Single-Shot Fast Spin Echo of Targeted Regions with Variable Refocusing Flip Angles and Quadratic Phase Pulses for Outer Volume Suppression

Valentina Taviani[1], Daniel Litwiller[2], Andreas M. Loening[1], Manojkumar Saranathan[1], Brian A. Hargreaves[1], and Shreyas S. Vasanawala[1]
[1]Radiology, Stanford University, Stanford, CA, United States, [2]GE Healthcare, Rochester, MN, United States

Target audience: Scientists and clinicians with an interest in body imaging.

Purpose: Fast spin echo imaging is a core component of abdominal and pelvic protocols, despite the long acquisition times and inherent motion sensitivity. Single-shot Fast Spin Echo (SSFSE) is fast and robust to motion, although the long echo train translates into high SAR (Specific Absorption Rate) and blurring due to T2 decay. The use of variable refocusing flip angles (VFA) allows faster imaging by reducing SAR [1], and decreases blurring by stabilizing signal levels along the echo train and by enabling full-Fourier (vs. half-Fourier) acquisition while retaining the desired T2 contrast. However, T2 relaxation ultimately dictates the maximum resolution achievable with single shot techniques. Quadratic phase Outer Volume Suppression (OVS) pulses have been used for cardiac SSFSE [2] and spectroscopic imaging in the brain and prostate [3]. While the quadratic phase modulation produces a uniform energy distribution, reducing the peak RF amplitude, OVS usually involves increased SAR levels. We developed a motion-robust T2-weighted imaging technique that achieves high scanning efficiency and minimal blurring by integrating both OVS with quadratic phase pulses and VFA into an SSFSE pulse sequence. The resulting method is termed reduced-FOV (r-FOV) SSFSE.

Methods: An OVS preparation [2] was added to a VFA SSFSE pulse sequence. The quadratic phase modulation was obtained by prescribing an almost linear frequency sweep across the pulse duration. A 6kHz bandwidth, with a pulse width of 2ms and peak B1 of 0.24G, gave stopband attenuation of about 30. Six saturation pulses, 3 for each side of the prescribed FOV, were applied to improve robustness to B1 and transmit gain errors, as well as to provide T1-insensitive saturation. Spoiler gradients were played on all 3 axes to prevent stimulated echoes and other undesired coherence pathways originating from the saturation train from contributing signal during the SSFSE readout [2]. The extent and positioning of the resulting saturation bands were automatically calculated to follow the prescribed FOV, with a user option to independently set the thickness of the saturated region for each side of the FOV. The use of inner volume (IV) in combination with OVS to reduce misregistration due to chemical shift was investigated. When required by the specific application, the saturation train was played during the time delay between an Adiabatic SPectrally-selective Inversion Recovery (ASPIR) pulse and the start of the SSFSE readout to ensure fat suppression without degrading OVS performance due to T1 recovery. The SSFSE echo train flip angle schedule was controlled by prescribing initial, minimum and final flip angles as well as the flip angle for the center of k-space [4]. Imaging was performed at 3T (GE MR750, GE Healthcare, Waukesha, WI) using multi-channel receive-only array coils, 2x ARC (Autocalibrated Reconstruction for Cartesian imaging, [5]) and full Fourier encoding (NEX) after informed consent.

Results and Discussion: The effect of OVS using quadratic phase pulses and conventional 3kHz SLR pulses in a water/fat phantom is shown in Fig. 1a and b, respectively. Due to the chemical shift of fat, the effective saturated areas for water and fat are misregistered with respect to each other (arrows), causing residual fat fold-over with r-FOV imaging (Fig. 1c). The extent of misregistration is proportional to the thickness of the saturation band and inversely proportional to the RF bandwidth. Due to the large saturation thicknesses required for body imaging, misregistration between fat and water can be significant. A slanted IV excitation is obtained by rotating the SSFSE excitation with respect to the refocusing train. While saturation bands are still necessary to saturate the tails of the IV, their thickness can be reduced, resulting in decreased fat fold-over. However, to avoid cross-talk and saturation effects during multi-slice imaging, the angle between the excitation and the refocusing train was found to be much lower than 90° (15° tilt), thus reducing the advantage of this technique (Fig. 1d) with respect to OVS alone (Fig. 1c). In addition, when compared with full FOV (Fig. 1e), IV+OVS (Fig. 1d) was found to blunt the T2 contrast, due to residual cross-talk and saturation. This effect was most noticeable *in vivo* (Fig. 2). Fig. 1f and 1g illustrate the effect of shifting one of the 2 saturation bands *inside* the FOV to compensate for the chemical shift of fat when OVS alone was used. All r-FOV images shown in Fig. 3-5 were obtained in patients using this technique and OVS alone, which was found to preserve T2 contrast while removing residual fat fold-over at the expense of a slightly reduced on-resonance FOV. Reduced blurring and improved anatomical delineation in the r-FOV images was evident by comparison with the corresponding full FOV images (cropped to the smaller FOV). The minimum TR of full and r-FOV SSFSE was similar (~500-700ms), resulting in similar scanning efficiency.

