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Clinical applications of diffusion tensor tractography of the spinal cord

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Abstract Diffusion tensor imaging (DTI) can visualize the white matter tracts in vivo. The aim of this study was to assess the clinical utility of DTI in patients with diseases of the spinal cord. Fourteen subjects underwent magnetic resonance imaging of the spine at 1.5 T. Preliminary diagnosis of the patients suggested traumatic, tumorous, ischemic or inflammatory lesions of the spinal cord. In addition to T2-weighted images, DTI was performed with the gradients in 30 orthogonal directions. Maps of the apparent diffusion coefficient and of fractional anisotropy were reconstructed. Diffusion tensor imaging showed a clear displacement and deformation of the white matter tracts at the level of the pathological lesions in the spinal cord. This capability of diffusion tensor imaging to reliably display secondary alterations to the white matter tracts caused by the primary lesion has the potential to be of great utility for treatment planning and follow-up.

Keywords Diffusion · Diffusion tensor imaging · Magnetic resonance imaging · Spinal cord · Spine

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Introduction

Spinal lesions sometimes remain insufficiently visualized by "conventional" magnetic resonance imaging (MRI) techniques; indeed very often the lesions seen on T2-weighted images do not completely display the effects of pathology on the long tracts. Diffusion imaging, which enables the imaging of molecular water motion, has been applied recently to spinal cord diseases [1–3]. A modification of diffusion imaging, diffusion tensor imaging (DTI) [4], can also display vectors corresponding to the strength and direction of the molecular water movement. This has also been applied recently to the spine using various techniques that minimize artifacts [5, 6]. The first reports of DTI being used in patients with spinal cord pathologies have recently been published [7–10].

Methods

Imaging was performed on a total of 14 subjects: nine patients (six men and three women, aged between 14 and 63 years) with suspected pathology (traumatic, tumorous, ischemic or inflammatory) of the spine and five volunteers. Table 1 presents the clinical information in detail. Imaging

Table 1 Clinical characteristics of patients

	Age (years)/sex	Pathology	Location	DTI finding	FA	ADC (mm^2/s)[a]
1	33/F	Ependymoma	Cervical	Displacement of fibers	308.2	2.497
2	25/F	Ependymoma	Cervical	Displacement of fibers	344	2.355
3	60/M	Ependymoma	Cervical	Displacement of fibers	247.7	1.216
4	16/M	Pilocytic astrocytoma	Cervico-dorsal	Displacement of fibers	194.5	1.628
5	63/M	Myeloma metastasis	Medullary cone	Deformation and interruption of fibers	345	1.107
6	14/M	Spinal ischemia	Cervico-dorsal	Interruption of fibers	652	D 0.506
					208.7	1.567
7	56/F	Neuromyelitis optica	Cervico-dorsal	Interruption of fibers	161.3	1.082
8	42/M	Spinal contusion	Cervical	Deformation of fibers	540.3	1.238
9	45/M	Herniated disc	Cervical	Normal	625	1.102
10	15/F		Dorsal	Normal	505.5	C 1.405
11	41/M		Cervico-dorsal	Normal	689	C 1.123
					526.7	D 1.062
12	31/M		Cervico-dorsal	Normal	666.7	C 1.040
					645.3	D 1.299
13	32/M		Cervico-dorsal	Normal	685.7	C 1.171
					645.7	D 1.131
14	38/M		Cervico-dorsal	Normal	647	C 1.093
					616.3	D 1.169

DTI, Diffusion tensor imaging; FA, fractional anisotropy
[a] C, Cervical; D, dorsal

was performed at 1.5 T on a clinical magnet (Siemens Avanto, Erlangen, Germany). For anatomical and diagnostic imaging of the spine, a sagittal T2 FSE (TR=3010 ms; TE=110 ms; fifteen 3-mm-thick slices) and axial medic T2 (TR=1380; TE=27 ms; twenty-five 3-mm-thick slices) was utilized as well as a sagittal (TR=460 ms; TE=8.9 ms; fifteen 3-mm-thick slices) and axial FSE T1 (TR=600 ms; TE=9.10; twenty 4-mm-thick slices) before and after the injection of a gadolinium chelate (Gadovist, Schering, Germany) at a regular dosage. The following parameters were used for acquiring the diffusion tensor images in the axial plane: TE=92 ms TR=iPAt=2, Nex 1; FOV 230; matrix 128×128; slice thickness 2 mm; voxel size 2×2×2 mm; 30 gradient directions; b values=0 s/m^2; 900 s/mm^2. The DTI sequence duration was 5 min and 44 s. Values of the apparent diffusion coefficient (ADC) were generated by a pixel-by-pixel method from the diffusion images at the minimum and maximum b values. For reconstruction, the NEURO 3D software from Siemens was utilized on a Leonardo console. Regions of interest were defined manually and measured on the ADC and fractional anisotropy (FA) maps.

