ELSEVIER

NeuroImage

www.elsevier.com/locate/ynimg
NeuroImage 42 (2008) 739–749

# Detection of multiple pathways in the spinal cord using q-ball imaging

J. Cohen-Adad,[a,c,*] M. Descoteaux,[b,e] S. Rossignol,[c] R.D. Hoge,[d] R. Deriche,[b] and H. Benali[a]

[a]*INSERM U678, Université Pierre et Marie Curie (Paris VI), CHU Pitié-Salpêtrière, Paris, France*
[b]*Odyssée Project Team, INRIA/ENPC/ENS, INRIA Sophia Antipolis, France*
[c]*GRSNC, Faculty of Medicine, Université de Montréal, Montreal, QC, Canada*
[d]*Unité de Neuroimagerie Fonctionnelle, CRIUGM, Université de Montréal, Canada*
[e]*CEA Neurospin, NMR Lab, Gif-sur-Yvette, France*

Received 15 February 2008; revised 3 April 2008; accepted 14 April 2008
Available online 30 April 2008

**Magnetic resonance diffusion tensor imaging (DTI) has been extensively applied to the spinal cord for depicting its architecture and for assessing its integrity following spinal lesions. However, DTI is limited in representing complex white matter architecture, notably in the presence of crossing fibres. Recently, q-ball imaging (QBI) has been proposed as a new method for recovering complex white matter architecture. We applied this technique to both *ex vivo* and *in vivo* spinal cords of cats using a 3T scanner. For the purpose of comparison, gradients have been applied in 55 and 100 encoding directions and *b*-values varied from 800 to 3000 s/mm$^2$. As a result, QBI was able to retrieve crossing fibre information, where the DTI approach was constrained in a unique diffusion direction. To our knowledge, this is the first study demonstrating the benefits of QBI for detecting the presence of longitudinal, commissural and dorso-ventral fibres in the spinal cord. It is a first step towards *in vivo* characterization of the healthy and injured human spinal cord using high angular resolution diffusion imaging and QBI.**


*Keywords:* Diffusion tensor imaging; High angular resolution diffusion imaging; Q-ball; Spinal cord; White matter

## Introduction

Diffusion tensor imaging (DTI) is a method derived from magnetic resonance imaging (MRI) used for mapping white matter structure (Basser et al., 1994). It has been recently applied to the spinal cord and has demonstrated its benefits for assessing white matter integrity following injury (Agosta et al., 2007; Budde et al., 2007; Cohen-Adad et al., 2008; DeBoy et al., 2007; Deo et al., 2006; Ducreux et al., 2007; Fujiyoshi et al., 2007; Kim et al., 2007; Lammertse et al., 2007; Nevo et al., 2001; Ohgiya et al., 2007; Plank et al., 2007; Ries et al., 2000; Schwartz et al., 2005; Shen et al., 2007; Thurnher and Bammer, 2006; Valsasina et al., 2005; Vargas et al., 2008). Also, it has been shown that DTI can retrieve major longitudinal pathways, *i.e.*, axon bundles oriented in the rostro-caudal direction (Bilgen et al., 2005; Ciccarelli et al., 2007; Cohen-Adad et al., 2008; Ellingson et al., 2007; Fenyes and Narayana, 1999; Gullapalli et al., 2006; Maier, 2007; Wheeler-Kingshott et al., 2002). However, other types of fibres not oriented longitudinally are also present in some parts of the cord. These are for instance commissural fibres coursing in the medio-lateral direction, and dorso-ventral fibres that may originate from dorsal root afferents or terminal fibres of descending tracts. Since the diffusion tensor can only account for a single principal diffusion direction, these pathways might not be visible using DTI (Hagmann et al., 2006). Furthermore, after lesions or in the presence of tumours or cysts tracts can be displaced so that they are no longer following a longitudinal direction.

