Single Quadrature Echo Water-Fat Separation with Robust Phase Correction

H. Yu[1], S. B. Reeder[2], C. A. McKenzie[3], A. Shimakawa[1], A. C. Brau[1], N. J. Pelc[4], J. H. Brittain[5]

[1]Global Applied Science Laboratory, GE Healthcare, Menlo Park, CA, United States, [2]Departments of Radiology and Medical Physics, University of Wisconsin, Madison, WI, United States, [3]Department of Radiology, Beth Israel-Deaconess Medical Center and Harvard Medical School, Boston, MA, United States, [4]Departments of Radiology and Bioengineering, Stanford University, Stanford, CA, United States, [5]Global Applied Science Laboratory, GE Healthcare, Madison, WI, United States

Introduction Consistent water-fat separation or fat suppression is required for many clinical applications. Three-point (3-pt) chemical-shift based methods including the recently described IDEAL technique [1,2] (**I**terative **D**ecomposition of water and fat with **E**cho **A**symmetry and **L**east-squares estimation) offer robust water-fat separation that is insensitive to B_0 and B_1 inhomogeneities. However, these methods triple the minimum acquisition time. A variety of methods have been developed to accelerate these multi-point techniques. For multi-coil acquisitions, parallel imaging techniques can be utilized [3,4]. Alternatively, the "2^+-pt" IDEAL method [5] exploits the spatially low-resolution nature of the B_0 field inhomogeneity map by acquiring one of the three images with reduced spatial resolution. In this work, we extend this concept and propose a method that acquires only one full-resolution image, with two additional images acquired with low spatial resolution. The water-fat separation is enabled by a quadrature encoding scheme and a modified IDEAL reconstruction that have been applied to water-fat separation in dynamic imaging [6]. The overall scan time is close to a single acquisition. This "1^{++}-pt" method is valuable in applications that are sensitive to scan time including breath-held, high resolution, and dynamic studies.

Methods The 1^{++}-pt method collects images at three echo times. One full resolution image (*S2*) is acquired with an echo time chosen so that the phases of water and fat are in quadrature, ie: $\pi/2 + k\pi$ (k is any integer). Two additional images ($S1_{lr}$, $S3_{lr}$) are acquired in low-resolution. In S2, water (*W*) and fat (*F*) are in quadrature, represented by $S2 = (W \pm jF)e^{j\phi}$. ϕ is the phase shift introduced by the B_0 and B_1 field inhomogeneities. To estimate *W* and *F*, the following algorithm is performed:

1). *S2* is low-pass filtered in k-space to match the resolution of $S1_{lr}$ and $S3_{lr}$, denoted by $S2_{lr}$.
2). IDEAL reconstruction is performed based on the three low-resolution images ($S1_{lr}$, $S2_{lr}$, $S3_{lr}$) using a robust field map estimation method [7]. As a result, the separated low-resolution water and fat images, W_{lr} and F_{lr}, are obtained.
3). The $S2_{lr}$ can be described as: $S2_{lr} = (W_{lr} \pm jF_{lr})e^{j\phi_{lr}} \approx (W_{lr} \pm jF_{lr})e^{j\phi}$. We have assumed the phase is spatially smooth, or $\phi_{lr} \approx \phi$, which is calculated from the estimated W_{lr}, F_{lr} and $S2_{lr}$.
4). The phase of the high resolution *S2* image is then demodulated using the estimate of ϕ, i.e.: $S2 \cdot e^{-j\phi} = (W \pm jF)$. Finally, the water (*W*) and fat (*F*) images are obtained from the real and imaginary channels of the phase demodulated *S2*. Recombined "in-phase" (*W*+*F*) and "out of phase" (|*W*-*F*|) images can also be calculated.

All patient and volunteer scanning was approved by our IRB and informed consent was obtained. A 3D-SPGR (Spoiled Gradient Echo) IDEAL sequence was used. Three full-resolution images were collected, corresponding to water-fat phase shifts of [$5\pi/6+k\pi$, $3\pi/2+k\pi$, $13\pi/6+k\pi$] (k is any integer) [2]. The acquisitions were also accelerated with a parallel imaging reduction factor of 2 (R=2). For the 1^{++}-pt reconstruction, the center echo signal is the quadrature encoded full-resolution echo. The images at the two other echoes were filtered in k-space (32x256) to simulate the low-resolution signals. The algorithm described above was then used to separate water and fat images. The full-resolution data from all three echoes were also reconstructed using the 3-pt IDEAL method, and the results were compared with the 1^{++}-pt separated images.

