Advancing diffusion MRI: improving image quality and getting rid of the fat

Dong, Y.

Chapter 3

SENSE-based multipeak water/fat separation for diffusion-weighted imaging using self-navigated interleaved EPI

Yiming Dong, Kirsten Koolstra, Malte Riedel, Matthias J.P. van Osch, Peter Börnert

In Proceedings of the Annual Meeting of ISMRM, London, 2022

Synopsis

The presence of fat signals is one challenge for diffusion-weighted EPI, especially when considering the multi-peak spectrum nature of fat. In this work, we propose an improved SENSE-based water/fat separation algorithm to suppress multi-peak fat signals and apply this specifically to diffusion-weighted multi-shot EPI. The motion-induced shot-to-shot phase variations, an inevitable challenge in multi-shot DWI, are incorporated into the signal model using either a self-navigation or an extra-navigated method. The results show that the proposed SENSE-based algorithm yields good water/fat separation for non-diffusion and diffusion data with a multi-peak fat spectrum model.

3.1 Introduction

Multi-shot interleaved EPI (msh-EPI) provides significant improvement for diffusion-weighted imaging (DWI) to allow images with higher spatial resolution and less geometric distortions[1]. However, multi-shot acquisitions for DWI applications are susceptible to physiological motion-induced phase variations between the shots. This difficulty is usually addressed by 1) acquiring additional navigator images[1,2], or 2) employing self-navigation approaches[3,4]. Moreover, residual fat artefacts represent another difficulty in DWI due to large water-fat shift in phase-encoding direction. Fat suppression[5] techniques widely used for eliminating fat, often fail for large B_0 inhomogeneities. Moreover, they do not fully take into account the multipeak nature of the fat spectrum (e.g., Olefinic peak, 0.61 ppm to water). Recently, chemical-shift encoding has been proposed to jointly separate water and fat images while estimating the B_0 inhomogeneities[6-8]. Nevertheless, the need to acquire images at multiple TEs may limit its efficiency in clinical applications. Alternatively, Uecker et al. has proposed an approach exploiting the chemical-shift-induced spatial shift of fat using sensitivity encoding (SENSE) to disentangle water and fat signals. The method is validated with a single-peak fat spectra and single-shot EPI images.

In this work, we propose to include the multipeak nature of the fat spectrum into the approach by Uecker et al.[9] to separate water and fat in EPI based on SENSE. This approach is extended to multi-shot, in-vivo DWI using a novel water-fat phase self-navigation method to compensate for motion-induced phase errors, making the need for measuring an extra-navigator echo obsolete.

3.2 Method

The forward model of the DW msh-EPI data at a certain b-value can be written as:

$$s = \sum_{n}^{N} Q_n(\hat{F}\hat{C}\hat{\Phi}_{w,n}\rho_w + \alpha_m \sum_{m}^{M} \hat{\Phi}_{f,m}\hat{F}\hat{C}\hat{\Psi}_{f,n}\rho_f) \tag{1}$$

where $\hat{F}$ is the Fourier transform operator, $\hat{C}$ the SENSE operator, $\hat{\Phi}_{w,n}$ and $\hat{\Phi}_{f,n}$ the operators of motion-induced phase errors for water and fat, respectively. α_m is the relative amplitude weight, $\hat{\Psi}_{f,m}$ denotes the fat off-resonance operator for peak m, and Q_n represents the k-space trajectory for each shot n. s and ρ_w/ρ_f are the vectorized representations of the measured multi-shot k-space signal and the target water/fat images. The water/fat images can be calculated by minimizing:

$$\{\rho_w, \rho_f\} = \underset{\rho_w,\rho_f \in \mathbb{C}}{\operatorname{argmin}} \left\| \hat{A}X - s \right\|_2^2 \tag{2}$$

where $X = [\rho_w, \rho_f]^T$ and $\hat{A}$ is the coefficient matrix, containing all the operators described above. For multi-shot acquisition, the relatively small spatial shift of fat compared to single-shot EPI makes the accuracy of coil-sensitivity maps (CSM) particularly important. Therefore, the advanced JSENSE described in Shin et al.[10] is used to self-calibrate the CSM for b=0 s/mm^2 . Two threshold water/fat masks can be calculated using the separated ρ_w and ρ_f images to mask the CSM and stabilize the phase estimation step.

