Use of Simulated Annealing for the Design of Multiple TR bSSFP Sequences in Positive Contrast Imaging

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Introduction With low flip angles, the balanced steady-state free precession (bSSFP) spectral profile shows a broad minimum on resonance, and sharp off-resonance maxima. The FLAPS (Fast Low Angle balanced steady-state free Precession) method [1] exploits this to generate positive contrast with low SAR from susceptibility-induced field variations, e.g. from superparamagnetic iron oxide particles (SPIO). With FLAPS, off-resonant spins in regions near SPIOs show increased signal relative to on-resonant spins away from the SPIOs. However, the achievable positive contrast is limited because on-resonant water signals are only reduced, not eliminated, and the fat-signal also appears bright in bSSFP images. The PARTS (Positive contrast with Alternating Repetition Time SSFP) method [2] improves contrast by using alternating repetition times (ATR) [3] to create a stopband at the on-resonance water frequency. To suppress fat, a second acquisition is required, with the stopband placed over the fat resonance. In this abstract, we introduce a novel positive contrast bSSFP sequence with *simultaneous* water and fat suppression, with no need for a second acquisition. We used simulated annealing to design a 3-TR multiple repetition times (MTR) bSSFP sequence (Fig. 1) with a spectral profile having a passband over off-resonant frequencies, and stopbands over both water and fat. By requiring only one acquisition for fat and water suppression, our method has a shorter minimum acquisition time compared with PARTS.

Method We searched for an optimal parameter vector $\mathbf{x} = [\alpha_1\ \alpha_2\ \alpha_3\ \phi_2\ \phi_3\ TR_1\ TR_2\ TR_3]$, where α_n are flip angles and ϕ_n the phase of the nth RF pulse (NB $\phi_1=0$ to reduce parameter space). The SA algorithm used is described in [4]. To calculate the cost function $C(\mathbf{x})$, the spectral profile was first computed by Bloch simulation. Combinations of stopbands in the profile were evaluated. The off-resonance angle between the centers of the two stopbands being considered was scaled to the difference between fat and water frequencies. This determines TR_n, as well as the water stopband width W and fat stopband width F in Hz, defined as the full width at a fraction of the peak amplitude. The interval between the centers of the stopbands was divided into three bands, and the mean, M, of the spectral profile normalized to peak amplitude in the middle band was computed. The best stopband pair was chosen as the one with the lowest value of $p = -(g_M M + g_W W + g_F F)$ where g's are weights. To include the effect of B_1 field inhomogeneity, the cost function value was taken as the mean of p and the corresponding values, p_+ and p_-, obtained with flip angles altered by $\pm 10\%$. Thus, a low $C(\mathbf{x})$ implies high off-resonant signal, and large water and fat stopband widths over a range of flip angles.

Results The solution found was $\mathbf{x} = [6°\ 4°\ 8°\ 43.9°\ 112.9°\ 3.33ms\ 1.13ms\ 0.70ms]$. The water and fat stopbands are centred at an off-resonance shift of $1266°$ and $1526°$. This MTR sequence was compared with an ATR sequence with parameters: $\alpha_1/\alpha_2=5°/5°$, $\phi_1/\phi_2=0°/135°$, $TR_1/TR_2=3.42/1.14ms$. The spectral profiles were verified by imaging a phantom with a linear gradient shim on a 1.5T Siemens scanner, and show close agreement with calculated profiles (Fig. 2). The spectral response of the MTR sequence at the fat resonance frequency is reduced compared with ATR. The simultaneous fat and water suppression of the MTR sequence is demonstrated in Fig. 3. To evaluate dependence on B_1 inhomogeneity, Fig. 4 shows the profile of the MTR sequence with three times the original flip angle ie. $\alpha_1/\alpha_2/\alpha_3 = 18°/12°/24°$. The off-resonant central peak is broadened, and the stopbands are narrowed, but the position and amplitude of the stopband minima remains remarkably unchanged.

Discussion Multiple TR bSSFP sequences without symmetry restrictions on parameters (e.g. that flip angles in all TRs be equal) can produce surprising and useful spectral profiles. However, finding suitable MTR sequence parameters which result in a given spectral profile is difficult. Nevertheless, our results show that simulated annealing can successfully search the parameter space to find excellent solutions for positive contrast imaging with simultaneous water and fat-suppression. Unlike PARTS, this novel sequence does not require a second acquisition to suppress the fat signal. As a result, the minimum scan time is only 56% of PARTS, which requires two ATR acquisitions. Moreover, Fig. 4 suggests that the off-resonant peakwidth can be broadened by increasing the flip angle at the expense of narrowing the stopbands, thus effecting a trade-off between off-resonance visibility and robustness against B_0 field inhomogeneity. Lastly, we note that the spectral profile resembles a notch filter, and can be used in other applications, for example, chemical shift selective imaging of hyperpolarized ^{13}C [5].

References [1] Dharmakumar R *et al.* Phys Med Biol 51:4201, 2006. [2] Çukur T *et al.* MRM 63:427, 2010. [3] Leupold J *et al.* MRM 55:557-565, 2006. [4] Lee KJ. *et al.* Proc. ISMRM 2010, #2823. [5] Grant AK. *et al.* Proc. ISMRM 2010, #3514.
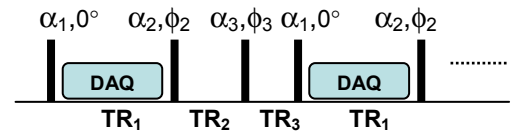
Fig 1. Schematic of the general 3-TR SSFP sequence with parameters to be optimized.
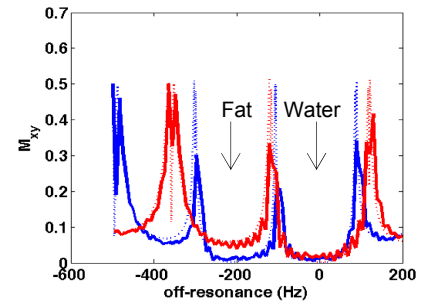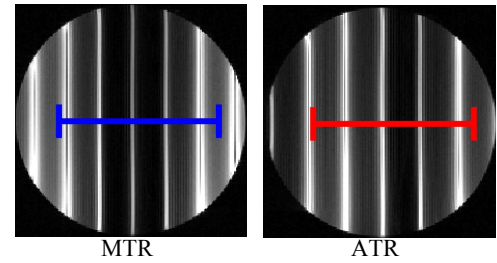

Fig 2. Above: phantom images with linear shim. MTR (blue) and ATR (red). Below: measured spectral profiles (solid); simulated profiles (dotted).
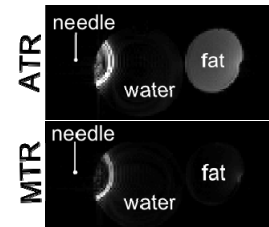

Fig 3. Field inhomogeneity was induced by a needle. Unlike the ATR image, the MTR image shows *simultaneous* water and fat suppression with bright off-resonant spins.
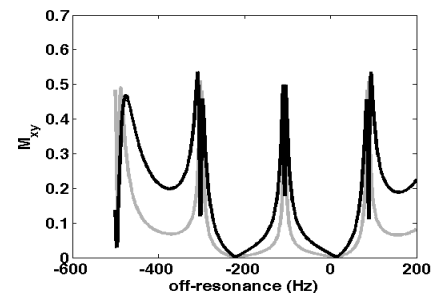

Fig 4. MTR spectrum with designed flip angles (gray) and with flip angles ×3 (black).