Results Figure 1 illustrates typical results from breath-held abdominal imaging. The acquisition was performed at 3.0T. The separated water and fat images from the 1^{++}-pt method (first row) and the 3-pt IDEAL method (second row) are shown for comparison. Excellent water-fat separation was seen with both methods, although the expected SNR reduction of the 1^{++}-pt method compared with 3-pt IDEAL is apparent. Calculated in-phase (water+fat) and out-of-phase (water-fat) images using the 1^{++}-pt separated water and fat images are also shown (third row). The liver signal decreases in the out-of-phase image, which is diagnostic of fatty infiltration. Further analysis from the "fat fraction" image (fat/in-phase, not shown) suggested approximately 20%-30% of the signal from this liver was from fat. Figure 2 shows axial water images from a contrast enhanced breast study acquired at 1.5T (left: 1^{++}-pt, right: 3-pt IDEAL). The enhancing lesion (arrows) is clearly seen in the post-contrast water images (bottom), demonstrating that 1^{++}-pt method provides similar diagnostic value to the 3-pt method.

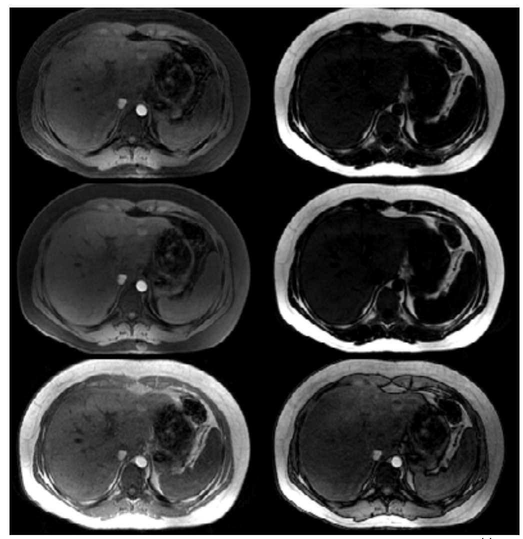

Figure 1. Breath-held abdominal imaging at 3T: 1^{++}-pt separated water and fat images (first row) and 3-pt IDEAL separated water and fat images (second row). In-phase and out-of-phase images (third row) suggested the presence of fat infiltration for this patient. TE=[2.2,3.0,3.8]ms, resolution=1.5x2.4x7mm, α=18°, BW=±83.3kHz, parallel imaging R=2.

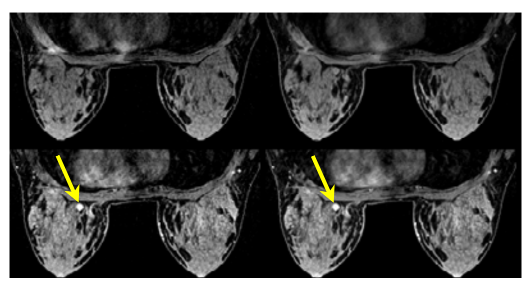

Figure 2. Contrast enhanced breast imaging at 1.5T: water images from 1^{++}-pt (left) and the 3-pt IDEAL method (right) at the pre-contrast (top) and the post-contrast (bottom) stages. The lesion enhancement can be clearly seen (arrows). TE=[2.0,3.6,5.2]ms, resolution=1.3x1.3x3.6mm, α=10°, BW=±62.5kHz, parallel imaging R=2.

Discussion and Conclusion We have proposed a reduced sampling strategy for the IDEAL water-fat separation algorithm. The scan time is significantly reduced without sacrificing the robustness of the water-fat separation. For example, for images with the full-resolution of 256x256, the 1^{++}-pt method acquires a total of (256 + 32x2) = 320 phase encoding lines, leading to an acceleration factor of 2.4, compared with 3-pt IDEAL. The method relies on the fact that field inhomogeneities are spatially smooth [5, 6]. While this work suggests that 32 phase encoding lines are sufficient for phase estimation, the impact of phase encoding resolution on image quality needs further evaluation. Our previous investigation [6] shows that the SNR of the decomposed images from the quadrature separation is equivalent to that of the source image, provided that the phase is correctly estimated. Future SNR analysis will explore the effects of noise on the phase estimation and will explore echo time optimization for the first and third echoes. The combination of this method with parallel imaging provides potential for more acceleration. Although we used an external parallel imaging calibration, the calibration can be integrated into the acquisition itself, providing a self-calibrated parallel imaging approach that may offer more accurate calibration in the presence of motion [4]. In conclusion, the 1^{++}-pt method enables robust water-fat separation with a 60% reduction in scan time, enabling breath-held and dynamic imaging applications.

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