Optimizing the data acquisition strategy for quantitative susceptibility mapping in the liver

Samir D. Sharma[1], Diego Hernando[1], Debra E. Horng[1,2], and Scott B. Reeder[1,2]
[1]*Radiology, University of Wisconsin, Madison, WI, United States,* [2]*Medical Physics, University of Wisconsin, Madison, WI, United States*

Target Audience: Researchers who are interested in quantitative susceptibility mapping (QSM).

Purpose: QSM techniques for the liver[1,2] enable an imaging biomarker of liver iron overload that is based on a fundamental physical property of tissue (i.e. magnetic susceptibility). The development of QSM in the liver has thus far focused on the reconstruction of the susceptibility map from the B_0 field map, whereas little consideration has been given to the data acquisition component. In particular, the choice of echo times significantly affects the variance (i.e. precision) of the estimated susceptibility map. Therefore, the ***purpose of this work*** was to optimize the data acquisition scheme for QSM in the liver as a quantitative imaging biomarker of liver iron overload.

Theory: The estimated susceptibility distribution ($\hat{\chi}$) can be reconstructed from the B_0 field map (ψ) using an l_2-regularized reconstruction[2] that can be written as $\hat{\chi} = R\psi$, where R denotes the reconstruction matrix. The covariance matrix of $\hat{\chi}$ is written as $cov(\hat{\chi}) = Rcov(\psi)R^H$, where R^H is the conjugate transpose of R. Assuming a shift-invariant reconstruction model, the sum of the variances of $\hat{\chi}$ [i.e. $trace(cov(\hat{\chi}))$] is minimized by minimizing the sum of the variances of ψ [i.e. $trace(cov(\psi))$]. Further, the variance of the B_0 field estimate can be characterized using Cramér-Rao Bound (CRB) analysis, which derives the minimum variance of an unbiased estimator. In this work, we calculated the CRB on the B_0 field estimate as a function of the first echo time (TE_1), the echo spacing (ΔTE), and the number of echoes (nTE), to determine the optimal data acquisition parameters for QSM in the liver.

Methods: ***Signal Model***: The measured signal at echo time TE can be written as a function of the water component (ρ_w), fat component (ρ_f) with known multi-peak fat spectrum modeling (c_{TE}), B_0 field (ψ), and R2* value, in the presence of complex additive white Gaussian noise: $s(TE) = (\rho_w + c_{TE}\rho_f)e^{j2\pi\psi TE}e^{-R2^*TE} + N(0,\sigma^2)$ [**Eq. 1**].

Cramer-Rao Bound Analysis: The CRB on the B_0 field estimate is a function of the water and fat components and the R2* value. We calculated the CRB as a function of liver fat fraction (FF) [i.e. $\rho_f/(\rho_w + \rho_f)$] ranging over clinically observed values (0-40%) and R2* values ranging from 0-1000s^{-1} (at 1.5T) for the following data acquisition parameters: TE_1 = [0–2.3 ms], ΔTE = [0.1–2.3 ms], and nTE = [3–12]. We adopted a *min-max* criterion whereby we sought to *minimize* (over the acquisition parameters) the *maximum* (over R2* and FF) variance of the B_0 field estimate. The analysis also included the following three practical considerations: 1) minimum echo spacing for one acquisition shot was set to 1.0 ms, which is achievable by most modern MR systems, 2) flip angle was set to the Ernst angle to maximize SNR in the liver and, 3) the scan time was equalized based on the TR of each candidate data acquisition scheme, which manifested as a scaling of the SNR for those schemes with multiple signal averages.

