Estimation of water/fat images, B_0 field map and T_2* map using VARPRO

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INTRODUCTION

Conventional water/fat separation methods based on Dixon-type acquisitions do not account for the T_2* decay effect, which leads to underestimated intensities of the water/fat components in regions where the decay is significant [1,2]. It is, therefore, desirable to estimate the T_2* in order to improve the quality of water/fat decomposition. Furthermore, the T_2* map itself is of clinical value, e.g., for the diagnosis of iron overload [2,3]. Here we propose a novel method, based on the variable projection (VARPRO) formulation [4], for robust and efficient estimation of water/fat images, field map and T_2* map.

METHODS

In a Dixon acquisition with N images acquired at echo times $TE=t_n$, $n=1,\ldots,N$, the signal at a given voxel can be modeled as

$$\mathbf{s}(\rho_W,\rho_F,f_B,R_2^*)=\begin{pmatrix} e^{j2\pi t_1 f_B}e^{-t_1R_2^*} & e^{j2\pi t_1(f_B+f_F)}e^{-t_1R_2^*} \\ \vdots & \vdots \\ e^{j2\pi t_N f_B}e^{-t_NR_2^*} & e^{j2\pi t_N(f_B+f_F)}e^{-t_NR_2^*} \end{pmatrix}\begin{pmatrix}\rho_W\\ \rho_F\end{pmatrix}=\mathbf{\Phi}(f_B,R_2^*)\boldsymbol{\rho} \quad (1)$$

where $\mathbf{s}=[s(t_1)\ \ s(t_2)\ \cdots\ \ s(t_N)]^T$ is the signal vector, ρ_W and ρ_F are the complex-valued water and fat amplitudes, respectively, f_F is the fat chemical shift (e.g., -220 Hz at 1.5 T), f_B is the frequency shift due to B_0 field inhomogeneity, and $R_2^* = 1/T_2^*$. Assuming white Gaussian noise, the maximum-likelihood estimation of (ρ_W, ρ_F, f_B, R_2*) is a nonlinear least-squares problem (i.e., minimizing $L(\boldsymbol{\rho},f_B,R_2^*)=\|\mathbf{s}_{\text{meas}}-\mathbf{\Phi}(f_B,R_2^*)\boldsymbol{\rho}\|_2^2$). However, using VARPRO, this problem is equivalent to minimizing $L(f_B,R_2^*)=\|\mathbf{s}_{\text{meas}}-\mathbf{\Phi}(f_B,R_2^*)\mathbf{\Phi}^\dagger(f_B,R_2^*)\mathbf{s}_{\text{meas}}\|_2^2$, where † denotes pseudoinverse. This minimization can be performed by evaluating $L(f_B,R_2^*)$ on a 2D grid and directly picking the minimum.

The VARPRO formulation has several desirable features: it avoids the local convergence of iterative search algorithms. It also enables the use of prior constraints on R_2*. Finally, it allows effective field map regularization (which is the most challenging aspect of the whole estimation process).

One drawback of this approach is its computational cost, since evaluation of $L(f_B,R_2^*)$ on a 2D grid is relatively time-consuming. However, Cramer-Rao bound (CRB) analysis of the signal model in Eq. (1) indicates that, for an efficient estimator, the estimates for f_B and R_2* are uncorrelated (i.e., the corresponding cross-term in the CRB matrix is zero for all the combinations of parameter values we have tried). This observation leads to the following efficient *decoupled* VARPRO method: 1) Estimate the regularized field map using the original VARPRO method (assuming no decay). 2) Given the estimated field map, obtain R_2* at each voxel using VARPRO. 3) Given the field map and R_2* map, estimate ρ_W and ρ_F at each voxel by solving the corresponding linear problem in Eq. (1). This method requires two 1D searches, instead of one 2D search, resulting in notable computational savings.

RESULTS

Cardiac images were acquired using a multi-echo GRE sequence on a Siemens ESPREE 1.5T. A total of 13 TEs were acquired to provide a "gold standard". Estimates were obtained using both joint and decoupled estimation, from a varying number of TEs, producing the results shown in Fig. 1.

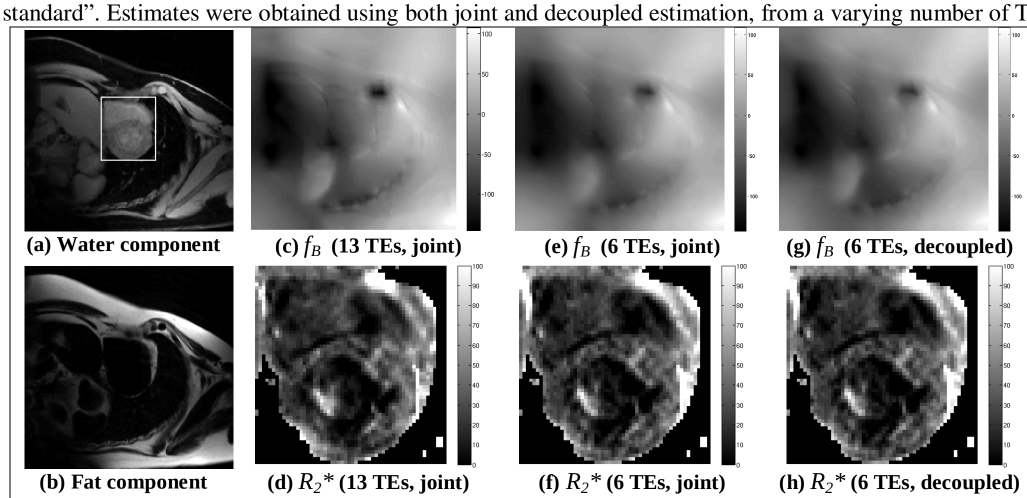

Figure 1. (a)-(b) Water/fat decomposition estimated from 13 TEs. (c)-(d) "Gold-standard" field map and R_2* map, jointly estimated using all 13 TEs. The estimated R_2* is shown for the ROI displayed within the water image. (e)-(f) Field map and R_2* map, jointly estimated using 6 TEs. (g)-(h) Field map and R_2* map, estimated using *decoupled* VARPRO with the same 6 TEs. Note the high-quality of the estimates obtained from 6 TEs. Furthermore, the joint and decoupled estimation of field map and R_2* map produce very similar results (the relative difference in R_2* over the ROI was *1.2%*). However, joint estimation required *15,000* evaluations of $L(f_B,R_2^*)$ per voxel, whereas decoupled estimation required *350*.

Equation (1) assumes a unique R_2* value per voxel. In voxels where both water and fat are present, this estimation will provide an "effective" R_2* estimate [2]. VARPRO can be easily adapted to estimate two distinct decay constants, although this will result in noisier estimates and increased computational times. Note also that a common method for R_2* estimation is to assume a single spectral component and fit an exponential to the signal magnitude. This method produces significantly worse results than the method proposed here in the presence of several spectral components.

CONCLUSION

This work presents a method for estimating B_0- and T_2*-maps along with water/fat images from Dixon acquisitions, by extending a recently proposed variable projection method. This method provides accurate estimates regardless of the nonconvexity of the corresponding estimation problem.

REFERENCES

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