Optimization of Echo Time Shifts for 3-Pt Fat/Water Separation

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Introduction: Suppression of fat in clinical images is important because the fat signal is bright and can obscure underlying pathology in the water signal. One approach to suppress the fat signal which is insensitive to B_0 field inhomogeneities acquires images at multiple echo time shifts from the spin echo and estimates both the water and fat along with the B_0 field map i.e. "Dixon" imaging. Previous work regarding the noise considered the linear estimation of the water and fat which ignores the uncertainty from the field map [1]. We extend the noise analysis to account for the uncertainty in the field map and also study the noise performance of estimating the phase and field map. The phase is important for applications such as flow and thermometry. Optimization based on estimating each of these parameters leads to different optimal choices in echo time shifts. The optimal choice for magnitude was used recently for the **I**terative **D**ixon water-fat separation with **E**cho **A**symmetry and **L**east-squares estimation (IDEAL) method [2-5].

Theory: Our signal model has five unknowns: the water and fat magnitude and phase and the field inhomogeneity (field map). We consider fast-spin echo (FSE) in which the water and fat are aligned at the echo (t=0) and both positive and negative time shits are possible. In steady-state free precession (SSFP) both positive and negative time shifts are also allowed but the water and fat are anti-aligned at the echo (t=0) in the midpoint of RF pulses. In spoiled gradient-echo (SPGR), the echo (t=0) occurs at the time of excitation and we only consider measurements with positive echo times. Our goal is to choose those echo time shifts to optimize the noise performance for the shortest imaging time. In our analysis we use the largest distance from t=0 among all echo time shifts as a surrogate for time. A convenient measure of noise efficiency which is independent of the noise in the source images is the effective number of signals averaged (NSA). For water and fat estimates, it is the variance of the source images divided by the variance of the quantity being estimated. In this work, we generalize it for nonlinear parameters [2] such that for all quantities it varies from 0 to 3, with 3 being efficient estimation. We use the Cramér-Rao bound (CRB) to find the minimum variance of any unbiased estimator (independent of reconstruction algorithms) [2] which in turn gives the maximum achievable NSA.

Results and Discussion: Using the expression for the CRB derived in [2] we computed the minimum NSA across all fat:water ratios for all echo time shifts from -4π to 4π at intervals of 0.02π. The optimization plots (Figs.1-3) are monotonically increasing since we allow all echo time shifts with less imaging time than the one being considered. This is because we are looking for the choice of echo time shifts with least imaging time. For magnitude estimation the ideal choice of echo time shifts is $(-\pi/6, \pi/2, 7\pi/6)$ for both FSE and SSFP. For SPGR results, the ideal choice was shifted by π. In general, echo time shifts with $(-\pi/6 + \pi k, \pi/2 + \pi k, 7\pi/6 + \pi k)$ with k an integer have optimal noise performance for magnitude estimation. The optimization for phase estimation lead to a choice of $(-2\pi/3, 0, 2\pi/3)$ which is also the optimal choice of echo times for the linear problem [1,5], and being symmetric about t=0, has poor noise performance at muscle/fat interfaces (Fig. 4). Its optimality with respect to phase estimation was not previously appreciated. SPGR never achieves the maximum possible NSA of 3 for the range of echo times we considered. In order to achieve maximum noise efficiency for phase it is necessary to have both positive and negative echo time shifts. Field map estimation is optimal for both SSFP and FSE at $(-\pi, 0, \pi)$. Like in phase estimation, SPGR does not achieve noise efficiency. Over the range which we considered, it achieves its maximum at $(0, 0.04\pi, 2.02\pi)$ where two images are basically obtained at the echo and one at 2π. At that choice of echo time shifts, it estimates the field map well but is unable to estimate the other unknowns [2]. Fig. 5 shows the noise performance of $(-\pi/6, \pi/2, 7\pi/6)$ for all quantities being estimated. Even though this choice of echo time shifts produces optimal noise performance for the magnitude, its NSA for phase and field map is highly dependent on the fat:water ratio. The achievability of the theoretical bound was verified with Monte Carlo studies using an iterative nonlinear least-squares estimation algorithm, showing that this algorithm is efficient at high SNR [5].

Conclusions: The incorporation of the uncertainty in the field map into the noise analysis lead to a better understanding of the noise dependence on the fat/water ratio and imaging sequence. The Cramér-Rao bound provides a practical way to choose echo time shifts. This general approach was used to explain and correct artifacts seen at the interfaces between water and fat in clinical images [2,3].

References: **1.** Glover, JMRI 1991; 175:545-552. **2.** Pineda et al, submitted to MRM **3.** Reeder et al, submitted to MRM **4**. Pineda et al, ISMRM 2004; p2197. **5**. Reeder et al, MRM, 2004; 51:35-45.

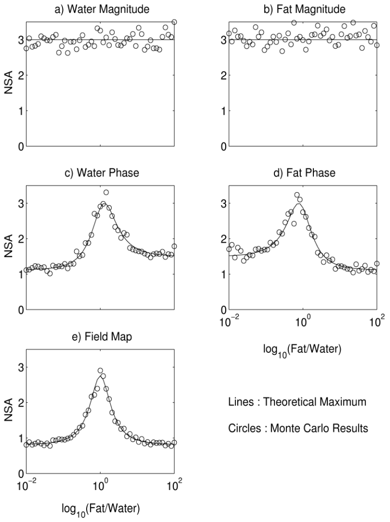

Figure 5. NSA for $(-\pi/6, \pi/2, 7\pi/6)$

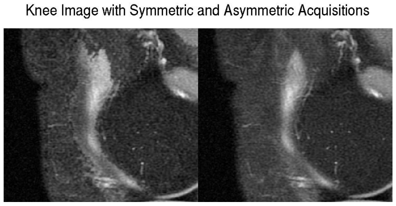

Figure 4. Clinical benefit of ideal magnitude estimation across all fat/water ratios. Image to the left shows jagged edges at fat/water interfaces. The image to the right uses an acquisition which has uniform noise properties.

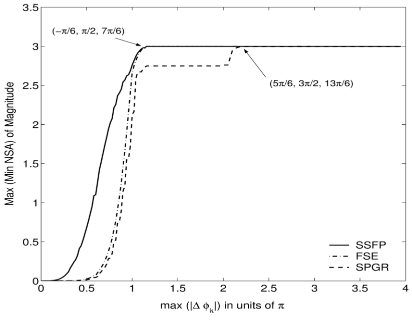

Figure 1. Optimization for magnitude estimation.

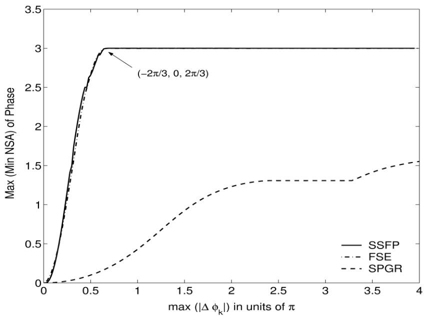

Figure 2. Optimization for phase estimation.

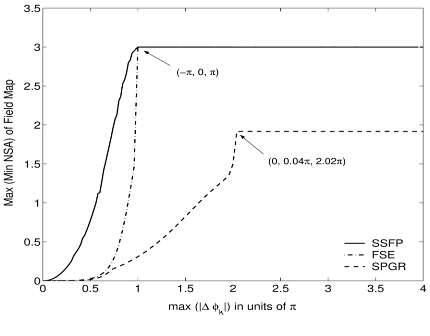

Figure 3. Optimization for field map estimation.