Four-Dimensional Spectral-Spatial Pulse for Fat Saturation with Parallel Excitation: Preliminary Results on 3T Scanners

Introduction: Fat saturation techniques that use spectrally selective pulses [1] suffer from inaccurate excitation due to inhomogeneous B_0 or B_1 maps. Others have proposed to mitigate this problem with parallel excitation by tuning the center frequency of each coil to match the variation of B_0 maps [2], however in this approach, it is difficult to address complex patterns of B_0 and to insure uniform tip angle. In addition, a water selective imaging method using parallel excitation was proposed to handle the B_0/B_1 inhomogeneity problem based on weighted binomial pulses in k_z-k_f of k-space [3]. However, absence of traversing k_x-k_y may perform poorly in compensating larger transverse B_0/B_1 variations. In this work, we propose a 4D spectral-spatial (SPSP) pulse with parallel excitation to uniformly saturate fat in presence of non-uniform B_0 field and inherently compensate for B_1 inhomogeneity.

Theory: The 4D SPSP pulse is tailored to match local spectral profiles of the 3D space, i.e., 90^0 tip angles for the fat spectrum and 0 for the water spectrum in each pixel. The pulse is designed numerically by the following two steps. Shown valid for 90^0 designs in [4], a small-tip-angle (STA) design is applied to determine the pulse "shape" as the first step. In this step, the gradient waveforms are predetermined in the form of excitation k-space (k_x-k_y-k_z-k_f) where we adopt the fast k_z trajectory [5] in k_x-k_y-k_z and repeat it to cover k_f, as $k_f \triangleq t - T$ where T is the pulse length. Due to slow variation of B_0 and B_1 maps, k_x-k_y-k_z coverage can be small enough to guarantees sufficient sampling rate along k_f. Since the phase of fat is unimportant, magnitude least square optimization [6] is applied for this design. Finally, the cost function for the pulse design is $\Psi(b(t)) = \left\| P(x,y,z,f) - \left| i\gamma \sum_r S_r(x,y,z) \int b_r(t) e^{i2\pi[(x,y,z,f)\cdot\boldsymbol{k}(t)]} dt \right| \right\|_W^2 + R(b(t))$, where $P(x,y,z,f)$ is desired pattern, $S_r(x,y,z)$ is the transmit sensitivity, $b(t) = [b_1(t), \dots, b_R(t)]$ is the pulse, $\boldsymbol{k}(t)$ is the 4D k-space trajectory, $\|\cdot\|_W$ denotes the weighted L2 norm that masks out the "don't care" regions of the target pattern, and $R(\cdot)$ controls RF power and RF peak. Gaining more degrees of freedom by numerical computation of the whole pulses, the design is slower than that in [3], but we still achieve a practical design speed in 3T designs because (a) slow-varying 4D desired pattern and smooth B_0/B_1 fields require small numbers of 4D space samples and k-space samples; (b) 4D samples outside the object or water/fat bands, which usually constitute 80%~90%, are masked out in the design. This STA design produces pulses that have the right "shape" but insufficient amplitude, so a second step is needed to properly scale the pulse for fat saturation. Thus we designed a simple strategy: choose a few (<50) fat pixels that is closest to 90^0 tip angle according to STA, and use them to iteratively update the pulse amplitude according to the difference between their Bloch simulation results and 90^0 tip angle. This process is a simplified version of the additive-angle large tip design [7] but it is very efficient, e.g., it only takes a few seconds in Matlab.

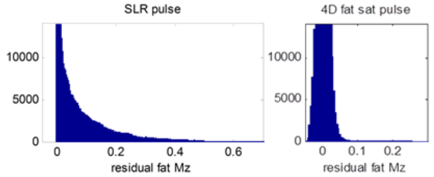

Fig.1: histgrams of the residual fat Mz of all spatial

Methods and Results: We compared the proposed method with a conventional Shinnar-Le Roux (SLR) [8] fat saturation pulse for 3T data. The SLR pulse is 5 ms with 400 Hz passband for fat. We firstly did a simulation study where the 4D fat sat pulse was designed for a multi-slice B_0 map (-140~200 Hz, 40*40*14.4 cm) in abdomen acquired by a 3T GE scanner [9] and transmit sensitivity maps of an 8-coil custom parallel excitation system. This 5 ms pulse samples 5 points in k_x-k_y during each 0.56 ms k_f sampling interval. The SLR pulse was simulated on a uniform volume coil. We simulated the residual Mz (normalized) of water and fat bands after playing the two pulses respectively for the whole object. Water and fat bands in each pixel are assumed to be Gaussian distributed peaks with 60 Hz and 80 Hz bandwidth respectively, and the residual Mz for each component is the weighted average of Mz over each band. Fig. 1 compares the results by the two pulses where the irrelevant peaks around 0 are clipped off to highlight the tails, so the proposed method produced much less residual fat Mz than the conventional SLR pulse. The result of water is not shown, as both methods produced nearly perfect results (residual water Mz: mean > 0.998, variance < $2*10^{-7}$).

