Spectral Profile Design for Multiple Repetition Time Balanced SSFP

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Introduction: Balanced SSFP (bSSFP) enables rapid image acquisition with high SNR but elicits an undesirable bright fat signal. Several steady-state sequence designs permit varying degrees of spectral shaping, allowing the fat signal to be suppressed by designing a stopband centered around the lipid resonant frequency [1-3]. Previous work on multiple repetition time (multi-TR) bSSFP has often relied on hand-selection and tuning of a large number of free parameters to achieve sequences with broad stopbands and uniform passbands. In general, the automatic selection of parameters for a desired spectral profile is a difficult non-convex optimization problem. In this work, we propose a method for optimizing a given multi-TR bSSFP sequence to yield an improved spectral profile, such as an increased passband-to-stopband ratio.

Methods: To optimize the spectral profile of a given steady-state sequence, a linear model of magnetization versus flip angle is constructed and used to compute the flip angles that minimize the squared error with a desired spectral profile. The reference sequence and its profile serve as an initialization point for the linearization technique. Various sets of RF flip angles are perturbed, and a linear model is constructed relating changes in flip angles to changes in spectral profile.

To create a passband at the water resonant frequency (0 Hz), the transverse magnetization must be nonzero, which requires the sequence of excitations during a single period to result in no net excitation. Neglecting relaxation, the flip angles (α_j) and RF phases (φ_j) of a multi-TR bSSFP sequence with N excitations per period should be constrained by $\alpha_1\exp(i\varphi_1)+\ldots+\alpha_N\exp(i\varphi_N)=0$. The manner in which the flip-angles are perturbed must satisfy this constraint, otherwise a sharp null can occur at 0 Hz.

This method is demonstrated on a reference multi-TR bSSFP sequence [1] with four 60° RF pulses with alternating 0°-180° phases, $TR_1=TR_2=3.45$ ms, and $TR_3=TR_4=1.725$ ms (Fig. 1). Bloch simulation shows that small perturbations of the RF flip angles result in approximately linear changes in the profile (Fig. 2). For 0°-180° phase cycling, the flip angle constraint reduces to $\alpha_1-\alpha_2+\alpha_3-\alpha_4=0$, and pairs of flip angles with opposite RF phases, i.e., (α_1,α_2), (α_3,α_4), (α_1,α_4), and (α_2,α_3), can be perturbed without violating the constraint. Least-squares analysis is used to compute the four flip angles that yield the best fit to a desired magnetization profile of 0 in the stopband (-470 Hz to -110 Hz) and a constant value in the passband (-50 Hz to 50 Hz). The optimization procedure results in a new flip angle sequence of α=(89, 114, 89, 64)°. Both sequences are simulated using T_1/T_2 = 1000/200 ms for arterial blood, and the resulting normalized profiles are shown in Fig. 3. The designed sequence has a superior passband-to-stopband ratio of 13 dB in comparison to 7 dB for the reference sequence. The improvement in stopband attenuation comes at the expense of a slightly less uniform passband and higher SAR due to increased flip angles.

Results: Spectral profiles of the reference and designed sequences were acquired by imaging a phantom with a linear gradient shim, resulting in a vertically-varying precession frequency (Fig. 4). Images were acquired on a 1.5 T GE scanner with a 24x24 cm^2 FOV, 0.9 mm in-plane resolution, 5 mm slice thickness, and a readout bandwidth of ±62.5 kHz. Profiles taken from a central cross-section of the reference and designed images are plotted in Fig. 5. Both measured profiles agree closely with the simulated profiles shown in Fig. 3. The passband-to-stopband ratio of the designed sequence is improved by 6 dB, in agreement with the simulation results. The notches in the center of the passband are the result of relaxation and other phase effects. This phenomenon is denoted "central signal dip" and is explained in greater detail in [4].

Conclusions: A method for optimizing the spectral profile of a given multi-TR bSSFP sequence has been proposed and analyzed via Bloch simulations and phantom imaging. The technique resulted in significant improvement in stopband attenuation. Future work includes investigation of a similar technique based on perturbations of TRs and RF phases.

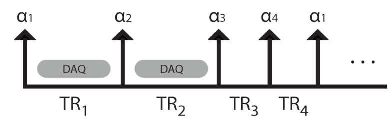

Figure 1. Diagram of one period of a 2-2-1-1 multi-TR SSFP sequence. $TR_1=TR_2=3.45$ ms, $TR_3=TR_4=1.725$ ms. RF phase = (0°,180°,0°,180°). Flip angle = (α_1, α_2, α_3, α_4).

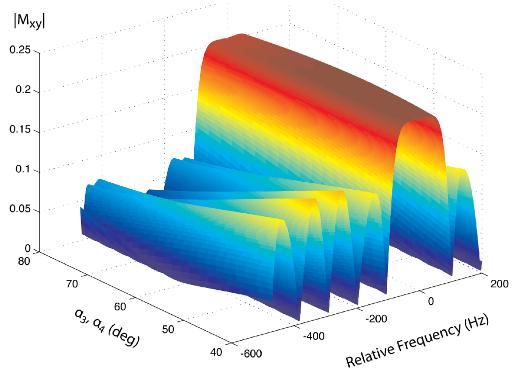

Figure 2. Simulated spectral profiles showing approximately linear change in magnetization as α_3 and α_4 are varied from 40° to 80°.

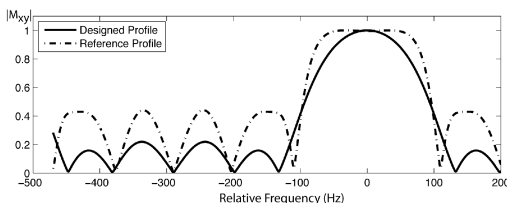

Figure 3. Normalized spectral profiles for 2-2-1-1 multiple-TR sequences. The reference profile (dashed) was obtained using four 60° excitations. The designed profile (solid) was obtained using a flip angle sequence of α=(89,114,89,64)°. Although the reference profile has slightly better passband uniformity, the designed profile has a superior passband-to-stopband ratio of 13 dB in comparison to 7 dB for the reference profile.

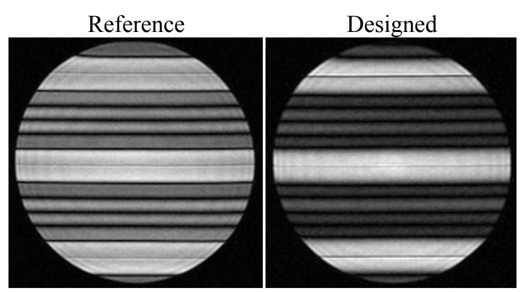

Figure 4. Phantom spectral images taken with vertically-varying gradient shim. The left image shows the spectrum of the 60° reference profile, and the right image shows the spectrum of the designed profile. The designed profile has a higher passband-to-stopband ratio (same window levels).

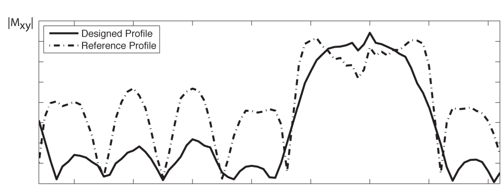

Figure 5. Cross-sectional spectral profiles taken from reference and designed spectral images in Fig. 4. The reference profile (dashed) and designed profile (solid) are in close agreement with the simulated profiles in Fig. 3.

References:
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