For the diffusion-weighted cases, the SENSE-based water/fat separation is performed for each shot data to calculate motion-induced phase errors for water/fat individually. Inspired by MUSE[3], the water/fat-adapted SENSE formalism is used to recover ghost-free images for each shot n. First, this can be done by solving the equation:

$$s_n = Q_n(\hat{F}\hat{C}\rho_{w,n} + \alpha_m \sum_{m}^{M} \hat{\Psi}_{f,m}\hat{F}\hat{C}\rho_{f,n}) \tag{3}$$

using conjugate gradient (CG), to estimate $\rho_{w,n}$ and $\rho_{f,n}$ for each individual shot n from the measured data s_n. Then, the motion-induced phase $\phi_{w,n}$ and $\phi_{f,n}$ can be calculated separately for water and fat by:

$$e^{i\phi_{w/f,n}} = \frac{\rho_{w/f,n}}{|\rho_{w/f,n}|}. \quad (4)$$

In addition, k-space triangular window[11] is applied individually on $e^{i\phi_{w,n}}/e^{i\phi_{f,n}}$ to enforce smoothness and construct the operators $\widehat{\Phi}_{w,n}/\widehat{\Phi}_{w,n}$ in Eq.1. The window width is chosen to be half of the matrix size. The whole pipeline is illustrated in figure 1.

DW msh-EPI spin-echo data of the lower leg of a normal volunteer was acquired using a 3T-MRI (Philips Healthcare, Best, Netherlands) with the following parameters: TR/TE=2000/60ms, resolution 1.5×1.5×4 mm^3, three b-values (0, 300, 600 s/mm^2), 3 shots, an 8-channel knee coil. For comparison, an extra-navigator[2] was acquired for each shot. In addition, another fat suppressed DWI scan was acquired using SPIR[5] and reconstructed through IRIS algorithm[2].

3.3 Results and Discussion

Figure 2 shows the non-diffusion dataset comparing the JSENSE-calibrated CSM with single-peak/multi-peak[8] fat model and the SPIR scan. The result for a conventional pre-scan CSM with a multi-peak fat model is shown for comparison. The JSENSE results show improved water images compared to the pre-scan for both spectral fat models. This is mainly due to the geometric distortion mismatch between the EPI images and the reference scan. Besides, the water images with adjusted level/window show the capability of the algorithm to deal with the multi-peak fat spectrum, which is superior to fat-suppression by SPIR. Figure 3 shows water images with different b-values and the associated ADC maps for (1) SPIR, (2) the SENSE-based water/fat separation with extra-navigators and (3) with self-navigation. SPIR shows an unsuppressed fat rim, probably arising from strong B_1^+ inhomogeneities. Some artefacts can be seen in the SENSE-based water image with extra-navigators, which are not present for the self-navigated results. Figure 4 shows the estimated water/fat phases derived for self-navigation.