Results

Five patients had histologically proven spinal tumours with displacement of the fibres visible on the tractograms. Three patients had ependymomas where the fibres were spread by the tumour (Fig. 1). One patient had had an operation for a spinal pilocytic astrocytoma and had a small residue: on the tractogram there was a horizontal displacement of the fibres in the cranial part of the lesion (Fig. 2). One patient had a metastasis of a multiple myeloma into the medullary cone with deformation and interruption of the fibres clearly visible on the tractogram. One patient had spinal ischemia

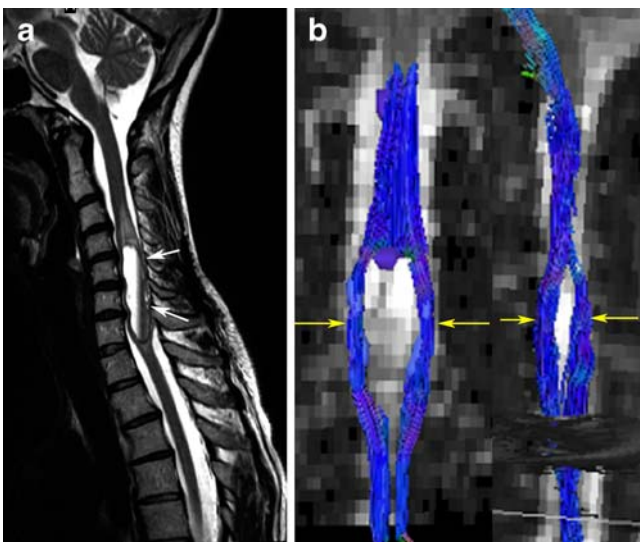

Fig. 1 Ependymoma: there is a tumour in the lower cervical spinal cord (**a**) with displacement of the fibres visible on the tractogram (**b**)

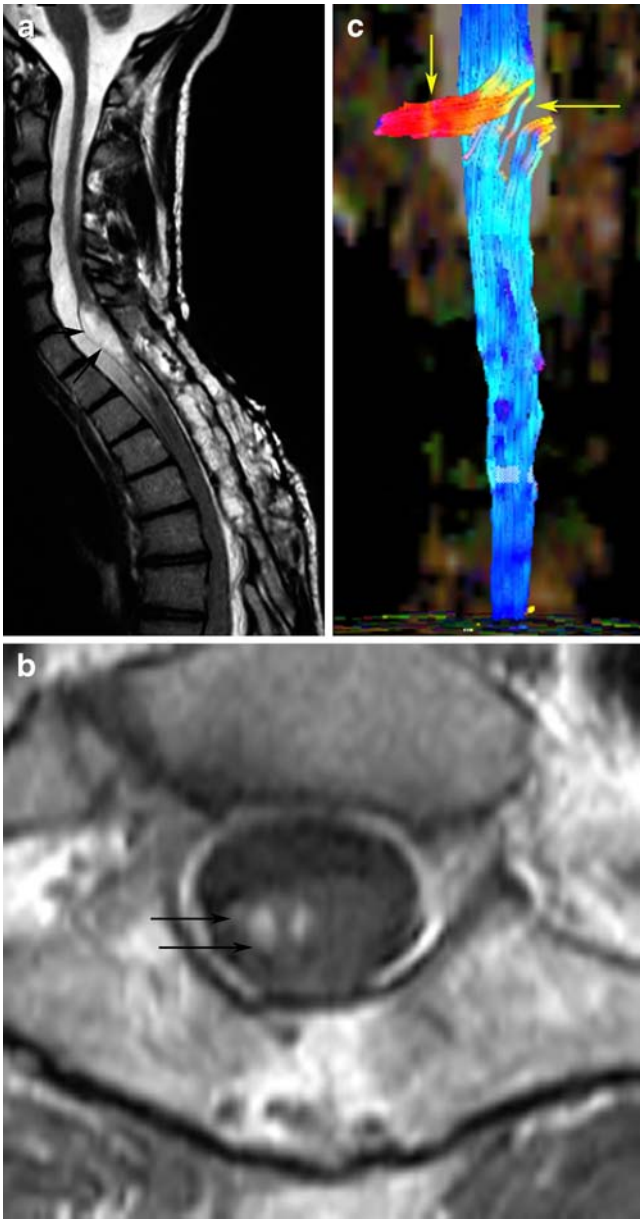

Fig. 2 Pilocytic astrocytoma. **a** The sagittal T2-weighted image shows an expansive lesion in the spinal cord (*arrows*). **b** There is some enhancement on the right side in the cord (*arrows*). **c** The tractogram shows that the fibres have an altered course, probably due to a previous operation (*arrows*)

