPF) is widely used for cardiac[1,2], neurologic, musculoskeletal, thoracic, abdominal, and breast MRI. The sensitivity of bSSFP to off-resonance[3] and flow[4] has been well described. The off-resonance sensitivity, in particular, limits the use of bSSFP for clinical exams at field strengths greater than 1.5T. At these higher field strengths the main-field (B_0) inhomogeneity induces off-resonance banding artifacts and flow artifacts that corrupt the images, despite the short repetitions times (TR) achievable with state-of-the-art gradient hardware. Herein we highlight the signal characteristics of the bSSFP pulse sequence for high and low flip angles in regions that are on- and off-resonance. Low flip angle bSSFP can be used to map off-resonance bands with bright image contrast.

Theory: The bSSFP signal amplitude with sign alternating RF phase for on-resonant and π off-resonant spins are:

$$\mathrm{bSSFP}_{On} = M_0 \sin\theta \frac{1-E_1}{1-(E_1-E_2)\cos\theta - E_1E_2} e^{-TE/T_2} \quad \text{Eqn. 1}$$

$$\mathrm{bSSFP}_{Off} = M_0 \sin\theta \frac{1-E_1}{1-(E_1+E_2)\cos\theta + E_1E_2} e^{-TE/T_2} \quad \text{Eqn. 2}$$

Note that the bSSFP_{Off} equation is equivalent to the signal amplitude equation for on-resonant spins without sign alternating RF phase (the phase accumulation of off resonant spins counteracts the sign alteration of the RF phase). The signal response for Eqn. 1 & 2 is plotted in Figure 1. Over a wide range of practical T1, T2, TR, and TE values that the peak signal amplitude for bSSFP_{On} occurs at >30°, but is much lower (~1°) for bSSFP_{Off}. Note also that the achievable signal amplitude for low flip angle bSSFP_{Off} is of similar amplitude as bSSFP_{On} for high flip angles. The optimum flip angle (peak signal amplitude) for the bSSFP_{Off} signal for a given T1, T2, TR, and TE was derived from partial differentiation of Eqn. 2 with respect to θ, setting the result equal to zero, and solving for θ. This yields Eqn. 3 after significant algebra if TR<<T2<T1.

$$\theta_{Optimal} \approx \frac{\mathrm{TR}}{\sqrt{\mathrm{T_1 T_2}}} \quad \text{Eqn. 3}$$

$\theta_{Optimal}$ (radians) for a wide range of practical T1, T2, and TR values is approximately one degree.

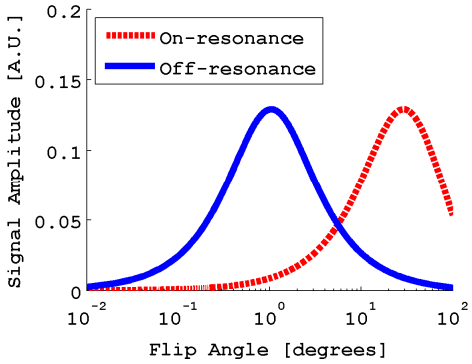

Figure 1. Signal amplitude for on-resonance and off-resonance spins in balanced SSFP with sign alternating RF phase. Note that off-resonance spins have high signal amplitudes for low flip angles (T1=750ms, T2=50ms, TR=3.5, TE=1.8ms).

Methods: A healthy, female volunteer underwent an MRI examination using a 3T Siemens (Trio) system. bSSFP images from this exam are shown in Figure 2 (450mm FOV, 5mm slice thickness, 930Hz/pixel, 60° or 1° flip angle, TE/TR=1.4/3.2ms, 256x192 matrix size).

Results: Figure 2 shows balanced steady-state free precession (bSSPF) imaging in a healthy adult female in the knees and thighs. Note the presence of numerous dark banding artifacts at the location of π off-resonance per TR when using a flip angle of 60° (left). These same regions of off-resonance are very bright when bSSFP imaging is acquired using a flip angle of 1° (middle). The images can be combined (right) to highlight the off-resonance bands. This technique is useful for distinguishing off-resonance bands from areas of on-resonance with low signal amplitude.

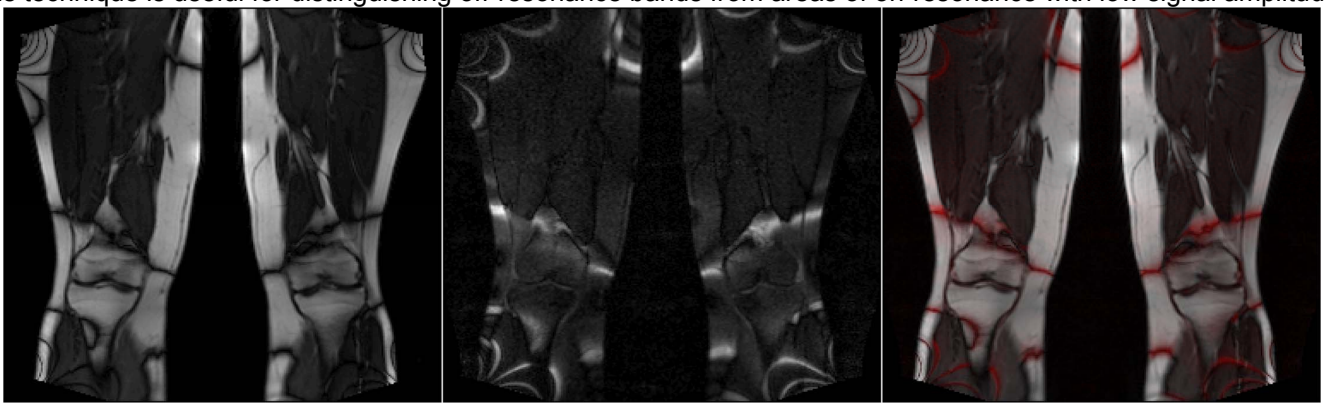

Figure 2. Balanced steady-state free precession (bSSPF) imaging in a healthy adult female. Note the presence of numerous dark banding artifacts at the location of π off-resonance per TR when using a flip angle of 60° (left). These same regions of off-resonance are very bright when bSSFP imaging is acquired using a flip angle of 1° (middle). The images can be combined (right) to highlight the off-resonance bands.

Conclusion: Low flip angle bSSFP can be used to map off-resonance bands with bright image contrast. This is useful for discriminating image features that have low bSSFP signal intensity when high flip angles are employed and regions of off-resonance.

References: 1. Oppelt A *Electromedica.* 1986;54:15-18. **2.** Carr JC *Radiology.* 2001;219(3):828-834. **3.** Scheffler K *European Radiology.* 2004;13:2409-2418. **4.** Markl M *Magn Reson Med.* 2003;50(5):892-903.