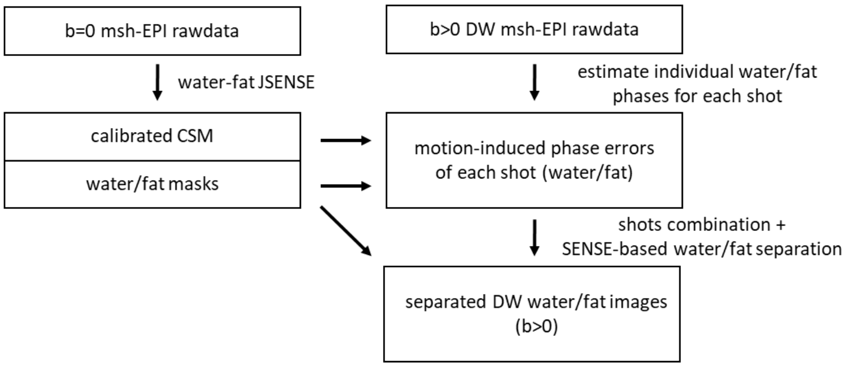

Figure 1. Pipeline of the reconstruction. Self-calibrated coil-sensitivity maps (CSM) can be acquired by performing water-fat JSENSE[10] on non-diffusion msh-EPI data. Two separated water/fat masks can be calculated at the same time to mask the CSM for water/fat channels individually. Then, the calibrated CSM will be used to estimate water/fat phase maps for each individual shot. Finally, the DW water/fat images can be obtained by performing SENSE-based water/fat separation after shots combination.

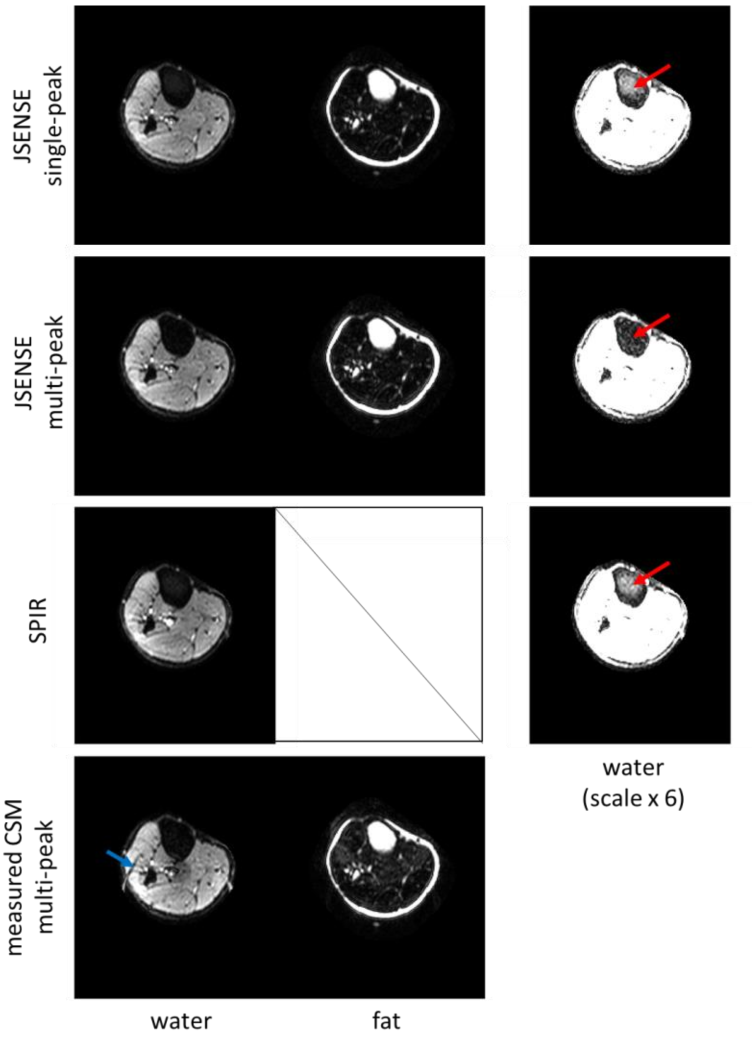

Figure 2. Comparison of different reconstructions for the non-diffusion 3-shot data. First three rows show separated water/fat results using single-peak and multi-peak fat model, and a SPIR image. In the

level/window adjusted water images, the signals of olefinic peak are suppressed in the multi-peak result, while still survive in the water images with single-peak fat model and SPIR (red arrows). Last row shows water/fat image using CSM acquired by a pre-scan. Some artefacts appeared in the water image (blue arrow), which can be mitigated by using self-calibration (JSENSE).

