Noise Analysis for Chemical Shift Based Water-Fat Separation with Independent T2* Correction for Water and Fat

V. V. Chebrolu[1], H. Yu[2], A. R. Pineda[3], C. A. McKenzie[4], J. H. Brittain[5], and S. B. Reeder[1,6]

[1]Biomedical Engineering, University of Wisconsin Madison, Madison, WI, United States, [2]Applied Science Laboratory, GE Healthcare, Menlo Park, CA, United States, [3]Department of Mathematics, California State University, Fullerton, CA, United States, [4]Department of Medical Biophysics, University of Western Ontario, London, Ontario, [5]Applied Science Laboratory, GE Healthcare, Madison, WI, United States, [6]Radiology, University of Wisconsin Madison, Madison, WI, United States

Introduction: Non-invasive biomarkers of intracellular accumulation of fat within liver (hepatic steatosis) are urgently needed for detection and quantitative grading of non-alcoholic fatty liver disease, the most common cause of chronic liver disease in the US. Accurate quantification of fat with MRI is challenging due the presence of several confounding factors including T_2^* decay[1,2]. The specific purpose of this work is to model and compare the theoretical SNR behavior of chemical shift imaging methods for quantifying liver fat that model a common value of T_2^* of water and fat (single T_2^*)[1-3] and model T_2^* independently for water and fat (dual T_2^*)[4], over clinically relevant fat-fractions.

Theory and Methods: The signal at time t from a voxel containing water (modeled as a single discrete peak) and fat (modeled as a sum of weighted peaks[5]) having independent T_2^* decay is:

$$s(t)=(W\exp(-R_w t)+F\exp(-R_f t)\textstyle\sum_{p=1}^{P} r_p \exp(2\pi i\Delta f_p t))\exp(2\pi i\psi t) \quad [1]$$

where W and F are the water and fat signals, ψ is the shift (Hz) in the spectrum caused by local Bo field inhomogeneities, R_w is the R_2^* of water and R_f is the R_2^* of fat, Δf_p is the frequency offset of the p^{th} fat peak, r_p are the relative proportions of the fat peaks such that $\sum_{p=1}^{P} r_p = 1$. The spectral content of fat in liver was estimated using MRS by Middleton et al[6]. If we assume that the T_2^* of fat and water are equal, ie: $R_w=R_f=R_2^*$, we obtain the single exponential T_2^* signal model first described by Yu et al for T_2^*-corrected chemical shift based water-fat separation[1,3].

Theoretical noise behavior was computed using the Cramér-Rao bound (CRB) for the single T_2^* model and also for the dual T_2^* model described in Equation 1. CRB analysis uses the Fisher information matrix[7,8] to estimate the sensitivity of data acquired to the parameters being estimated in the presence of noise. Noise performance of a water-fat decomposition was measured using the metric of effective number of signal averages[7,8] (NSA). For a particular echo combination, theoretical NSA values of water and fat were computed with fat-fractions ranging from 0 to 100% fat and displayed in various manners with different imaging parameters to elucidate differences between single and dual T_2^* methods.

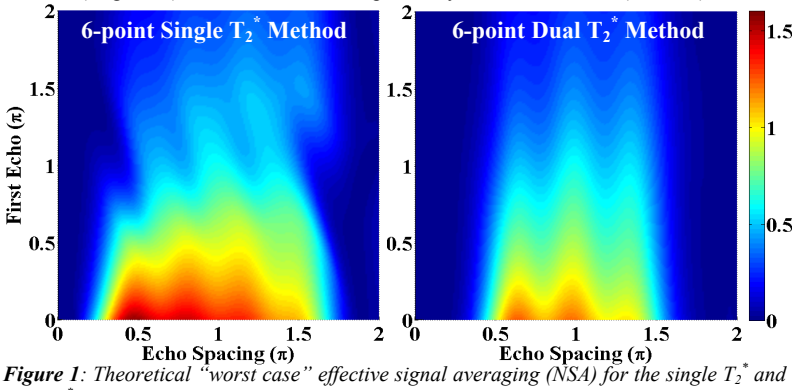

***Figure 1**: Theoretical "worst case" effective signal averaging (NSA) for the single T_2^* and dual T_2^* correction methods calculated as the minimum NSA over a range of 0-100% fat-fraction. Plots demonstrate significant differences between the two reconstruction methods indicating decreased SNR performance of the dual T_2^* correction method. These plots also demonstrate the importance of using the shortest first echo possible. Echo times are plotted in units of phase shift between the water peak and main fat peak (3.5 ppm).*

Results: Figure 1 shows the theoretical "worst-case" NSA of fat calculated as the minimum NSA over all fat-fractions (0-100%) and plotted at different echo times for a 6-echo acquisition using single and dual T_2^* correction methods, assuming the T_2^* of water and fat to be 20 ms. Figure 2 plots the NSA performance for water and fat for single and dual T_2^* models using a representative set of acquisition parameters with T_2^*=20 ms, 6-echoes, the first echo at 1.3 ms and echo spacing equal to 2.0 ms. Figure 3 shows the NSA performance at different number of echoes for single and dual T_2^* methods at clinically relevant fat-fractions for liver fat quantification (0, 25 and 50%) for water and fat.

