Accelerating water-fat separation for intragastric fat distribution with a signal model-based dictionary

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Introduction: Multipoint gradient echo chemical shift-based water-fat separation methods such as IDEAL have been used to quantify fat fractions and allow visualizing the dynamics of gastrointestinal fat layering and fat digestion in vivo [1]. For quantitative studies, high-resolution coverage of the complete stomach or intestine is necessary. In addition, data acquisition with a sufficient number of echo times is essential to obtain accurate results, which further prolongs the total scanning time. Since scan duration is limited by breath hold constraints, imaging efficiency must be improved by employing undersampling schemes. Parallel imaging and compressed sensing have already been introduced for the acceleration of water-fat separation [2]. Overcomplete dictionaries have been employed to enforce sparsity either on undersampled image patches emphasizing local structure [3] or on multipoint MR measurements using signal models [4]. In this study, an iterative reconstruction of fat fraction maps for parallel MRI using signal model-based dictionaries is proposed. This approach was studied using prospective and retrospective data acquisition of intragastric fat distribution.

Methods: In compressed sensing, image acquisition is accelerated by a factor $R = P/Q$ using a reduced number of Q instead of P phase encoding steps according to a variable sampling density pattern. The reconstruction problem is solved iteratively and is formulated as $\mathrm{argmin}_x \; \|\boldsymbol{F}_u \boldsymbol{S} x - y\|_2^2 + \lambda_\Psi \|\boldsymbol{\Psi} x\|_1$
where $\boldsymbol{S}$ is the coil sensitivity matrix and $\boldsymbol{F}_u$ is the undersampled Fourier transform. The L_1-term enforces sparsity on the image estimate upon application of wavelet operator $\boldsymbol{\Psi}$. Since this constraint becomes insufficient at high acceleration factors, it is proposed here to incorporate a signal model-based overcomplete dictionary $\boldsymbol{D}$. Accordingly, the voxel-based reconstruction problem is formulated as

$$\mathrm{argmin}_\gamma \; \|\boldsymbol{D}\gamma - x\|_2^2 \text{ s.t. } \|\gamma\|_0 \leq K$$

where γ is the sparse representation of a voxel with respect to D at sparsity level $K = 1$. The dictionary is generated using simulated signal intensities at echo time T_E subject to the N-peak fat model $s_{T_E}(\mathrm{ff}, \hat{\psi}) = (1 - \mathrm{ff} + \mathrm{ff} \cdot \sum_{n=1}^{N} \alpha_n e^{-i2\pi\Delta f_n T_E}) e^{-i\hat{\psi} T_E}$ with fat fraction ff and B0 inhomogeneity $\hat{\psi}$ as free parameters.

We propose an approach using both compressed sensing-parallel imaging and overcomplete dictionaries by combining both reconstruction problems: γ is solved for using dictionary reconstruction and inserted as an initial estimate $x = \boldsymbol{D}\gamma$ in the compressed sensing-parallel imaging reconstruction. Both terms are repeatedly solved in an alternating fashion until convergence is reached.

Experiments were conducted on a 1.5T whole-body MRI scanner (Achieva, Philips Healthcare, Best, the Netherlands) with a standard 4-element coil array. Two different test meals designed to interact within the stomach in different ways were prepared: an acid stable (LE1) and acid unstable fat emulsion (LE4). The test meals were isovolumetric (200 ml) with a fat fraction of 20% and droplet sizes of 0.6 µm.

Multi-echo data were acquired using a 6-point gradient-echo sequence with flyback gradients, TR 11ms, TE 1.25ms, dTE 1.54ms, flip angle 10°, FOV 350x258mm^2, voxel size 2.3x1.0mm^2, slice thickness 6mm. For each scan, 30 transversal slices covering the complete stomach volume were acquired. Fully sampled and 4-fold undersampled data were obtained in six healthy volunteers in right decubitus position after receiving the test meal in randomized order at two separate visits to assess different states of lipid stability. Images were acquired at different time points to assess different states of gastric fat emptying.

