Improving Parameter Mapping in MRI Relaxometry and Multi-Echo Dixon using an Automated Spectral Denoising

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Synopsis

Magnitude-based parameter fitting is commonly used for relaxometry and multi-echo Dixon but introduces a bias for relaxation and fat fraction estimates, particularly for a low signal-to-noise ratio and high relaxation. The application of an automated, patchwise denoising to the multi-echo image series prior to parameter fitting, considerably increased the SNR; thus, reducing the bias and standard deviation in the estimates of the fit. Our findings were validated on both numerical and in-vivo experiments.

Purpose

This study evaluated the impact of an automated denoising technique on magnitude-based parameter mapping of R2* and fat fraction (FF) values. Two related applications were investigated: multi-echo relaxometry for R2* and multi-echo Dixon for water, fat and R2* estimation. Magnitude-based fitting is often used because it is robust against phase estimation errors. For complex-based multi-echo Dixon, errors in the phase estimation can lead to a clinically relevant bias at low fat percentages[1]. However, for higher R2* values or low SNR, the magnitude-based fitting introduces an increasing bias due to noise floor effects, making a correct delineation of high R2* values infeasible[2]. Additionally, the SNR of a multi-echo series for quantification is rather sensitive to the choice of the signal model, echo spacing and initial TE[2]. Yet, pathological R2* values of 1000 $\mathbf{s}^{-1}$ and higher do occur, and an accurate iron staging during therapy would be desirable. This is prohibited with magnitude-based methods unless noise effects are compensated, e.g., through echo truncation, noise fitting or denoising. This abstract demonstrates that an automated spectrum-based noise removal on the multi-echo signal leads to a large reduction in bias and uncertainty that is associated with magnitude-based parameter mapping.

Methods and Materials

In order to improve the noise-affected magnitude fitting, we propose to denoise the complex-valued multi-echo series prior to parameter estimation using an automated sliding-window locally low-rank (LLR) denoising[4]. It reconstructs the signal by patchwise minimization of the rank of the multi-echo series which can be considered as a noise averaging across contrast images. Advantages of this type of denoising include that it is model-consistent with relaxometry and Dixon, parameter-free and edge-preserving[4].

Experimental setup:

Numerical simulations were performed using 2500 averages with additive complex noise with unit normal distribution to match the specified SNR setup. The noise-affected data was fitted in the first pass, followed by a fit of the same but denoised data using the LLR processing with a block-size of $5^2\,\mathbf{x}$ #TE. Both results were compared to the ground truth. The fitting was based on variable projection with line search, and a non-linear Levenberg-Marquardt optimization, for relaxometry and multi-echo Dixon, respectively.

Relaxometry:

12 TEs with short spacing ΔTE = 1 ms and an initial TE$_1$ = 1 ms, yielding a good SNR performance were used. Based on a mono-exponential signal model, $S(t) = \mathrm{SNR} \cdot \mathrm{e}^{-R_2^* t} + \mathcal{N}_{\mathbb{C}}(0, 1)$, R2* values ranging from 0 to 1200 $\mathbf{s}^{-1}$ were generated for a fixed SNR 25.

Multi-echo Dixon:

A typical 6-echo protocol with TEs = 1.26, 2.60, 3.94, 5.28, 6.62, 7.96 ms and a signal model with a predefined fat calibration $\boldsymbol{c}_t$ at 1.5 T, single R_2^*, and without modeling phase effects $S(t) = \mathrm{SNR}((1 - \mathrm{FF}) + \boldsymbol{c}_t \mathrm{FF})\mathrm{e}^{-R_2^* t} + \mathcal{N}_{\mathbb{C}}(0, 1)$ was used. R2* values were ranging from 0 to 1200 $\mathbf{s}^{-1}$ and FF values from 0 to 100% for SNRs of 60 and 30.

In-vivo multi-echo Dixon:

Data from a patient with high iron overload was acquired using 6 TEs = 1.05, 2.20, 3.35, 4.50, 5.65, 6.80 ms and a TR = 15.6 ms on a 1.5 T MRI Scanner (MAGNETOM Aera, Siemens Healthcare, Erlangen, Germany). Matrix: $160 \times 112 \times 64$. Flip angle $= 4°$.

Results and Discussion

The results of the R2* mapping for relaxometry are given in Fig. 1. There is an increasing bias for higher R2* values, making a correct delineation of rapid relaxation values infeasible due to noise floor effects at SNR 25. Denoising largely removes this bias and reduces the standard deviation.

Figs. 2 to 4 show the results of FF and R2* estimation for a multi-echo Dixon technique based on two SNR setups of 30 and 60. A small bias for FF values at low fat percentages can be seen even for normal relaxation values which gets worse for high iron deposition. Also, due to noise floor fitting, the R2* bias for higher values increases further for faster relaxations. The denoising prior to the fitting largely removes the bias and increases the SNR by a factor of more than 2.