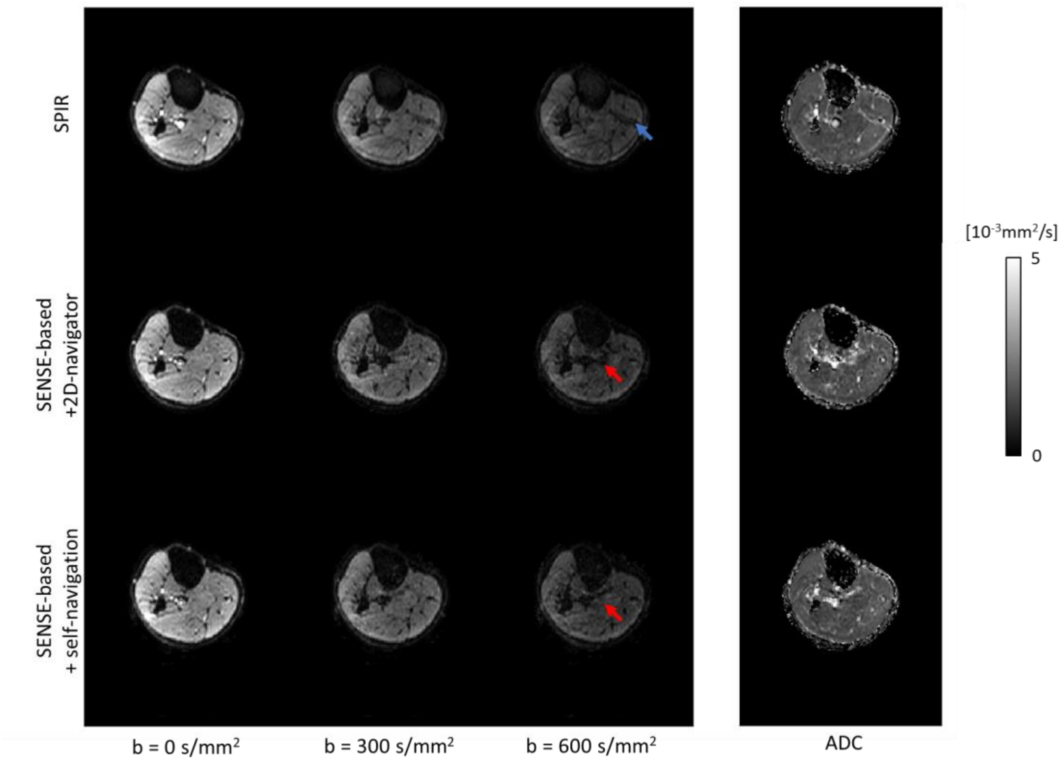

Figure 3. Comparison of the three fat suppression methods for a 3-shot DW msh-EPI scan. Some artefacts can be seen in the SPIR results mainly due to B_1^+ inhomogeneities (blue arrow). Signal dropouts can be seen for the SENSE-based separation using an extra 2D-navigator, which can be mitigated using self-navigation (red arrows). The effects of all the above described artefacts can also be seen in the final ADC maps for each method.

