Prospective compressed sensing accelerated spectroscopic imaging for use in geometrically accurate in vivo imaging

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Introduction:

Frequency encoded MR imaging techniques suffer from geometric distortions and displacement artifacts due to off-resonance effects including chemical shift and local susceptibility differences, which hamper accurate spatial encoding and signal characterization. Spectroscopic imaging (SI) is insensitive to these effects as it uses phase encoding in all directions. Therefore, when SI is used as an imaging tool it provides a means to acquire geometrically undistorted images and signal decay curves with extremely high temporal resolution [1]. This information can be advantageous when high geometric accuracy is required, such as in radiotherapy treatment planning [2, 3], for investigations near large field perturbations, such as caused by implants [4] or when the goal is to characterize the signal decay after administration of paramagnetic particles, for instance in internal radiation therapy with Holmium microspheres [5]. To achieve more accessible scan times for this inherently slow technique, k-space undersampling strategies such as Compressed Sensing (CS) [6] potentially are an attractive option. The k-space data in SI is acquired through point by point sampling, therefore offering maximum flexibility to randomly undersample k-space and making SI a perfect candidate for CS reconstruction. In addition to the sampling flexibility the number of measured time points per TR can easily be adjusted in SI to either decrease the TR or increase the spectral resolution depending on the research goal. In this work we investigate the use of complex averaging of multiple consecutive data points to increase the SNR, which is expected to have a positive effect on CS reconstruction, while maintaining an acceptable TR and thus acquisition time for *in vivo* imaging. The objective of this work is twofold; first we aim to retrospectively determine the optimal undersampling factor and the number of data points to include for low error CS reconstructions, and second, we aim to implement these undersampling schemes for an adapted 2D-Free Induction Decay (FID) SI sequence on a MR system so as to be able to optimally undersample SI data for *in vivo* imaging prospectively.

Methods:

Prospective undersampling of 2D-FID-SI data was implemented using pseudo-random sampling patterns on a Cartesian grid with a variable density weighting to ensure sufficient data points in the center of k-space. To evaluate the error from the CS reconstructions, the fully acquired SI data was retrospectively undersampled with a factor of 2, 3, 4 and 5 and reconstructed with CS using a wavelet transform as the sparsifying transform operator. We evaluated to what extent the reconstruction error of the total image was affected by complex averaging of data at sequential time points of the FID before CS reconstruction. For this purpose the CS reconstructions were compared to the corresponding fully sampled data sets with the same number of complex averaged data points. Note that the optimal number of points to be averaged before reconstruction depends on characteristics of the region of interest. For instance, if T_2^* is short, less points can be effectively used to positively affect the SNR. As quality measures we used the Normalized Mean Square Error (NMSE) and the Correlation Coefficient (CC):

$$NMSE = \frac{\sum_m \sum_n (|A_{mn} - B_{mn}|)^2}{\sum_m \sum_n |B_{mn}|^2} \qquad CC = \frac{\sum_m \sum_n (A_{mn} - \bar{A})(B_{mn} - \bar{B})}{\sqrt{(\sum_m \sum_n (A_{mn} - \bar{A})^2 \sum_m \sum_n (B_{mn} - \bar{B})^2)}}$$

A = reconstructed magnitude image, $\bar{A}$ = mean of A
B = fully sampled image, $\bar{B}$ = mean of B

Imaging: A healthy volunteer was scanned on a 3T MR system (Philips Achieva) with an 8 channel head coil. A transverse head image including the sinuses was acquired with an acquisition matrix of 256x256, voxel size 0.94x0.94x5m, FOV 241x241x5mm and flip angle 10^0. 100%, 50%, 33%, 25% and 20% of k-space was sampled in separate FID-SI acquisitions with TR/TE= 10/2.6 ms, a spectral width of 8000Hz and 16 data points. These acquisitions resulted in 16 single point images with different T_2^* weightings corresponding to 'echo times' of t_0+(n-1)dt, with t_0=2.6ms and dt=0.125ms. Fully sampled k-space data was acquired in 10 min 50 sec. Undersampled k-space data was acquired in 5 min 25 sec (factor 2), 3 min 36 sec (factor 3), 2 min 43 sec (factor 4) and 2 min 10 sec (factor 5). The scan time of the prospectively undersampled SI data was reduced proportionally with the k-space undersampling factor as each measured k-space point corresponds to a separate repetition.

Results:

Increasing the undersampling factor enlarges the NMSE between the fully sampled image and the reconstructed image, although the correlations (CC) within the image remain high (table 1). Complex averaging of time points in k-space before reconstruction decreases the total error in the reconstructed image. The image quality in the CS reconstructed prospectively undersampled images (figure 1) shows high correlation with the fully sampled images up to a factor 5 undersampling, although the loss of detail increases for larger undersampling factors. The images reconstructed with 4 averaged time points appear clearer than that of a single time point, which is substantiated by the reduced error measures and corresponds to the expectation of an increased SNR of the data after complex averaging. The presented images at TE=2.8ms correspond to the third time point.

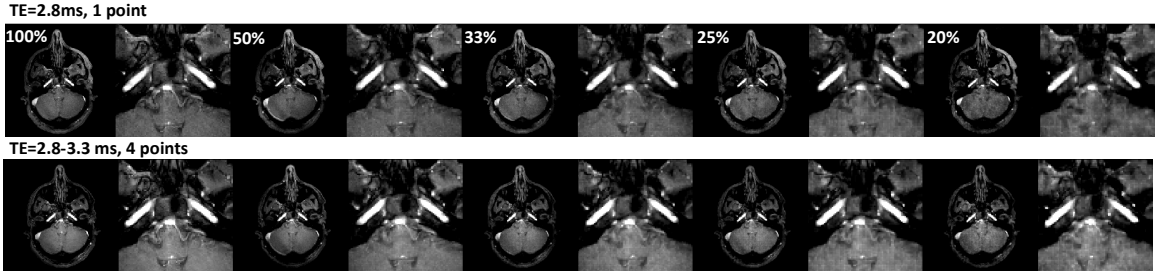

Fig 1 Left to right: fully sampled FID-SI data, prospective reconstructions from 50%, 33%, 25% and 20% of the data, Top row: image reconstructions with 1 point at TE=2.8ms; bottom row: image reconstructions with 4 points averaged resulting in an averaged T_2^* weighting from TE=2.8-3.3ms

Data sampled	No. of points	NMSE	CC
50%	1	0,007	0,994
50%	2	0,005	0,996
50%	4	0,003	0,996
33%	1	0,012	0,990
33%	2	0,010	0,992
33%	4	0,008	0,993
25%	1	0,018	0,985
25%	2	0,015	0,987
25%	4	0,015	0,988
20%	1	0,019	0,984
20%	2	0,016	0,987
20%	4	0,017	0,987

Table 1: CS reconstruction errors

Conclusion:

In this work we prospectively accelerated a 2D-FID-SI sequence with CS to obtain geometrically undistorted images while retaining high correlation between the fully sampled and CS reconstructed images and introducing only modest errors. Increasing the SNR of the FID-SI data by complex averaging of the time points further decreased the reconstruction error of the total image at no additional computation or measurement cost, while introducing an T_2^* weighting over the used temporal information. The CS accelerated FID-SI acquisition presented in this study constitutes an important step towards the development of a 3D-FID-SI scheme for *in vivo* imaging, which ensures correct spatial encoding in all three dimensions. The acquisition time of the presented method may be expected to be further reduced using parallel imaging and partial fourier undersampling techniques [7], which is work in progress.

References:

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