Whole-brain DSI in 4 minutes: sparse sampling in q-space with simultaneous multi-slice acquisition

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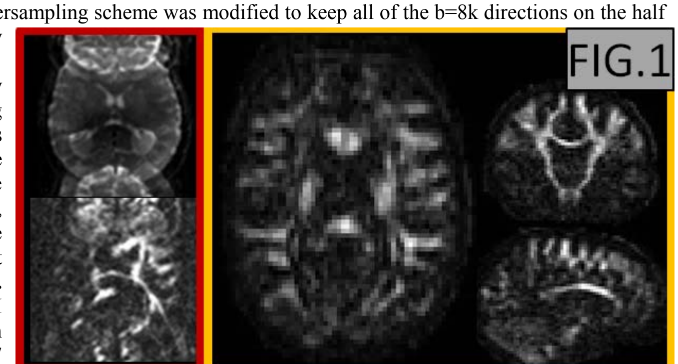
Introduction: High angular resolution diffusion imaging (HARDI) techniques (1-3) have been developed to provide robust and detailed information about the local diffusion environment in the brain white matter, particularly in regions of crossing fibers. A drawback of these techniques is their requirement for a large number of diffusion encoded acquisitions with strong diffusion encoding which can lead to low SNR and lengthy acquisitions. This is particularly true for DSI (2) where a 515 direction whole brain scan takes an hour or longer, limiting its utility in clinical and research studies. In this work, we aim to significantly improve the efficiency of HARDI acquisitions using three orthogonally beneficial technologies: (i) high strength gradient hardware, (ii) Simultaneous Multi-Slice (SMS) acquisition with Blipped-CAIPI acquisition scheme (4) with a highly parallelized reception coil array, and (iii) q-space compressed sensing reconstruction (5). Together, these improvements allow for an acquisition of high-quality whole-brain DSI data in just over 4 minutes. While this initial demonstration focuses on DSI, the general approach should be applicable to other HARDI acquisition schemes.

Methods: Stejskal-Tanner based diffusion EPI acquisitions were obtained from a healthy volunteer using a novel 3T system (MAGNETOM Skyra CONNECTOM†, Siemens Healthcare, Erlangen, Germany) equipped with the AS302 "Connectom" gradient with G_{max}=300 mT/m and Slew=200 T/m/s. A custom-built 64-channel RF head array (6) was used for reception. A 3x slice-accelerated SMS acquisition with Blipped-CAIPI acquisition scheme was used to reduce the acquisition time 3-fold. Here, a FOV/2 inter-slice image shift between the 3 simultaneously excited slices was utilized to reduce the g-factor penalty (we previously demonstrated <5% penalty at this slice acceleration factor with a 32 channel array (4)). Imaging parameters for the 3xSMS accelerated acquisition were: 2.5mm isotropic; FOV = 210 x 210 x 130 mm; Partial Fourier = 6/8; matrix size = 84x63x17; b_{max} = 8000 s/mm^2, 515 directions full sphere q space sampling on 11x11x11 grid, TR/TE = 1.9s/72 ms, total image time ~16 min. The max gradient strength for this preliminary acquisition was limited to 100 mT/m to reduce eddy current distortions. To minimize aliasing artifacts, slice-GRAPPA (4) with modified even/odd grappa kernel (7) was used to reconstruct the slice collapsed dataset. Optimal coil combination was performed to provide improved SNR and mitigate the non-central Chi-squared noise bias (8) of the root sum of square (rSOS) reconstruction. Eddy current related distortion and subject motion was corrected using a modified *eddy_correct* function in the FMRIB's diffusion toolbox (9) with sinc interpolation.

A 4x undersampling of the reconstructed 515 directions *full* sphere q-space dataset was then performed using a 2x-avg Gaussian undersampling scheme on a *half* sphere (with full sampling in the central q space region and increasing undersampling as a function of radius). The resulting dataset corresponded to 4 min of DSI data acquisition. To fill in the missing q-space directions of this data, the FOCUSS compress sensing algorithm (10) and conjugate symmetry assumption of q-space were utilized. Here a ℓ_1 constraint on the probability distribution function (pdf) was used. For both the 3xSMS+1xQspace (16 min) and the 3xSMS+4xQspace (4 min) accelerated acquisitions, the pdf and odf were estimated and tractography was conducted and compared using the Diffusion ToolKit (11).