To overcome this issue, model-free approaches have been proposed to measure the microscopic diffusion without constraining its representation. These methods are known as q-space imaging (Callaghan et al., 1988) or diffusion spectrum imaging (Wedeen et al., 2005) and have already demonstrated benefits for imaging the brain (Schmahmann et al., 2007) and the spinal cord (Assaf et al., 2000). However, long acquisition time is required for adequate sampling of q-space to retrieve the three-dimensional diffusion profile. To reduce acquisition times, a similar method has been proposed where sampling of q-space is restricted to a single sphere in many directions. This method is known as high angular resolution diffusion imaging (HARDI). A popular HARDI reconstruction method is q-ball imaging (QBI), which allows the retrieval of crossing fibres information with shorter acquisition time (Campbell et al., 2005; Tuch, 2004).

In the present study, we applied this technique in both *in vivo* and *ex vivo* feline spinal cord. We show that QBI can recover longitudinal pathways as DTI does, but can also recover medio-lateral and

* Corresponding author. UNF, CRIUGM, 4565 Queen-Mary, Montreal, QC, Canada H3W 1W5. Fax: +1 514 340 3530.
*E-mail address:* julien.cohen-adad@imed.jussieu.fr (J. Cohen-Adad).
**Available online on ScienceDirect (www.sciencedirect.com).**

1053-8119/$ - see front matter © 2008 Elsevier Inc. All rights reserved.
doi:10.1016/j.neuroimage.2008.04.243

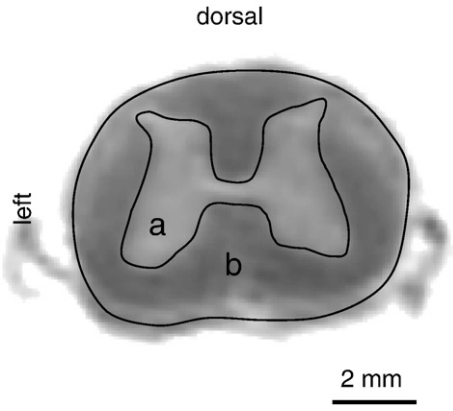


Fig. 1. Axial slice (L5 spinal level) of the *ex vivo* PD scan showing both ROIs in the grey (a) and in the white matter (b). These ROIs are used for FA and GFA quantifications.

dorso-ventral directions which are consistent with the known architecture of the spinal cord.

## Material and methods

### *Ex vivo acquisition*

The experiments were conducted in accordance with the Ethics Committee of the University of Montreal. One cat was sacrificed with an overdose of barbiturate (Somnotol). A laminectomy was performed at the lumbar level followed by the dissection of the dura matter. Dorsal and ventral roots were sectioned. The cord corresponding to lumbar segments 3 to 7 was extracted and put in saline solution (0.9%). Thirty minutes after extraction, the cord was placed into a gelatine solution (6%). It was imaged five hours later. We chose not to fix the cord because this chemical process induces a significant decrease of transverse relaxation time in the white matter (Carvlin et al., 1989; Pfefferbaum et al., 2004). Based on previous tests performed on fixed samples, we have concluded that constraints on our diffusion sequence parameters prevented us from reaching a echo time (TE) small enough to obtain sufficient signal in the white matter.

Datasets were acquired on a Siemens Trio system (3T) using an 8-channel spine array coil allowing parallel imaging. RF transmission was performed using the body coil integrated into the magnet bore. Anatomical scans were conducted using proton-density (PD) weighting as these provide good contrast between white and grey matter. Parameters were: Turbo Spin-Echo sequence (turbo factor of 13), matrix = 320 × 320, voxel size = 0.25 × 0.25 × 3 $mm^3$, TR = 3500 ms, TE = 11 ms, flip angle = 120 °. PD scans were used to generate regions of interest (ROIs — see section on Data processing).

