Whole-Brain, Multi-Shot, Diffusion-Weighted Imaging in Humans at 7T with 1 mm Isotropic Resolution

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Introduction: Diffusion-weighted, readout-segmented EPI (rs-EPI) with parallel imaging and 2D navigator correction [1] can provide substantially improved image quality compared to single-shot EPI (ss-EPI) with parallel imaging. The technique achieves a reduction in susceptibility artefacts and T_2^* image blurring by allowing a very short echo-spacing, which unlike ss-EPI does not increase with the image resolution. Readout-segmented EPI is particularly well-suited to applications at ultra-high field strength due to the low number of RF refocusing pulses, thereby avoiding the problems with SAR and B_1 field variation that affect multi-shot sequences using multiple 180 degree RF refocusing pulses. Previous work has demonstrated the ability of rs-EPI to reduce the high level of susceptibility and blurring artefact seen in ss-EPI images at 7T, even when large acceleration factors (AF) are used [2]. This previous study described a preliminary application of the method, in which technical limitations reduced the number of slices and diffusion directions that could be measured. This paper describes a follow-up study using a modified version of the sequence that has been adapted to allow whole-brain coverage using an isotropic resolution of 1mm with 30 diffusion-encoding gradient directions. Despite the small voxel size, the images acquired had sufficient SNR to resolve fibre crossings by using constrained spherical deconvolution (CSD) to estimate the fibre orientation density function [3].

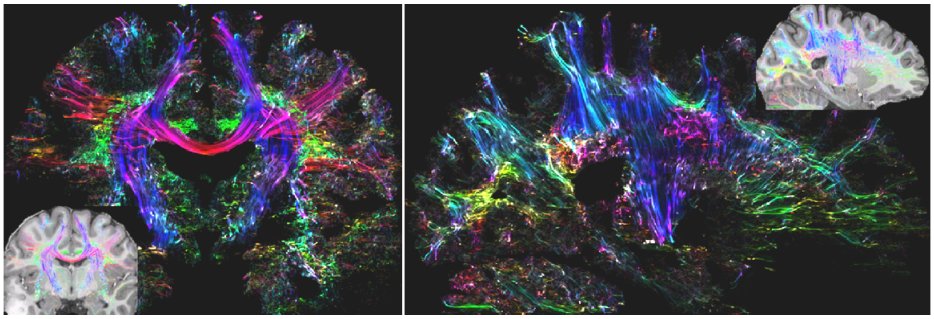

Fig. 1: Tract-density imaging maps derived from the 1mm isotropic resolution rs-EPI acquisition showing the coverage of the DWI. The small images in the corner show the TDI maps overlaid onto the anatomy.

Methods: All experiments were performed on a 7T whole-body MR scanner (MAGNETOM 7T, Siemens Healthcare, Erlangen, Germany) using a 24-element phased array head coil (Nova Medical, Wilmington, MA, USA). Scans were performed on two healthy volunteers and informed consent was obtained before each study. Multi-shot DW images were acquired using the rs-EPI sequence in conjunction with 2D navigator correction, a navigator-based re-acquisition scheme [4] and parallel imaging. The GRAPPA reconstruction was performed with a 2D convolution kernel [5] with three source points along the readout direction and two source points along the phase-encoding direction. The following protocol was used to acquire data from 104 axial slices (acquired as two sets of 54 slices with 4 overlapping slices): image matrix 220x220, FOV 220mm, slice thickness 1.0mm without a gap, TR 7500ms, TE 76ms, AF 3, 7 readout segments. 5 scans were performed with a b-value of zero and diffusion weighting was applied along 30 directions [6] with a b-value of 1000 s/mm^2. Total scan time (including all reference scans and re-acquisition scans) was 78 min. For all acquisitions, fat suppression was applied using the Ivanov method [7]. The DW images were filtered with a two-stage hybrid image restoration procedure [8], corrected for subject motion and registered to a T_1-weighted anatomical image (1mm resolution) of the same participant using a rigid-body transformation computed with FLIRT [9]. For each voxel, multiple fibre orientations were modelled by CSD [3] followed by whole-brain fibre-tracking using *MRtrix* [10]. Finally, a colour-coded track-density image (TDI) [11] was generated from 2,500,000 tracks resulting in an image with a grid resolution of 0.25 mm.

