

Performance of the Steiglitz-McBride Algorithm for Spectral Parameter Estimation from a Rapid Multi-Gradient Echo Acquisition

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Introduction

Two-dimensional multiple fast gradient-echo (MFGRE) acquisitions that rapidly collect a limited number of echoes (2-32) are now standard on many MR platforms for T_2^* mapping, chemical shift encoding for fat-water separation and fast cardiac applications. With the limited sampling window provided by so few echoes, the use of the Fast Fourier Transform (FFT) of these echoes for fast spectral analysis becomes sub-optimal owing to the extensive filtering required to control truncation artifacts and subsequent tradeoff in spectral resolution. Recently, the iterative Steiglitz-McBride (SM) algorithm was proposed as an alternative to the FFT to facilitate rapid calculations of spectra acquired from the sparsely-sampled MFGRE acquisition (1). In this work, we investigate the accuracy and precision of this algorithm in estimating the chemical shifts, apparent spin-spin relaxation times (T_2^*) and complex amplitudes of a multi-peak system from a limited number of echoes (≤ 16) (2).

Methods

The SM algorithm was tested on simulated signals for one-peak and two-peak systems. In the one-peak signal, acquisition parameters included $T_1=500$ ms and $T_2^*=60$ ms with the $TR=70$ ms. The minimum TE was set to 2 ms with an echo-spacing of 3.3 ms. For a two-peak signal, a fat signal with 25% of the amplitude of the water peak was added with a $T_1=300$ ms and $T_2^*=30$ ms. Gaussian noise was added to the complex time domain signal and the SNR was defined as the amplitude of each spectral component divided by the standard deviation of the magnitude noise. 20,000 random trials were performed at each SNR value. The number of trials was determined by the number of measurements needed to obtain the uncertainty measurement at the lowest SNR=5. Accuracies and uncertainties of the spectral parameters (chemical shift, T_2^* and complex amplitude) were calculated using the algorithm for an echo-train length (ETL) of up to 16 echoes to determine, as a function of SNR Uncertainties were compared to the Cramer-Rao Lower Bound (CRLB) which represents the minimum uncertainty attainable and provides a theoretical basis of the noise performance as a function of acquisition parameters (2). To test the performance of the SM algorithm on real CSI data from a MFGRE acquisition, measurements were made in phantoms and compared to expected values of the chemical shift and T_2^* . An agarose gel phantom (3% w/v) and a phantom consisting of approximately half mayonnaise and half lemon juice (by volume) (1,3) was set in an agarose gel (3 % w/v). Both phantoms were scanned with the same acquisitions parameters (16-echoes, $TR/TE=70$ ms/1.9 ms, $ESP=3.3$ ms, flip angle=30, receiver bandwidth = 279 Hz/pixel, acquisition matrix = 128×128 , acceleration factor = 2, voxel size = $1.6 \times 1.6 \times 5.0$ mm³, 4.5 s/image, eight-channel high resolution brain array). In the water-agar phantom, the T_2^* measurements calculated by the SM algorithm was compared to a spoiled-gradient echo (SPGR) acquisition with exponential fitting of the signal at different TE values. Additionally, uncertainties in the chemical shift, T_2^* and amplitude were measured over ten acquisitions and compared to the CRLB. In the fat-water phantom, the uncertainties of the water and fat chemical shifts, T_2^* and amplitude values were also calculated over ten consecutive acquisitions and compared to the CRLB. Spatial variations of the chemical shift differences between water and fat were measured across the phantom.

