# High angularly resolved diffusion imaging with short scan time and low distortion

Tzu-Cheng Chao[1,2], Jr-Yuan George Chiou[3], Stephan E. Maier[3], and Bruno Madore[3]

*[1]Department of Computer Science and Information Engineering, National Cheng-Kung University, Tainan, Taiwan, [2]Institute of Medical Informatics, National Cheng-Kung University, Tainan, Taiwan, [3]Department of Radiology, Brigham and Women's Hospital, Harvard Medical School, Boston, M.A., United States*

**Target Audience**: Researchers interested in accelerated low-distortion diffusion imaging.

**Purpose**: While multi-direction diffusion methods such as 'High Angular Resolution Diffusion Imaging' (HARDI) are valuable tools for investigating cerebral microstructure[1, 2] their translation to clinical use has been limited by long scan times and geometric distortions. Combinations of accelerated imaging and segmented imaging[3-5] have emerged as potential solutions to these problems but often require the use of an additional 'navigator' echo for motion compensation, which in turn slows down the acquisition process by reducing the number of slices that can be acquired per unit of time. A recent method was proposed for multi-shot diffusion imaging with multiplexed sensitivity encoding[6], to achieve robust reconstruction of multi-shot data without the need of a navigator echo. The present work aims at the rapid acquisition of low-distortion diffusion data by combining ideas from accelerated multi-shot diffusion imaging[5] in conjunction with compressed sensing[7,8], with no navigator echo[6].

**Methods**: Six volunteers were scanned on 3.0T systems (GE HDx and Discovery MR750, Milwaukee, WI) following informed consent. In each case, three scans were acquired with the proposed navigator-free accelerated multi-shot diffusion method: With 128, 64 and 48 diffusion encoding directions (40 slices, 3-mm slice thickness, TE/TR = 75.9/4000 ms, 22 cm FOV, 128×128 matrix size). The four-fold accelerated ($R$=4) $k$-space sampling scheme is depicted in Fig. 1a. The diffusion encoding scheme is shown in Fig. 1b, it is a double-spiral scheme that provides sparse signal profile in the reconstruction space while preventing dramatic changes in eddy currents from one encoding to the next. The first 8 TR periods were used to fully acquire two T2-weighted ($b$=0) images, and each following TR a $b$=1500 s/mm$^2$, $R$=4 accelerated diffusion-encoded image was acquired.

Sensitivity maps were obtained from the $b$=0 data. In a first reconstruction step, each $R$=4 image was individually reconstructed using parallel imaging alone, and then filtered down to about one fifth its original resolution (from 128×128 down to 64×48). These low resolution intermediary results were used, in essence, to synthesize the navigator data that were never acquired in the present navigator-free method. Once these synthesized navigator data are available, the multi-shot accelerated, navigated and regularized reconstruction algorithm form Ref [5] can be applied to generate full-resolution diffusion-weighted (DW) images. These reconstructed DW images were used in turn to generate maps of diffusion indices such as fractional anisotropy (FA) and principal orientation, and finally, input into the 'crossing fiber angular resolution of intravoxel structure' (CFARI)[7] algorithm to resolve intra-voxel fiber structures with Compressed Sensing. The tensor model for CFARI was: Prolate shape, ratio of principal diffusion coefficients equal to 4:1:1, 512 base tensors.

For validation purposes a diffusion scans with $b$ values of 0 and 1500 s/mm$^2$ was performed, using a two-fold accelerated product sequence ($R$=2, 3-mm slice thickness, TE/TR = 101.7/5600 ms, 22 cm FOV, 128×128 matrix size).

Fig.1

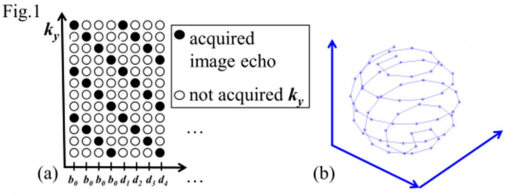



Fig. 2

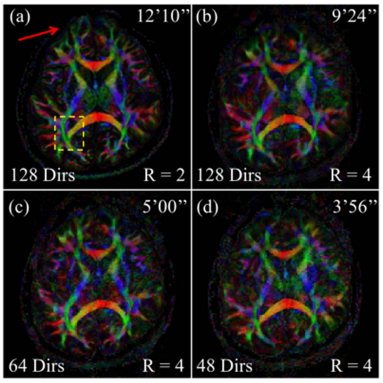
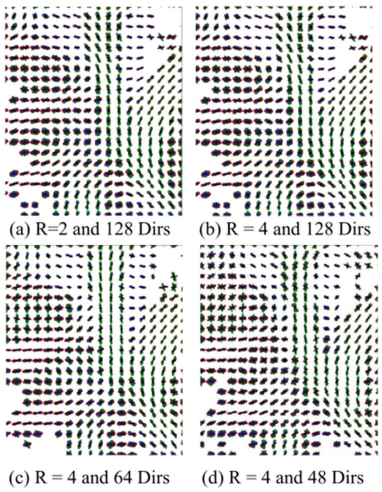



Fig. 3




**Results**: Fig 2 shows reconstructed color FA maps, scan time is indicated in the upper-right corner of each image. As expected, distortion was greater in the $R$=2 results from the product sequence (red arrow in Fig. 2a) than in the proposed $R$=4 results. Scan time was also longest with the product sequence (12'10''), and as much as three-fold shorter in Fig. 2d (3'56''). Shorter scan times do, however, come at a price in SNR, as can be judged from Fig. 2. Although subjective, Fig. 2c with a 5'00'' acquisition time for nearly full-brain low-distortion coverage might be considered a reasonable tradeoff.

Orientation maps are shown in Fig. 3 in the same order as FA maps were shown in Fig. 2, from longest (Fig. 3a) to shortest (Fig. 3d) scan time. Spatial patterns and distributions remain similar with decreasing scan time, even in especially-important locations where fiber crossings occur. Close inspection does reveal subtle changes in the shape of the orientation density functions with decreasing SNR, as could be expected, and again the 5'00'' results in Fig. 2c and 3c might be considered a reasonable tradeoff.

**Discussion**: Reconstructed color FA maps and orientation maps suggest that the proposed method might provide relatively-fast low-distortion HARDI results while maintaining microstructural information. Scan time was reduced by three fold and distortion was decreased by two fold in comparison to the two-fold accelerated product sequence. If comparing to non-accelerated imaging, the geometric fidelity can be improved by as much as four fold. Although SNR tradeoffs are often unavoidable with accelerated scans, the echo time reduction achieved with the proposed multi-shot accelerated acquisition scheme can help partly compensate the increase in noise level by an increase in signal.

**Conclusion:** Accelerated, relatively-fast and low-distortion scans may help HARDI-like approaches to transition toward clinical use.

**References:** [1] Tuch DS,et al, Phil trans of Royal Soc of London Series B. 2005;360:869-79. [2] Tuch DS. MRM. 2004;52:1358-72. [3]Atkinson D, et al. MRM. 2006;56:1135-39. [4] Chuang TC, et al. MRM. 2006;56:1352-58. [5] Madore B, et al. MRM. 2014;72:324-336. [6] Chen NK, et al. NeuroImage. 2013;72:41-47. [7] Landman BA, et al. Soc of Photo-Optical Instr Eng 2010;7623:76231H. [8] Chao TC, et al. ISMRM proc. 2014:334.

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