Balanced SSFP Imaging with Variable Tip Angles and Repetition Times

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Introduction: The balanced (b)SSFP response can be modified to suppress the bright fat signal, or to provide immunity against B0 inhomogeneity. Previous work mainly focused on periodic patterns of either tip angles or repetition times (TRs) [1-3]. In this work, we propose to combine variable-tips and variable-TRs. We analyze these patterns as spectrally selective RF pulses applied within a single-TR of a regular bSSFP sequence. Improved designs can significantly enhance the selectivity while allowing flexible parameter selection.

Methods: For a constant-tip excitation **θ**, the bSSFP pass-band signal (i.e., outside the null region) is $S_{pass}(\boldsymbol{\theta}) \approx M_o\sin\theta/(T_1/T_2(1-\cos\theta)+(1+\cos\theta))$, which is significantly reduced at small tip angles ($\boldsymbol{\theta} < 5^o$). Therefore, the signal can be selectively suppressed by using an RF excitation that has a frequency response $M_{xy}(f)$ to generate a frequency-dependent $\boldsymbol{\theta(f)} = \arcsin(M_{xy}(f)/M_o)$. Binomial pulses, quite immune to B1 inhomogeneity [4], are excellent candidates (Fig.1a).

Fat-suppressing ATR [1] uses a '1 -1' pulse to turn a $(0\text{-}180)^o$-cycled bSSFP pass-band into a stop-band (Fig.1b). In contrast, wideband SSFP (also '1 -1', but building upon $(0\text{-}0)^o$-cycled bSSFP) [2] yields poor suppression, partly because small **θ** does not effectively reduce the signal around the bSSFP null (0 Hz). Our simulations indicate that '1 -1' interestingly acts as a 1^{st}-order differentiator on the underlying bSSFP profile in the vicinity of 0 Hz, where no phase is accrued due to precession between the subpulses. ATR has a perfect stop-band null because the bSSFP pass-band is flat around 0 Hz. Contrarily, the large 1^{st}-order derivative of $(0\text{-}0)^o$-cycled bSSFP compromises the suppression in wideband SSFP (Fig.1b).

We propose to improve the suppression in this wider band with higher-order designs (e.g., '1 -2 1') that exploit the near-zero higher-order derivatives (Fig.1b). **1)** At 1.5 T, we can use the 2^{nd} pass-band centered at f_c = 1.5/TR Hz to image the water resonance. TR can be optimized by equating the fat-water frequency shift to f_c: TR = 6.8 ms. For 3 T, we can use the 3^{rd} pass-band (f_c = 2.5/TR) with TR = 5.7 ms. Since the broad stop-band can be off-centered, we use TR = 5.7 ms at both field strengths to avoid banding artifacts. **2)** Decreasing τ (subpulse spacing) expands θ(f) in frequency and improves the suppression, but reduces the pass-band signal. θ(f) is sufficiently high in the pass-band for τ = 0.9 ms at 1.5 T, while the increased fat-water shift at 3 T allows τ = 0.6 ms. **3)** The tip angles can be optimized by maximizing the pass-band signal for a given T_1/T_2. **4)** The pass-band can be shifted by Δf to 0 Hz with a 2π(Δf)t phase-cycling, where t is the time from the start of the period to each subpulse.

