Robust Water-Fat Separation Using Binomial Rectangular Pulses

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Introduction: Separating water and fat signal is very important for a number of MR clinical applications, such as evaluation of traumatic or degenerative cartilaginous lesions. The simplest way to do this is to use RF pulse method for selective saturation or excitation, which, however, suffer from either inefficient signal suppression due to the narrow stopbands or reduced passband signals [1]. Moreover, trade off of these methods includes longer scan time, increased SAR level and/or complicated RF pulse design. In this study, we propose using a dual rectangular pulse scheme, which features in very broad pass- and stopband and virtually complete signal nulling, for robust MR water-fat separation without increasing scan time or SAR level.

Theory: Consider the spin procession during two consecutive rectangular pulses echo with the same duration τ and B_1 field but opposite phase (Fig.1), the final magnetization can be described using the rotation matrix:

$$\mathbf{M}(2\tau, B_1, \Delta B^{'}) = R_x(-\theta)R_z(-\Omega\tau)R_x(\theta)R_x(\theta)R_z(-\Omega\tau)R_x(-\theta)M(0)$$

Where $\Delta B' = \Delta B + \Delta f/\gamma$ is the total local field variation as the sum of the field inhomogeneity ΔB and RF frequency offset Δf, θ is the angle between the B_{eff} and z-axis, and Ω is the frequency at which M precesses about B_{eff}. Simulation is performed using Matlab and the frequency response profile (FRP) of M_{xy} is shown in Fig.2a for both water and fat. In the simulated FRPs, very broad passbands and stopbands are observed, and the signals at the stopbands are virtually suppressed down to zero.

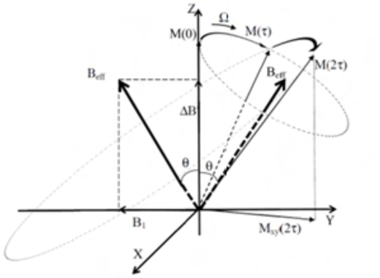

Fig.1 Illustration for Spin precession under dual-rect pulse in right handed rotating. The two sub-pulses are applied on +y and –y axis consecutively.

Experimental and Results: The MR sequence was developed on the basis of a 3D GRE by replacing the excitation pulse with the dual-rect pulses. According to simulation, τ was set to 1.28ms so that the stopband for fat (water) is located at the center of the passband of water (fat). To experimentally reveal the FRP, a three-vial phantom containing 0.2% Gadolinium doped water, 3% agar gel and vegetable oil was scanned, and images were acquired with Δf ranging from -1000 to 1000Hz. The FRP of the three samples are shown in Fig.2b. Using Δf of 340Hz or -820Hz can best suppress fat or water accordingly. For the knee scans, four healthy volunteers participated in the scans with written consent forms. 2 volunteers underwent optimization scans to determine the optimal value for Δf and τ. The other 2 volunteers then were scanned using following parameters: TR/TE = 30/4ms, FOV = 160×130mm, voxel size = 0.6×0.6×2mm^3, τ = 1.5ms, FA= 8°, Δf = 160Hz for fat suppression and -760Hz for water suppression. 3D GRE images with selective saturation or excitation pulses or without were also acquired on the phantom and the last two volunteers using identical parameters but with flip angle of 16°. The results are shown in Fig.3. All scans were done on a Siemens 3T Verio System.

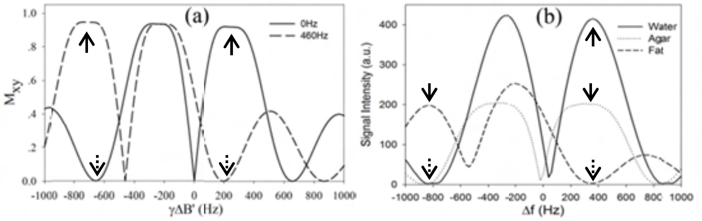

Fig.2 (a) Simulated (with Δf of 0 for water and 460Hz for fat) and (b) experimentally acquired frequency response profiles. Solid arrows indicate the passbands and dotted arrows indicate the stopbands.

