Tailored Saturation Pulses for Abdominal Imaging at 3 Tesla

H. H. Hu[1], K. Sung[2], and K. S. Nayak[1]

[1]Ming Hsieh Department of Electrical Engineering, University of Southern California, Los Angeles, CA, United States, [2]Department of Radiology, Stanford University, Stanford, CA, United States

Introduction – The preparation of longitudinal magnetization using saturation pulses is necessary in many abdominal applications, such as dynamic contrast enhanced imaging [1], arterial spin labeling [2], and RF transmit ($B1^+$) mapping [3]. At 3T, B0 and $B1^+$ variations are substantial across the abdomen and require careful consideration during the RF pulse design. A recent work demonstrated in cardiac imaging at 3T that tailored RF hard-pulse trains (with varying sub-pulse areas) provided better saturation performance than both constant-area 90° hard-pulse trains and adiabatic BIR-4 approaches, while keeping SAR relatively low [4]. In this work, the tailored saturation **(TSAT)** approach is extended to 3T abdominal imaging. Due to increased dielectric resonance and susceptibility effects, B0 and $B1^+$ variations across the abdomen are larger than those previously experienced in the heart. In simulations and *in vivo*, we demonstrate greater immunity to B0 and $B1^+$ variations and more robust saturation performance with TSAT (n=3-5 sub-pulses) than widely used constant-area 90° pulse trains and 8-ms BIR-4 pulses.

Methods and Results – Fig. 1a shows a B0-$B1^+$ scatter plot from an abdominal slice of a healthy volunteer. Similar plots were obtained in ten volunteers on separate occasions. $B1^+$ was estimated from a n=3 90° pulse train SDAM scan by dividing the actual by the nominal (prescribed) flip angles. Note two distributions of data points (red arrows), one near 0 Hz for water spins and one near -440 Hz for fat spins at 3T. $B1^+$ variations equally affect both distributions. Fig. 1a was used to guide the design of TSAT pulse trains. Bloch simulations were performed over (i) a 1-kHz range centered about -220 Hz, which is one-half of the fat-to-water chemical shift at 3T (Fig. 1a horizontal axis), and (ii) a more conservative $B1^+$ range of 0.5-1.4 (Fig. 1 vertical axis). We refer to this as the "*B0-$B1^+$ footprint*" (red contour, Fig. 1a). A slightly larger $B1^+$ range was chosen to account for errors from the n=3 90° pulse train SDAM data due to possible insufficient saturation. An exhaustive search was used to determine TSAT weights $\{\alpha_1 \ldots \alpha_n\}$ that minimized the mean residual Mz/Mo distribution over the footprint. The search range was from 60° to 300° in 1° (n=3) and 5° (n=4-5) increments. Fig. 1b-d compares simulations of the residual Mz/Mo distribution over the footprint for three select saturation schemes. The BIR-4 pulse (Fig. 1b) has excellent saturation for on-resonance spins and is quite insensitive to $B1^+$ scaling. However, saturation performance is weaker for off-resonance spins, especially at low $B1^+$ scales. TSAT (n=5) (Fig. 1d) is more immune to low and high $B1^+$ scales compared to 90° pulse train (n=3) (Fig. 1c). Table 1 lists the mean, standard deviation, and maximum of residual magnetization over the footprint for all seven approaches considered. Performance improves with longer pulse trains for both 90° and TSAT cases. For a fixed n, TSAT provides improved overall saturation than 90° pulse trains. Table 2 lists the TSAT weights used.

