The effect of echo time sampling on B0 field map estimation for QSM of liver iron overload

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Target Audience: Researchers interested in quantitative susceptibility mapping.

Purpose: Precise estimation of the B0 field map is a critical component of many applications such as chemical shift encoded water-fat imaging[1] and quantitative susceptibility mapping (QSM)[2,3]. In particular, QSM consists of estimating the tissue magnetic susceptibility distribution from a measured B0 field map. Further, when using a mapping between magnetic susceptibility and liver iron concentration (LIC)[4], it is possible to derive a relationship between the B0 field map and the LIC[5]. In order for this B0-based measurement of LIC to be precise (i.e. have low standard deviation), the estimate of the B0 field map itself must be precise. Therefore, ***the purpose of this work*** was to analyze the theoretical effects of echo time sampling on the precision of the B0 field map estimate, and further, translate these results into precision limits of the LIC estimate.

Theory: The B0 field map (as well as an R2* map and separated water-fat images) can be estimated from a multi-echo SPGR sequence using a chemical shift encoded reconstruction[1]. With QSM, the LIC is estimated from the B0 field map. Therefore, the precision of the LIC estimate will depend on the precision of the B0 field estimate. To measure precision, Cramer-Rao Lower Bound (CRLB) analysis can be used to derive a lower bound on the standard deviation of the B0 field map estimate. Recent work, which used a susceptibility-based fat-referenced boundary approach, has derived a linear relationship between the B0 field and the LIC[5]. From that relationship, the standard deviation of the LIC estimate (δ_{LIC}, in mg/g, dry tissue) can be calculated as: $\delta_{LIC} \approx 19.91\delta_{B0}$ **[1]**, where δ_{B0} is the standard deviation of the B0 field estimate (in ppm) that was derived from the CRLB analysis.

Methods: In this work, the CRLB on the standard deviation of the B0 field estimate was calculated as a function of the number of echo times, liver fat fraction values (0-20%) that are typically observed, and R2* values (0-500s^{-1}, at 1.5T) that correspond to clinically relevant concentrations of liver iron overload. It was especially important to consider R2* in the analysis because a high R2* value in the liver, which is indicative of high LIC, causes a rapid transverse signal decay. The low SNR at the later echoes propagates into the estimate of the B0 field map, as shown in Figure 1. The CRLB analysis used a signal model with multi-peak fat spectrum and common R2* value between water and fat. The baseline SNR values (at TE = 0) used in the analysis were chosen to be 10, 20, and 50, and the initial echo time (TE_{init} = 1.2ms) and the echo spacing (ΔTE = 2.0ms) were chosen from a typical 1.5T clinical, multi-echo, 3D SPGR liver acquisition. The lower bound on the standard deviation of the LIC estimate, δ_{LIC}, was calculated from δ_{B0} using Eq. 1. Further, liver iron treatment recommendations reported by Olivieri et al.[6] set a maximum LIC equal to 1.2 mg/g dry tissue for normal individuals and minimum LIC equal to 3.2 mg/g for patients who would be considered for chelation treatment. To separate these groups with a 95% confidence interval, a maximum value on δ_{LIC} was chosen to be 1mg/g.

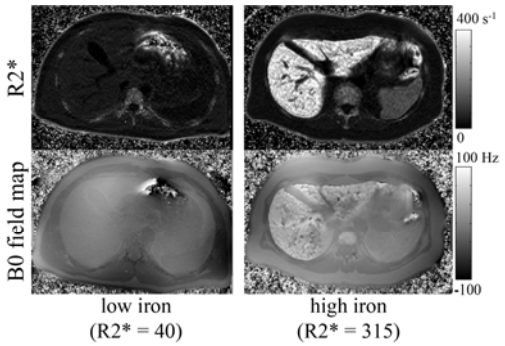

Figure 1: R2* and B0 field map estimates in the liver from one patient without liver iron overload (left) and another patient with high liver iron overload (right). Notice that the field map estimate in the liver with high iron (i.e. high R2*) exhibits greater noise than the liver with low iron (and low R2*). This demonstrates the importance of including R2* in the CRLB analysis.

Results: Figure 2 plots the lower bound on the standard deviation of the LIC estimate (δ_{LIC}) as a function of R2* value and the number of echo times (N_{te}) at SNR = 10. The standard deviations were averaged over the fat fraction values. The dashed lines mark the boundary where δ_{LIC} = 1mg/g for each SNR used in the analysis. With a threshold of 1mg/g at SNR = 10, it is seen that only a limited range of low R2* values ($\leq$ 100s^{-1}) and any number of echoes $\geq$ 6 would yield an acceptable estimate of LIC with current acquisition parameters. With higher SNR, a broader range of R2* values and number of echoes yield an acceptable estimate. Generally, δ_{LIC} decreases as the number of echoes increases. However, even with SNR = 50, after R2* reaches 300s^{-1}, sampling beyond six echoes results in very little improvement in the standard deviation of the LIC estimate because the transverse signal has significantly decayed away. Improved performance would require shorter TE_{init} and/or ΔTE.

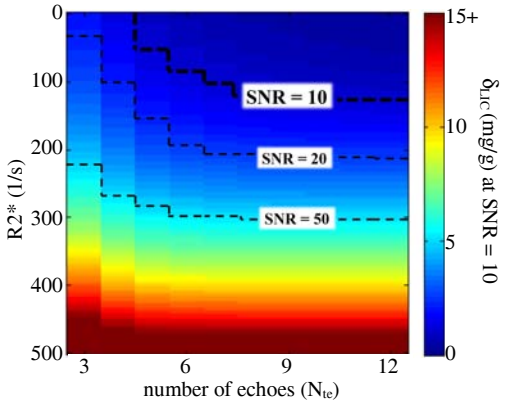

Figure 2: Cramer-Rao Lower Bound analysis showing the standard deviation of the liver iron concentration (δ_{LIC}) estimate (in mg/g dry tissue) as a function of R2* (=1/T2*) and the number of echoes at SNR = 10. The dashed boundaries mark where δ_{LIC} = 1mg/g for SNR = 10, 20, and 50. Above and to the right of the boundary, the δ_{LIC} < 1mg/g, whereas below and to the left of the boundary, δ_{LIC} > 1mg/g.

Discussion and Conclusion: We have developed a framework for characterizing the effects of echo sampling on the precision of the B0 field map estimate. Using previous work that derived a relationship between the B0 field map and LIC, we have applied this framework to analyze the precision of the LIC estimate. It was found that only a very limited range of clinically relevant R2* values and number of echoes would provide an LIC estimate with $\delta_{LIC} \leq$ 1mg/g. Further, it was found that for R2* values greater than 300s^{-1}, sampling beyond six echoes had very little benefit on the precision of the LIC estimate. The CRLB analysis was done on a per-voxel basis; averaging the LIC estimate over a homogeneous region of interest would reduce the standard deviation of the estimate, as would higher SNR. While this work has focused on the effect of the number of echoes on the precision of the B0 field and LIC estimate, the framework can be easily modified to examine the effects of other acquisition parameters such as initial echo time and echo time spacing.

References: [1]Reeder et al., MRM 2005;54:636-644. [2]Schweser et al., Neuroimage 2011;54:2789-2807. [3]Liu et al., MRM 2011;66:777-783. [4]Schenck, Med Phys 1996;23:815-850. [5]Hernando et al., MRM 2013;70:648-656. [6]Oliveri et al., Blood 1997;89:739-761.

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