Simultaneous Fat Saturation and Magnetization Transfer Preparation with Steady-state Incoherent Sequences

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Introduction: Combining fat sat(uration) and magnetization transfer (MT) prep(aration) is beneficial in many clinical applications, such as cartilage imaging [1,2], cardiac imaging [3], intracranial angiography [4], breast imaging [5] and lung imaging [6]. The use of both fat sat and MT prep with steady-state incoherent (SSI) sequences, e.g., spoiled gradient echo (SPGR), may be limited by long minimal T_R. Also, the conventional fat sat is sensitive to field inhomogeneity [7]. Zhao et al. proposed to use a multi-dimensional (MD) spectral-spatial (SPSP) fat sat pulse [8] for a SSI sequence, i.e., small-tip fast recovery imaging (STFR) [15], to produce B_0 insensitive fat suppression and MT preparation simultaneously [9]. In this work, we extend this idea to SPGR and apply fat sat and MT (FSMT) prepared SPGR or STFR to two clinical applications, i.e., cartilage imaging and MR angiography in brain, at 3T.

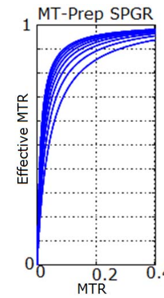

Fig. 1: Effective MTR vs MTR

Theory: When fat sat is applied to every repetition of SPGR, the conventional RF spoiling scheme, which applies quadratic RF phase variation over repetitions, guarantees the signals reach steady state only when fat is perfectly suppressed. However, this is rarely the case in practice due to B_0/B_1 inhomogeneity, so fat spins can be excited by both the excitation pulse and the fat sat pulse. The crusher in fat sat can then alter the fat signals' progression to steady state. Therefore, to guarantee that SPGR with fat sat reaches steady state, we need to use the adapted RF spoiling proposed in [10], which applies linear phase increment to "every part before a crusher" instead of every repetition.

Suppose MT ratio (MTR) is defined as the ratio between the reduced magnetization caused by MT and the original magnetization, then the steady-state longitudinal magnetization of MT-prep SPGR prior to each excitation pulse is: $M_z(r) = M_0 \frac{(1-r)E_{1s}(1-E_{1d})+(1-E_{1s})}{1-(1-r)E_{1s}E_{1d}\cos\alpha}$, where r is MTR, M_0 is equilibrium magnetization, $E_{1s} \triangleq e^{-T_s/T_1}$, $E_{1d} \triangleq e^{-T_d/T_1}$, T_s is the duration of each gradient crusher, T_d is the duration of each repetition excluding the MT prep, α is the flip angle, and relaxation during the MT pulse is ignored. Fig. 1 shows the plot of the function $1 - M_z(r)/M_z(0)$, defined as "effective MTR", for a MT prep SPGR with parameters: T_d = 10 ms, T_s = 1 ms, 0.5 s $\le T_1 \le$ 2s, 50 ms $\le T_2 \le$ 200 ms, and it demonstrates that this sequence is highly sensitive to magnetization changes due to MT, which is similar to the results in [9]. The MD SPSP fat sat is very efficient and addresses the spectral and spatial variations by traversing the excitation k-space very rapidly, so it typically produces much higher RF energy than the conventional fat sat pulse [8]. It can also mitigate the field inhomogeneity problem with fat sat. Therefore, we predict using the MD fat sat with SPGR can potentially produce B_0 insensitive fat suppression and sufficient MT contrast simultaneously.

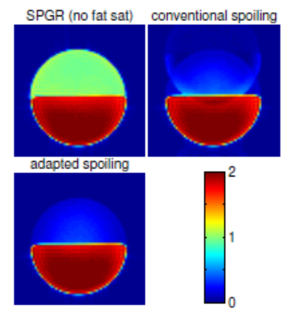

Fig. 2: An axial slice of the 3D SPGR images of the cylindrical phantom (oil on top of water). The images are at the same color scale.

Methods and Results: First, we performed a phantom experiment on a 3T GE scanner to demonstrate the necessity of the adapted RF spoiling scheme. We used a cylindrical phantom filled with distilled water and vegetable oil, and applied a conventional Shinnar-Le Roux (SLR) [11] fat sat pulse. With this fat sat pulse, a 3D SPGR with spin-warp readout was applied using the conventional and the adapted RF spoiling schemes respectively, and the imaging parameters were: T_R = 13 ms, FOV = 14 cm × 14 cm × 14 cm. Fig. 2 shows that the image with the conventional RF spoiling has ghosting artifacts due to data inconsistency, while the image with the adapted RF spoiling is free of such artifacts, which shows that the proposed sequence can reach steady state.

