Maximum Entropy Reconstruction of Non-Uniformly Under-Sampled Multidimensional Spectroscopic Imaging in vivo

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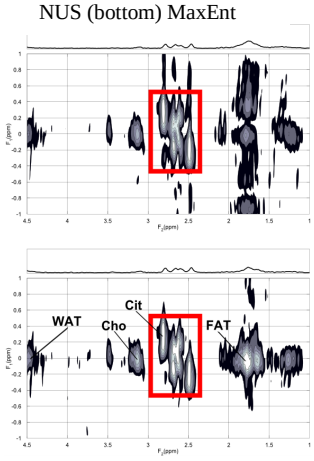
Intended Audience: Researchers working in spectroscopic imaging in vivo and image reconstruction.

Purpose: The Echo-Planar based Correlated Spectroscopic Imaging (EP-COSI) and Echo-Planar J-Resolved Spectroscopic Imaging (EP-JRESI) sequences allow for the simultaneous acquisition of two spatial (ky, kx) and two spectral (t2, t1) dimensions in a single recording to form 4D MRSI [1]. Their scan times are directly proportional to the number of increments in the k_y and t_1 dimensions and can take 20 to 40 minutes using typical parameters which is too long to be used for a routine clinical protocol. Reducing 4D EP-COSI and EP-JRESI scan times requires the reduction of either the k_y spatial or t_1 spectral dimensions through truncation or lower sampling rates, and a corresponding unwanted reduction in resolution or bandwidth with the potential for aliasing. However, non-uniform under-sampling of the spatial-spectral k_y-t_1 plane in combination with iterative Maximum Entropy (MaxEnt) reconstruction can be used to accelerate the collection of 4D MRSI data in vivo while preserving the spatial and spectral resolution [2].

Figure 1: Select 2D J-resolved spectra (top) 25% NUS (bottom) MaxEnt



Methods: The under-sampled k_y-t_1 planes of the simulated EP-COSI and *in vivo* EP-JRESI scans were iteratively reconstructed using MaxEnt. The MaxEnt algorithm uses a variant of the conjugate gradient method to solve the constrained convex optimization problem [3,4]:

$$maximize\ S_{1/2}(m)\ s.t.\ ||F^{-1}Kf - D||_2 <= \sigma \qquad (1)$$

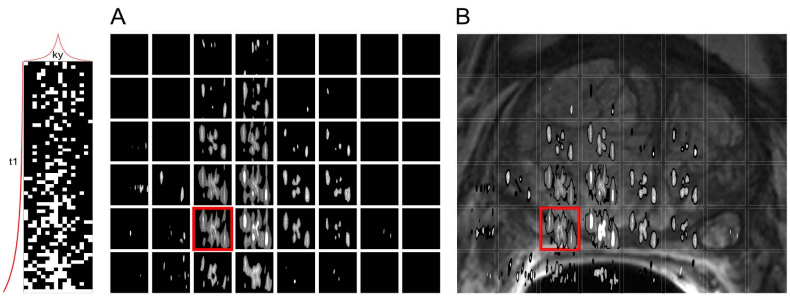
where m is the estimated fully-sampled 4D data set at each iteration, F^{-1} is the inverse Fourier transform, K is the under-sampling mask, D is the time-domain acquired data, σ is the standard deviation of the noise, and $S_{1/2}(m)$ is the spin-½ entropy of the estimated spectra. Entropy in the context of MRSI represents a measure of the phase coherence of an ensemble of spins within a given voxel volume. High-amplitude NMR signals represent states of full phase coherence and low entropy, while low amplitude NMR signals represent states of lower phase coherence and high entropy. By maximizing the entropy of the spatial, spectral-domain, under-sampling artifacts are removed from the reconstruction because they represent states of higher phase coherence and lower entropy that are not present in the sampled data.

A prospective MaxEnt reconstruction was performed on a 4D EP-JRESI scan of a 71 year old human prostate with malignant lesions in the left and right base (Gleason score of 3+3, prostatic specific antigen of 8). The scan was acquired on a Siemens 3T Trio scanner using the single-channel endorectal coil with the following parameters: 1x1x1 cm^3 voxel size, 64 t_1 increments, TR/TE/averages = 1.5s/30ms/1, a 16x16cm^2 FOV, and spectral bandwidths of ±500Hz and 1190Hz along F_1 and F_2, respectively. The k_y-t_1 mask shown in Figure 2 was used during the scan to acquire 25% of the k_y-t_1 plane during the acquisition. Eddy current correction was applied to the 4D prostate data after MaxEnt reconstruction.

Results: Figure 1 shows a select voxel from the 25% under-sampled 4D EPJRESI scan with the NUS data on top and the MaxEnt reconstruction on bottom. The citrate (Cit) diagonal and its cross peaks around F2=2.6ppm in the NUS spectrum are not easily resolved. There is significant aliasing of the Cit peaks along t_1 as well as the fat peaks around F2=1.5ppm. In the MaxEnt reconstruction, the Cit diagonal and cross peaks are fully resolved with no aliasing along t_1. The fat peaks can be fully resolved around F2=1.5ppm with no aliasing. Figure 2 shows the spatial distributions of the Cit peaks highlighted in figure 1 for the NUS data on the left and MaxEnt reconstruction on the right. The MaxEnt reconstruction shows the SNR of the Cit peaks in healthy tissue decreasing further from the endorectal coil, as expected. However, the spatial distribution of the under-sampled data set shows aliased Cit peaks near the top of the prostate as well as high SNR peaks within the rectum. The spatial distribution of Cit in the under-sampled data is noisier and shows significant spectral-spatial artifacts when compared to the MaxEnt reconstruction.

Discussion: Prior to processing the in vivo data, simulated datasets were used to characterize the algorithm at different SNRs and percent under-sampling and fully sampled retrospective scans of prostate phantom data were used to verify the spectral characteristics of in vivo metabolites. We have shown that it is possible to under-sample the k_y-t_1 plane of an *in vivo* MRSI sequence down to 25% and reconstruct the spectra with similar spatial distributions and spectral characteristics to what is expected of fully sampled data.

Figure 2: (left) Sample Mask. Spatial distribution of citrate before and after MaxEnt.



Conclusion: MaxEnt can successfully reconstruct under-sampled 4D MRSI data by reconstructing a mixed domain spectral-spatial plane. Simulated 4D MRSI data provided a quantitative characterization of the MaxEnt reconstruction at different percent under-sampling and SNR and it was shown that in vivo 4D EP-JRESI scans could be reconstructed. This acceleration translates into a clinically viable 6 minute EP-JRESI prostate scan. Additional work optimizing the sample mask and spectral filters is in-going as well as comparisons to competing methods of iterative reconstruction, such as Compressed Sensing [5,6].

References – [1] Lipnick *et al*, Magn. Reson. Med. 2010; 64: 947-956 **[2]** Skilling & Bryan, Mon. Not. Roy. Astr. Soc. 1984; 211: 111-124 **[3]** Daniell & Hore Mag. Res. 1989; 84: 515-536 **[4]** Hoch & Stern, 1996, Wiley-Liss, New York **[5]** Donoho, IEEE Trans Info Theory. 2006; 52: 1289-1306 **[6]** Lustig *et al*, Magn. Reson. Med. 2007; 58:1182-1195

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