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Tradeoff between fat-suppression and partial-voluming in weighted combination alternating repetition-time (ATR) balanced SSFP

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Purpose/Introduction

Balanced steady-state free precession (SSFP) imaging yields high SNR efficiency within short scan times. Yet, the undesired fat signal is a major problem. Linear combination SSFP (LCSSFP) was proposed as a multi-acquisition solution to this problem that shapes the spectral response to selectively suppress the fat resonance[1]. The stringent limitations on TR in LCSSFP were later relaxed by a linear combination of multiple alternating repetition-time (ATR) SSFP acquisitions. However, in both cases, the linear combination yields inhomogeneous level of signal suppression within the stop-band. Here, we adopt nonlinear *p*-norm combinations of multiple ATR-SSFP data to improve fat-suppression efficiency[2]. Note that nonlinear combinations are susceptible to partial-volume effects. To examine this potential issue, we provide a quantitative analysis of the tradeoff between fat-suppression and partial-voluming for a comprehensive set of tissue relaxation times and imaging parameters. We propose a guideline to select the optimal *p*-norm to yield desired level of fat-suppression while limiting partial-voluming artifacts.

Subjects and Methods

The in-phase and out-of-phase ATR-SSFP profiles have 180° phase difference at the water resonance. Hence, weighted combination of the in-phase (X_I) and out-of-phase (X_O) signals would yield the water-only (D_w) and fat-only (D_f) signals[3]

$D_w=(|X_I|^p X_I+i|X_O|^p X_O)^{1/1+p}$

$D_f=(|X_I|^p X_I-i|X_O|^p X_O)^{1/1+p}$

where $p \in (-1,0]$. We quantified a fat-suppression index (FS) as the mean ratio of the pass-band ([−80,80] Hz) in the water signal to the mean ratio of it in the fat signal. Linear combination of the phase-cycled datasets (p=0) yields partial-voluming-free reconstruction. Thus, we quantified the level of partial voluming (PV) in terms of deviation from the ideal case of linear combination. We then calculated p that yields specific FS and PV and analyzed its dependence on tissue properties and imaging parameters using a simulated phantom.

Results

Figure 1 shows reconstructions of phantom acquisitions using different *p* and dependence of FS and PV on *p*. Fat signal gets more suppressed as *p*→-1 at the cost of higher partial-voluming. This assessment is supported by in vivo reconstructions of Figure 2. Figure 3 shows calculated *p* using different FS and PV. Optimal *p* depends on α and T1/T2 but has little dependence on imaging resolution and SNR.

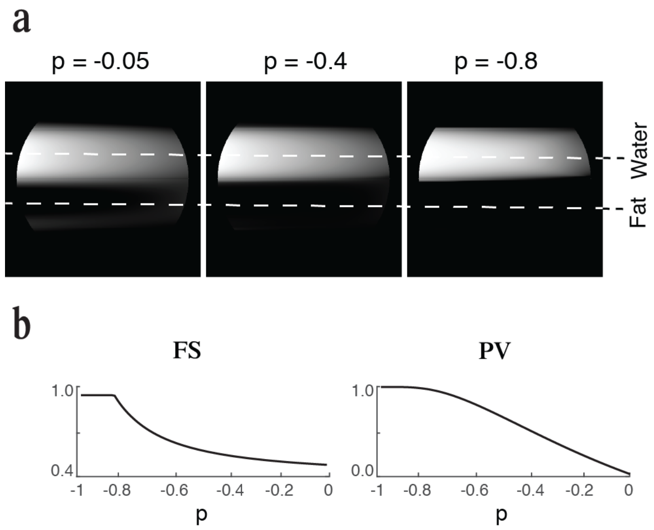


Figure 1. Fat-suppressed reconstructions for the simulated phantom. Phase-cycled ATR-SSFP acquisitions were simulated for a circular phantom for α=45, TR1/TR2/TE = 3.45/1.15/1.7ms, T1/T2 for water = 1000/100ms, T1/T2 for fat= 270/85ms. Ratio of water in voxels varies between 0 to 1 from right to left. Off-resonance varies in [-380,380]Hz from bottom to top. **(a)** Fat-suppressed reconstructions using various *p* show enhanced fat-suppression at the cost of increased partial-voluming as *p* approaches to -1. **(b)** Fat-suppression index (FS) and partial-voluming index (PV) calculated using the simulated phantom. Both FS and PV increase as *p* approaches to -1.