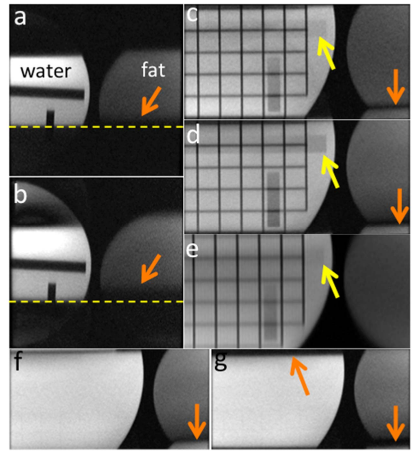

Figure 1: OVS using quadratic phase (a) and SLR pulses (b). IV + OVS (d) offers little advantage over OVS alone (c) to remove residual fat fold-over (orange arrows). Shifting one saturation band inside the FOV (g) removes this artifact at the expense of a reduced on-resonance FOV (cfr. f-g). IV+OVS had a slightly different contrast than full FOV due to saturation (e; yellow arrow).

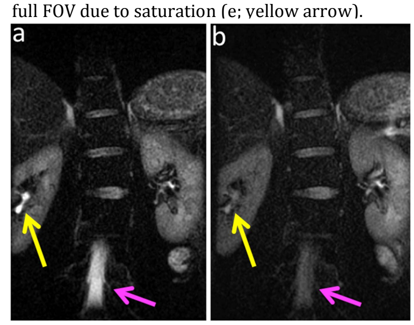

Figure 2: T2 contrast (TE = 100ms) with OVS alone (a) and IV + OVS (b). Note the brighter CSF and collecting system when OVS alone was used. Images were not cropped.

Conclusion: We have shown feasibility of r-FOV SSFSE using OVS with quadratic phase pulses and VFA to offset the increased SAR levels. High-resolution abdominal and pelvic images of targeted regions with minimal blurring and free from motion artifacts were demonstrated in patients. The use of IV in conjunction with OVS only marginally reduced misregistration due to chemical shift with the side effect of blunting the T2-contrast. The use of higher bandwidth pulses for OVS could further reduce the misregistration artifact between fat and water typically found in body imaging.

References: [1] Busse R.F. et al. MRM 2006; 55:1030; [2] Le Roux P. et al. JMRI 1998; 8:1022; p. 2775; [3] Tran T.K.C. et al. MRM 2000; 43:23; [4] Saranathan M. et al. ISMRM 2014; p.2175; [5] Brau A.C. et al. MRM 2008; 59:382.

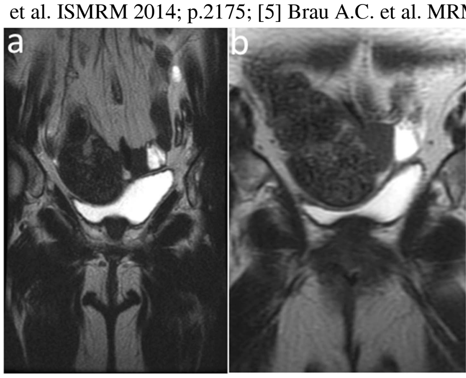

Figure 3: (a) Coronal r-FOV (24x17cm² FOV; 0.7x1.2x4mm³ res; TE=150ms, non-cropped) and (b) coronal (oblique, cropped) full FOV SSFSE (42cm² FOV; 1x1.9x4mm³ res; TE=140ms). fa_{min}=70°, fa_{cen}=100° for both. Note better delineation of the bladder wall in (a).

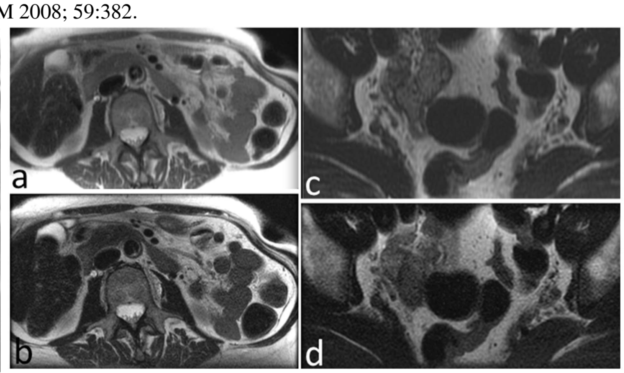

Figure 4 (above): (a) Breath-held axial full-FOV (1x1.4x4mm³ res, cropped) and (b) r-FOV SSFSE (0.7x0.9x4mm³ res, non-cropped). (c) Axial full-FOV (1x2x5mm³ res, cropped) and (d) r-FOV SSFSE (1x1x5mm³ res, non cropped)

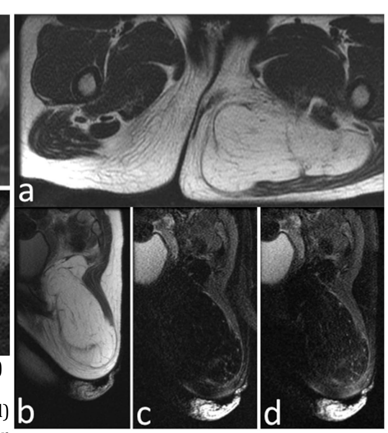

Figure 5 (right): Axial (a) and Sag. (b-d) r-FOV SSFSE of a lipoma in a 5-year-old. Note OVS failure OVS is played before ASPIR (c).