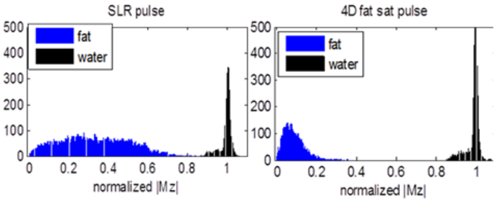

Fig. 2: histgrams of residual fat/water |Mz|

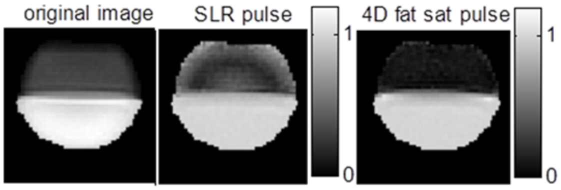

Fig. 3: left: original image; middle & right: normalized residual Mz images. Water (bottom)/oil (top).

We demonstrated the method by phantom and in-vivo data on a 3T GE scanner equipped with a single-channel head coil. In the phantom experiment, we designed a 4.8 ms 4D fat sat pulse for a 6.8 cm axial slab of a cylinder filled with distilled water ($CuSO_4$ doped) and mineral oil (B_0 map is -99~240 Hz). We implemented the standard fat saturation scheme where the fat sat pulse is followed by a 2D multi-shot spiral-out readout. To measure the residual Mz, we play each sequence twice (turn fat sat on or off) with the same parameters: TE = 6 ms, TR = 15s, 15 slices. We get the absolute value of the normalized residual Mz by |Mz| = |the fat saturated image|/|the non-fat-sat image|, which is only valid for long TR. Fig. 2 compares the results by the two pulses, where the residual fat and water Mz by the proposed method are more concentrated to the ideal values (fat is 0, water is 1). Fig. 3 shows images of one slice for comparison; clearly, we can see a better fat part by the proposed method, though the water parts look nearly the same. Furthermore, we applied the proposed method to optic nerve imaging that needs fat suppression [10]. A 5.1 ms 4D fat sat pulse was designed for a 7.6 cm axial slab around eyes of a healthy volunteer (B_0 map: -157~236 Hz). The 2D spiral-out sequence was used for imaging with parameters: TE = 6 ms, TR = 1s, 4 mm slice thickness, 24 cm FOV, 256*256 matrix size, 16 shots, 90^0 tip angle. Fig. 4 shows the performance of the proposed method, where optic nerves are successfully visualized in fat tissue.

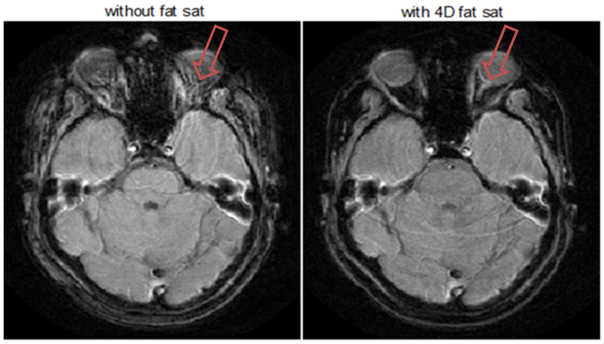

Fig. 4: a slice that contains the right optic nerve

Conclusions: By simulation studies and real experiments on 3T scanner, we demonstrated that the proposed 4D fat sat pulse design can produce improved fat suppression in presence of inhomogeneous B_0 field compared to the conventional fat sat pulse. Future investigation of the proposed method for B_1 inhomogeneity problems could be based on data from 7T scanners.

References: [1] Frahm et al., Radiology 1985: 156. [2] Heilman et al., ISMRM 2009: 251. [3] Malik et al., MRM 2010: 63. [4] Grissom et al., MRM 2006:56. [5] Yip et al., MRM, 2006: 56. [6] Setsompop et al., MRM, 2008: 59. [7] Grissom et al., MRM, 2008: 59. [8] Pauly et al., IEEE TMI, 1991: 10. [9] Data from "ISMRM Reconstruction Challenge 2010". [10] Tien, AJR, 1992: 158.

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