Fig. 5 demonstrates the impact of the denoising on in-vivo data, where a moderate bias in relaxation and a strong bias in FF values occurred. The effects of an 2.4% rise in relaxation and 28.7% reduction in the FF due to denoising are in accordance to our simulations for an SNR of about 60.

Conclusion

We confirmed the noise bias in magnitude fitting from previous studies which can lead to misinterpretations for the biomarker, FF and R2*, using magnitude-based fitting.

Based on numerical simulations, an LLR-based denoising of the original echo series improved the SNR by a factor larger than 2 and, thereby, reduced the bias and the uncertainty in all biomarkers.

For in-vivo data with a high iron overload, denoising strongly reduced the bias for FF and moderately for R2* values, matching the findings from our simulations.

References

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Figures
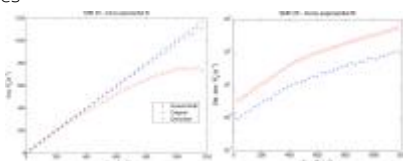
Magnitude-based relaxometry for an SNR of 25: an increasing bias for higher R2* values makes a correct delineation of very high relaxation values due to noise floor effects infeasible. Spectral denoising of the multi-echo series prior to the fit largely removes this bias, and also reduces the standard deviation (uncertainty) by about a factor of 3.
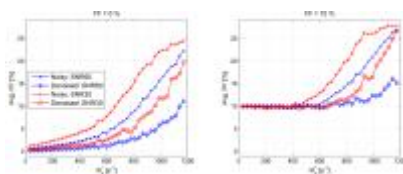

The measured FF is plotted against increasing R2*s for a true FF of 0% (left) and 10% (right). The fit using original and denoised data is drawn for a SNR of 60 and 30. Even for low, normal R2* values, a bias in the

FF estimation is introduced which rises for increasing R2* values (left). For higher FFs, there is a bias only for a pathological R2*. Effects are very sensitive to the SNR. Spectral denoising increased the SNR by more than factor 2, and, thus, considerably reduced the bias.
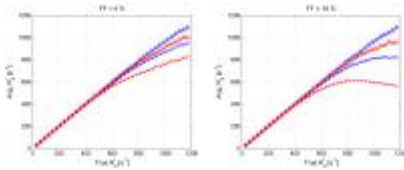
The measured R2* is plotted against increasing R2*s for a true FF of 0% (left) and 10% (right). The fit using original and denoised data is drawn for a SNR of 60 and 30. The bias in R2* values increases with higher iron overload but is also worse for higher FFs (right). Effects are very sensitive to the SNR. The denoising largely removed the bias in R2* values and seems more effective at low SNRs due to the SNR-sensitivity of the bias.
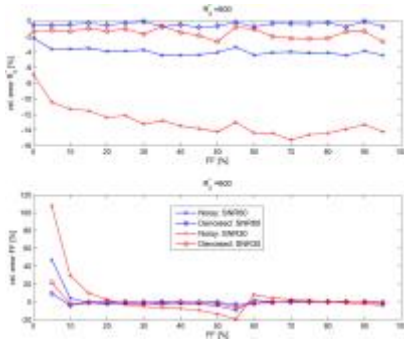
Relative errors for FF and R2* values are shown for a high R2* w.r.t. to a SNR of 60 and 30. For a low SNR, the R2* error rises with higher FFs to an underestimation of about 14%, while for a higher SNR a constant underestimation of about 4% occurs. For both SNR setups, the denoising reduced the bias to about 1% and 2% underestimation. The bottom plot shows a drastic FF overestimation of more than 20% for both SNR setups which was considerably reduced by denoising, indicating a strong SNR gain.
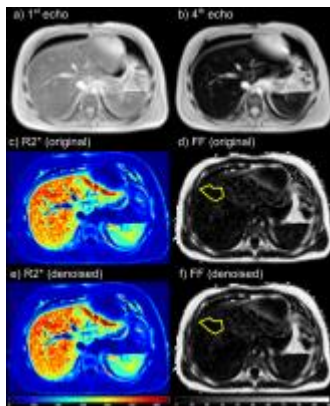
Iron deposition leads to a strong signal decay which is noticeable when comparing the first and the fourth echo where most of the signal is already vanished (a, b). Accordingly, the hepatic R2* values indicate a rapid relaxation of 600 s^{-1} (yellow ROI at FF, also used for R2*) using the original and 614.1 s^{-1} using the denoised data (c,e). The combination of iron overload and noise floor yields an FF bias towards an overestimation of low FF values: 3.5% to 2.1% before and after denoising (d,f).