High Spatial and Angular Resolution Diffusion Imaging Using Compressed Sensing

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Introduction: Both high angular and spatial resolution are desirable in diffusion imaging for several reasons. High angular resolution enables the detection of crossing fibers and high spatial resolution limits confounds such as partial volume effects allowing accurate derivation of parameters from the diffusion measures [1][2]. Both are highly desirable for accurate fiber tracking, which has several clinical applications. However, due to the long acquisition durations, the approach in the field so far has been to enhance the resolution in one of the dimensions at the expense of the other dimension [3]. This study aims to simultaneously enhance the resolution in both the dimensions in a reasonable scan time using Compressed Sensing (CS).

Recently several groups have proposed the utility of compressed sensing to accelerate diffusion imaging [4][5]. Previously parallel imaging was also proposed in this context [5]. However, these previous studies decoupled the acquisition in the k-q domain and focused on down-sampling in either the k-space or the q-space. The main novelty of the present study is that we are proposing to under-sample the combined k-q acquisition space of diffusion imaging. This enables us to simultaneously enhance the resolution in both dimensions of diffusion imaging.

Methods: A Self Navigated Interleaved Spiral (SNAILS) sequence was used to achieve high spatial resolution. The savings in acquisition time was made possible by joint under-sampling of the k-q acquisition space. A schematic of the various acquisition schemes is shown in Fig (1). The combined k-q under-sampling was achieved by skipping random interleaves of the spiral for each diffusion direction. A model–based scheme was used to reconstruct the diffusion Orientation Density Function (ODF) from the under-sampled data. The sparse Gaussian Mixture Model (GMM) given was used to represent the diffusion image data: $S_k = S_0[f_0 \exp(-bd) + \sum_i f_i exp(-bd g_k^T D_i g_k)]$ where S_k is the diffusion weighted data for the kth diffusion direction g_k, S_0 is non-diffusion weighted image, f_i is the unknown anisotropic volume fraction of the ith tensor D_i, b is the diffusion sensitizing constant and d is the mean diffusivity. The k-space data is the Fourier transform of the above. The basis vectors for CS reconstruction were assumed to be Gaussians oriented along all possible orientations defined by a set of uniformly distributed q-space basis vectors generated along 256 directions. The following parameters were used in the model: b=1200 s/mm^2, d=1x10^{-3}mm^2/s, $D_i=R_i$*[1700 0 0;0 300 0;0 0 300]*R_i^T where R_i rotates the tensor to the ith basis vector. The unknown f_i's in the model gives a linear system of equations to solve for. If y_k is defined to be the acquired k-space samples, A the Fourier transform of diffusion encoding matrix, f can then be solved as $\hat{f} = argmin_f \|y - Af\|_{l2}^2 + \lambda_1\|f\|_{l_{TV}} + \lambda_2\|f\|_{l1}$. In addition to the CS criteria, the total variation norm of the f's was also penalized to constrain the solution. Once f is solved for, the diffusion ODF can be analytically computed [6].
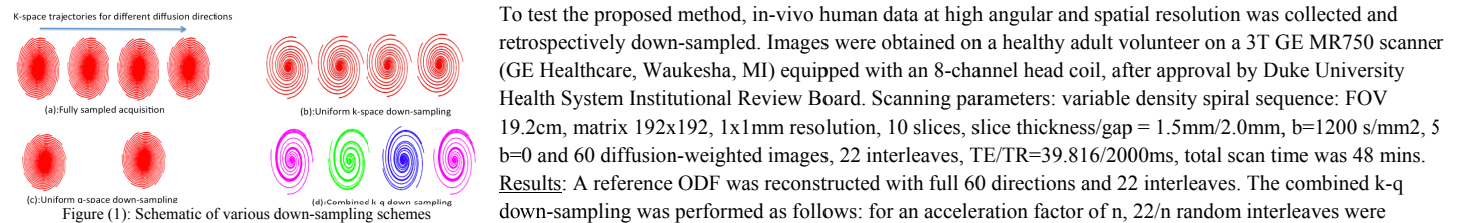

Figure (1): Schematic of various down-sampling schemes

To test the proposed method, in-vivo human data at high angular and spatial resolution was collected and retrospectively down-sampled. Images were obtained on a healthy adult volunteer on a 3T GE MR750 scanner (GE Healthcare, Waukesha, MI) equipped with an 8-channel head coil, after approval by Duke University Health System Institutional Review Board. Scanning parameters: variable density spiral sequence: FOV 19.2cm, matrix 192x192, 1x1mm resolution, 10 slices, slice thickness/gap = 1.5mm/2.0mm, b=1200 s/mm2, 5 b=0 and 60 diffusion-weighted images, 22 interleaves, TE/TR=39.816/2000ms, total scan time was 48 mins.

