In vivo Assessment of Nervous Fiber Distribution in the Intervertebral Disc

Tien Tuan Dao, Philippe Pouletaut, Fabrice Charleux, and Marie-Christine Ho Ba Tho

Abstract— **This present study aims to assess *in vivo* the nervous fibers distribution in the intervertebral disc using diffusion tensor imaging technique. Five healthy subjects participated into the data acquisition. Fiber extraction and tracking algorithms were used. The number of fibers in L4/5 disc ranges from 314 to 679 and the mean fiber length L4/5 in disc ranges from 8.22±2.36 mm to 11.24 ± 5.17 mm. This study showed the feasibility of using diffusion tensor imaging technique to detect and assess the nervous fibers in the intervertebral discs. This could be of great clinical interest for the study of the correlations between these useful characteristics with pain levels on the low back pain patients.**

I. Introduction

Low back pain is one of the common chronic disorders of the human beings during their lives [1]. The depiction of the possible causes of the back pain is still a challenging research topic. The early detection of abnormal behavior of involved tissues such as lumbar spine muscles, bones and intervertebral discs plays in important role in the better management of this chronic disorder [2].

Research studies have been done to provide evident facts to early detect the abnormal symptoms of the low back pain at the organ and tissue levels leading to better treatment prescription [3-5]. Lumbar spine discs are common structures affected by the pathophysiological process. Conventional (Computed Tomography (CT) and Magnetic Resonance Imaging (MRI)) and advanced ($T_{1\rho}$, T2 mapping, diffusion tensor) medical imaging techniques have been widely used to assess the geometrical and material changes of the intervertebral discs (IVD) during disc degeneration process [5-6]. However, the correlation between characterized properties such as $T_{1\rho}$ time, T2 relaxation time, and apparent diffusion coefficients with chronic pain is still misunderstood.

Pain arises from damaged tissues. The dorsal root ganglia and nervous fibers are main actors which transmit the painful signals to the spinal cord. In fact, the nervous fibers could be an effective indicator to study the pain. To get the information of the nervous fiber, diffusion tensor imaging could be used. This technique has been used to track the nervous fibers in the brain [7-9]. However, this imaging technique has not been applied on the intervertebral disc. The objective of this present study was to apply this non-invasive technique to assess *in vivo* the nervous fiber distribution in the intervertebral disc.

II. Materials and Methods

A. Diffusion Tensor MRI Acquisition

Five healthy and male subjects (mean ± standard deviation: 32.2±7.8 years old, 73.8±18.7 kg body mass, 1.75±0.09m body height, 24.8±6.9 kg/m² body mass index (BMI)) participated into this study. The data acquisition was performed at the Polyclinique Saint Côme (Compiègne, France). All participated participants signed their informed written consent agreement before the data acquisition. The diffusion tensor MRI sequence (1.5T GE machine) was used to scan the participant's L4/5 disc in the axial plane.

The diffusion tensor MRI sequence included six different directions [10]. The repetition (TR) and echo (TE) times were 3000 ms and 90.5 ms respectively. Each acquisition had 21 adjoining slices. The slice thickness was 4mm. The voxel resolution was 1.21x1.21x4 mm³ (around 5.86 mm³). The field of view (FOV) was 310×310 mm². The acquisition time of one subject was around 5.39 minutes. An example of MRI image is shown in Fig. 1.

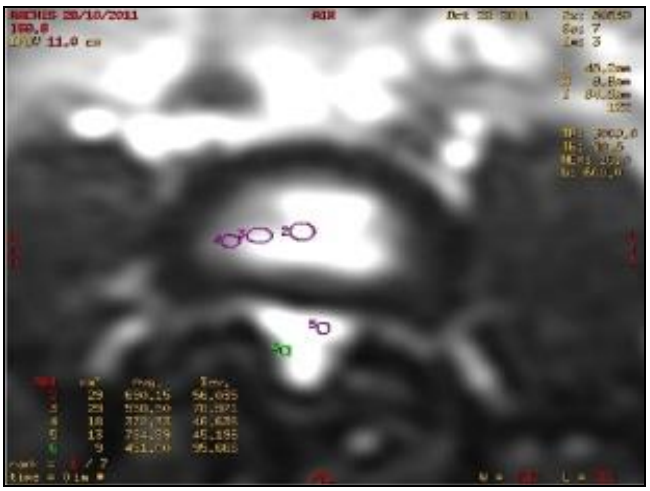

Figure 1. Diffusion tensor image of the intervertebral disc of the subject #1.