Results: *Fig1 left* shows the aliased images from a selected group of 3xSMS slices at b = 0 and 8000 s/mm^2 (top and bottom respectively). Here, the collapsed images were reconstructed using rSOS coil combination resulting in a strong non-zero mean noise bias in the b = 8k image that obscures some image features. *Fig1 right:* shows the unaliased and optimally coil combined images of the same b = 8k acquisition illustrating that relatively high SNR and contrast that can be obtained in a single shot at b = 8000s/mm^2. The g-factor penalty for this 3x-slice accelerated acquisition is negligible but the TR reduction from 5.7s to 1.9s (allowed by the SMS acquisition) results in a T_1 recovery related SNR loss of 14.6% *per shot* (WM T_1 ~1s) but a net gain in SNR *per unit time of* 48%. On a standard gradient coil (G_{max}: 40 mT/m) with no slice acceleration, the 515 DSI acquisition would have had a TR/TE of 8s/112ms and taken 1 hr and 10 min to acquire. The TE increase from 72ms to 112ms would have resulted in an SNR reduction of 44% (WM T_2 ~70ms). To match the SNR of the standard acquisition to our 16 min scan, 2.3x averaging would be required to compensate for a 35% net SNR reduction (accounting for TE signal loss & TR signal gain); resulting in a 2 hr and 40 min scan. *Fig2* shows a comparison of the tractography results obtained from 3xSMS + fully sampled q-space (16 min) and 3xSMS + 4x undersampled q-space (4min) acquisitions. The tracts from both datasets clearly depict the fiber crossing regions, with minor additional noisy tracks in the 4 min dataset. Also shown are the diffusion images of the missing q-space directions at b= 4500 and 7000 s/mm^2 (top and bottom respectively). It can be seen that application of q-space compressed sensing algorithm at a per voxel level results in good reconstruction of the images of these missing directions with close resemblance to the 'ground truth' image of the 1x q-space data. We note that at very high b-values the compressed sensing reconstruction produces images that are somewhat nosier and lower intensity when compared to the 'ground truth' data (as can be seen in b=7k in Fig2). This is most prominent at the maximal b=8k. To overcome this, our undersampling scheme was modified to keep all of the b=8k directions on the half sphere, resulting in an increased acq time of 17s. *Fig3* shows additional tractography results from the 4 min acquisition where detailed fiber structures can be observed.



whole brain b=8000 s/mm^2 ,TR/TE = 1.9s/72ms

Conclusion: In this work, we significantly improved the efficiency of DSI acquisitions by utilizing the SMS blipped-CAIPI acquisition scheme and q-space compressed sensing algorithm. The data was acquired using an MRI system equipped with strong gradients and large array coil hardware which also provides significant SNR boost. With the combination of these software algorithms and hardware technologies, high quality whole brain DSI data was obtained in 4 min of acquisition. **Support:** NIBIB K99EB012107, NIBIB R01EB006847, NCRR P41RR14075 and the NIH Blueprint for Neuroscience Research U01MH093765 The Human Connectome project. **References: 1.** Tuch DS. et al, MRM 2004 **2**. Tournier JD. et al, Neuroimage2004 **3.** Wedeen VJ. et al, MRM2005 **4.** Setsompop K. et al, MRM 2011 **5.** Menzel M. et al MRM 2011 **6.** Keil B. et al, ISMRM 2012 **7.** Setsompop K. et al, ISMRM 2012 **8.** Constantinides CD. et al, MRM9 7 **9.** Smith SM. et al, Neuroimage2004 **10.** Gorodnitsky I and Rao BD., IEEE T. Signal Proces.1997 **11.** Wang R. et al, ISMRM 2007 † Works in Progress. The information about this product is preliminary. The product is under development and is not commercially available in the U.S. and its future availability cannot be ensured.