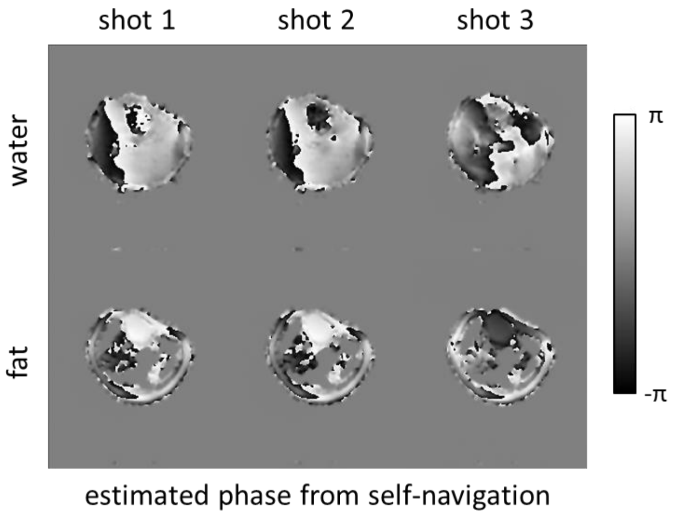

Figure 4. Estimated phase maps of the three shots DW data (b=600 s/mm^2). Separated water/fat phases are obtained by treating each shot dataset of the DW msh-EPI as an individual water/fat

SENSE problem. The proposed self-navigation algorithm can estimate the water/fat phase maps for each shot and provide effective water/fat separation shown in figure 3.

3.4 Conclusion

The proposed method allows for an efficient SENSE-based water/fat separation of non-DW and DW msh-EPI data. The SENSE-based solution requires only one acquisition for each b-value to separate water/fat with a multi-peak fat model. This directly increase the flexibility and is important when different b-values/diffusion directions are desired. Future studies will include undersampling for acceleration and use of phased array coils with more channels to support higher segmentation factors.

Acknowledgement

The authors would like to acknowledge NWO-TTW (HTSM-17104).

References

1. Butts, K., Pauly, J., De Crespigny, A. and Moseley, M. (1997), Isotropic diffusion-weighted and spiral-navigated interleaved EPI for routine imaging of acute stroke. *Magn. Reson. Med.,* 38: 741-749.

2. Jeong H-K, Gore JC, Anderson AW. High-resolution human diffusion tensor imaging using 2-D navigated multishot SENSE EPI at 7 T. *MRM.* 2013;69(3):793-802.

3. Chen NK, Guidon A, Chang HC, Song AW. A robust multi-shot scan strategy for high-resolution diffusion weighted MRI enabled by multiplexed sensitivity-encoding (MUSE). *Neuroimage.* 2013 May 15;72:41-7.

4. Guo H, Ma X, Zhang Z, Zhang B, Yuan C, Huang F. POCS-enhanced inherent correction of motion-induced phase errors (POCS-ICE) for high-resolution multishot diffusion MRI. *Magn Reson Med.* 2016 Jan;75(1):169-80.

5. Zee CS, Segall HD, Terk MR, et al. SPIR MRI in spinal diseases. *J Comput Assist Tomogr* 1992;16:356-360.

6. Hernando D, Karampinos DC, King KF, Haldar JP, Majumdar S, Georgiadis JG, Liang ZP. Removal of olefinic fat chemical shift artifact in diffusion MRI. *Magn Reson Med.* 2011 Mar;65(3):692-701.

7. Burakiewicz J, Charles-Edwards DG, Goh V, Schaeffter T. Water-fat separation in diffusion-weighted EPI using an IDEAL approach with image navigator. *Magn Reson Med.* 2015 Mar;73(3):964-72.

8. Dong Y, Koolstra K, Riedel M, van Osch MJP, Börnert P. Regularized joint water–fat separation with B0 map estimation in image space for 2D-navigated interleaved EPI based diffusion MRI. *Magn Reson Med*. 2021; 00: 1– 18.

9. Uecker, M. & Lustig, M. Making SENSE of Chemical Shif: Separating Species in Single-Shot EPI using Multiple Coils. In Proc. Intl. Soc. *Mag. Reson. Med*., 20, 2490 (Melbourne, 2012).

10. Shin PJ, Larson PE, Uecker M, Reed GD, Kerr AB, Tropp J, Ohliger MA, Nelson SJ, Pauly JM, Lustig M, Vigneron DB. Chemical shift separation with controlled aliasing for hyperpolarized (13) C metabolic imaging. *Magn Reson Med*. 2015 Oct;74(4):978-89.