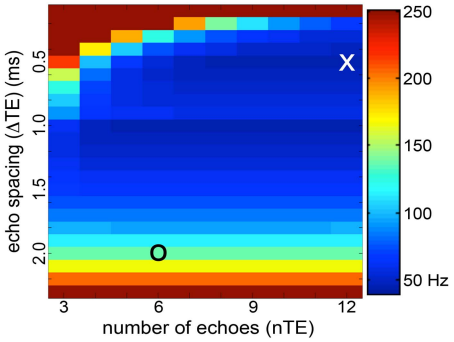

Figure 1: CRB on the B_0 field estimate as a function of ΔTE and nTE, for TE_1 = 0.7 ms. The optimal min-max acquisition scheme is denoted by the white 'x'. A standard acquisition scheme that has been used for QSM in the liver[2] is denoted by the black 'o'.

Monte-Carlo Simulations: Numerical susceptibility phantoms were created with FF values ranging from 0–40% and R2* values ranging from 0–1000s^{-1}. The true B_0 field map was calculated from the susceptibility distribution using the dipole response function[3]. Source images were then generated using Eq. 1 with SNR [i.e. $(\rho_w + \rho_f)/\sigma$] equal to 14, based on our previous in-vivo liver experiments. A chemical shift encoded reconstruction[4] was used to estimate the B_0 field map. Finally, the susceptibility map was estimated from the B_0 field map using an l_2-regularized QSM reconstruction[2].

Results: CRB analysis revealed that, in general, a shorter TE_1 results in a lower variance of the B_0 field estimate. Using TE_1 = 0.7 ms as the shortest achievable first echo, Figure 1 plots the CRB as a function of ΔTE and nTE. The optimal min-max acquisition was determined to be ΔTE = 0.5 ms and nTE = 12, although there exists many combinations of ΔTE and nTE that result in only slightly higher standard deviation (dark blue regions in Fig. 1). The results from Monte-Carlo simulations (Figure 2) agree with the CRB analysis, showing that the optimal min-max acquisition yields B_0 field and susceptibility estimates with lower standard deviation.

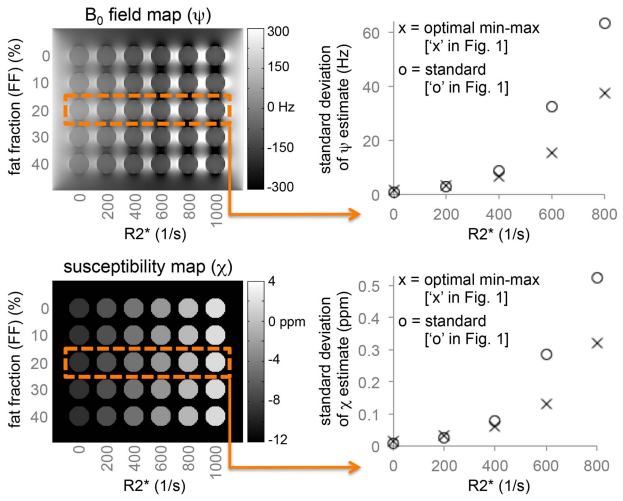

Figure 2: ***(left)*** Reference B_0 field map and susceptibility map. ***(right)*** Representative results from Monte-Carlo simulations using the optimal min-max acquisition (white 'x' in Fig. 1) and a standard acquisition scheme (black 'o' in Fig. 1). The optimal min-max acquisition yields B_0 field and susceptibility estimates with lower standard deviation at the higher R2* values. Monte-Carlo results are not shown for R2* > 800s^{-1} because the B_0 field estimates exhibited bias.

Discussion and Conclusion: We have used CRB analysis and Monte-Carlo simulations to optimize the data acquisition for QSM in the liver. Future work will use phantom and in-vivo studies to further validate our findings.

References: [1]Dimov et al. ISMRM 2014 p.2147. [2]Sharma et al. MRM DOI:10.1002/mrm.25448. [3]de Rochefort et al. MRM 2010;63:194-206. [4]Reeder et al. MRM 2005;54:636-44. **Acknowledgements:** The authors acknowledge the support of the NIH (R01DK083380, R01DK088925, R01DK100651, and UL1TR00427). We also wish to thank GE Healthcare for their support.