We then investigated the FSMT prep SSI sequence in the application of cartilage imaging where contrast between synovial fluid and cartilage is desired. Fat suppression is generally beneficial because it can eliminate the surrounding fat that would obscure the tissue of interest [12, 13]. MT-prep is useful for T_2 weighted [14] or T_2/T_1 weighted cartilage imaging [12], where synovial fluid appears brighter than cartilage, so MT-prep can enhance the fluid-cartilage contrast by attenuating cartilage signals. Thus, we applied the FSMT-STFR proposed in [9] which produces T_2/T_1-like contrast [15]. The experiment was carried out on human knees at 3T. The 3D fat sat pulse was 2.1 ms long, and imaging parameters were: T_R = 18.5 ms, flip angle = 16^0, 1.09 mm× 1.09 mm resolution. Fig 3. shows that fat suppression removed the fat tissue surrounding the cartilage and joint fluid areas as well as the posterior parts. In particular, the 3D fat sat worked very well in regions with large B_0 inhomogeneity, such as the posterior fat regions. In addition, MT effects suppressed cartilage and muscle signals, and thus highlighted the synovial fluid signals indicated by the red arrows.

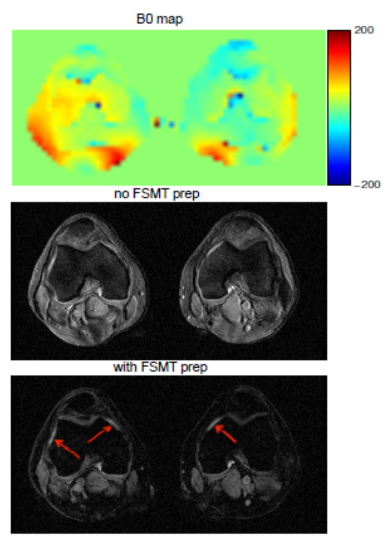

Fig. 3: The resulting images of the cartilage imaging and the corresponding B_0 map (top, in Hz). These bottom two images are in the same gray scale.

Furthermore, we applied the proposed FSMT-SPGR to MR angiography (MRA) in human cerebral arteries where fat suppression and MT can help suppress surrounding fat and other background tissue, respectively. We acquired 3D time-of-flight (TOF) images at a 4 cm thick axial slab around the circle of Willis with a 3D SPGR sequence. In addition, a 2.5 ms 4D fat sat pulse was designed based on the 3D B_0 map. The imaging parameters are: T_R = 11.4 ms, flip angle = 20^0, 0.94 mm× 0.94 mm resolution. Fig. 4 shows maximum intensity projections (MIP) of the image with no FSMT prep (left) and the one with FSMT prep (right). The 4D fat sat largely suppressed the fat tissue around skull, except that part of fat around the left optical nerve is not suppressed well due to large off-resonance (about 300 Hz). Furthermore, MT effects produced by the 4D fat sat pulse largely reduced the background signals, and the arteries are better delineated compared to the one without FSMT prep.

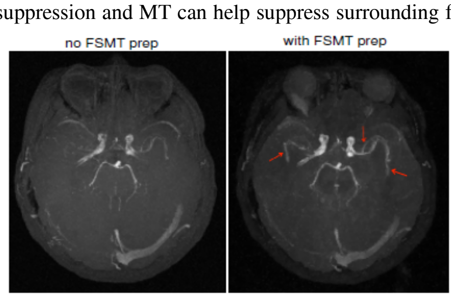

Fig. 4: The MIP of the resulting images of the MRA experiments. (The images are in the same gray scale)

Conclusions: We have demonstrated that with the efficient ($\le$ 2.5 ms) MD fat sat pulses and the adapted RF spoiling, the proposed SSI sequences can robustly produce B_0 insensitive fat suppressed and MT contrast images at 3T.

References: [1] Flame et al., MRM 1992: 26. [2] Wolf et al., Radiology 1991: 179. [3] Li et al., Radiology 1993: 187. [4] Ozsarlak et al., Neuroradiology 2004: 46. [5] Santyr et al., JMRI 1996: 6. [6] Jakob et al., MAGMA, 2002: 15. [7] Frahm et al., Radiology 1985: 156. [8] Zhao et al., Proc. ISMRM 2012: 636. [9] Zhao et al., Proc. ISMRM 2013: 2507. [10] Zhao et al., Proc. ISMRM 2013: 252. [11] Pauly et al., IEEE TMI, 1991: 10. [12] Gold et al., Radiology 2006: 240. [13] Disler et al., AJR 1995: 165. [14] Lang et al., Radiologic Clinics of North America 2005: 43. [15] Nielsen et al., MRM 2012: 69. **Acknowledgements**: This work is supported by NIH Grants R01NS58576 and R21EB012674.