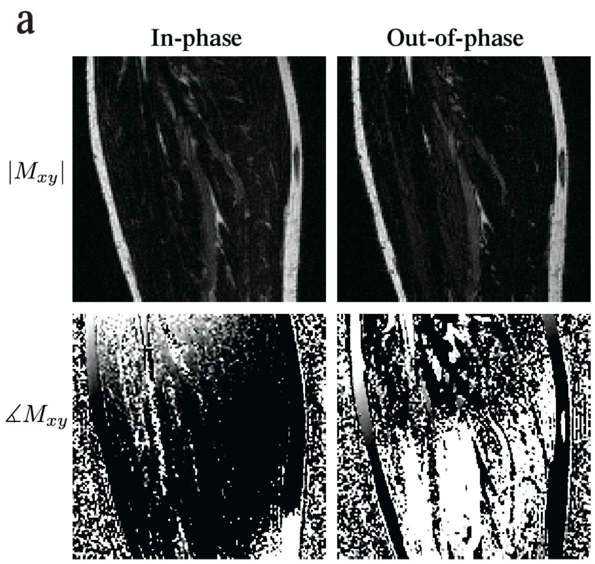
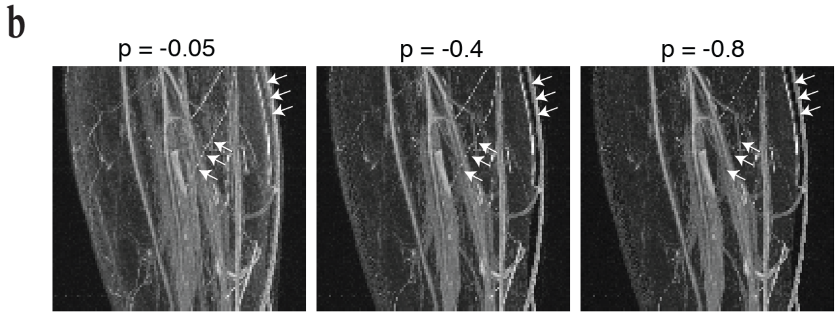


Figure 2. Fat-suppressed reconstructions for the in vivo calf. Phase-cycled acquisitions were performed using a 3D ATR-SSFP sequence with α =60, TR1/TR2/TE = 3.45/1.15/1.7ms, 1mm isotropic resolution. **(a)** Magnitude and phase of in-phase and out-of-phase images of the central coronal slice. **(b)** Fat-suppressed maximum-intensity projection (MIP) reconstructions using various *p*. Fat-suppression enhances as *p* approaches to -1 which is reflected as better suppression of the background fat tissue. Partial-voluming also increases as *p* approaches to -1. This is apparent as degraded depiction of vessels having sub-voxel dimensions (white arrows).