Results: A reference ODF was reconstructed with full 60 directions and 22 interleaves. The combined k-q down-sampling was performed as follows: for an acceleration factor of n, 22/n random interleaves were chosen for each diffusion direction such that the selected interleaves differ for each diffusion direction. Acceleration rates corresponding to n=2,4,6 (corresponding to \ 11, 5, 3 interleaves) were tested. The results were compared to a q-only down-sampling scheme where, instead of skipping shots, diffusion directions were skipped such that the sampled diffusion directions spanned the q-space uniformly. The same acceleration rates corresponding to n=2,3,4 (corresponding to 30, 20 and 15 diffusion directions) were tested. The ODFs from both under-sampling schemes were reconstructed and compared to the reference ODF. Fig (2) shows the reference ODF and reconstructed ODF from a crossing fiber region. A plot of the Normalized sum-of-squares error (NSSE) at various acceleration rates for the two down-sampling schemes is also given.
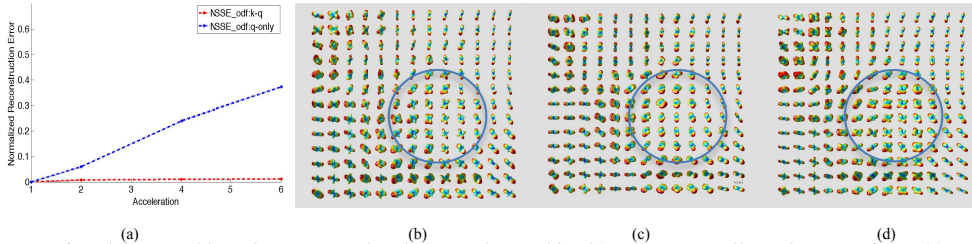

(a)   (b)   (c)   (d)

Figure 2: (a) shows the plot of NSSE error of the reconstructed diffusion ODF from the two down-sampling schemes. (b) shows the reference ODF from a crossing fiber region (c) shows reconstructed ODF of the region using q-only down-sampling at an acceleration rate of 4. (d) shows reconstructed ODF from k-q down-sampling at an acceleration rate of 4.

It was found that to achieve the same acceleration rate, the combined k-q down-sampling scheme performed better than q-only down-sampling. This can be seen from the plot of Figure (2). The error in the k-q down-sampling scheme is much lower than that of the q down-sampling scheme for all acceleration factors. From the reconstructed ODFs, it can be seen that the ODF peaks becomes less pronounced as the q down-sampling rate is increased, whereas the peaks are still preserved accurately in the k-q down-sampling schemes for the same acceleration rates. Results show that even at 6-fold acceleration of the k-q down-sampling scheme, the diffusion ODF can be reconstructed reasonably accurately.

Conclusion: In spite of the obvious benefits of combining high angular and spatial resolution, prohibitively long acquisition times have made such goals impractical with conventional diffusion imaging schemes. The proposed method can achieve both high spatial and angular resolution simultaneously within a reasonable scan-time. We have shown that the combined k-q acquisition space of diffusion can be substantially down-sampled and diffusion ODFs accurately reconstructed using compressed sensing. Our results show that the acquisition time can be reduced by at least 6-fold by appropriately under-sampling the combined k-q acquisition space. 6-fold acceleration translates to achieving 1mm inplane resolution in 8 mins as opposed to 48 mins.

References: [1] Tuch D.S. et al, Magn Reson Med 2002. [2] H. Oouchi et al, Am. J. Neuroradiol, 2007. [3] N Jahanshad et al ,ISBI 2010 [4] B. A. Landman et al, ProcSPIE, 2010. [5] O. Michailovich et al, IEEE Trans. Med. Imag.,2011. [6] Bammer R et al., Magn Reson Med 2002. [7] I. Aganj et al, Magn Reson Med, 2010.