following an intervention for a kyphotic spine: this was seen on the first MR image where DTI showed an interruption of the fibres at the cervico-dorsal junction level; ischemia was confirmed by the second follow-up spinal MRI (Fig. 3). One patient had a Devic-type neuromyelitis optica with interruption of the fibres visible on the diffusion tractogram at the cervico-dorsal junction level (Fig. 4). The lesion seen between the fibres on tractography was much smaller than suggested on the conventional images where a much larger lesion was observed; the follow-up image revealed a much smaller lesion corresponding closely to the diffusion tractography image. Clinically, there was dramatic improvement as well since the patient can now walk with assistance. One patient had a traumatic spinal contusion with deformation of the fibres. Detailed results of the ADC and FA are reported in Table 1.

Discussion

We found that DTI with tractography reconstruction can reliably demonstrate fibre tracts and alterations to these resulting from pathological processes located in the spinal cord . In cases where a slow-growing process, such as a tumour, was involved, we were able to observe displacement of the fibres that surround the tumour. In cases of more acute changes, such as those occurring in trauma or ischemia, we observed an interruption and a deformation of the fibres. When diffusion-weighted imaging and DTI were first introduced, technical limitations rendered their use difficult or impossible for imaging in the spinal canal; however, technical advances now render such applications feasible. Protocols utilizing modified acquisition schemes , such as line-scan imaging [5], or triggering to diminish flow effects [6] are now being used with certain degrees of success. This has allowed spinal diffusion to become a reality for clinicians and researchers. In a study comparing DTI acquired at 1.5 and 3T, Rossi et al. found a mean increase in SNR of 95.7±4.6% at the higher field strength compared to 1.5 Tesla. Improved quality of the DTI parametrical maps was observed at a higher field strength, whereas these researchers found comparable FA and ADC maps [7]. Some initial patient studies on the use of DTI in the spinal cord have been reported. Using a series of patients with spinal cord inflammation, Renoux et al. found that all T2-weighted abnormalities had a significantly decreased FA value. Our case with spinal inflammation (Devic syndrome) also had a reduced ADC. However, they found more variable alterations outside of lesions: decreases in FA in normal appearing T2 white matter in some cases as well as increased FA values in five patients [9]. Ducreux et al. reported the alterations to spinal cord integrity caused by astrocytomas using a 3D fibre tracking algorithm [8]. While they found their results encouraging, they warned that the fibre tracking algorithm is unable to distinguish between extracellular edema and white matter tracts destroyed by tumour cell involvement, which remains a problem. Most of the tumours in this series had an increase in the ADC, with the exception of two cases (one ependymoma and one metastatic multiple myeloma), whereas the FA was decreased in all cases. Schwartz et al.