Diffusion-weighted (DW) scans were acquired with a single-shot spin echo EPI pulse sequence. Parallel acquisition using GRAPPA (GeneRalized Autocalibrating Partially Parallel Acquisition) was used with an acceleration factor of 4 to limit the extent of susceptibility artifacts induced by the gelatine-air interface and by ferromagnetic micro-particles contained in the gelatine. To limit the effect of eddy-current distortions, the sequence included a twice refocusing pulse (Reese et al., 2003). Parameters were: matrix = 120 × 120, voxel size = 1 × 1 × 3 $mm^3$, TR = 4000 ms, TE = 96 ms, flip angle = 90°, three repetitions, *b*-value = 0 and 1500 s/$mm^2$, 100 directions using a polyhedron scheme (Madi et al., 2005). To evaluate the impact of different *b*-values, three additional datasets were acquired using a circularly polarised transmit–receive wrist coil to get higher signal-to-noise ratio (SNR). No parallel imaging was used for these scans. Parameters were: matrix = 128 × 128, voxel size = 0.65 × 0.65 × 3 $mm^3$, TR = 4700 ms, TE = 152 ms, flip angle = 90 °, three repetitions, *b*-value = 1000, 2000 and 3000 s/$mm^2$, 100 directions.

### *In vivo acquisition*

One healthy cat was used for the *in vivo* study. It was anaesthetized in the scanner (isoflurane 2% through an endo-tracheal tube) and breathed freely. The cat was positioned feet-first-supine over an 8-channel phased-array coil, as done in (Cohen-Adad et al., 2008). The centre was aligned on the fourth lumbar vertebral (L4) level. The cat was well propped up in the coil using bags to avoid any motion during the acquisition.

Anatomical PD-weighted scans were conducted with the following parameters: Turbo Spin-Echo sequence (turbo factor of 7), axial orientation, matrix = 512 × 512, voxel size = 0.35 × 0.35 × 3 $mm^3$, 20 slices, TR = 2000 ms, TE = 14 ms, flip angle = 150°.

DW data were acquired using the same single-shot spin echo EPI sequence as for *ex vivo* acquisitions. Parameters were: matrix = 128 × 128, voxel size = 1.1 × 1.1 × 1.1 $mm^3$, 15 slices, TR = 9500 ms, TE = 109 ms, flip angle = 90 °, *b*-value = 0 and 800 s/$mm^2$. We performed two acquisitions to compare QBI at various sampling schemes. In the first acquisition, DW gradients have been applied in 28 directions (6 $b_0$ repetitions, 4 repetitions, 22 min scan). In the second acquisition, DW gradients have been applied in 55 directions (3 $b_0$ repetitions, 4 repetitions, 38 min scan). Although cardiac-gated

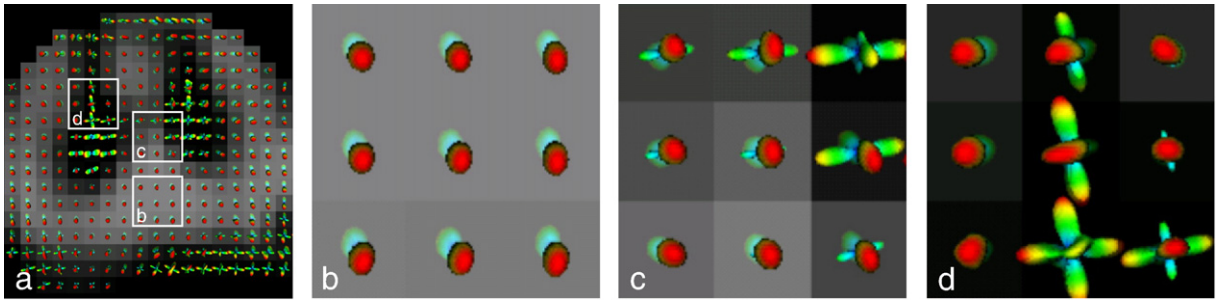


Fig. 2. a: Results of QBI in the spinal cord. ODFs were overlaid on an axial GFA map (top is dorsal, left is left). Zoomed panels show ODFs in the ventral white matter (b), in the central canal (c) and in the right grey matter posterior horn (d). ODF colour code goes from red to blue for maximal to minimal values on the sphere, respectively. Also, the radius of the ODF is proportional to its value on the sphere.