Qualification of the Most Statistically "Sensitive" Diffusion Tensor Imaging Parameters for Detection of Spinal Cord Injury

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Qualification of the most statistically "sensitive" diffusion parameters using magnetic resonance diffusion tensor imaging of the control and injured spinal cord of a rat *in vivo* and *in vitro* after the trauma is reported. Injury was induced in TH12/TH13 level by a controlled "weight-drop". *In vitro* experiments were performed in a home-built magnetic resonance microscope, with a 6.4 T magnet, *in vivo* samples were measured in a 9.4 T/21 horizontal magnet. The aim of this work was to find the most effective diffusion parameters which are useful in the statistically significant detection of spinal cord tissue damage. Apparent diffusion tensor weighted data measured *in vivo* and *in vitro* on control and injured rat spinal cord in the transverse planes and analysis of the diffusion anisotropy as a function of many parameters, which allows a statistical expose of the existence of the damage, are reported.

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1. Introduction

Diffusion tensor imaging (DTI) has become one of the important contrast mechanisms in magnetic resonance imaging (MRI), when it has been found that ischemic injury of nerve tissues changes a diffusion coefficient. Initially DTI has been used to investigate brain and then spinal cord tissue [1]. Recent progress of MRI provides new possibilities to examine central nerves tissue *in vivo* [2].

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The aim of this study was to define of the most sensitive DTI parameters for detection of the presence and extent of spinal cord tissue damage. Of special interest is statistical comparison of diffusion tensor components (DTC) measured *in vivo* and *in vitro* for control and injured spinal cord of the rat.

2. Subjects

A well-characterized "dynamic load" rat spinal cord injury model [3] was used to induce injury. Male Wistar rats of 250 g to 300 g were used for all experiments. For *in vitro* and *in vivo* experiments laminectomy was performed at the Th13 level under general anesthesia.

3. MR experiment

In vitro samples were measured in a home-built magnetic resonance (MR) microscope, with a 6.4 T magnet and *in vivo* ones were done in a 9.4 T/21 horizontal magnet. MR images (256×256) were acquired at room temperature (21 C) with an in-plane resolution 40×40 mm, slice thickness 800 mm, TR = 0.8 s, TE = 47 ms, gradient b-factor up to 800 mm^2/s.

In vivo experiments were done in a 9.4 T/21 horizontal magnet. MR images in the form of a 128×256 matrix were acquired with a FOV of 2 cm, TR = 2 s, TE = 40 ms, gradient b-factors up to 2000 mm^2/s, slice thickness of 1 mm.

A conventional spin-echo imaging sequence with diffusion gradients was used to measure the effect of diffusion on MR images in both *in vitro* and *in vivo* experiments [4]. DTC were evaluated for each pixel of the image using below equation:

$$\ln\left(\frac{A(b)}{A(0)}\right) = -\gamma^2 \sum_{\alpha,\beta=1}^{3} b_{\alpha\beta} ADT_{\alpha\beta}.$$

The diffusion tensor components were determined by minimizing χ^2 function from above equation, where: $A(b)$, $A(0)$ — the echo intensities with and without the diffusion gradients, $b_{\alpha\beta}$ — component of the known diffusion gradient matrix, $ADT_{\alpha\beta}$ — component of the apparent diffusion tensor (ADT).

To examine differences between control and injured rats unpaired samples t-Student's test was used for samples comparison.