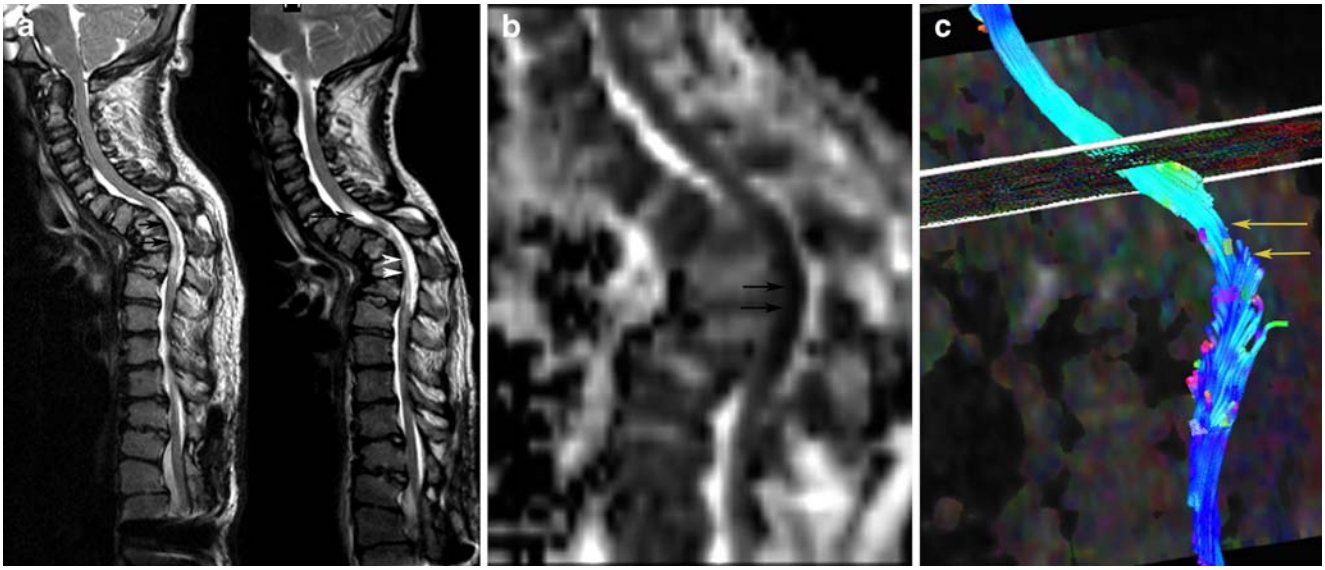

Fig. 3 Post-operative ischemia. **a** On the first magnetic resonance image (MRI) (*left*) there is hyperintensity in the spinal cord (*black arrows*), which is better seen on the control MRI (*right*) with partially cystic formation (*black arrow*) and atrophy (*white arrows*). **b** There is a decrease of the apparent diffusion coefficient (*arrows*), signalling infarction. **c** The tractogram shows a disruption of normal fibre anatomy (*arrows*)

found that injured animals showed disruption of the rubrospinal tract axons while the axon tracts were preserved and that reactive astrocytes in adjacent gray matter appeared to orient themselves perpendicular to white matter tracts [11]. In ischemia, as expected, we found a decrease in the ADC in the lesion [12].

Conclusion

Diffusion tensor imaging has the potential to demonstrate in vivo alterations to white fibres due to an underlying pathology. It is therefore has great potential for applications associated with the diagnosis and treatment of patients with

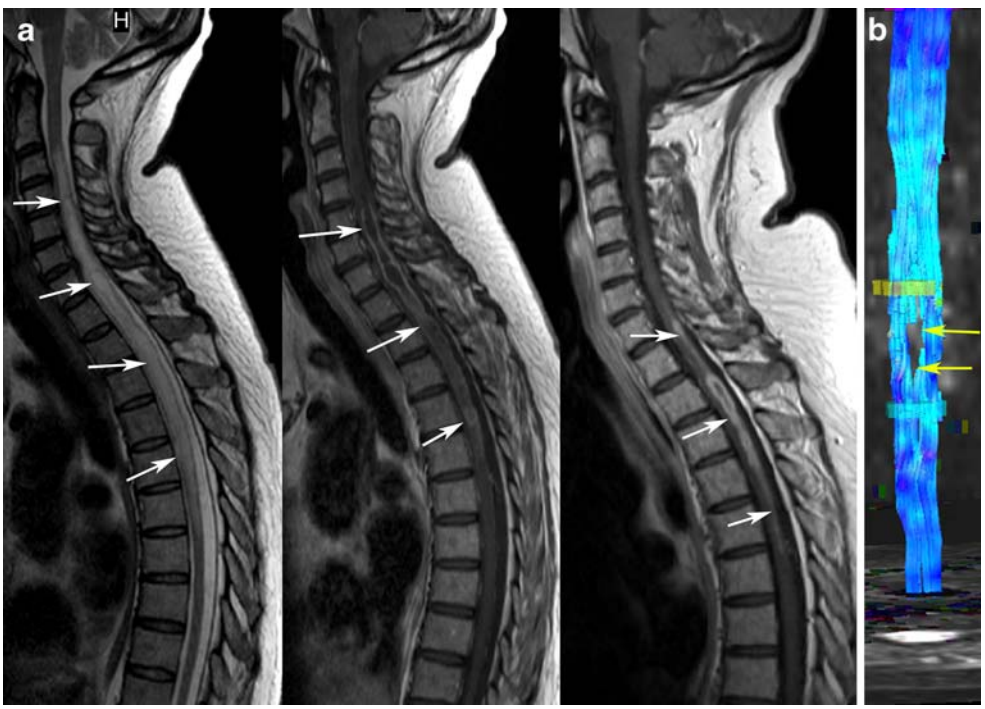

Fig. 4 Devic syndrome. **a** On the initial sagittal T2-weighted image there is a long hyperintensity in the spinal cord (*white arrows*) going from the upper cervical region to the mid-thoracic cord (*left*); there is also peripheral enhancement (*middle image*, *white arrows*); the control MRI shows a decrease of contrast enhancement (*white arrows*). **b** The tractography shows an interruption of the fibres in the spinal cord (*arrows*)

diseases of the spinal cord. Such a tool should improve surgical planning in patients with intramedullary lesions.

Conflict of interest statement We declare that we have no conflict of interest.

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