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B. *Fiber spatial distribution analysis*

First, the diffusion tensor (D) and relative anisotropy (RA) were computed [10-12]. Then the threshold-based fiber extraction and tracking algorithm [13] were performed.

This analysis was performed using MedInria software[1] (Asclepios Research Team, Inria, France). All constitutive equations are expressed as follows:

$$D = \frac{1}{b} \sum_{k=1}^{6} (\ln \frac{S_0}{S_k}) \; G_k . \tag{1}$$

$$RA = \frac{\sqrt{3}}{\sqrt{2}} \times \frac{\left| D - \frac{1}{3} trace(D) I \right|}{trace(D)} \tag{2}$$

$$C = \left| \vec{\mu}_L . \vec{\mu}_{L-1} \right| \tag{3}$$

$$R = \sum_i^s \sum_j^s \left| \vec{u}_i . \vec{u}_j \right| / s(s-1) \tag{4}$$

$$\vec{u}_i = FA_i . \vec{\mu}_L \tag{5}$$

where D is the diffusion tensor; S_0 and S_i are the signal intensity without diffusion weighting and with diffusion weighting for 6 directions respectively; G_i is the dual 3x3 tensor basis; λ_1 and λ_3 are the greatest and lowest eigenvalues of the diffusion tensor. The *b*-value coefficient was set up as 600 s/mm² [10]; R is the local connectivity with the tracking threshold set up as 0.1 [13]; C is the transition smoothness with the tracking threshold set up as greater than 0.7 (approximately cosinus of 45°) [13]; s is the number of the voxels referred in the neighborhood. The vector $\vec{u}_i$ is the scaling vector. The vectors $\vec{\mu}_L$ and $\vec{\mu}_{L-1}$ are the unit vectors at the current location and at the voxel prior to the current on the tracked fiber respectively.

To assess the fiber distribution on each intervertebral disc, the number of the extracted fibers and their length were computed and presented. Disc volume property was also computed to give geometrical information of the IVD. The volume computing is based on cumulative pixel principle [14].

III. Results

Diffusion apparent coefficient maps of the IVDs are illustrated in Fig. 2.

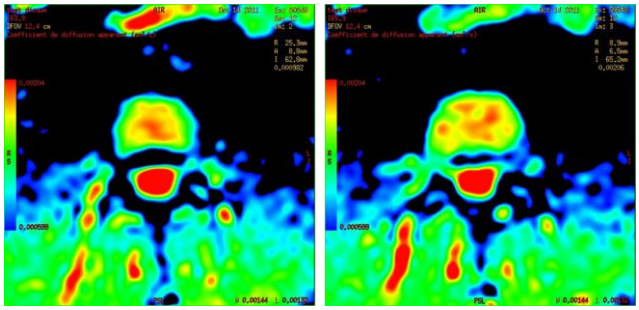

Figure 2. Illustration of diffusion apparent coefficient maps of the the L4/5 of 2 subjects.

The disc volume, the number of the extracted fibers and their length properties are depicted in Table 1.

TABLE I. FIBER DISTRIBUTION RESULTS OF THE L4/5 IVD OF ALL SUBJECTS

Subject	Extracted Properties on the L4/5 IVD			
	Volume (mm^3)	*Number of fiber*	*Mean Length (mm)*	*SD Length (mm)*
1	3126.1	314	8.22	2.36
2	3906.2	382	8.28	2.83
3	4064.5	447	8.42	3.09
4	5900.3	632	9.84	4.96
5	5853.4	679	11.24	5.17

The fiber length property was transformed into probability space. Thus, a cumulative distribution function (CDF) [15] of the mean fiber lengths is illustrated in Fig. 3.

