A Reliable, Efficient and Flexible multi-echo FSE based Water-Fat Separation Method

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Introduction Multi-echo chemical shift based water-fat separation methods have been applied to Fast Spin Echo (FSE) sequences to offer robust water-fat separation [1]. In particular, the 3-point IDEAL technique with FSE has been shown to offer reliable water-fat separation with optimal SNR performance [2]. However, the minimum scan time is tripled compared to a standard fat-saturated methods. Therefore, it is desirable to collect all 3 echoes between refocusing pulses of one repetition [3-5], an approach that brings unique challenges. In this work, we present a multi-echo FSE-IDEAL implementation that offers superior noise performance, high quality water-fat separation and flexible echo time choices. Several approaches are used to address the challenges. First, a bipolar read-out gradient that collects echoes with both positive and negative polarities is applied to improve acquisition efficiency [3-5]. High order eddy-current induced phase errors are removed with reference data collected with reversed gradient polarities. Second, with the data from opposite gradient polarities, we will show that the separated water images are free from chemical shift artifact for certain protocols. Finally, a flexible echo shift strategy is introduced to achieve optimal trade-off between noise performance and spatial resolution.

Methods *Bipolar Phase Correction:* In bipolar acquisitions, eddy-current induced phase errors are modulated in opposite directions for positive and negative gradient polarities, and therefore must be corrected [3-5]. In this work, in addition to the 1D read-out direction phase error [3-5], high order phase errors are also removed. This is achieved by collecting phase encoded reference data with reversed gradient polarity at each echo (M lines) (Figure 1). From the pair of data collected with opposite gradient polarities, the 2D phase errors are estimated and removed. The phase corrected data are then recombined for water-fat separation. For single excitation (i.e. average) scans, low resolution reference data are collected (M<N). For multi-excitation protocols, the number of excitations are divided to collect both gradient polarity data in full resolution (M = N), which allows correction of full-resolution phase errors without extra scan time.

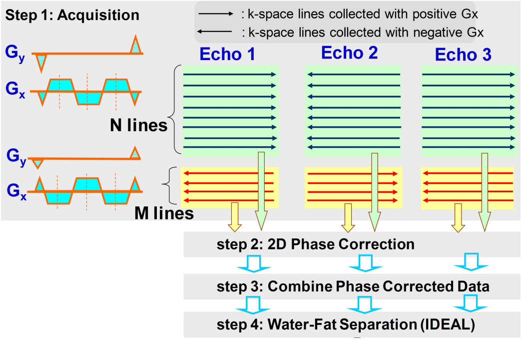


Figure 1: opposite gradient polarities data are collected and processed for high order phase correction.

Chemical Shift: When full resolution pair of data (M=N) are collected, the recombined source data after phase correction can be described as:

$$S(x,y)=\frac{1}{2}\cdot(S^{+}(x,y)+S^{-}(x,y))=\{W(x,y)+\frac{1}{2}\cdot[F(x+\Delta x,y)+F(x-\Delta x,y)]\cdot e^{j2\pi\cdot\Delta f\cdot t_i}\}\cdot e^{j2\pi\cdot\psi\cdot t_i}\ .$$

Thus, the chemical shift effect is limited to the fat images with the water images free of the chemical shift artifact.

Parallel Imaging: As described above, having the full resolution pair of data minimizes chemical shift artifact. For single-excitation protocols, an auto-calibrated parallel imaging technique [6] was used to compensate the scan time increase when collecting full resolution reference data.

Echo Shift Choices: Symmetric 3-pt echoes are in general associated with poor noise performance at water-fat interfaces [7]. The optimal noise performance is achieved with [-π/6, π/2, 7π/6] echo shifts (in water-fat phase shifts) [7]. However, 2π/3 shift (1.6ms at 1.5T, 0.8ms at 3T) can be problematic for high resolution bipolar acquisitions. In our approach, the last echo is fixed at 7π/6 to maintain the echo asymmetry. The echo shifts are determined by the minimum ΔTE for the desired resolution with the lower limit fixed at 2π/3. For low-resolution scans, 2π/3 is achieved. For higher resolution scans, minimum ΔTE is used. The maximum echo shift is limited to π which sets the resolution limit. As shown in Figure 2, the effective Number of Signal Averages (NSA) ranges from 2.7 (ΔTE=π) to 3 (ΔTE=2π/3). For comparison, the [-π, 0, π] echo times result in NSA=2.66 with a singular point (NSA=0) when water and fat signals have equal magnitude [7].