Results

Performance of the SM algorithm on the one-peak signal demonstrated agreement between chemical shift and amplitude uncertainties and the CRLB values for $SNR \geq 5$ and $ETL \geq 4$. Figure 1(a-c) displays the uncertainties in the signal-peak model using the SM algorithm for the chemical shift, T_2^* , and amplitude estimates as a function of SNR for ETL = 4-16 echoes. T_2^* measurements generally showed higher uncertainty than the CRLB primarily at lower SNR, an effect that was expectedly exacerbated when using truncated ETL's (< 8) due to the reduced TE_{max} . The algorithm maintained high accuracy for the chemical shifts (< 0.01 ppm) and amplitudes ($< 1.0\%$) for $ETL=4-16$. T_2^* values also maintained high accuracy but increased to above 1% (0.6 ms) for $ETL \leq 5$ at $SNR=20$. The measured uncertainty of the chemical shift and T_2^* estimates demonstrated an inverse proportionality to the ETL, as expected from the derivation of the CRLB. For $SNR = 20$, the chemical shift and T_2^* dependence on the number of echoes have a relationship of $N^{-1.01}$ (Pearson's $R^2 = 0.990$) and $N^{-1.02}$ (Pearson's $R^2 = 0.980$), respectively, where N is the number of echoes. The amplitude estimates exhibited less of a dependence of the number of echoes with a $N^{-0.22}$ relationship (Pearson's $R^2 = 0.982$). Figure 1(d-f) are plots of the uncertainties and corresponding CRLB for a simulated two-peak model of water and fat for an $ETL=16$. Uncertainties in the chemical shifts and amplitudes of both water and fat signals approached the CRLB. For each parameter, the accuracy decreased with decreasing ETL and SNR, as expected. As with the one-peak signal, the algorithm maintained high accuracy for the chemical shifts (< 0.01 ppm) and amplitudes ($< 1.0\%$) for $ETL=4-16$. At $ETL \leq 6$, the T_2^* RMS error were greater than 6% for the longer T_2^* peak (water) so T_2^* measurements required a larger ETL to lower bias when the ESP is fixed. In the water agar phantom ($SNR=88.6$), the mean T_2^* value in a ROI using the MFGRE acquisition with the SM algorithm and a simple SPGR acquisition where each echo was acquired separately was 34.8 ± 0.2 ms and 34.6 ± 0.2 ms, respectively ($p=0.0923$). Noise estimates in the phantom were 0.00105 ± 0.0004 ppm, 0.356 ± 0.149 ms, and $0.28 \pm 0.16\%$ for the chemical shift, T_2^* and amplitude, respectively. Each noise measurement encompassed the calculated CRLB at the 95% confidence interval which were calculated as 0.0010 ppm (chemical shift), 0.419 ms (T_2^*), and 0.16 % (amplitude). The mean T_2^* values in the fat-water phantom were 25.0 ± 0.240 ms and 12.7 ± 1.09 ms for water and fat, respectively. The water T_2^* measured using linear least squares fitting of the magnitude images from standard fat-suppressed SPGR acquisition was 24.6 ± 0.525 ms which, despite the different acquisition technique, did not statistically differ with the water T_2^* from the MFGRE acquisition ($p=0.124$). Across the entirety of the phantom (3704 voxels) the water chemical shift had a standard deviation of 0.237 ppm and the fat 0.234 ppm, indicating that these deviations may be due in part to magnetic field changes across the sample. The mean difference between the fat and water chemical shift across the phantom was 3.4853 ± 0.0301 ppm (an 87 % reduction in the standard deviation) illustrating the power of the technique to use fat as an internal reference for susceptibility correction.

Discussion

We investigated the performance of the Steiglitz-McBride algorithm using a limited number of echoes (≤ 16) returned from a fast chemical shift imaging sequence for accurate and precise determination of spectral parameters in one and two peak systems. This is demonstrated via simulation by the chemical shift and amplitude uncertainties reaching the CRLB over a wide range of SNR values and ETL lengths along with accurate and precise T_2^* measurements at higher SNR and ETL values. Results were corroborated by phantom measurements. The accuracy and precision of this technique in resolving fat and water shifts make it attractive for monitoring of dynamic processes such as thermal therapies and chemical ablations.

References

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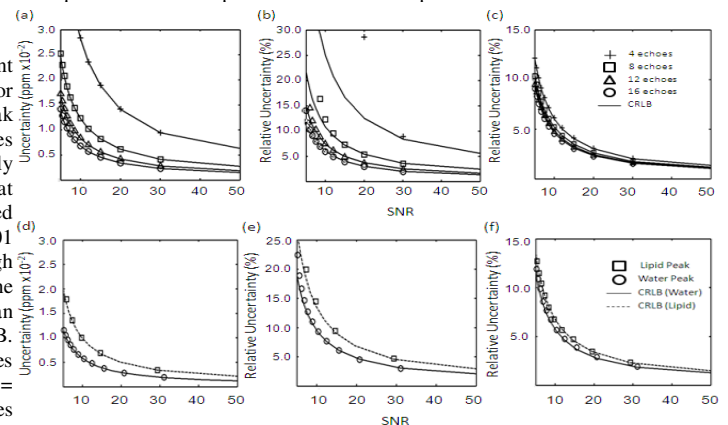


Figure 1: Uncertainty measurements of chemical shift (a,d), T_2^* (b,e), and amplitude (c,f) of a water signal model with 4-16 echoes (a-c) and a fat/water model with 16 echoes (d-f).