Quadratic Fat/Water Separation in Balanced SSFP

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Introduction: Balanced steady-state free precession (SSFP) imaging suffers from bright fat signal and sensitivity to off-resonance [1,2]. Of the numerous proposed fat/water separation techniques for balanced SSFP, two are very SNR-efficient: Dixon SSFP [3] offers high image quality, but demands three or more acquisitions with varying echo times and a non-trivial reconstruction. Conversely, phase-sensitive SSFP [4] requires only one acquisition, but suffers from partial-volume effects. Neither method addresses the off-resonance sensitivity of balanced SSFP. Here we present a novel 2 point fat/water separation technique that (a) uses a simple reconstruction to separate water and fat, (b) avoids partial volume effects and (c) correctly identifies fat and water in the presence of SSFP signal nulls.

Theory: A signal S_1 with the repetition time TR and echo time TE_1 chosen such that $TR = 2TE_1 = (2n+1)/\Delta f$ (where n is an integer and Δf is the fat-water chemical shift) results in refocused fat and water signals with opposite sign [4]. The slowly varying phase (ϕ) can be removed robustly [5,6] leaving the real-valued water-fat difference, d. A second signal, S_2, acquired at $TE_2 = TE_1 - \nu/(2\pi\Delta f)$ results in a phase angle ν between water and fat. With $\nu = \pi/2$, $|S_2|^2 = W^2 + F^2 = (d - F)^2 + F^2$ (Eq. 1)

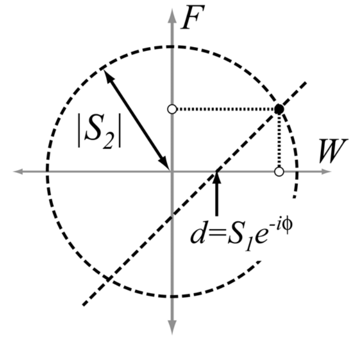

Figure 1. *Geometric interpretation of Eq. 1: The (W,F) content is the intersection in W-F space of a line of slope 1 and W-intercept d, with a circle of radius $|S_2|$.*

Using $|S_2|$ and d, the simple positive solution of (the quadratic) Eq. 1, shown graphically in Figure 1 gives the values of W and F. Although not essential for water/fat separation, the field map, f, can be determined (from d, W, F, S_1 and S_2) and used to detect pixels where crossing of an SSFP signal null has caused an incorrect sign of d. Negating d at these points, gives the accurate estimates of W, F and f. This is of particular significance for high-field SSFP or high-resolution SSFP, where acquisitions with and without alternating the RF phase [6,7] can be combined to remove SSFP signal nulls resulting from off-resonance.

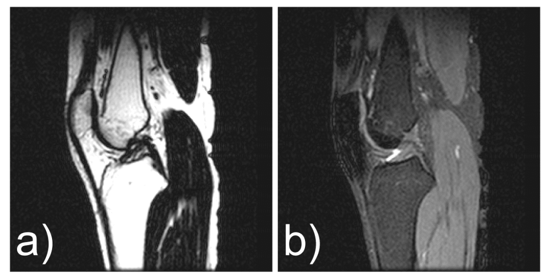

Figure 2. *Sagittal knee images of separated fat (a) and water (b) components for TR=2TE=5.6 ms.*

Methods and Results: Using a 1.5T GE Excite scanner (40 mT/m gradients with 150 mT/m/ms slew rates) and a transmit/receive extremity coil, images were acquired with $TR = 2TE_1 = 5.8$ ms, $TE_2 = 1.75$ ms, 30º flip angle, 160x160x64 matrix, 20x20x12.8 cm^3 FOV for 3:00 scan time. A standard shim was sufficient to keep water and fat oppositely aligned in S_1. Figure 2 shows accurate fat (a) and water (b) images after phase correction of S_1 and solving Eq. 1.

A second image set acquired with $TR = 2TE_1 = 13.8$ ms, $TE_2 = 6.75$ ms, and 30º flip angle, was repeated twice, first with RF phase alternating by 180º, then with constant RF phase [6,7] for 4 total signals. The total scan time was 15:05 for a 256x256x64 matrix over a 16x16x12.8 cm^3 FOV. W, F and f were calculated as above for both phase cycles. At points where f deviated by more than an empirically determined threshold of 140 Hz, d was negated and W and F were recalculated. Finally, at each pixel, the maximum [7] from the two phase cycles was taken for both W and F images, which are shown in Figure 3.

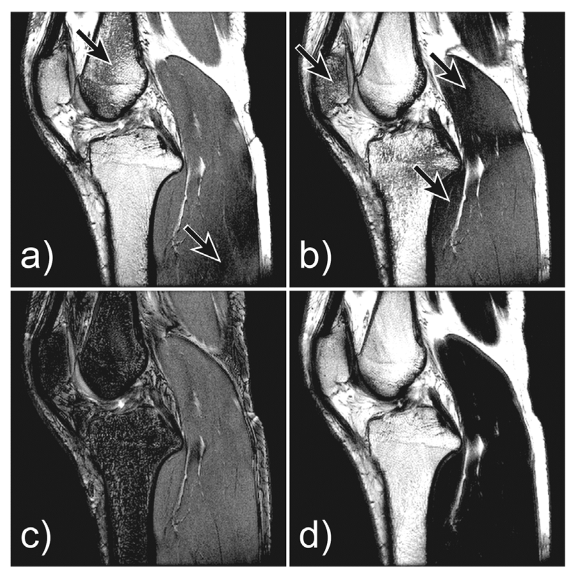

Figure 3. *Sagittal knee images for TR=2TE=13.8 ms. Source S_2 images (a) and (b) with alternating and non-alternating RF phase have null-signal areas (arrows). Water (c) and fat (d) images after maximum-combination of separated images for each RF phase scheme.*

Discussion: We have presented a quadratic water/fat separation technique for balanced SSFP that is simpler and requires fewer acquisitions than recent Dixon methods, while eliminating the partial-volume effects of phase-sensitive SSFP. This method is similar to that shown by Xiang [8], but also exploits the refocusing effect of balanced SSFP. The value of ν can be any non-zero angle, but will, along with fat/water fraction, affect the propagation of noise. Extending TR minimizes efficiency loss from use of multiple echo times, and the multiple-phase-cycle approach here enables accurate fat/water separation for high-field or high-resolution SSFP in reasonable scan times.

References:

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