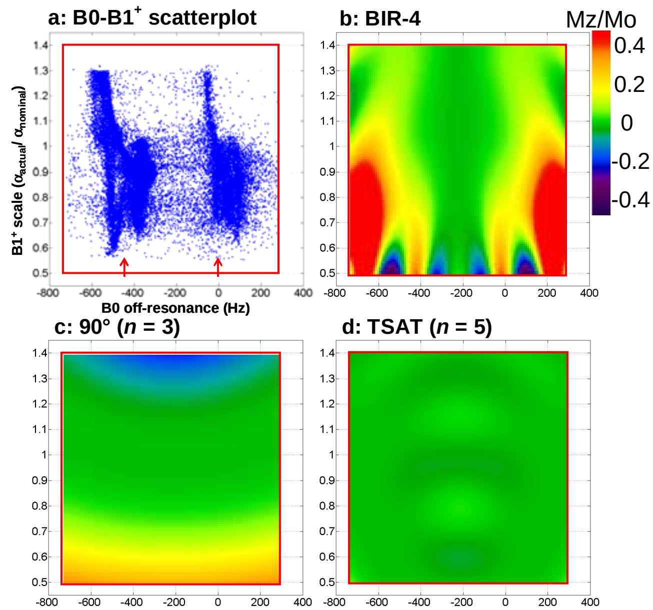

Fig. 1: (a) B0-B1+ scatter plot from an axial abdominal slice in one volunteer. Vertical B1+ scale; horizontal frequency offset. Note two data distributions (arrows), one near water spins (0 Hz) and one near fat spins (-440 Hz chemical shift at 3T). Red contour highlights target saturation footprint. Simulation of residual Mz/Mo for **(b)** 8-ms BIR-4 pulse, **(c)** 90° hard-pulse train (n = 3), and **(d)** TSAT (n = 5) hard-pulse train.

saturation scheme	(Mz/Mo) mean ± (SD)	(Mz/Mo) max
BIR-4	0.17 ± 0.24	0.93
90° (n=3)	0.046 ± 0.12	0.41
90° (n=4)	0.042 ± 0.06	0.30
90° (n=5)	0.018 ± 0.05	0.22
TSAT (n=3)	0.016 ± 0.07	0.27
TSAT (n=4)	0.011 ± 0.04	0.18
TSAT (n=5)	-0.001 ± 0.012	0.06

◀**Table 1:** Mean and maximum residual magnetization from simulation.

TSAT (n=3)	97°-188°-213°
TSAT (n=4)	90°-200°-225-125°
TSAT (n=5)	130°-300°-85-190°-215°

▲**Table 2:** TSAT weights.

▪ ***In Vivo Study*** – Saturation performance was evaluated in five subjects with a saturation-no-recovery 2DFT GRE sequence using centric view-order [4]. Acquisition time was 104 ms / saturation scheme with FOV=40 cm, a 5-mm slice, and 64×64 sampling matrix. All experiments were performed with an eight-element array on a 3T GE scanner. All saturation pulses had a center frequency that was shifted -220 Hz relative to that of ^1H in water. This centers the saturation profiles half-way between the two data distributions in Fig. 1a. Fig. 2 illustrates results from one volunteer, and the same color map from Fig. 1 is used. In the anterior and posterior aspects of the abdomen where $B1^+$ non-uniformity is expected in the anatomic image, 90° pulse train and BIR-4 approaches are inadequate at suppressing the local magnetization (dashed regions). Much more uniform saturation is achieved with TSAT. The mean Mz/Mo over the abdomen for n=4 (0.009±0.017) and n=5 (0.008±0.013) is comparable.

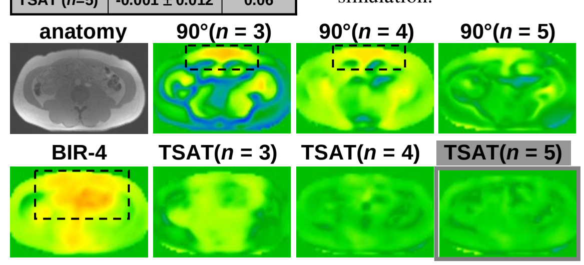

Fig. 2: *In vivo* measurement of residual Mz/Mo in the abdomen. TSAT n = 4 and n = 5 schemes exhibit the most uniform saturation in fat, and in areas of known $B1^+$ variations (dashed).

Discussion – We have demonstrated a TSAT scheme that achieves near-perfect magnetization saturation across the abdomen at 3T. Simulations (not shown) suggest that the mean residual Mz/Mo for these pulses rises slightly from 0.015 to 0.025 for T1 as low as 50 ms, indicating robust saturation performance over a wide range of physiological T1, including fat. It would have been similarly possible to tailor the BIR-4 pulses based on the B0-$B1^+$ footprint, although RF energy deposition would be an additional constraint. For certain applications such as arterial spin labeling and perfusion imaging, minimizing the *maximum* Mz/Mo value may be more advantageous and is a straightforward adaptation of our approach. Thus, the proposed TSAT method is promising and will be useful in many quantitative abdominal applications [5, 6].

References – **[1]** Low RN, et al. *JMRI* 28:946-956, 2008. **[2]** Martirosian P, et al. *MRM* 51:353-361, 2004. **[3]** Cunningham CH, et al. *MRM* 55:1326-1333, 2006. **[4]** Sung K, et al. *MRM* 60:997-1002, 2008. **[5]** Merwa R, et al. ISMRM 2008, 3092. **[6]** Hu HH, et al. ISMRM 2008, 3794.