Magnitude Fitting Following Phase Sensitive Water-Fat Separation to Remove Effects of Phase Errors

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Introduction Chemical shift-based water-fat separation techniques rely on different water-fat phase shifts generated at the multiple echo times to estimate Bo field map, water and fat. By utilizing the *a priori* information of field map smoothness, the intrinsic water-fat ambiguity can usually be resolved (1-3). However, such methods that utilize complex data may be sensitive to phase errors in the source images, such as those from eddy currents. Although the effect of these phase errors is acceptable for most qualitative applications, they may create clinically important errors for some applications such as fat quantification, as we discuss in this work.

Water-fat separation can be also achieved using only the magnitude of the complex source signals (4, 5). Magnitude methods are insensitive to phase errors in the source images, however, the known water-fat ambiguity of chemical shift methods cannot be resolved when phase information is discarded. As a result, the fat-fraction cannot be uniquely determined for fat fractions over 50% (5). Additionally, sophisticated nonlinear curve fitting algorithms are needed, particularly when T2* decay is also included in the signal model. The non-convex nature of the optimization problem requires good initial conditioning in order to converge to the correct solution.

In this work, we introduce a two-step water-fat separation approach that combines the strengths of both complex and magnitude reconstruction approaches. Using the new two-step method, the effects of phase errors can be removed without introducing water-fat ambiguity.

Methods Three echoes are collected for the purpose of qualitative water-fat separation and six echoes are collected for measuring fat-fraction in liver. Informed consent and permission from our Institutional Review Board (IRB) were obtained. The 2-step approach is illustrated in Figure 1. In the first step, an investigational version of the 3-pt IDEAL (6) or T2*-IDEAL (7) algorithms is used. In T2*-IDEAL, water-fat separation is performed with the estimation and correction of T2* relaxation (7). A region-growing algorithm (3) is applied to avoid water-fat swaps. The second step is water-fat separation using the magnitude source images. Such a reconstruction is challenging due to the non-convex nature of the curve fitting. We first correct the source signals using T2* estimated from step 1, in the case of a 6-pt reconstruction. A simple Gauss-Newton nonlinear curve fitting is then used to solve for a refined estimate of water and fat by fitting the signals to the following equation: $|S_i|^2 = |w + f \cdot e^{j2\pi\Delta f t_i}|^2 = w^2 + f^2 + 2\cdot\cos(2\pi\Delta f t_i)\cdot w \cdot f$, where Δf is the fat chemical shift. Note that water (w) and fat (f) can be swapped without changing the value of $|S_i|$, directly reflecting the intrinsic ambiguity of water-fat separation when using magnitude only methods. In our approach, the solutions from step 1 are used as the initial guesses in step 2. In this way, the water-fat ambiguity can be resolved and fast convergence is ensured. Step 2 can be considered "fine tuning" of the solutions from step 1 to remove the effects of unwanted phase errors.

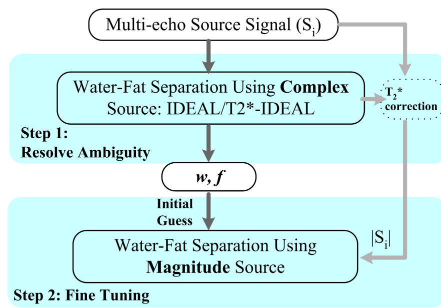
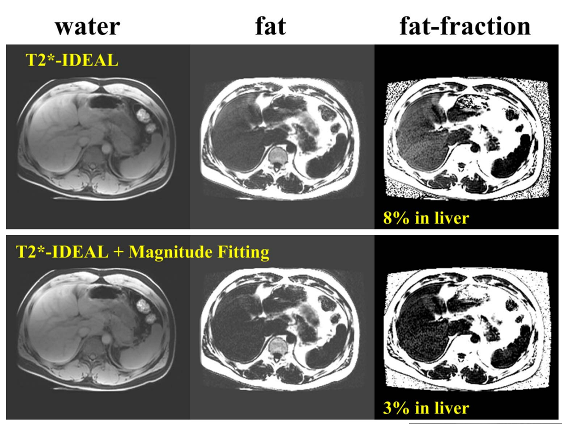


Figure 1: Flow diagram of the 2-step approach.

