Diffusion tensor imaging of porcine spinal cord at 7 Tesla using readout-segmented EPI, GRAPPA and a distortion correction tool

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Target Audience: Ultra-High-Field MRI community interested in spinal cord imaging.

Purpose: Diffusion tensor imaging (DTI) of the spinal cord (SC) is a useful tool providing structural information about SC tissue alteration in several diseases such as amyotrophic lateral sclerosis [1] and multiple sclerosis [2,3]. Similarly to anatomical MRI, DTI could benefit from the higher signal-to-noise ratio (SNR) available at 7 Tesla to achieve high-resolution images. However image quality will be highly impaired by increased susceptibility effects, especially when dealing with echo-planar imaging (EPI). Indeed, SC imaging is outstandingly challenging, as it has a very tiny anatomy and is surrounded by large bone structures (vertebral body, transverse and spinous processes), whose magnetic susceptibilities could generate very severe image distortions. In this preliminary work performed on porcine SC on a whole-body 7T, we combine a DTI module based on readout-segmented echo-planar imaging (rs-EPI) used in conjunction with parallel imaging [4] to allow a reduction in echo spacing (ES) during the EPI readout, and a post-processing tool called "Topup" [5,6] to further correct distortions and thereby obtain robust DTI images and metrics.

Methods: All experiments were performed with a 7T whole-body MR scanner (Magnetom; Siemens Healthcare, Erlangen, Germany), using a 32-element phased array head coil (Nova Medical, Wilmington, MA) on an ex-vivo porcine neck. DTI were performed in the axial plane, at the cervical C3 level, with a monopolar rs-EPI prototype sequence, using the following parameters: TR: 4000 ms, TE: 49 ms, 9 readout segments, ES: 0.38 ms, matrix: 124x124, FOV: 100x100 mm^2, slice thickness: 3 mm, 10 slices, GRAPPA [7] acceleration factor: 3, 12 independent gradient directions, 2 b-values (0-800 s/mm^2), for an acquisition time of 8 min. The Topup package required two acquisitions with opposed phase-encode directions to correct for susceptibility-induced distortions [5]. Given the two images and knowledge of the acquisition parameters, the Topup tool estimates the off-resonance field by finding the field that will maximise the similarity of the two unwarped volumes when applied to the two original volumes [6]. This similarity is gauged by the sum-of-squared differences between the two unwarped images. To qualitatively evaluate the distortion corrections, a reference T_2-weighted anatomical image was generated with a 2D TSE sequence with same FOV, same number of slice and an in-plane resolution of 0.3 mm (subsequently interpolated using c3D (c3D, ITK-SNAP, University of Pennsylvania) to match DTI data resolution). Last, a brief comparison between rs-EPI and single-shot-EPI (ss-EPI) was also run using the same spatial resolution, number of slices and repetition time (ss-EPI parameters: TE: 54.8 ms, ES: 1.19 ms, matrix: 108x108).

Results: The ss-EPI sequence exhibited very severe image distortions despite a GRAPPA acceleration factor of 4 and a relatively small acquisition matrix. These were corrected to some extent by the Topup tool but the overall result was still unsatisfactory on the whole volume, notably near the disks (data not shown here). When considering the rs-EPI sequence, several distortions were still visible in the phase-encode direction, particularly in the anterior part of the cord, presumably due to the presence of the nearby vertebral body (Figure a. and b.). The final resulting image (Figure c.) is almost free of distortions and fits reasonably well with the interpolated anatomical reference image, even on the more unfavourable slice which was chosen here to illustrate the potential of the presented method (Figure d.). Computed magnetic field map obtained by Topup is also provided, where a dipolar pattern around the anterior part of the spinal cord can be observed (Figure e.). The calculated Fractional Anisotropy (FA) value for the whole cord was 0.63 ± 0.16, showing a good agreement with the literature, including on post mortem tissues, where FA is the only metrics expected to remain stable [8].

