Water-Fat Separation Using a Locally Low-Rank Enforcing Reconstruction

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INTRODUCTION: Multi-contrast water-fat separation based on the Dixon method is steadily gaining importance in clinical routine. An accelerated examination using dedicated acquisition schemes in combination with an iterative reconstruction is therefore highly desirable. A direct reconstruction of water and fat images incorporating field inhomogeneities, relaxation effects as well as gradient delays and eddy current effects is, however, not straightforward as the optimization problem is rendered non-convex[1,2]. Here we demonstrate that the reconstruction problem can be decoupled by first reconstructing the multiple echo images using a locally low-rank enforcing (LLR) regularization[3,4], followed by a conventional voxel-wise fit of the non-linear parameters. The regularization enforces a local representation of the contrast images with as few chemical components as possible and assumes a low resolution for the phase evolutions. Both are common assumptions in water-fat separation. The approach also allows for varying sampling patterns across contrasts (blipping), adding further regularization terms, as well as the support of bipolar acquisitions and, in consequence, faster acquisitions.

THEORY: For water-fat separation the N_E contrast images at a given voxel x and at echo times $\{T_e\}_{1,\dots,N_E}$ are modeled as $I_{x,e} = (W(x) + c(T_e)F(x))e^{i\varphi(T_e,x)}$. Here $W(x)$ is the water signal, $F(x)$ the fat signal, $c(T_e)$ the fat dephasing at echo time T_e and $\varphi(T_e,x)$ the phase at time T_e. The phase evolution includes effects from field inhomogeneities, gradient delays and eddy currents in the case of bipolar acquisitions as well as the phase right after excitation for real-valued water and fat signals. The imaginary part addresses R_2^* relaxation. A common assumption in water-fat separation is that the phase evolution is spatially very smooth[1]. If we assume it to be spatially constant in sufficiently small patches $\{x_i^P\}_{i=1,\dots,N_P}$, we directly see that the matrix

$$I^{(P)} = \begin{pmatrix} W(x_1^P) & F(x_1^P) \\ \vdots & \vdots \\ W(x_{N_P}^P) & F(x_{N_P}^P) \end{pmatrix} \begin{pmatrix} e^{i\varphi(T_1)} & \cdots & e^{i\varphi(T_{N_E})} \\ c(T_1)e^{i\varphi(T_1)} & \cdots & c(T_{N_E})e^{i\varphi(T_{N_E})} \end{pmatrix}$$

has at most rank 2. Therefore, a LLR regularization is particularly suited for multi-echo Dixon as it addresses the chemical components as well as the phase evolution properly. This motivates the use of the nuclear norm as a regularization term[3] which we exploit in the optimization problem

$$\min_I \left(\|A\,I - D\|_2^2 + \lambda \sum_P \left\| I^{(P)} \right\|_* \right),$$

where A is the system matrix that multiplies each contrast with the coil sensitivities, Fourier transforms and masks the signal onto the measured samples. Furthermore, D is the measured data, λ is the Lagrange multiplier and $I^{(P)}$ $(N_P x N_E)$ is the local Casorati[4] matrix of a patch P which is the stack of local patches for all contrasts. The regularization couples and constraints the different contrasts in a way that is consistent with the signal model. Once the images are reconstructed, a conventional Dixon algorithm can be used for further processing.

METHODS: LLR reconstruction and multi-echo water-fat separation for bipolar acquisitions were implemented as an offline C++ program. An efficient Split-Bregman formulation was used for optimization of the readout-decoupled reconstructions. LLR regularization was applied with overlapping patches of size 5x5. Fully sampled measurements of a healthy volunteer were performed on a 3T MRI scanner (Siemens MAGNETOM Skyra) using a prototype bipolar 3D spoiled GRE sequence. Acquisition parameters included FoV = 40x28x22cm^3, image matrix = 256x172x64, TR= 8.48ms, TE = 1.19, 2.32, 3.45, 4.58, 5.71, 6.84ms and flip angle = 15°. A variable density undersampling of factor 6 was retrospectively applied to the fully measured data.

RESULTS AND DISCUSSION: In Fig. 1 we present exemplary images for the first image contrast and the extracted water image using the coupled LLR reconstruction compared to a decoupled reconstruction of the various contrast images using optimized wavelet and TV regularization. The same sampling is used for both methods. It is apparent by undersampling artifacts that the acceleration of the decoupled reconstruction is limited to lower acceleration rates, whereas the locally low-rank reconstruction still allows for a good image quality.

CONCLUSION: LLR reconstructions are generically suited for accelerating water-fat imaging as they are based on common and well justified assumptions about the number of chemical species and the smoothness of the phase evolution. They allow an application also to bipolar acquisitions and support blipping between contrasts. Conventional water-fat separation algorithms can be applied after reconstruction of the contrast images as a post-processing step. This promises not only an application for water-fat quantification, but may also be suited for accelerating conventional dynamic imaging where so far single or dual echo acquisitions are used.

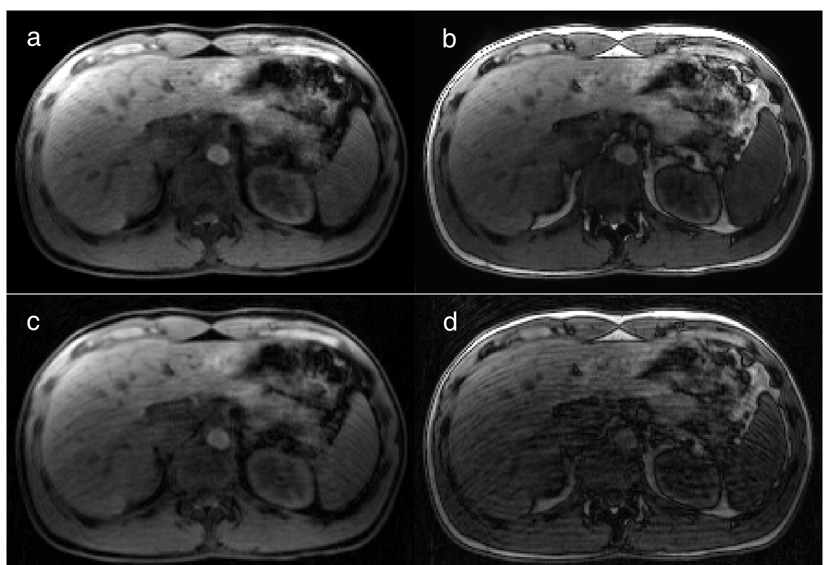

Fig. 1: Water and first contrast image for the low rank approach in the first row (a,b) compared to regularized decoupled reconstructions in the second row (c,d) for a 6-echo acquisition with a retrospective undersampling of 6. Note the noise and artifact reduction as well as the enhanced detail in case of the LLR reconstruction.

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