Systematic study of signal models for fat quantification at 3T using chemical shift imaging

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Purpose: Liver fat fraction (FF) quantification is an important tool that can help staging non-alcoholic fatty liver disease. The gold-standard procedure for FF quantification, is percutaneous biopsy, which is expensive and prone to post-surgical complications. Non-invasive alternatives include magnetic resonance spectroscopy and chemical shift imaging (CSI) using multi-echo gradient-echo (ME-GRE) pulse sequences. The latter method is very appealing because data acquisition is typically fast and well tolerated by patients. Models based on the analysis of magnitude and complex data have been used to separate water and fat components from ME-GRE images and several studies have been dedicated to advantages and disadvantages of each. It is accepted that the complex model is, in general, more accurate in estimating FF values, particularly those above 50%, while magnitude model is easier to implement [1]. In an attempt to combine the advantages of both methods, a "mixed" approach has been recently proposed [2]. Despite all the advances, the fact remains that clinical applications of FF quantification using CSI largely overlook these aspects. In this paper, we provide a systematic analysis of different signal models to quantify FF at 3T using ME-GRE pulse sequences with twelve echoes, with a view on optimizing the combination of echo times (TEs). We furthermore study the influence of magnetic field heterogeneities in the accuracy of the complex model for FF estimation.

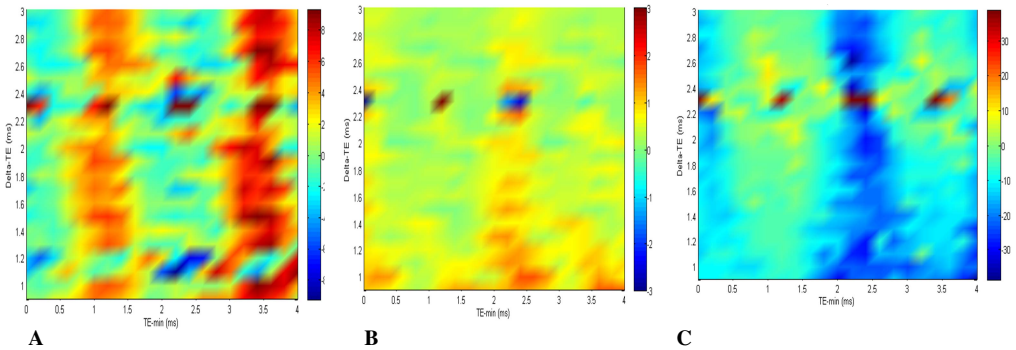
Methods: The full complex signal in ME-GRE images can be described as: $S = \left[S_{water}e^{-t/T^*_{2,water}} + S_{fat}e^{-t/T^*_{2,fat}}e^{i\Delta\omega_{cs}t}\right]e^{i\Delta\omega t}$ (1)

where $S_{water(fat)}$ is the signal intensity of the water (fat) component, $T^*_{2,water(fat)}$ is the T_2^* relaxation constant of water (fat), $\Delta\omega_{cs}$ is the chemical shift at 3T and $\Delta\omega$ is the off-resonance effect due to magnetic field heterogeneities. In order to systematically study the accuracy of FF estimation as a function of echo time combination, Monte Carlo simulations, with 1000 (Rician or Gaussian) noise realizations, were carried-out in four situations: a(b)) Calculations with magnitude data ($|S|$) and $T^*_{2,water} = (\neq)T^*_{2,fat}$; c(d)) Calculations with complex data (S) and $T^*_{2,water} = (\neq)T^*_{2,fat}$. The accuracy of FF estimation was quantified using the following parameters:

$$\text{NSA}=\sqrt{\sigma_{noise}/\sigma_{FF_E}};\ \text{Bias}=(\overline{FF_E} - FF)/FF \times 100;\ \text{Error}=\sigma_{FF_E}/FF \times 100 \quad (2)$$

where σ_{noise} and σ_{FF_E} are the noise and FF standard deviation respectively and $\overline{FF_E}$ is the average of the FF estimations (FF_E) over all noise realizations. Further simulation parameters were $T^*_{2,water} = 23.8\,ms$ and $T^*_{2,fat}$=18.5 ms, FF=5, 25, 50 and 75%, 5% relative noise amplitude. FF was estimated from (1) using the Levenberg-Marquardt minimization procedure.

Results: Results of simulations with model (d) (fig. 1) show that, according to previous results, the complex model is robust in providing unbiased estimations of FF, even if the FF is of the same order magnitude as the noise level. On the contrary, the magnitude model (results not shown) fails completely in providing unbiased FF estimations in all FF ranges and particularly for values above 50%. For all models, the accuracy of the estimation is highly dependent on the combination of TEs. Furthermore, in the case of the complex model, Bias and Error are lower if the assumption $T^*_{2,water} \neq T^*_{2,fat}$ is made, whereas for the magnitude model, the opposite occurs. Finally, performance of the complex model heavily (fig.2) degrades under the effects of phase errors due to magnetic field heterogeneities.



A **B** **C**

Figure 1. Bias (%) as a function of minimum TE (*TE-min*) and echo spacing (*Delta-TE*) for: A) FF=5% B) FF=50% C) FF=75%.

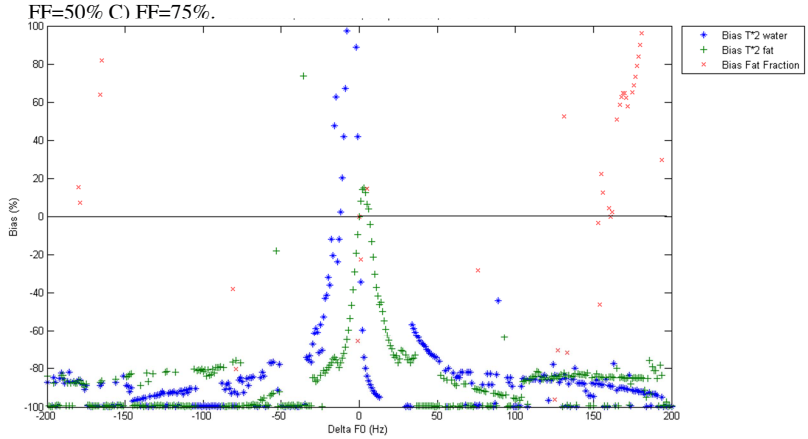


Figure 2. Bias (%) as a function off-resonance (*DeltaF0*) where estimations were performed with model (d).

Discussion: The signal models for FF quantification using ME-GRE images provide different degrees of accuracy in FF estimation. In line with previous studies, the use of complex data to estimate FF and assuming $T^*_{2,water} \neq T^*_{2,fat}$ provides more accurate and unbiased estimations of FF. However, the combination of TEs that is used to sample the data is influential in the performance of the complex (magnitude) model for FF quantification. Finally, the presence of phase errors are a great confounding effect in estimating FF using the complex model.

Conclusion: The use of ME-GRE images for FF quantification is an attractive method because it is non-invasive, fast and easy to implement in a clinical routine. However, in order to obtain estimations that concur with those obtained by other more established methods, complex images should be used in the analysis and changes to the pulse sequenced should be carried-out in order to minimize the effects of phase errors.

References: [1] Hernando et al., MRM, 64: 811-822, 2010 [2] Hernando et al., MRM, 67:638-644, 2012