Results and Discussion: Fig. 1 shows coronal and sagittal views of colour-coded TDI maps derived from the rs-EPI images. The TDI demonstrate the coverage of the brain with the rs-EPI acquisition. The corresponding anatomy is shown in the small images at the corner of each view. Fibre orientation distributions (FOD) of the rs-EPI images are shown in Fig. 2 as orientation plots on a coronal slice and corresponding fibre tracks at the level of the pre-motor cortex. In this slice, fibres from the corpus callosum (CC, pink) cross the corona radiata (CR, blue) and the superior longitudinal fasciculus (SLF, green, tracks not shown). The zoomed section (bottom left) highlights the combination of high spatial and angular resolution, which to our knowledge has not previously been reported in human studies *in vivo*. The spatial consistency of the FOD demonstrates the high SNR of the data. The data show that despite the high spatial resolution crossing fibres still must be taken into account.

Conclusion: rs-EPI with GRAPPA and a 2D navigator based re-acquisition at 7T enables high-quality whole brain DWI at 1mm isotropic resolution with sufficient SNR to allow crossing fibres to be resolved.

References: [1] Porter, et al. ISMRM 2006, #1046. [2] Heidemann, et al. MRM 2010;64:9-14. [3] Tournier, et al. NeuroImage 2007;35:1459-72. [4] Porter, et al. ISMRM 2006, #1047. [5] Griswold, 2nd Workshop on Parallel Imaging 2004, 16-8. [6] Jones, et al. Human Brain Mapping 2002;15:216-30. [7] Ivanov, et al. MRM 2010;64:319-26. [8] Lohmann, et al. MRM 2010;64:15-22. [9] Jenkinson, et al. NeuroImage 2002;17:825-41. [10] http://www.brain.org.au/software [11] Calamante, et al. NeuroImage 2010;53:1233-43.

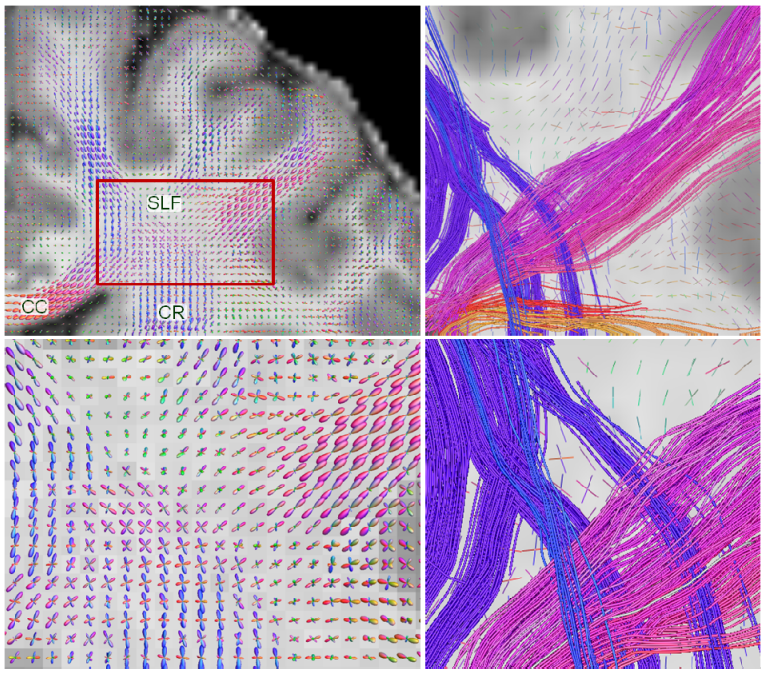

Fig. 2: (left) Fibre orientation plots on a coronal section at the level of the pre-motor cortex superimposed on the T_1-weighted anatomy. (right) Selected tracks of the corpus callosum (CC, pink) which are crossing the corona radiata (CR, blue) reaching the pre-motor cortex. The lines in the background illustrate the main fibre orientations in each voxel. (bottom) Enlarged sections.