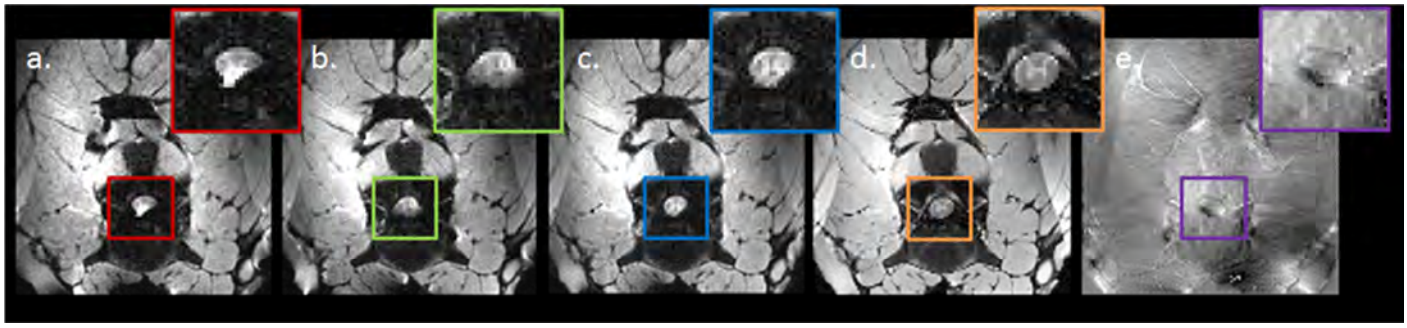

Figure: Diffusion tensor imaging of ex-vivo porcine spinal cord at 7 Tesla using an rs-EPI sequence. **a:** b_0 rs-EPI image, resolution : 0.8x0.8x3 mm, right-to-left phase-encode direction, GRAPPA acceleration factor of 3. **b:** b_0 rs-EPI image with opposite left-to-right phase-encode direction. **c:** Corresponding distortion-corrected image with Topup (worse slice). **d:** Reference subsampled anatomical T_2-weighted image. **e:** Corresponding off-resonance field map [-200 Hz; 200Hz] provided by Topup.

Discussion: In terms of magnetic susceptibility-induced image distortions, this ex vivo pig scan can presumably be considered as "a worst case scenario" of a human in vivo scan, since the vertebral column of pigs is much thicker than a human one. This consideration therefore gives some latitude to further adapt and simplify the rs-EPI protocol for in vivo scanning, apart from the already developed movement-correction techniques needed. In any case, a further decrease of the number of phase-encode lines by using a higher acceleration factor seems too detrimental to overall SNR and might likely be avoided. An alternative to the use of rs-EPI sequences for cervical spinal cord imaging is the combination of a reduced-FOV imaging technique and the use of a standard ss-EPI sequence, yet this method might be challenged at 7 Tesla by the related increased power deposition. Nevertheless, both methods open great perspectives to reach higher spatial resolution and explore WM and GM substructures of the spinal cord.

Conclusion: An adapted rs-EPI protocol was elaborated to obtain preliminary results of an ex vivo scan of a porcine spinal cord at 7 Tesla. With the imminent supply of commercial MR coils dedicated to spinal cord imaging, in vivo magnetic susceptibility distortion-free DTI of the human spinal cord at 7 Tesla is now within reach.

References: [1] El Mendili et al, PLoS One 9, 2014. [2] Kearney et al, J Neurol Neurosurg Psychiatry, 2014. [3] Ciccarelli et al, J Neurol 250, 2003. [4] Heidemann et al, MRM 64, 2010. [5] Andersson et al, NeuroImage 20, 2003. [6] Smith et al, NeuroImage 23, 2004. [7] Griswold et al, MRM 47, 2002. [8] Kim et al, NMR in Biomed 20, 2007.

Acknowledgments: ANR and A*MIDEX for grant supports; Siemens Healthcare for providing the ss-EPI and rs-EPI prototype sequences.