Addressing phase errors in fat-water imaging using a mixed magnitude/complex fitting method

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Introduction: Fat quantification using MRI has multiple important applications, including the early diagnosis and quantitative staging of non-alcoholic fatty liver disease (NAFLD). Accurate measurements, particularly at low fat-fractions, are critical for detection/classification of NAFLD. Chemical shift-based fat quantification methods acquire images at multiple echo times (TEs) using multi-echo SPGR, and provide fat-fraction measurements through post-processing. However, phase errors, such as those caused by eddy currents, can affect fat quantification. These phase errors are typically most significant at the first echo of the echo train, and introduce bias in complex-based fat quantification techniques. These errors can be overcome using a magnitude-based technique (where the phase of all echoes is discarded) [1,2], but at the cost of degraded SNR (especially for certain choices of echo time combinations). The purpose of this work is to develop a reconstruction method that overcomes the phase errors without the SNR penalty incurred by magnitude fitting.

Theory: The complex-valued signal in a fat-water imaging acquisition can be modeled as [3]:

$$s_{\text{model}}(TE, \text{W}, \text{F}, \text{R}_2{*}, \text{f}_\text{B}) = \left(W + F\sum\nolimits_m \alpha_m \exp(j2\pi f_m TE)\right)\exp(-R_2{*}\,TE)\exp(i2\pi f_B TE)$$

where W and F are the water and fat signal amplitudes, respectively, fat has multiple peaks with frequencies f_m and relative amplitudes α_m [3], $R_2{*} = 1/T_2{*}$ and f_B is the local frequency offset due to B_0 field inhomogeneity. However, the acquired signal s_{acq} can be corrupted by phase errors (e.g., due to eddy currents). In multi-echo SPGR acquisitions, phase errors often occur in the first echo, whereas the phase remains unperturbed in the remaining echoes (see Figure 1). If these errors are not accounted for, fitting the signal model s_{model} to the acquired complex signal s_{acq} will result in systematic error (bias) in the fat-fraction estimates. Magnitude fitting has been proposed to address this problem [1], and has been shown to produce unbiased fat-fraction estimates in the presence of phase errors. However, magnitude fitting results in significant SNR loss, particularly for certain echo time combinations. In this work, we propose a mixed fitting method that uses the magnitude of the first echo (where phase errors typically occur), and the complex-valued signal from the remaining echoes (where phase is unperturbed):

$$\min_{\text{W,F,R}_2{*},\text{f}_\text{B}} \left\{ [|\, s_{\text{model}}(TE_1, \text{W}, \text{F}, \text{R}_2{*}, \text{f}_\text{B}) \vdash - |\, s_{\text{acq}}(TE_1)\,|]^2 + \sum_{n=2}^{\text{Necho}} |\, s_{\text{model}}(TE_n, \text{W}, \text{F}, \text{R}_2{*}, \text{f}_\text{B}) - s_{\text{acq}}(TE_n)\,|^2 \right\}$$

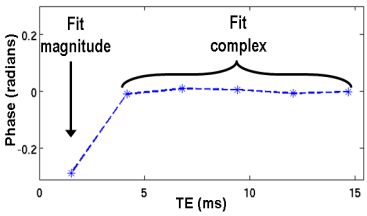

Figure 1: Measured phase evolution in a phantom (water-only vial), after demodulating the linear phase caused by B_0 inhomogeneities. Ideally, the phase should be a straight line. The proposed method seeks to overcome the phase errors while using all the reliable data available, by discarding only the phase of the first echo.

Experiments: An oil-water phantom was constructed as in Ref. [4], with fat-fractions 0, 5, 10, 20, 30 and 100%. Phantom data were acquired at 1.5T using an investigational version of a 3D SPGR multi-echo "IDEAL" sequence, with two different sets of 6 TEs: (TE_{min}=1.52ms, ΔTE=2.63ms) and (TE_{min}=1.26ms, ΔTE=2.11ms). Liver data were acquired, in accordance with our Institutional Review Board, from 10 subjects using the same sequence (TE_{min}=1.30ms, ΔTE=2.18ms). Each subject was scanned twice, and a STEAM-MRS spectrum was obtained as the reference standard.