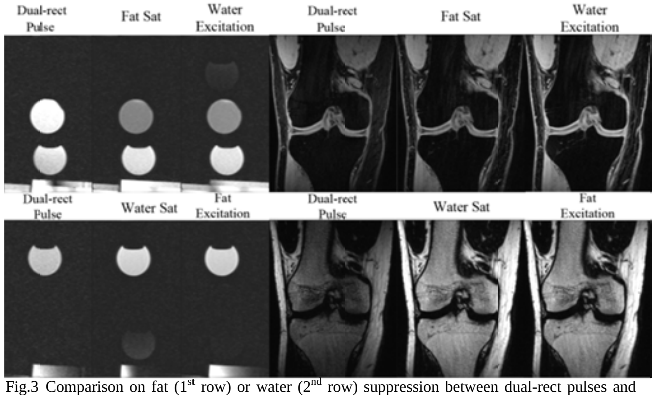

Fig.3 Comparison on fat (1st row) or water (2nd row) suppression between dual-rect pulses and saturation pulse and binomial excitation pulses. Samples in the phantom are (from top to bottom): vegetable oil, agar gel and doped water.

Discussion and conclusions: By using opposite phase dual-rect pulses, we have demonstrated a robust RF-based water-fat separation method, which offers very broad stopbands as well as very high signal suppression efficiency. In comparison to routine selective saturation or excitation methods, our dual-rect pulses is demonstrated to be more robust and efficient with best signal suppression (Fig. 3).

Intuitively, RF pulses with opposite phases will negate the tipping effects of each other, which is the case for on-resonance spins as clearly demonstrated by the central dips (Fig.2). Actually, Morrell [2] proposed a dual hard pulse scheme for fat suppression by utilizing this central dip at fat's on-resonance frequency, albeit the RF pulse they used had very short duration (160us) and high flip angle (60°). However, the bandwidth of this central dip is very narrow, and thus is susceptible to field inhomogeneities and end up with insufficient suppression. Also, it is not possible to completely suppress the fat signal with the narrow stopband because of the multi-peak signal contribution, as evidenced in fat's FRP in Fig.2b. Another important limitation was that as the water signal was 'off-resonance' relative to the RF pulses, plus that the pulse duration they used (160us) was not optimized to place water's passband center at fat's central dip, the resultant water signal was rather low (only equivalent to 13° of on-resonance excitation [2]), wasting the high RF energy used, and may raise the SAR issue for fast imaging especially at high fields. Our dual-rect pulse scheme, on the other hand, is not subject to such problems as it makes use of the much broader stopbands located further off-resonance by properly offsetting the RF frequency. The condition for forming this stopband is that the magnetization precesses about B_{eff} for exactly one round during each sub-pulse. As a result, M(τ) is returned to the z-axis immediately after both pulses and yields virtually zero signal. However, an exact 2π precession is not necessary to maintain high suppression efficiency, as a slight over- or under-precession during the first pulse will be largely compensated by the similar amount of opposite precession during the second pulse. This is the underlying mechanism for the broad stopband, ensuring the method's robustness against moderate frequency variations.

If the stopband bandwidth is defined as such that the signal intensity within is less than 3 times the noise level, then it is ~100Hz in the simulated data (assuming SNR = 100), and ~140Hz for water, ~120Hz for agar and oil in the phantom data (using the background noise mean). With such wide bandwidths, the frequency variation induced by field inhomogeneity across the whole object can fall within the stopband, offering spatially uniform suppression efficiency. Another major advantage of such broad stopband is that it's able to simultaneously suppress multiple resonance peaks in fat. At 3T, the chemical shift between the nearest two peaks located on either side of the main CH2 peak is about 150Hz, so that these two peaks, along with the main peak, can be simultaneously suppressed. The other three fatty peaks farther away, such as the olefinic fatty acid peak that's located near water's resonance frequency [3], may not be suppressed though. However, their contribution is rather small and can be considered insignificant as evidenced by the totally suppressed fat signal in Figs. 3.

In conclusion, we have demonstrated a novel opposite phase dual-rect pulse method for robust MR water-fat separation. This method offers very broad passband and stopband, which increase the robustness against field inhomogeneities and the signal suppression efficiency even for the multiple resonance peaks of fat. Since the dual-rect pulses excite water (fat) signal and suppress fat (water) signal at the same time, this method does not introduce extra scan time or RF power deposition, both are advantageous for high field fast imaging. The major issue is that due to the non-selectiveness of the rectangular pulses, this method currently only support 3D sagittal or coronal scanning with RO direction along z-axis. Future study should involve improving the RF design to enable 3D scanning with arbitrary views.

References: [1] Thomason *et al*, MRM, 1996;35(4):563 [2] Morrell, JMRI, 2006;24(5):1172 [3] Mao *et al*, MRI, 1993;11(3):385