Multiple Repetition Time Balanced SSFP for Improved Spectral Response

T. Çukur[1], and D. G. Nishimura[1]
[1]Electrical Engineering, Stanford University, Stanford, CA, United States

Introduction: Balanced SSFP (bSSFP) produces bright signal from fat which is often undesired. A group of methods, including FEMR [1] and alternating repetition time (ATR) SSFP [2], shape the bSSFP spectrum to suppress fat signal. However, the level of stop-band suppression is limited and the pass-band is narrow due to its non-uniform shape. We propose a new multiple-TR SSFP scheme that achieves robust suppression over a broad stop-band without compromising the pass-band width.

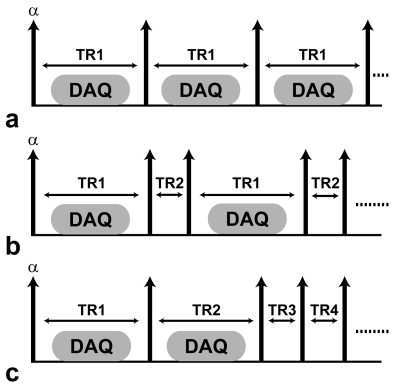

Figure 1. a: bSSFP, **b:** ATR, **c:** '1-2-2-1' sequences. Data is acquired only within the labeled intervals.

Methods: A multiple-TR (or multiple-excitation) SSFP sequence, with a period consisting of N TRs, produces a periodic spectral response. The relative TR-durations determine the coefficients of the Fourier series representation of this response, by forming a sparse sampling pattern on a fine grid -where the grid spacing is the greatest common divisor of all TRs-. ATR is a basic example to multiple-TR sequences, which increase the flexibility in shaping the spectral response.

An important special case is when all excitations have the same tip angle to avoid artifacts due to RF inhomogeneity. Flipping the sign of every other RF pulse yields a zero net excitation at the water-resonance after a period (or two periods if N is odd) and creates a pass-band. Increasing N gives more flexibility in spectral shaping, but scan efficiency considerations limit the plausible set of sequences. Within separate TRs, the magnitude profiles can be the same if there is symmetry in the periodic TR pattern. Hence, patterns with mirror symmetry and only a few TRs are excellent candidates.

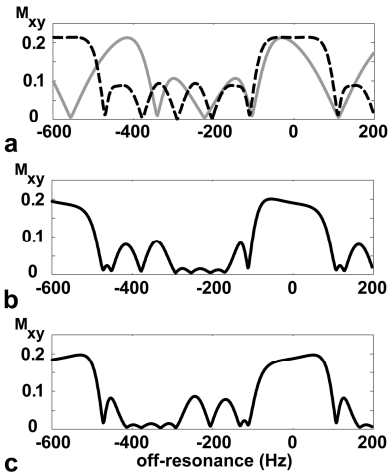

Figure 2. a: Magnetization for ATR (solid-gray) and '1-2-2-1' (dashed-black) sequences. **b:** Selective phase-cancellation can improve stop-band suppression around -220 Hz. **c:** The same cancellation can be achieved around -370 Hz.

A design based on a '1-2-2-1' relative TR pattern improves fat suppression with scan efficiency comparable to ATR. The bSSFP ('1'), ATR ('1-3') and '1-2-2-1' sequences are shown in Fig.1. Fig.2.a compares the profiles for the ATR and '1-2-2-1' sequences. $\alpha=60^o$, TR1/TR2=3.45/1.15 ms (ATR), (TR1-TR2)/(TR3-TR4)=3.45/1.725 ms ('1-2-2-1'), T1/T2=5 were assumed. Although the echoes in TR1 and TR2 have the same magnitude for the '1-2-2-1' sequence, they are used for separate acquisitions due to a non-linear phase difference increasing with off-resonance. Interestingly, this difference can be exploited to put the echoes out-of-phase over a certain frequency band, and a subsequent summation improves the stop-band (shown in Fig. 2.b for -220 Hz and 2.c for -370 Hz). A minimum-intensity projection of these two combinations can further enhance suppression, while degradation of the pass-band signal can be avoided by thresholding the mentioned phase difference.

