Robust Water/Fat Separation in the Presence of Large Field Inhomogeneities Using a Graph Cut Algorithm

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INTRODUCTION

Water/fat separation in the presence of large field inhomogeneities has spurred significant research efforts in recent years, due to its many important clinical applications [1-3]. The main challenge in solving the problem accurately and reliably lies in: (a) nonlinearity of the signal model, (b) non-uniqueness of the separation at an isolated voxel, and (c) presence of noise. This abstract presents a novel, robust solution to the problem, based on a statistically-motivated formulation and a graph cut optimization algorithm. This solution has good theoretical properties, an efficient implementation and has been shown to provide good results in a number of challenging cardiac imaging cases.

METHODS

In Dixon imaging, the signal obtained at voxel q and echo time t_n can be expressed as $s_q(t_n) = [\rho_{W,q} + \rho_{F,q}\, exp(i2\pi f_F t_n)]\, exp(i2\pi f_{B,q} t_n) + \eta$, where $\rho_{W,q}$ and $\rho_{F,q}$ are the water and fat amplitudes, respectively, f_F is the fat frequency offset, $f_{B,q}$ is the local frequency offset due to field inhomogeneity, and η is noise. The goal is to estimate $(\rho_{W,q}, \rho_{F,q}, f_{B,q})$ for $q=1,\dots,Q$, where Q is the number of voxels. The proposed method solves the problem jointly for all the voxels, using the penalized maximum-likelihood (PML) formulation. More specifically,

$$(\hat{\boldsymbol{\rho}}_{\mathrm{W}}, \hat{\boldsymbol{\rho}}_{\mathrm{F}}, \hat{\mathbf{f}}_{\mathrm{B}}) = \underset{\boldsymbol{\rho}_{\mathrm{W}}, \boldsymbol{\rho}_{\mathrm{F}}, \mathbf{f}_{\mathrm{B}}}{\arg\min} \sum_q R_q(\rho_{\mathrm{W},q}, \rho_{\mathrm{F},q}, f_{\mathrm{B},q}) + \Psi(\mathbf{f}_{\mathrm{B}}) \quad (1)$$

where $\boldsymbol{\rho}_W = [\rho_{W,1}, \rho_{W,2}, \dots, \rho_{W,Q}]^T$, $\boldsymbol{\rho}_F = [\rho_{F,1}, \rho_{F,2}, \dots, \rho_{F,Q}]^T$, $\mathbf{f}_B = [f_{B,1}, f_{B,2}, \dots, f_{B,Q}]^T$, $R_q(\rho_{W,q}, \rho_{F,q}, f_{B,q}) = \Sigma_n |s_q(t_n) - [\rho_{W,q} + \rho_{F,q}\, exp(i2\pi f_F t_n)]\, exp(i2\pi f_{B,q} t_n)|^2$, and $\Psi(\mathbf{f}_B)$ penalizes roughness in the field map. The PML formulation is desirable (as compared to conventional voxel-based estimation methods) because of its ability to reduce noise and remove ambiguities associated with the non-convexity of R_q, as illustrated in Fig. 1 [4]. However, Eq. (1) results in a difficult (high-dimensional and non-convex) optimization problem; so another key contribution of the work is the development of an effective solution to the optimization problem. Our proposed solution is characterized by: (a) use of variable projection for dimensionality reduction, (b) conversion of Eq. (1) to a discrete optimization problem to overcome the non-convexity of R_q, and (c) use of a novel graph cut-based algorithm to efficiently solve the discretized problem, with strong performance guarantees [4,5].

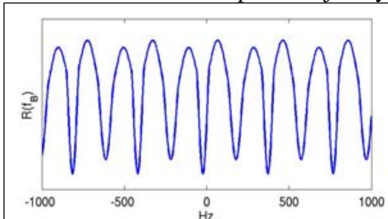

Fig. 1 Non-convexity of R_q, with multiple local minima. The challenge in Dixon water/fat separation resides in selecting the correct "valley". Errors in this selection may result in incorrect water/fat images.

RESULTS AND DISCUSSION

The proposed method has been applied to several imaging studies. The most challenging one is cardiac imaging, where susceptibility effects, as well as the short, wide bore scanner (Siemens MAGNETOM Espree 1.5 T), result in rapid field variations. In this study, 25 cardiac datasets were acquired at different slice orientations using an echo-train GRE sequence with monopolar readout. A representative example is shown in Fig. 2, where the results from a previous method (IDEAL) [2] are included for comparison. As illustrated in this example, the proposed method produced excellent separation of water and fat, with only two water/fat swaps overall (both in regions of low signal, away from the heart).

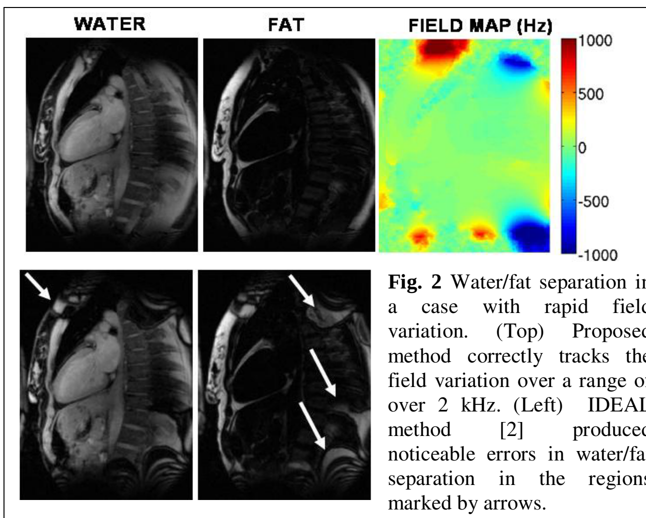

Fig. 2 Water/fat separation in a case with rapid field variation. (Top) Proposed method correctly tracks the field variation over a range of over 2 kHz. (Left) IDEAL method [2] produced noticeable errors in water/fat separation in the regions marked by arrows.

Our study demonstrated significant improvements of the proposed method over previous, voxel-based methods (IDEAL, ICM [2,4]), which frequently failed to correctly separate water and fat (although these methods have produced good results in less challenging cases). The improved performance of the proposed method enables reliable tissue characterization in cardiac imaging, e.g., for the detection of fatty infiltration in the myocardium [6], as shown in Fig. 3.

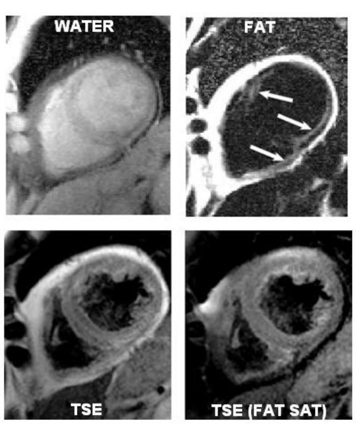

Fig. 3 Fatty infiltration in the myocardium. This is difficult to detect with conventional fat saturation (bottom), but is clear in the fat-separated image (top, see arrows).

With these capabilities, this method should also prove useful for other clinical applications where large field inhomogeneities currently prevent reliable water/fat separation.

CONCLUSIONS

This abstract presents a novel method for robust water/fat separation. The proposed solution has several important properties: (a) robust separation in the presence of large field inhomogeneities; (b) fast implementation, (c) good characterization of the estimates, (d) easy extension to more advanced signal models. This method has enabled reliable detection of fibrofatty infiltration, and characterization of tumors and masses in cardiac MRI.

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