Evaluation of q-ball metrics for assessing the integrity of the injured spinal cord

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Introduction
Assessment of spinal cord integrity following injury is crucial for evaluating the potential for functional rehabilitation [1]. Previous studies showed the benefits of diffusion tensor imaging (DTI) for the non-invasive characterization of the healthy and injured spinal cord [2]. However, biases related to the incapability of DTI to represent complex diffusion profiles suggested the use of less constraining techniques. Recently, we demonstrated that q-ball imaging (QBI) is capable of partly solving fiber crossing information in the intact spinal cord [3]. In this study, we extended the application of QBI in a model of cat partial spinal cord injury and we compared various QBI quantitative metrics to the ones used in DTI. We also proposed an original QBI-based metric to quantify the homogeneity of major diffusion directions.

Materials and methods
Data acquisition. MRI acquisitions were conducted in five in vivo cats, one week after a left hemilesion at thoracic 11 (T11) level. We used a Siemens 3T system with two phased array coils. Diffusion-weighted scans were conducted using twice refocused single shot EPI (sagittal orientation, 1.5x1.5 mm2 in-plane resolution, TR/TE = 9500/109 ms, IPAT = 3, FOVp = 50%, b-value = 1000 s/mm², 64 directions, respiratory gating). Slice thickness was enhanced to 1 mm using supersolution methods [4]. With the same slice prescription but twice higher spatial resolution, T1-weighted turbo spin echo (TSE) and T2-weighted MPRAGE images were acquired.

Data processing. Images were corrected for susceptibility artifacts [5] and orientation distribution functions (ODF) were estimated using spherical harmonic basis functions [6]. Using the TSE image, regions of interest (ROI) were delineated in the right and left side of the cord. Various metrics derived from DTI and ODF were estimated and averaged in each axial plane of the ROI, to study the distribution of metrics along the spinal cord.

Results
ODF exhibited a quasi-anisotropic profile within the healthy white matter, with major direction oriented rostro-caudally (Fig 1). In spinal cord injured cats however, this diffusion profile was drastically modified ipsilateral, whereas contralateral pathways appear to remain intact and therefore anisotropic. In order to do a group analysis, metrics quantified along the cord were registered with respect to the location of each cat’s lesion (centered at 0). Results of selected metrics are shown in Fig 2 and stand in terms of lesion extent and quality of data. Future studies should aim at finding normalization procedures to better extract ODF metrics for assessing the integrity of the injured spinal cord.

Discussion
Both FA and GFA are obvious markers of white matter abnormality, with FA being sharper within the lesion. Interestingly, GFA varied with a low frequency ipsi- and contra-laterally along the cord, possibly due to its higher sensitivity to microstructure heterogeneity (e.g., variation of axonal architecture at spinal segments). Interestingly, FA and GFA remained abnormally low ipsilaterally up to 20 mm caudal and rostral to the lesion epicenter, suggesting abnormalities. Axial and radial diffusivities respectively decreased and increased within damaged tissue, confirming previous studies [7]. However, important inter-subject variability decreased the sensitivity of these two markers. MSE robustly detected the presence of a lesion with a relatively flat profile in other parts of the cord. However, MSE surprisingly increased number of afferents, secondary injuries, sprouting). Two important limitations arise from this study. The first one concerns partial volume effects and the relatively high inter-subject variability, shifting the data. Thick lines represent averaged values across cats (thin lines are standard deviations).

References

Fig 1. Sagittal (a) and axial (b-d) anatomical image with overlay of ODF rostral (b), caudal (d) and centered in the lesion (c), where abnormal diffusion profile is visible at the ipsilateral side.

Fig 2. Quantitative metrics derived from DTI and ODF. Abscissa stands for the location along the cord. For each cat, measurements were registered to the lesion (dashed line) by shifting the data. Thick lines represent averaged values across cats (thin lines are standard deviations).

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