Discussion: Adding an additional degree of freedom for dual T_2^* correction not only increases the complexity of the estimation problem[4], but also degrades the noise performance of water-fat decomposition, as predicted by theoretical differences in noise performance. Fat magnitude is affected more than the water magnitude because of the differences in spectral model between water and fat, with at least two fat peaks near the water peak.

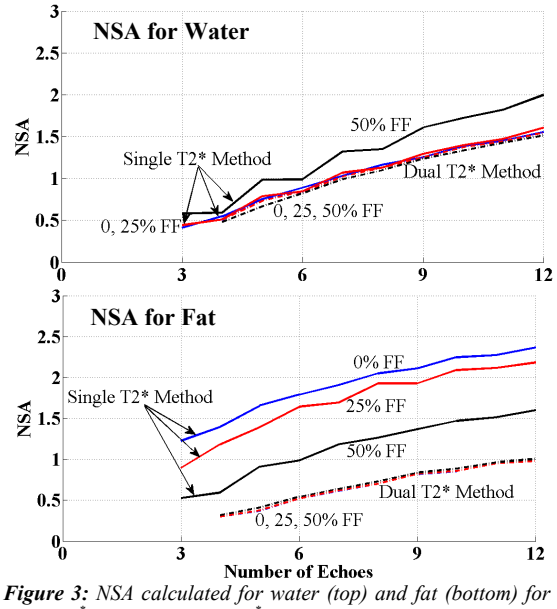

***Figure 3:** NSA calculated for water (top) and fat (bottom) for single T_2^* (solid) and dual T_2^* (dashed) correction methods, for increasing number of echoes. Calculations are performed at selected fat-fractions that are clinically relevant for liver fat quantification, assuming T_2^* of water and fat are both 20 ms, TE_{min}=1.3ms and echo spacing is 2.0ms. The SNR performance for water is similar with both methods, but single T_2^* SNR is markedly better for fat for all clinically relevant fat-fractions.*

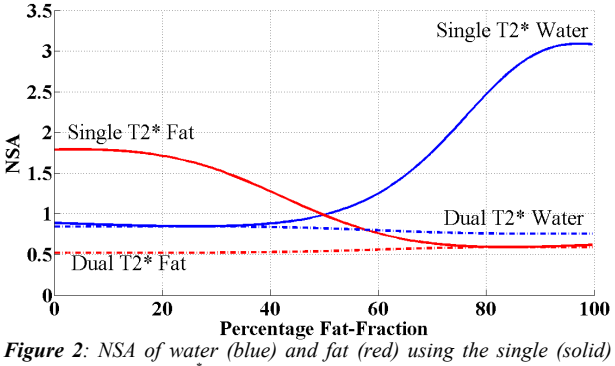

***Figure 2**: NSA of water (blue) and fat (red) using the single (solid) and dual (dashed) T_2^* correction methods. Calculated for a 6-echo acquisition with TE_{min}=1.3 ms and 2.0 ms echo spacing, assuming that the T_2^* of water and fat is 20 ms. Noise performance is highly dependent on fat-fraction and NSA for single T_2^* correction is greater than or equal to NSA for dual T_2^* correction especially in the range of fat-fractions that are relevant for quantification of liver fat (0-50%).*

Using typical acquisition parameters over a wide range of fat-fractions, we have shown that single T_2^* correction methods have consistently higher SNR performance than dual T_2^* methods. However, as shown by Hines *et al* in phantom experiments with water-fat-SPIO phantoms[9], inaccurate fat quantification can occur in phantoms with high fat-fractions and high SPIO concentrations, suggesting that a dual T_2^* correction may be necessary in patients with both high fat-fractions and high intrahepatic iron concentrations. While iron overload is known to occur in patients with NAFLD[9], it is not known how frequently severe steatosis and iron overload occur concomitantly, i.e.: what is the clinical necessity of a dual T_2^* model for accurate quantification of fat? Is the reduction in SNR performance and increased complexity of a dual T_2^* estimation method[4] necessary for accurate quantification of fat in a clinical setting? Future work will compare both T_2^* correction methods in vivo.

References: [1] Yu et al, JMRI 2007;26(4):1153-1161. [2] Bydder et al, MRI 2008;26(3):347-359. [3] Yu et al, MRM 2008;60(5):1122-1134. [4] Chebrolu et al, ISMRM 2009:2847. [5] Reeder et al. JMRI 2009;29(6):1332-1339. [6] Middleton et al, ISMRM 2009: 4331; [7] Reeder et al, MRM 2004;51(1):35-45. [8] Pineda et al, MRM 2005;54(3):625-635. [9] Hines et al, JMRI 2009;30(5):1215-1222 [10] George et al, JMRI 2009;30(5):1215-1222

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