Noise Analysis for 3-pt Chemical Shift Based Water-Fat Separation with Accurate Spectral Modeling

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Introduction: Most chemical shift based water-fat separation methods model fat as a single peak. However, fat has multiple distinct chemical moieties (protons on different carbon chains) each with different chemical shifts. The presence of multiple fat peaks, if not modeled accurately, leads to incomplete separation of fat signal for qualitative fat suppression methods, and confounds attempts at quantifying fat using quantitative approaches[1,2]. Previously, we have determined the optimum echo shifts for water-fat separation methods with single peak (SP) models of fat, both theoretically[3] and experimentally[4]. The inclusion of multiple fat peaks in the signal model is expected to change the noise performance. Therefore, the purpose of this work is to model the theoretical SNR behavior of chemical shift imaging with multipeak (MP) reconstruction, and provide experimental validation.

Theory and Methods: The signal from a voxel containing water and fat can be written as

$$s(t) = \left(W + F \sum_{p=1}^{P} r_p \exp(2\pi i \Delta f_p t)\right)\exp(2\pi i \psi t) \quad - (1)$$

where W and F are the water and fat signals, ψ is the local field inhomogeneity (Hz) , Δf_p is resonant frequency of the p^{th} fat peak, r_p are the relative amplitudes of the different fat peaks such that cumulative sum fat peak amplitudes (r_p) is 1.0. It is important to note that both the frequencies (Δf_p) and relative amplitudes (r_p) of the fat peaks are assumed to be known. The values of r_p can be calculated either by pre- or self-calibration techniques[1].

The phase between water and fat at a certain echo time is commonly used to describe echo shifts for single peak models. Although this notation has no meaning with multipeak fat signal models, we will use this notation for comparison purposes and use the phase shift between water and the -224 Hz peak of fat (at 1.5T, 22°C) as a reference for comparison. The resonance frequencies used for six different fat peaks in the multipeak signal model are at -224, -173, 33, -250, -131 and -37 Hz, with relative amplitudes 0.62, 0.15, 0.10, 0.06, 0.03 and 0.04[1].

Previously, we have demonstrated a strong dependence of the noise performance of three-point chemical shift imaging on the absolute echo positions and the amount of fat within a voxel[3,4]. For a single peak reconstruction, asymmetric echoes are optimally timed with the second echo acquired with water and fat in quadrature ($\pi/2+\pi k$, k = any integer) and the first and third echo acquired $2\pi/3$ before and after the first echo. Echoes acquired symmetrically ($-2\pi/3$, 0, $2\pi/3$) have particularly poor noise performance.

To measure the noise performance of the single and multi-peak signal models, a spherical phantom with peanut oil floating on 0.9% normal saline doped with 5 mM $NiCl_2$ was imaged 200 times for each echo combination. Imaging was performed with a modified FSE pulse sequence at 1.5T (Signa HDx TwinSpeed, GE Healthcare, Milwaukee, WI, USA), using a slab obliquely oriented across the fat-water interface to achieve a wide range of fat-water ratios (figure 1). Images were reconstructed using investigational versions of the MP IDEAL and SP IDEAL techniques. Noise variances from the water images and source images were computed on a pixel by pixel basis over the 200 images. Experimental values of water NSA at each individual pixel were computed as the ratio of variance from the source images to the variance from the calculated water images[4,5]. For comparison, theoretical noise behavior was computed using the Cramer-Rao bound for the single peak case[3] and also the Cramer-Bound for the modified signal model in Equation 1.

Results: Figures 1 (a) and (b) show the water images from an axial scan acquired using asymmetrically acquired echoes ($-\pi/6$, $\pi/2$, $7\pi/6$) reconstructed using single and multi-peak signal models, respectively. Improved separation of water and fat is achieved with the multipeak reconstruction, because of a more accurate modeling of the fat spectrum.