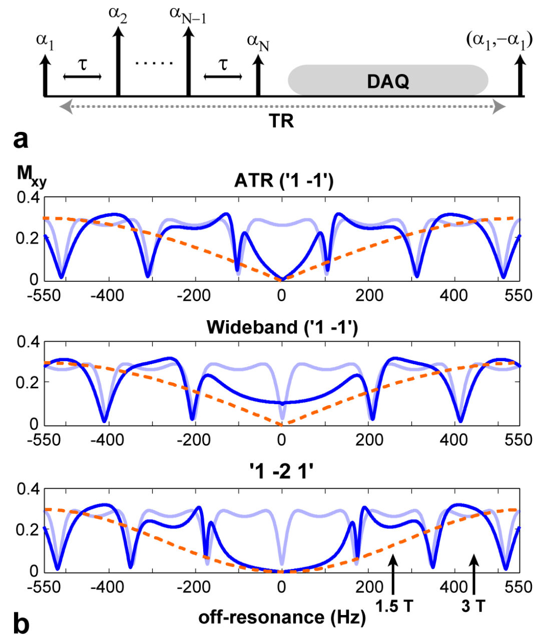

Figure 1. a: The diagram for a period (TR, i.e., the total time including all the pulses) of a binomial-pulse bSSFP sequence. **b:** The spectral responses for the FS-ATR and wideband ('1 -1') (TR = 4.9 ms), and '1 -2 1' (TR = 5.7 ms) sequences. **θ(f)** (dashed red in a.u.), the initial bSSFP spectrum assuming constant **θ** = max(**θ(f)**) (light blue), and the resulting response (blue) are displayed. The arrows mark the pass-bands used at 1.5 and 3 T.

Results: Phantom images (T_1/T_2=250/50 ms) were acquired with a linear field gradient to simulate the profiles (Fig.2). '1 -2 1' achieves a high level of suppression over a stop-band about two times wider than that of '1 -1'. '1 -3 3 -1' yields further improvements, but its prolonged TR decreases the pass-band width. 3D calf images were acquired on 1.5 and 3 T GE scanners with the following parameters: FOV=26 cm, 1 mm^3 resolution, ±62.5 kHz BW, and scan times of 1:21 ('1 -1': FS-ATR) and 1:34 ('1 -2 1'). α being the lowest-tip subpulse: $\alpha=40^o$ for '1 -1' and 20^o for '1 -2 1' at 1.5 T; $\alpha=32^o$ for'1 -1' and 16^o for '1 -2 1' at 3 T. The proposed method suppresses fat more reliably than '1 -1' (Figs.3,4).

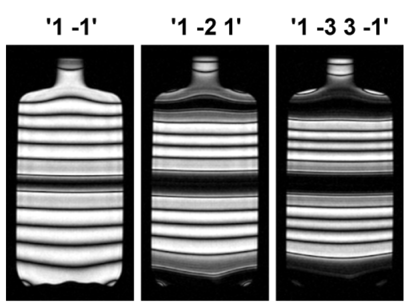

Figure 2. Phantom images with vertically varying precession frequency. '1 -2 1' and '1 -3 3 -1' significantly improve the width and suppression of the central stop-band.

Figure 3. 1.5 T: Fat-suppressed axial and sagittal slices acquired with '1 -1' (ATR) and '1 -2 1' sequences. The arrows point to regions of improved suppression with the '1 -2 1'-method.

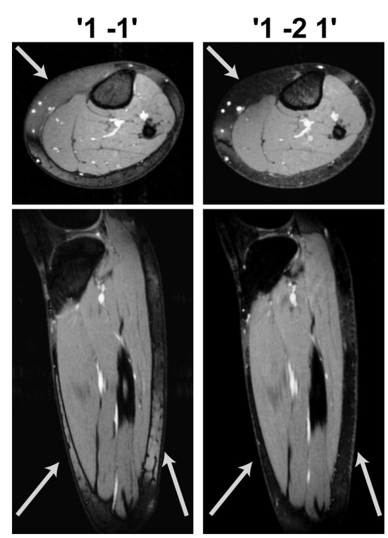

Figure 4. 3 T: Fat-suppressed axial and sagittal slices acquired with '1 -1' (ATR) and '1 -2 1' sequences. '1 -2 1' significantly improves the level level of fat suppression (arrows).

References:

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3. Hardy C, *et al.* Proc. 10th ISMRM, p.473, 2000. **4.** Hore P, *et al.* JMR 18:61, 1983.