Q-ball imaging of the spinal cord

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Introduction

The spinal cord white matter contains longitudinal ascending and descending tracts, but also crossing fibers, such as collaterals of descending tracts, commissural fibers and afferent fibers. Non-invasive assessment of the integrity and modification of such specific pathways following spinal cord injury would be of great interest for evaluating the extent of white matter damage as well as their potential reorganization after injury especially in experimental paradigms aimed at fostering axonal regeneration or sprouting [1]. Results from previous diffusion tensor imaging (DTI) studies showed that longitudinal tracts were discernible using DTI [2]. However, since it can be expected that damaged or growing pathways may take several directions, it is important to develop methods for studying diffusion profiles which are not restricted to a single principal direction. In the last five years, other methods such as q-ball imaging (QBI) have been developed, making it possible to account for crossing fibers in white matter [3]. In the present study, we show how the use of high angular resolution data imaging (HARDI) combined with QBI might benefit the characterization of axonal pathways in the *ex vivo* spinal cord. We first investigated the technical requirements to perform QBI successfully on the spinal cord. Then, we did a q-ball reconstruction of the diffusion orientation distribution function (ODF) [4] of water molecules to investigate the added value of QBI over DTI.

Methods

Ex-Vivo DWI Acquisition. The lower portion (from L3 to L7) of a cat spinal cord was excised. It was immediately placed in a 6% gelatin solution without fixation to limit the T2 decrease in the white matter [5]. A few hours later, different HARDI acquisitions were performed on a 3T Siemens scanner, using a receive-only spine coil. Diffusion-weighted data were acquired with the following parameters: spin-echo echo planar imaging, TR/TE/alpha = 4000/96/90, matrix = 120x120, 16 axial slices, voxel size = 1x1x3 mm, b-value = 1500 s/mm^2, number of uniformly sampled gradient directions = 60. Parallel acquisition technique was used (iPAT = 4) and the sequence included a twice refocusing pulse to limit eddy-current distortions [6].

Data Analysis. Several pre-processing steps were done on the DWI datasets: (i) over-sampling (x2) in the axial plane using bicubic interpolation ; (ii) rigid transformation to correct for the phase shift [7] ; (iii) geometric distortions correction to account for magnetic susceptibility [8] ; (iv) cropping of the datasets to keep only the spinal cord. Then, diffusion tensors (DTs) and q-ball ODFs were computed and their maxima extracted [9].

Results

Q-ball imaging yielded consistent results within spinal cord white matter, i.e., principal directions along the rostro-caudal axis (Figure 1a). More interestingly, this method allowed for the extraction of various diffusion directions within the grey matter (Figure 1b). We were able to distinguish lateral directions corresponding to commissural fibers, as well as antero-posterior directions corresponding presumably to the dorso-ventral fibers arising from the projection of dorsal roots. A comparison between DT and q-ball results on the same dataset clearly showed the benefits of q-ball imaging for observing secondary directions (Figure 2). A closer look at the region of the grey matter central canal showed that ODFs represented a large principal diffusion peak in the longitudinal direction and a smaller diffusion peak in the collateral directions. In the case of DTs, the "disk shape" suggests two major directions almost perpendicular, but the constraints imposed by the orthogonal projection scheme prevents us from distinguishing their individual anisotropic quantification from their actual directions (which might not be fully orthogonal).

Discussion

We showed that QBI can recover crossing fiber information in the *ex vivo* spinal cord, where the DTI approach is limited. To our knowledge, this is the first QBI study demonstrating the benefits of QBI for observing longitudinal, dorso-ventral and commissural fibers in the spinal cord. Although the use of the DT second eigenvector has been proposed to account for secondary perpendicular directions in the brain [10] as well as in the spinal cord [11], there is a restriction imposed by the tensor itself. When the primary direction is defined by the first eigenvector, i.e., longitudinal fibers in the case of the spinal cord, the second eigenvector is limited in degrees of freedom since its direction is necessarily in the plane orthogonal to longitudinal fibers. In the presence of non orthogonal fibers, the usual way of decomposing the tensor (i.e., in an orthogonal fashion) becomes less efficient. In such case, QBI provides a more accurate description of the diffusion processes. We also investigated the impact of sharpening q-ball ODFs [9], and shown an improvement in the detection of non-longitudinal fibers. QBI combined to an appropriate sharpening will provide significant improvement of q-ball tractography in the spinal cord.

References

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Figures

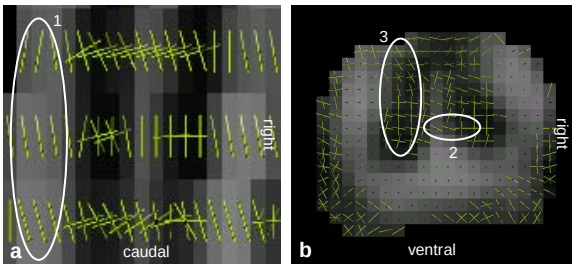

Figure 1. Coronal (a) and axial (b) view of fractional anisotropy map, with an overlay of ODF maxima. One is able to distinguish various directions corresponding presumably to longitudinal fibers (1), commissural fibers (2), and dorso-ventral fibers arising from the projection of dorsal roots (3).

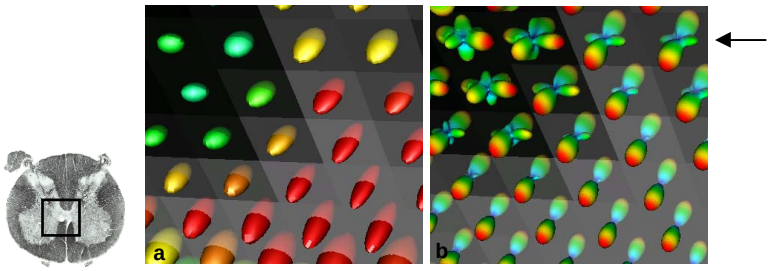

Figure 2. Axial view of fractional anisotropy centered on the central canal with an overlay of DTs (a) and ODFs (b). In this example, DT representation becomes limited in the presence of perpendicularly crossing fibers, whereas ODFs clearly distinguish the two principal directions (black arrow)