Water-Fat Identification in Dual-Echo Dixon Imaging

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Introduction

Two-point Dixon methods face an inherent ambiguity in the separation if the composite signal is sampled at echo times at which the water and fat signals are in- and opposed-phase [1,2]. This ambiguity is commonly resolved by first selecting a solution at one or more seed voxels heuristically and then imposing spatial smoothness on the field inhomogeneity, for instance in a region growing process. However, if the water and fat signals are only partially opposed-phase at one of the echo times, they can be determined directly near interfaces between water- and fat-dominant tissues [3]. In this work, a more widely applicable approach to such a water-fat identification is proposed for a two-point Dixon method with flexible echo times [4], which is inspired by a recent suggestion to exploit the spectral complexity of fat for this purpose [5].

Methods

The composite signal S in image space at echo time TE is modeled by

$$S_n = (W + c_n F)\mathrm{e}^{\mathrm{i}\varphi_n}, \text{ with } c_n = \sum_m w_m \mathrm{e}^{\mathrm{i}\theta_{n,m}}, \; \sum_m w_m = 1,$$

where W and F are the water and fat signals in image space, φ is a phase error, w is a weight, and θ is the angle between W and the signal from one spectral peak of fat. Both w and θ are assumed to be known a priori. Eliminating φ and combining the signal equations at two different echo times TE_1 and TE_2 leads to a biquadratic equation in F with the solutions

$$F = \pm\sqrt{\frac{-a_2 \pm \sqrt{a_2^2 - 4a_1a_3}}{2a_1}}, \; W = \frac{|S_1|^2 - |S_2|^2 - (|c_1|^2 - |c_2|^2)F^2}{2(c_{1R} - c_{2R})F},$$

where the constants $a_1 - a_3$ depend on c_1, c_2, $|S_1|$, and $|S_2|$, and c_{1R} and c_{2R} denote the real components of c_1 and c_2. Valid are only those solutions for which both F and W are real and non-negative. Their number can be calculated analytically as a function of the ratio $|S_1|/|S_2|$, for given TE_1, TE_2, c_1, and c_2. Taking into account suitable margins to accommodate the effects of noise and relaxation, the existence of only one solution generally permits a water-fat identification.

This approach was explored using a seven-peak spectral model of fat, which predicts the amplitude variation of a pure fat signal plotted in Fig. 1 [6]. Imaging was performed on 3 T scanners (Philips Healthcare, Best, The Netherlands) with dual-gradient-echo sequences.

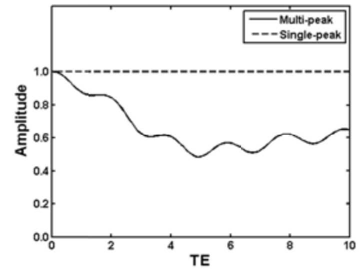

Fig. 1. Amplitude of a pure fat signal at 3T as function of TE [ms], simulated with a multi-peak and a single-peak spectral model.

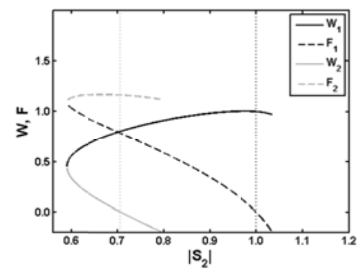

Fig. 2. Solutions of the signal equations for $TE_1/TE_2 = 1.8/3.2$ ms at 3 T as function of the signal amplitude $|S_2|$ for $|S_1| = 1$. The dotted lines indicate the $|S_2|$ values corresponding to pure fat (left) and pure water (right) signals.

Results

The solutions obtained for $\mathrm{TE}_1/\mathrm{TE}_2$ = 1.8/3.2 ms at 3 T are plotted in Fig. 2. Two valid solutions exist for a pure fat signal at $|S_1|/|S_2| = |c_1|/|c_2|$, but only one for a pure water signal at $|S_1|/|S_2| = 1$. A robust identification of water-dominant signals thus seems feasible. The theoretical possibilities of determining water or fat signals directly are illustrated in Fig. 3. For most combinations of short TEs at 3 T, either water- or fat-dominant signals are unambiguous under ideal conditions. Applying the proposed approach to a pelvic dual-gradient-echo acquisition with $\mathrm{TE}_1/\mathrm{TE}_2$ = 1.8/ 3.2 ms yields the results on the right in Fig. 4. The vast majority of water-dominant signals are correctly assigned for individual voxels, i.e. without considering the field inhomogeneity in a neighborhood. Other signals with higher $|S_1|/|S_2|$ were assumed to be fat-dominant. A single, local smoothing of the field inhomogeneity resolved remaining minor swaps at interfaces. By contrast, the results on the left in Fig. 4, produced by selecting from the two solutions obtained with a single-peak spectral model the one corresponding to the smaller field inhomogeneity, exhibit major swaps.

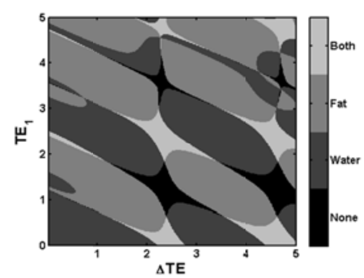

Fig. 3. Theoretical possibilities of an identification of water or fat signals at 3 T as function of TE_1 and $\Delta TE = TE_2 - TE_1$.

Conclusions

The presented approach relies on differences in the signal amplitude between two echo times, which have to be significant for fat signals to ensure a reliable differentiation from water signals. Given a spectral model of fat, the choice of echo times can be optimized in this respect. Unlike with previous approaches, a substantial part of all voxels can then be resolved immediately. Existing region growing, iterative filtering, and global optimization processes may thus be enhanced, by considerably decreasing their complexity and increasing their robustness. Alternatively, they may be eliminated completely, as demonstrated on the in vivo example.

References

1. Dixon WT. Radiology 1984; 153:189-194. 2. Ma J. Magn Reson Med 2004; 52:415-419. 3. Xiang QS. Magn Reson Med 2006; 56:572-584. 4. Eggers H, et al. Magn Reson Med 2011; 65:96-107. 5. Yu H, et al. Proc ISMRM 2010; 771. 6. Ren J, et al. J Lipid Res 2008; 49:2055-2062.

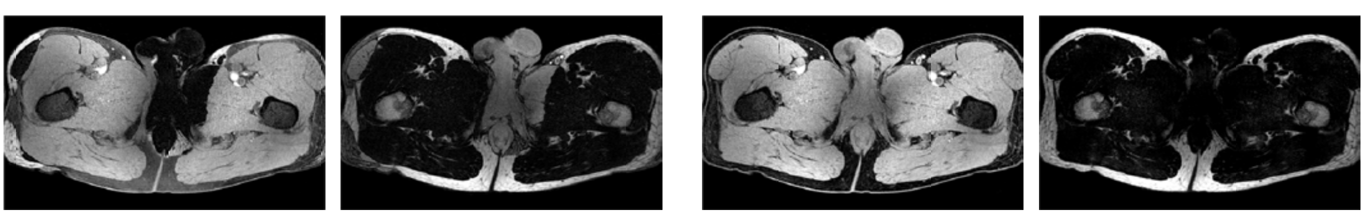

Fig. 4. Water and fat images reconstructed directly, i.e. without region growing, iterative filtering, or the like, from the same dual-echo acquisition, by choosing the solution with the smaller field inhomogeneity using a single-peak spectral model (left), and by taking the only solution or the fat-dominant solution using a multi-peak spectral model (right).