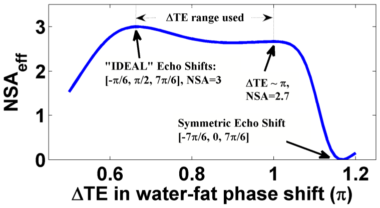
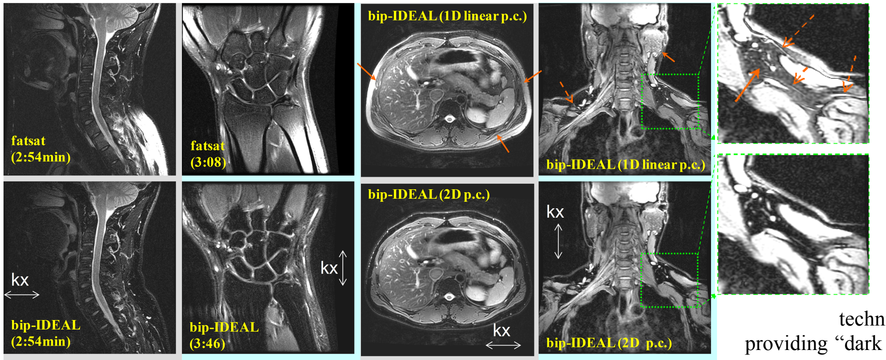


Figure 2: Calculated NSA for the flexible echo shift strategy, where last echo is fixed at 7π/6, while ΔTE is determined by the protocol.

Results Figure 3 shows representative results from volunteer scanning. (a) and (b) compare results from bipolar FSE-IDEAL ("bip-IDEAL") with fat saturation ("fatsat") scans. Fat saturated images show poor fat suppression in difficult anatomic regions, while uniform water-fat separation is obtained with bip-IDEAL. Note that bip-IDEAL achieves the same scan time as fat saturation for the spine scan, while the longer scan time in the wrist arises from slightly longer TR. The wrist scan demonstrates the use of bip-IDEAL for high resolution scans (10cm FOV). The 2D phase correction effectively removes the phase error in this obliquely oriented scan, challenging for traditional 1D phase correction methods due to anisotropic gradient delays [8]. Figure 3 (c) and (d) show that the 1D linear phase correction (top images) leads to significant residual phase errors, degrading the water-fat separation quality (arrows). In Figure 3(d), the chemical shift induced ringing artifact can be seen at the water-fat interface when the opposite polarity data are not recombined (dashed arrows). The fatsat abdomen protocol acquires 4 excitations, therefore bip-IDEAL is collected with 2-excitation in each of the opposite gradient polarity, and there is no additional scan time penalty.



(a): 1.5T Spine, FOV=24, 320x256, Parallel Imaging 1.5x, ΔTE = 0.98π, scan time: 2:54min for both

(b): 1.5T wrist, **small FOV (10cm), oblique sag**, 288x224, Parallel Imaging 1.9x, ΔTE = 0.95π, 3:08min (fatsat), 3:46min (bip-IDEAL)

(c): 3T abdomen, FOV=40, 288x224, 2-excitation, ΔTE = 0.95π, 3:52min

(d): 3T brachial plexus, FOV=30, 288x192, Parallel Imaging 1.88x, ΔTE = π, 3:00min

Figure 3: Representative results from the 4 scans. (a) and (b): comparison with fat saturation scans. (c) and (d): 2D phase correction leads to superior water-fat separation than 1D linear phase correction (arrows). (d) also shows the chemical shift induced ringing at water-fat interface when the opposite polarity data are not combined (dashed arrows)

Discussion and Conclusion Water-fat separation with multi-echo FSE is very attractive due to its favorable scan time. In this work, various tools are used to address the unique challenges of such an approach. The bipolar acquisition with high order phase correction allows efficient acquisition and superior water-fat separation. Echo shifts are adapted to the desired resolution, enabled by IDEAL algorithm's ability to utilize flexible echo shifts. By stretching echo shifts (including the last echo), the technique may permit spatial higher resolution scans than [-π, 0, π] approaches. In addition, the technique is compatible with "multipeak IDEAL" reconstruction, providing "dark fat" in the water images [9] (Figure 3). In conclusion, we have demonstrated a reliable, efficient and flexible multi-echo 3-pt IDEAL-FSE acquisitions, enabling robust water-fat separation without increasing the minimum scan time.

References

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