Results Figure 2 shows results of T2*-IDEAL reconstruction in a healthy volunteer (no fat was expected). Six echoes were collected in one TR with a "fly-back" gradient waveform (2). The original T2*-IDEAL estimates 8% liver fat. For a pixel without fat content, the phase of the signals should evolve linearly due to the Bo field inhomogeneity. However, as illustrated in the phase plot, the phase of the first echo (arrow) is slightly deviated from the linear curve that the last 5 echoes follow. This is because the eddy currents present during the first read-out gradient are slightly different from the other echoes, causing inconsistent phase errors. With magnitude fitting, the phase error is removed and the fat-fraction measured in liver is reduced to 3%. This improvement may be clinically significant as the diagnosis of steatosis is typically made when liver fat content exceeds 5-10% by weight (8). The remaining small fat-fraction is likely due to ghosting from the subcutaneous fat.

Water-fat separation with bipolar gradients (non-fly-back) is second application that is sensitive to eddy currents. In a bipolar acquisition, the multi-echo data are collected with both positive and negative gradient polarities. The phase errors from linear and higher order eddy currents follow opposite directions in space for even and odd echoes, disrupting the inter-echo phase consistency (9). In Figure 3, we show water images from a bipolar acquisition. Before water-fat separation, a linear phase error correction method was applied in the read-out direction (9). The IDEAL processing results in residual fat signals in the water image (arrows) due to the uncorrected higher order phase errors. The two-step approach successfully removes the remaining phase error and achieves uniform water-fat separation.



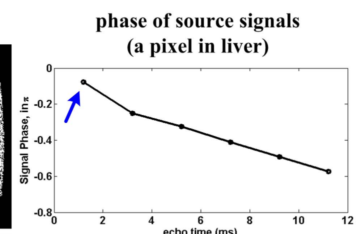


Figure 2: The use of the two-step approach for quantification of low fat-fraction. The original T2*-IDEAL in a healthy volunteer leads to artifactual 8% fat in liver due to an eddy current effect, which is corrected by the two-step approach.

Discussion and Conclusion Conventional multi-point water-fat separation methods rely heavily on phase information to separate water and fat; therefore, they are sensitive to phase errors, such as those from eddy currents. In this work, we introduced a two-step approach, where conventional phase-sensitive water-fat separation is followed by a fitting algorithm based on magnitude images. The second step relies on the results from the first step for initial conditioning of the fit. This concept can be extended to applications where step 2 may assume a "finer" model than step 1. For example, step 2 may model different T2* relaxation for water and fat, but uses the T2* estimated from step 1 as the initial guess for T2* of both water and fat. This can be considered as a "model multi-resolution" approach. The noise performance of the magnitude fitting approach remains to be investigated, particularly for voxels with comparable water and fat content. In conclusion, the proposed two-step approach is effective at removing undesired phase errors caused by eddy currents, while also offering unambiguous water-fat separation for fat fractions greater than 50%.

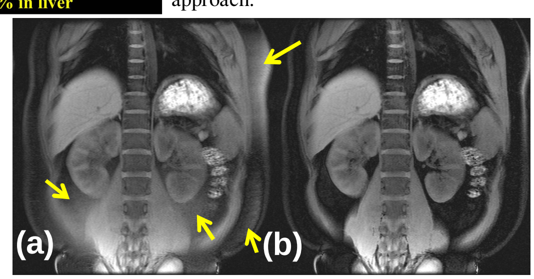


Figure 3: The use of the two-step approach for 3-pt water-fat separation with a bipolar acquisition. Water images from phase-sensitive IDEAL processing (a) and the two-step approach (b). A linear phase correction was applied before IDEAL in both cases. The residual fat signal in (a) (arrows) is due to the uncorrected higher order eddy currents that are resolved using the two-step approach (b).

References

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