Results: Figure 2 shows the theoretical noise performance of complex, magnitude and mixed fitting, for 6-echo acquisitions with various choices of initial echo (TE_{min}) and echo spacing (ΔTE). Magnitude fitting results in large SNR loss for choices near TE_{min}~1.3ms, ΔTE~2.2ms, while mixed fitting results in uniformly good SNR. Figure 2 (right) shows phantom reconstructions from two sets of TEs (marked A and B). Complex fitting results in a negative bias in FF estimates (*y=1.04x-1.41*), particularly at the lower FF vials (which were placed further from the magnet isocenter), while magnitude fitting results in very poor SNR for the "B" set of TEs (quantitative results are not shown for magnitude fitting due to unstable results). Mixed fitting provides low bias (*y=1.02x+0.22*) with good SNR for both sets of TEs. *In vivo* results (Figure 3) are in good agreement with phantom results. The 5% bias often produced by complex fitting may result in clinically relevant errors for the detection/classification of NAFLD.

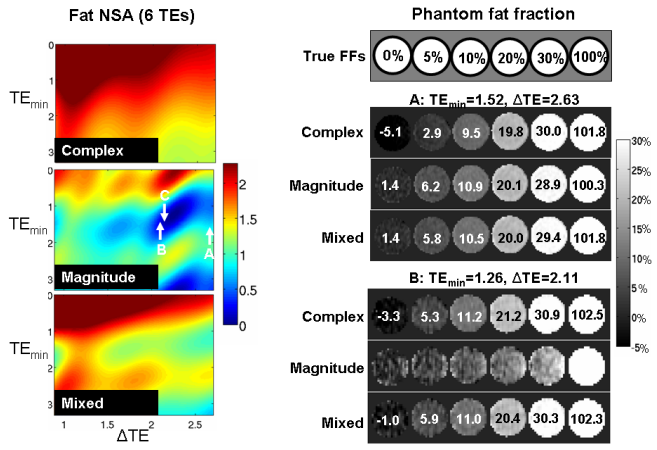

Figure 2: (Left) Number of signal averages (NSA) for fat estimation using various choices of six TEs at 1.5T (fat-fraction=10%, $R_2{*}$=40 s^{-1}) [5,6]. (Right) Phantom results for two different sets of echo times.

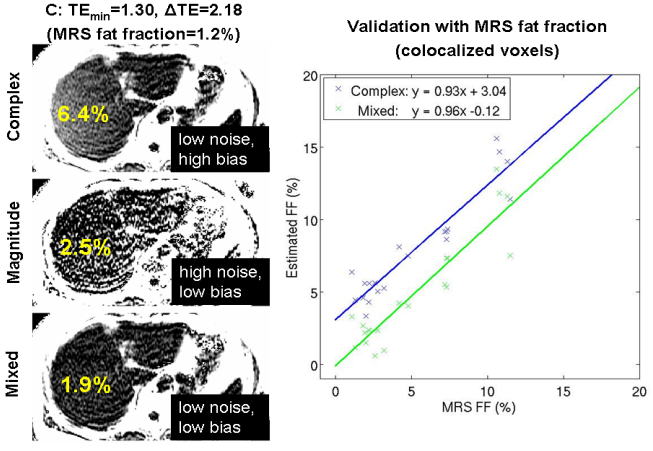

Figure 3: Liver fat-fraction results. Complex fitting produces biased fat-fraction estimates, particularly at low fat-fractions. Magnitude fitting introduces high noise. Mixed fitting is able to remove bias and maintain SNR.

Conclusion: Through careful modeling of the acquired signal, the proposed mixed fitting method enables accurate fat quantification in the presence of common phase errors, with good SNR performance, low bias and over a wide choice of echo time combinations.

References: [1] Yu H, et al, ISMRM 2009, p. 461. [2] Bydder et al, MRI 2008;26:347–359. [3] Yu et al, MRM 2008;60:1122–1134. [4] Hines CDG et al, JMRI 2009;30:1215-1222. [5] Pineda et al, 2005;54:625–635. [6] Karlsen et al, MRM 1999;41:614–623.

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