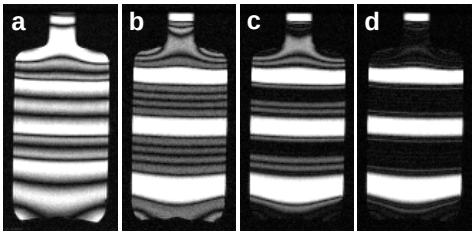

Figure 3. Phantom images were acquired with a vertical linear shim. **(a)** ATR, '1-2-2-1': **(b)** single echo, **(c)** improved for -220 Hz and **(d)** improved for both -220 and -370 Hz.

Results: Phantom images (T1/T2=250/50 ms) were acquired with a linear shim to simulate off-resonance. The '1-2-2-1' profile displayed in Fig.3 exhibits a more uniform pass-band. Both halves of the '1-2-2-1' stop-band can further be improved separately (shown for -220 Hz in Fig. 3.c) and combined (Fig. 3.d). At 3 T, the total TR can be reduced to increase the stop-band width and align the center its second half (at -370 Hz) with -440 Hz.

One potential application is SSFP-based MR angiography [3]. 3D calf images were acquired on 1.5 T and 3 T GE scanners with the following parameters: $\alpha=60^o$, FOV=26 cm (1.5 T) and 22 cm (3 T), 1 mm^3 resolution, ±125 kHz BW, NEX=2 for ATR. At 1.5 T, the TR selections were the same as before and the scan times were 2:50 ('1-2-2-1') and 2:30 (ATR). (TR1-TR2)/(TR3-TR4)=3/1.36 ms, TR1/TR2=3.38/1.12 ms and acquisition times were 2:40 and 2:46 at 3 T. The fat-suppressed images and the corresponding maximum-intensity projections (MIPs) are displayed in Figs. 4 and 5. The proposed method achieves more robust fat suppression than ATR.

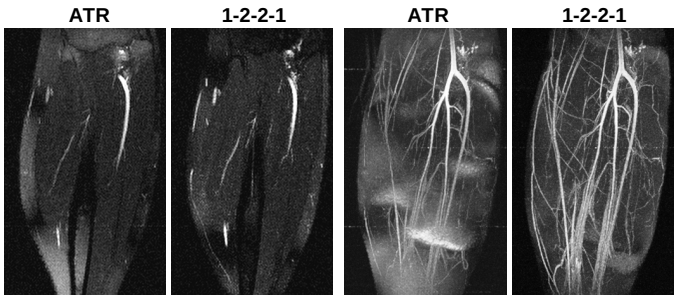

Figure 4. Coronal slices (left) and whole volume MIPs (right) for ATR and '1-2-2-1' acquisitions at 1.5 T.

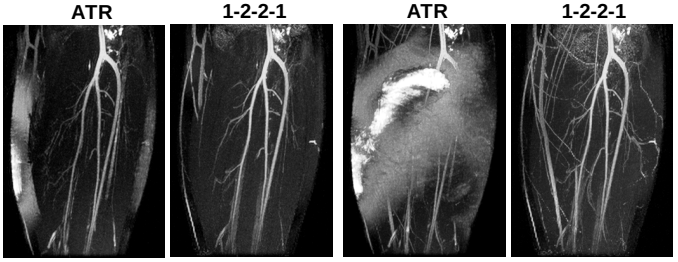

Figure 5. Thin-slab MIPs (left) and whole volume MIPs (right) for ATR and '1-2-2-1' acquisitions at 3 T.

References:
1. Vasanawala S, *et al.* MRM 42:876-83, 1999.
2. Leupold J, *et al.* MRM 55:557-65, 2006.
3. Bangerter NK, *et al.* 12th ISMRM, p.11, 2004.