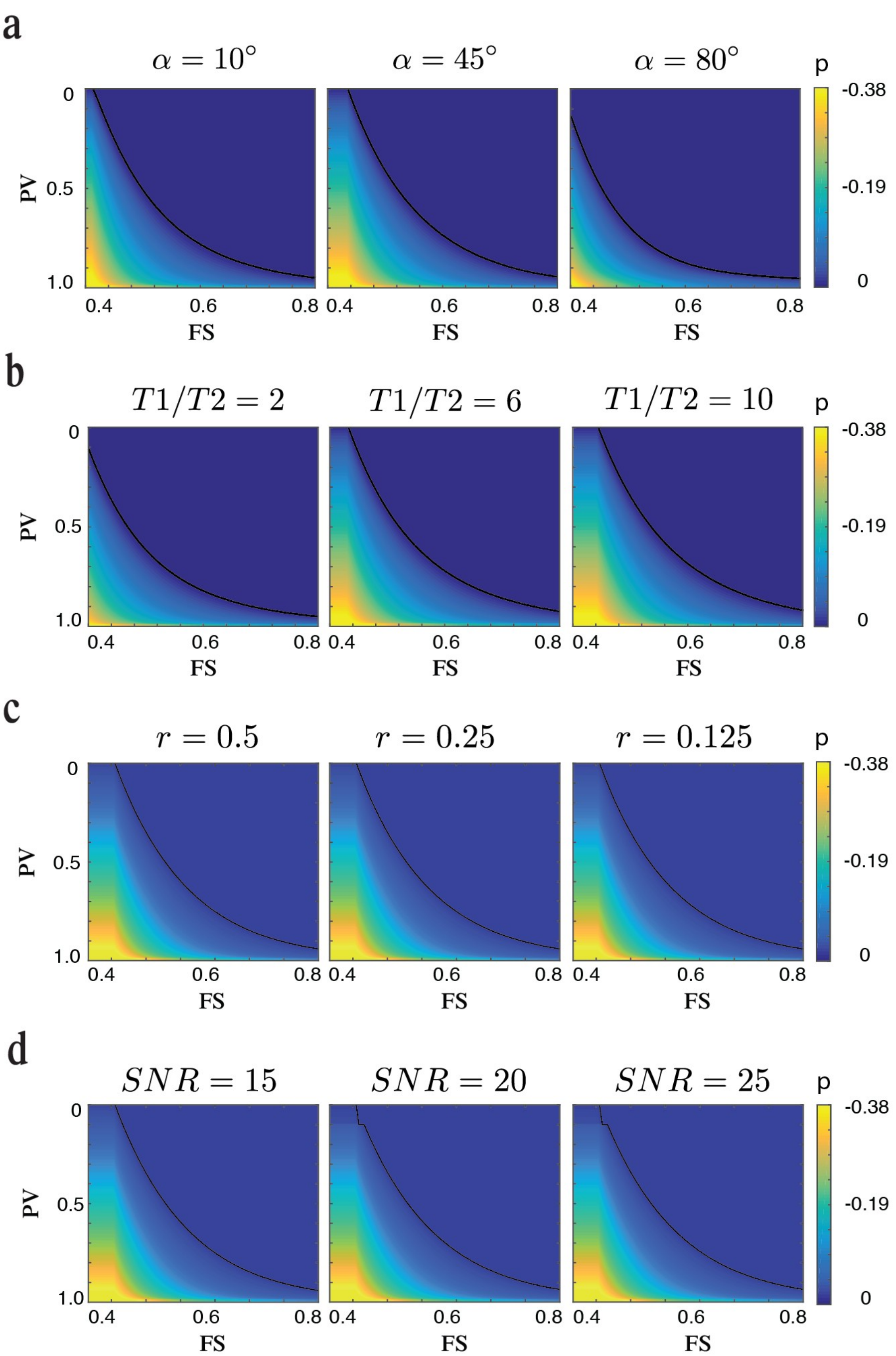


Figure 3. Optimal p as a function of FS and PV. Optimal p was taken as the median of the range of p which is lower-bounded by the allowed PV and upper-bounded by the desired FS for various **(a)** flip angles, **(b)** T1/T2 for the water tissue, **(c)** reduced phantom resolution by a factor of r, and **(d)** SNR. Solid lines specify the boundary of the achievable FS and PV. An intermediate value for flip angle allows for a broader range of achievable fat-suppression for a fixed level of partial-voluming. Achievable fat-suppression for a fixed level of partial-voluming increases with T1/T2 of water tissue. Imaging resolution and SNR have little effect on the applicable range of p.

Discussion/Conclusion

Weighted combination of ATR-SSFP acquisitions with $p \to -1$ leads to near complete fat-suppression at the cost of enhanced partial-voluming. We provided a comprehensive analysis of this tradeoff. Finally, we proposed optimal p that yields the desired level of fat-suppression while limiting the partial-voluming artifacts.

References

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2. Çukur T, et al. Enhanced Spectral Shaping in Steady-State Free Precession Imaging. Magn Reson Med 2007; 58:1216-1223

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