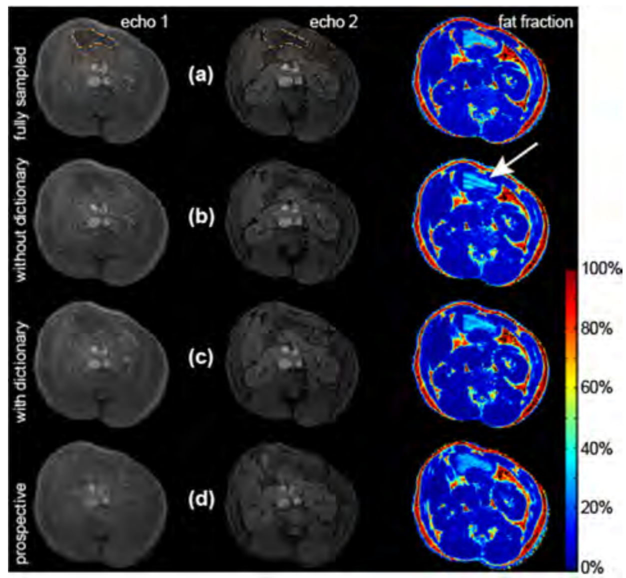

Figure 1: *Representative echo image slices and corresponding fat fraction maps (3rd column) of a fully sampled (a), retrospectively undersampled without (b), with dictionary (c) and prospectively undersampled (d) dataset. LE4 was given as a test meal, the contoured gastric content is shown by the dashed orange line. The arrow indicates artifacts, which are less pronounced in the proposed approach.*

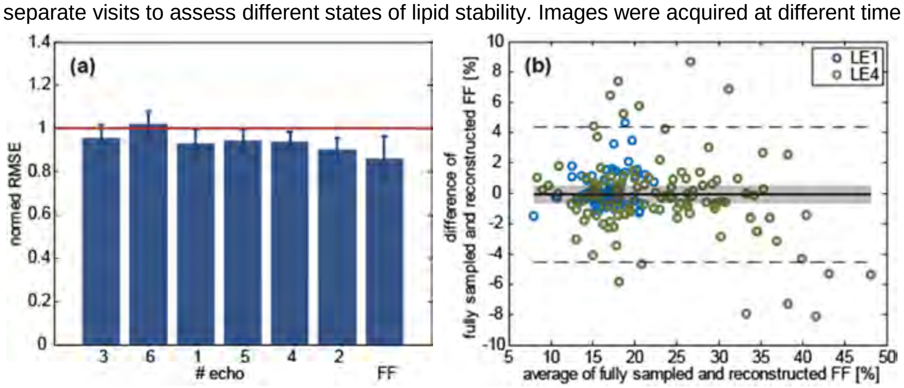

Figure 2: *Performance of the proposed method in terms of (a) RMSE of echo images and fat fraction (FF), sorted by decreasing water-fat phase shift relative to the RMSE of reconstruction without dictionary (red line) and (b) Bland-Altman plot of mean FF of different gastric slices with respective lower and upper limit of agreement (dashed lines). Bias (solid line) and standard error (gray area) show that the proposed approach is in agreement with the fully sampled.*

Results: Examples of reconstructed images of the first and fifth echo as well as the corresponding fat fraction (FF) maps are shown in Fig. 1. Reconstructions from a retrospectively and a prospectively undersampled dataset indicate comparable image quality. In contrast to the approach without the dictionary, the proposed approach resulted in reduced artifacts. The performance of the two approaches was quantified in terms of root-mean-square errors (RMSE) between the fully sampled and the reconstructed retrospectively undersampled echo images (Fig. 2a). It can be seen that the RMSE is subject to variations due to different water-fat phase shifts and SNR, which decreases with increasing echo number. In general, mean FF obtained from undersampled data were found to be in good agreement with the mean FF of the fully sampled acquisition. Larger differences were detected at higher FF, as seen in Fig. 2b.

Discussion: The proposed algorithm using a signal model-based dictionary improved the reconstruction of fat fraction maps at an acceleration factor of 4. At higher fat fractions of gastric content, i.e. in regions where fat flocculated, fat fraction was underestimated, which is however tolerable in terms of the relative error. Due to differences in reconstruction performance between different echoes, further improvement might be achievable by adapting reconstruction to the individual echo images. The use of dictionaries is not only promising for the reconstruction of water-fat images but could also be applied for other chemical shift-encoded species.

References: [1] Liu D ISMRM 2013; [2] Sharma S MRM 2013; [3] Ravishankar S IEEE Trans Med Imag 2011; [4] Doneva M MRM 2010.