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 T2* decay. 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 T2* of water and fat (single T2*) and model T2* independently for water and fat (dual T2*), 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) having independent T2* decay is:

\[ s(t) = W \exp(-R_w t) + F \exp(-R_{f} t) \exp(2\pi f \Delta f t) \exp(2\pi f \sigma t) \]  

where W and F are the water and fat signals, \( \sigma \) is the shift (Hz) in the spectrum caused by local Bo field inhomogeneities, \( R_w \) is the T2* of water and \( R_{f} \) is the T2* of fat, \( \Delta f \) is the frequency offset of the \( r_{p}\)th fat peak, \( \sigma_r \) are the relative proportions of the fat peaks such that \( \sum_{r} \sigma_r = 1 \). The spectral content of fat in liver was estimated using MRS by Middleton et al. If we assume that the T2* of fat and water are equal, i.e., \( \Delta f = R_{w} = R_{f} \), we obtain the single exponential T2* model first described by Yu et al for T2*-corrected chemical shift based water-fat separation.

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 T2* correction methods, assuming the T2* of water and fat to be 20 ms. Figure 2 plots the NSA performance for water and fat for single and dual T2* methods using a representative set of acquisition parameters with T2* of water and fat being 20 ms, 6-echoes, the first echo at 1.3 ms and echo spacing equal to 2.0 ms.

Figure 1: Theoretical “worst case” effective signal averaging (NSA) for the single T2* and dual T2* correction methods calculated as the minimum NSA over a range of 0-100% fat-fractions. Theoretical noise behavior demonstrates significant differences between the two reconstruction methods indicating decreased SNR performance of the dual T2* 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).

Figure 2: NSA of water (blue) and fat (red) using the single (solid) and dual (dashed) T2* correction methods. Calculated for a 6-echo acquisition with \( T_{E} = 1.3\) ms and 2.0 ms echo spacing, assuming that the T2* of water and fat is 20 ms. Noise performance is highly dependent on fat-fraction and NSA for single T2* correction is greater than or equal to NSA for dual T2* correction especially in the range of fat-fractions that are relevant for quantification of liver fat (0-50%).

Discussion: Adding an additional degree of freedom for dual T2* correction not only increases the complexity of the estimation problem, 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. 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).

Figure 3: NSA calculated for water (top) and fat (bottom) for single T2* (solid) and dual T2* (dashed) correction methods, for increasing number of echoes. Calculations are performed at selected fat-fractions that are clinically relevant for liver fat quantification, assuming T2* of water and fat to be 20 ms, \( T_{E} = 1.3\) ms and echo spacing is 2.0 ms. The SNR performance for water is similar with both methods, but single T2* SNR is markedly better for fat for all clinically relevant fat-fractions.


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