Design of a Spatially Varying Saturation Pulse through Least-Squares

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Target Audience: Medical physicists interested in MRI, fat saturation, excitation k-space, and RF pulse design.

Purpose: To improve breast fat saturation using spatially-varying pulses

Background: Fat saturation in breast MRI remains challenging. Spectral fat saturation is commonly used in T2-weighted (T2w) imaging of the breast as it enables a high signal-to-noise ratio (SNR) and short imaging time, but it is sensitive to field inhomogeneity[1]. In cases where inhomogeneity exists but is less than the chemical shift of fat with respect to water, the frequency transition band is reduced between fat and water, which may require a longer spectrally selective pulse for a cleaner saturation. When the inhomogeneity is greater than the chemical shift, incomplete fat saturation can be unavoidable. To improve fat saturation in the presence of field inhomogeneity, we propose to use spatially varying spectrally selective fat saturation pulses. The goal is to create a saturation pulse for each slice that bends with the field inhomogeneity to completely saturate fat within the slice without exciting water in the imaging volume. Our technique serves to relax the inhomogeneity-induced constraint of a reduced transition band suffered by spectral pulses by introducing the ability to vary spatially, thus improving the tradeoff between required magnetization and pulse length.

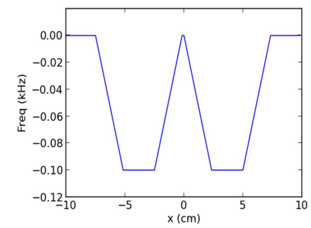

Fig. 1. Simulated field map.

Unlike previously proposed techniques that use spectral-spatial (SPSP) pulses to spatially limit the spectral excitation [2] or saturation [3], our approach only seeks to bend the spectral excitation in space, not limit its spatial extent; this creates a less constrained target for our pulse design problem. In this work, a simulation-based imaging experiment is carried out as a precursor to physical feasibility studies.

Methods: To demonstrate the capability of spatially bending the spectral saturation band to follow a B0 field map, a 1D field map was used (Fig. 1). The extent of B0 variation was chosen to be indicative of B0 variation in 1.5T breast imaging [4]. A 6 ms RF pulse was designed (Fig. 2a,b) to saturate a spectral band that spatially varied with the field map while not affecting spins 230 Hz away, targeting the frequency difference between fat and water at 1.5T. The x gradient was programmed to create a sinusoidal trajectory in excitation k-space (Fig. 2c,d) during the RF excitation. The frequency (1 kHz) of the sinusoid was chosen to enable sufficient spectral bandwidth for fat/water separation, while the amplitude was chosen to achieve a spatial resolution of 25 mm, giving sufficient freedom to spatially bend the saturation band. Note that the peak amplitude of the trajectory ($kx = 0.4\ cm^{-1}$) is significantly smaller than that required for a slice selecting SPSP pulse. The RF pulse was designed by solving the following least squares problem with Tikhonov regularization:

$$b1 = (E^H E + \delta I)^{-1} E^H m$$

where b1 is the RF pulse, E is the discrete Fourier transform operator for our kx,t trajectory, I is the identity matrix, δ is the Tikhonov regularization, and m is the desired magnetization.

Our pulse is simulated via Fourier transform over 20 cm and 1 kHz.

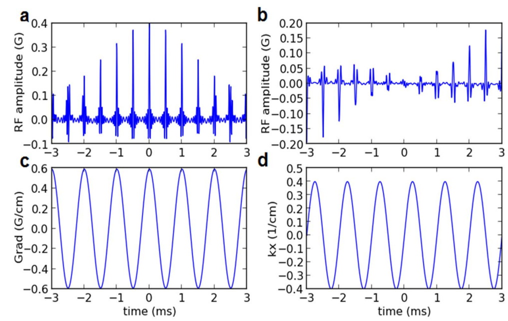

Fig. 2. (a) I-channel of optimized pulse. (b) Q-channel of optimized pulse. (c) Gradient waveform vs time. (d) Excitation k-space trajectory.

Results: The effect of the saturation pulse in (x,f)-space is shown in Fig. 3b. The simulation shows the ability of the optimized pulse to bend excitation of the saturation pulse in spectral-spatial space. All target points are within 3% of target excitation value (Fig. 4b). A spectral only selective pulse (8 ms duration) is simulated for comparison (Fig.3a); it can achieve target excitation values within 5% signal tolerance for pulses longer than 8 ms (Fig. 4a).

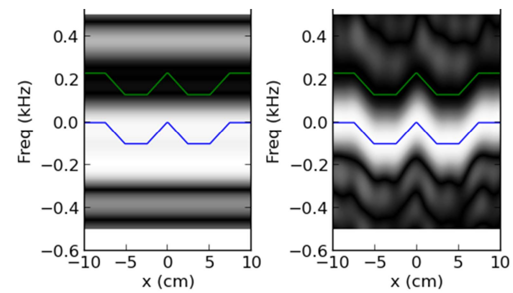

Fig. 3. (a) Target passband and stopband overlayed on simulated magnetization from spectral-selective only optimized pulse. (b) Passband and stopband overlayed on simulated magnetization from this work's spatially-varying saturating pulse.

Discussion: Our simulation demonstrates the ability to create a saturation profile that follows field inhomogeneity, resulting in better performance in less time than a spectral only pulse. A potential downside is that the proposed approach has higher SAR compared to a non-spatially selective spectral pulse. However, in lower-field breast imaging (i.e. 1.5T), we expect this issue can be effectively managed.

For the goal of application in breast fat saturation, future work includes verifying the pulse with a Bloch simulator, validating the results in phantom experiments, and increasing the spatial dimensions over which the pulse is bent/developing a method for choosing the spatial direction(s) to bend along. As our 1D pulse is very far from gradient hardware limits, we expect that bending our pulse along two or even three spatial dimensions is feasible.

Simulation results show that it is possible to design spatially-varying pulses in the presence of field inhomogeneity towards the goal of achieving robust fat saturation in breast imaging. We will aim to show in future work in vivo cases where the proposed approach is able to achieve more uniform fat suppression compared to spectral fat saturation.

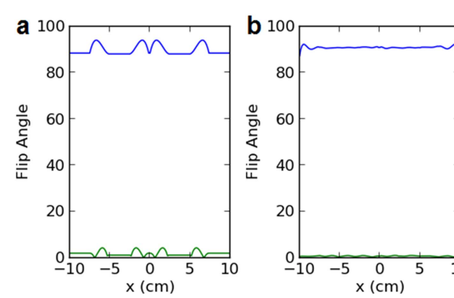

Fig. 4. (a) Flip angles along passband and stopband of spectral-selevtive only optimized pulse. (b) Flip angles along passband and stopband of this work's spatially-varying pulse

References: [1] Block W et al., Magnetic Resonance in Medicine 1997; 38(2):198-206 [2] Zur Y, Magnetic Resonance in Medicine 2000; 43:410-420 [3] Xu D et al., Magnetic Resonance in Medicine 2013; 69:825-831. [4] Jordan CD et al., J. Magnetic Reson. Imaging 2013; 37:227–232