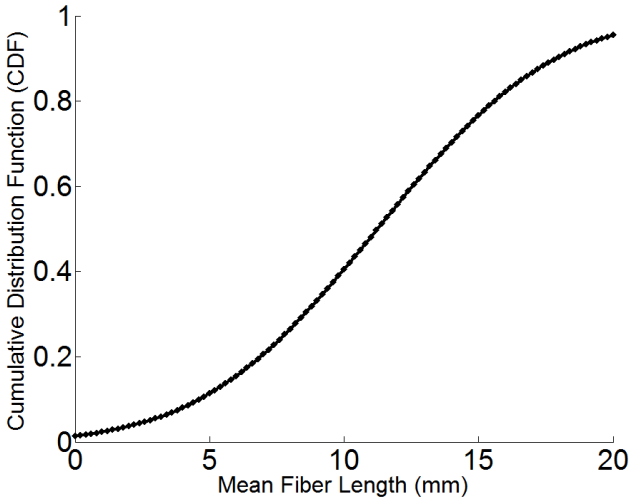

Figure 3. Cumulative probability function of the mean fiber lengths of 5 subjects.

An example of orientation of the first eigenvector extracted from a diffusion tensor MRI image is shown in Fig. 4.

[1] http://www-sop.inria.fr/asclepios/software/MedINRIA/

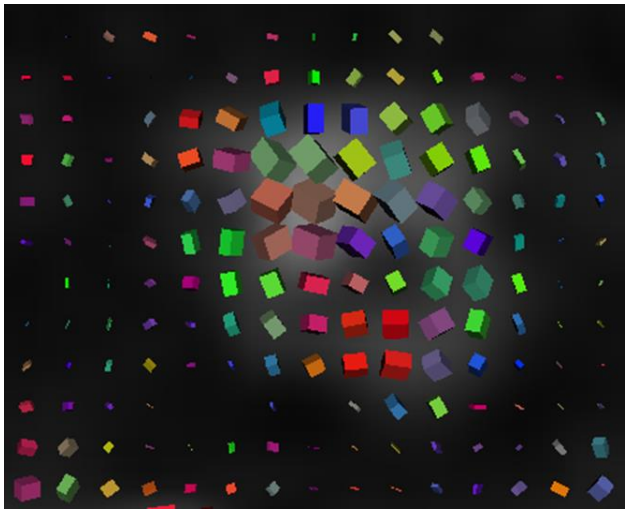

Figure 4. Orientation example of the first eigenvector of the L4/5 of the subject #4.

The relative anisotropy and fiber maps of all analyzed discs are illustrated in Fig. 5 and Fig. 6. Note that the fiber density of the IVD varies from one subject to another. Moreover, the fibers are more compact on the annulus fibrosus regions.

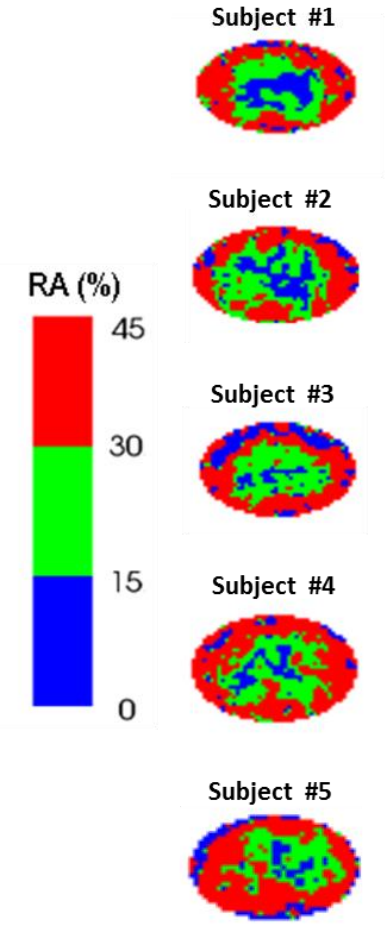

Figure 5. Relative anisotropy maps related to the L4/5 discs of 5 subjects.