4. Results

Figures 1 and 2 show a comparison of isotropy index ID, longitudinal DTC (DL), transverse DTC (DT) calculated from a set of regions of interest (ROIs) in gray matter (GM) and white matter (WM), registered for slices through the centre of laminectomy for control and injured spinal cord of the rat.
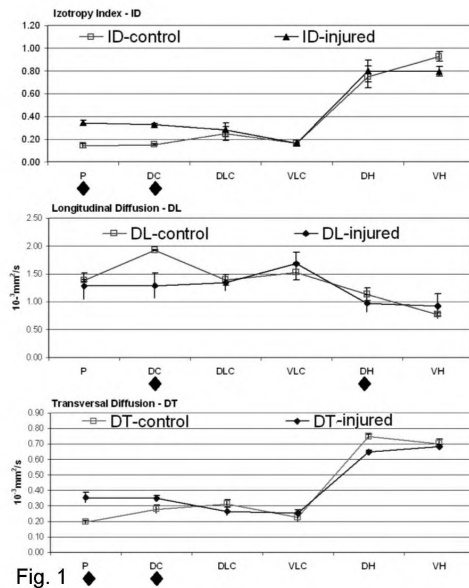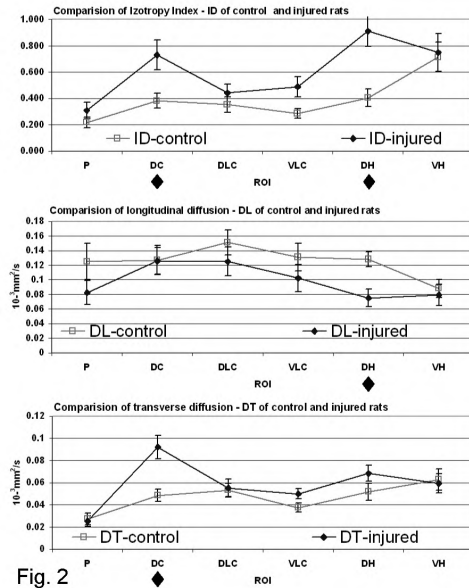
Fig. 1.

Fig. 2.

Fig. 1. Comparison of ID, DL, DT averaged over groups of injured and control rats *in vivo*, determined for slices through the centre of laminectomy. An "◆" indicates a statistically significant differences ($p < 0.05$) between control and injured samples for a given ROI.

Fig. 2. Comparison of ID, DL, DT averaged over groups of injured and control rats *in vitro*, determined for slices through the centre of laminectomy. An "◆" indicates the same as in Fig. 1.

The significant alterations of DT, DL, ID parameters observed for pyramidal (P), dorsal column (DC) regions for *in vivo* samples. In remaining ROIs: dorsal lateral column (DLC), ventral lateral column (VLC), ventral column (VC) in WM and dorsal horn (DH) and ventral horn (VH) in GM there are almost no changes of diffusion parameters. For *in vitro* significant changes were detected in DC for WM and DH for GM.

The results collected in the Table show the existence of statistically significant differences ($p < 0.05$) of ADT parameters between control and injured rats in P, DC, DH regions of interest for *in vivo* rats and in DC, VH for samples measured *in vitro*. The most sensitive for injury is the region in DC — dorsal column, placed in white matter and situated near the centre of injury in both *in vivo* and *in vitro* experiments.

The Table shows a statistical comparison of following parameters: ID, DL, DT, trace (Tr) and fractional anisotropy (FA) for different ROIs, obtained for the injured and control spinal cords *in vivo* and *in vitro*. The summarized results of statistically significant differences ($p < 0.05$) between DTC parameters for control and injured samples of spinal cord measured *in vivo* (index A) and *in vitro* (in-

TABLE

The summarized results of statistically significant differences $(p < 0.05)$ between DTC parameters for control and injured samples of spinal cord measured *in vivo* (index A) and *in vitro* (index X). An "+" indicates a statistically significant differences $(p < 0.05)$ between control and injured samples for a given ROI. P — pyramidal tracts, DC — dorsal column, DLC - dorsal lateral column, a VLC — ventral lateral column, DH — dorsal horn, VH — ventral horn.

ROI	ID_A	ID_X	DL_A	DL_X	DT_A	DT_X	Tr_A	Tr_X	FA_A	FA_X
P	+	−	−	−	+	−	−	−	+	−
DC	+	+	+	+	+	−	+	+	−	+
DLC	−	−	−	−	−	−	−	−	−	−
VLC	−	−	−	−	−	−	−	−	−	−
DH	−	−	+	−	−	−	−	−	+	−
VH	−	+	−	−	−	+	−	−	−	−

dex X). An "+" indicates statistically significant differences $(p < 0.05)$ between control and injured samples for a given ROI.

5. Conclusion

It was shown that DTI of the spinal cord can statistically $(p < 0.05)$ differentiate between injured and control tissue in both *in vitro* and *in vivo* experiments. The most insensitive parameter is Tr, which is averaged over all directions. The information provided by all other tensor parameters is complementary.

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