The theoretical NSA performance of water for SP and MP models with both symmetric echoes ($-2\pi/3$, 0, $2\pi/3$) and asymmetric echoes ($-\pi/6$, $\pi/2$, $7\pi/6$) are shown in figures 2 and 3. Excellent agreement between theory and experiment is seen with both echo combinations and both reconstruction methods. Importantly, the maximum noise performance is only slightly decreased (10%) when using the multi-peak reconstruction method. This indicates that the optimized asymmetric echo combinations for single peak reconstruction also perform well for multi-peak reconstruction. Moreover, MP reconstruction results in increased range of fat-water ratios seen in figs 2 and 3, where the maximum fat-water ratio increases from ~10 to ~100.

Discussion: The use of multi-peak spectral modeling of fat will alter the noise performance of water-fat decomposition, as predicted by differences in NSA both theoretically and experimentally. Fortunately, the optimum echo spacing for single peak models also provides excellent noise performance for water reconstructed with MP IDEAL. Future work will determine the optimum echo combination and best possible noise performance for multipeak acquisitions. It is expected that the optimum echo combination for the water image will be similar to the asymmetric case optimized for single peak strategies.

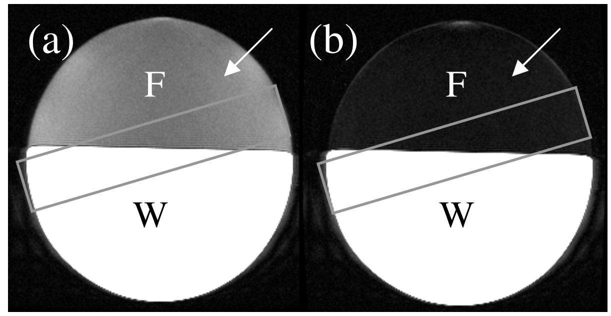

Figure 1: Improved fat-water separation can be seen by comparing the water images reconstructed with single peak IDEAL (a) and multipeak IDEAL (b). Residual fat signal in the water image of the single peak reconstruction is partially caused by fat peaks near the water peak (arrow in (a)). Window/levels are the same.

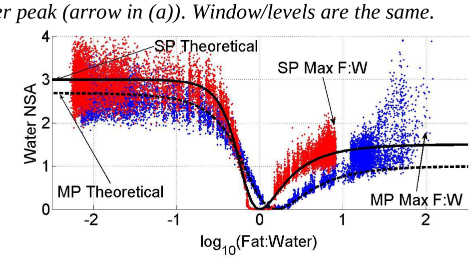

Figure 2: Theoretical and experimental effective signal averaging (NSA) of water for symmetric echoes ($-2\pi/3$, 0, $2\pi/3$) plotted for different fat-water ratios show poor noise performance when water and fat are in similar proportions within a voxel (i.e.: FWR=1), for both single and multi-peak reconstructions. Close agreement between theory and experiment was observed. Dots are data and line is theoretical prediction.

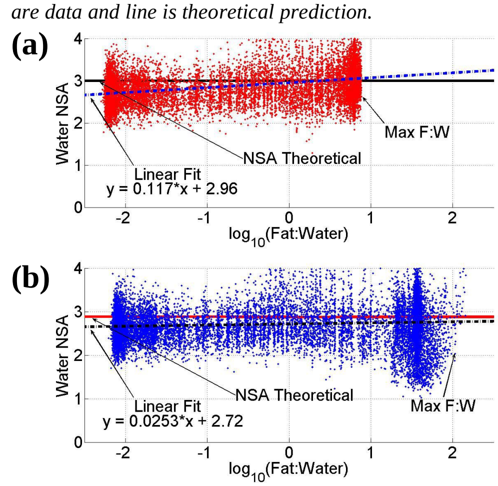

Figure 3: Using asymmetric echoes, tremendous improvement in the NSA is seen with both single (a) and multi-peak (b) reconstructions, with a small decrease in noise performance with multipeak. The drop in noise performance with multipeak reconstruction is relatively small and demonstrates that the optimal echo choice for single peak ($-\pi/6$, $\pi/2$, $7\pi/6$) also performs well for multipeak reconstruction.

References: [1] Yu et al, MRM 2008;60(5):1122-1134. [2] Bydder et al, MRI 2008;26(3):347-359. [3] Pineda et al, MRM 2005;54(3):625-635. [4] Reeder et al, MRM 2005;54(3):636-644. [5] Glover et al, JMRI 1991;1:521–530.

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