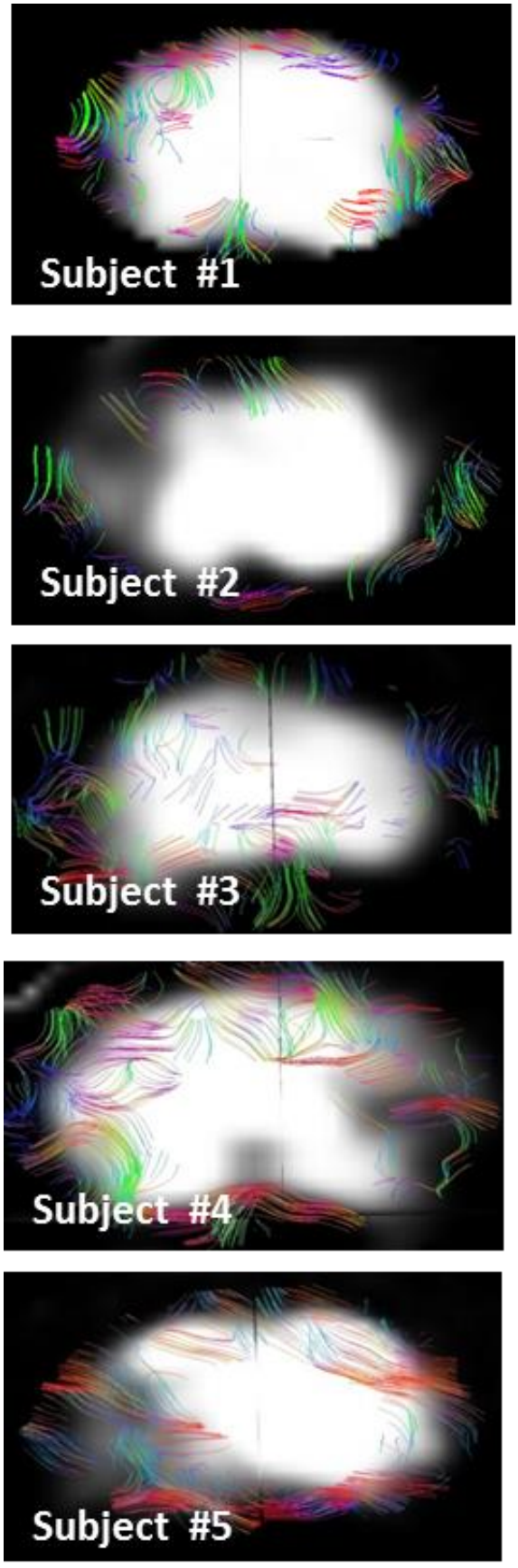

Figure 6. Fiber maps related to the L4/5 discs of 5 subjects.

IV. Discussion

Early detection of abnormal behavior of the intervertebral discs using *in vivo* approach plays an important role in the management of low back pain disorders. In this context, non-invasive medical imaging is an essential tool to provide *in vivo* assessment of human tissues and structures. Conventional medical imaging techniques such as CT or MRI allowed only contrast and spatial resolution to be used for the quantification of morphological and pseudo-biomechanical properties of the IVD leading to poor predictive specificity in the diagnosis of low back pain [17-18]. Besides, advanced magnetic resonance sequences such as T2 mapping, diffusion tensor have showed their efficiencies in the quantification of tissue change as well as the assessment of molecule motion in the IVD regions (annulus fibrosus and nucleus pulposus) [3], [5], [10]. In this present study, the diffusion tensor sequence allows nervous fiber distribution to be extracted and tracked leading to provide a new potential marker for the early detection of abnormal behavior of the IVD.

Diffusion tensor imaging has been successfully applied to assess the fiber distribution in the brain [9]. Based on the water diffusion properties (diffusion anisotropy and orientation) and the assumption of the alignment between largest principal axis of the diffusion tensor and fiber orientation, 3D vector fields at each voxel could be extracted. Then, fiber trajectories could be reconstructed in 3D [16]. In our present study, nervous fiber distribution was extracted and tracked on the IVD (Fig. 6). The fiber distribution was more concentrated in the annulus fibrosus region. This finding seems to be consistent with the anatomy of the intervertebral disc. Moreover, based on our unpublished data, the diffusion tensor sequence was applied on the cadaveric IVD and we noted that no fibers could be extracted due to the *in vitro* condition of the analyzed tissue. In fact, diffusion tensor imaging (DTI) allows the number of fibers and their respective length properties to be estimated in a non-invasive and *in vivo* manner. This information will be of great clinical interest for the better understanding as well as for the early detection of abnormal behavior of the low back pain.

V. Conclusion

This study showed the feasibility of the diffusion tensor MRI sequence on the assessment of nervous fiber distribution of the intervertebral discs. As perspective, the developed methodology will be applied on low back pain patients to verify the hypothesis on the correlation between the nervous fiber information and the low back pain.

Acknowledgment

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