

Original Paper

Magnetic Resonance Diffusion Tensor Imaging (MR-DTI) in Spinal Cord Lesions: a Feasibility Study

Stefan Leis^a Fritz Klausner^b Mark Mc Coy^b Eugen Trinkla^{a,c,d} Mahdi Safdarian^e

^aDepartment of Neurology, Neurocritical Care and Neurorehabilitation, Christian Doppler University Hospital, Centre of Cognitive Neuroscience, Paracelsus Medical University, Salzburg, Member of EpiCARE, Austria, ^bInstitute of Neuroradiology, Christian Doppler University Hospital, Paracelsus Medical University, Salzburg, Austria, ^cNeuroscience Institute, Christian Doppler University Hospital, Centre of Cognitive Neuroscience, Paracelsus Medical University, Salzburg, ^dKarl Landsteiner Institute for Neurorehabilitation and Space Neurology, Salzburg, ^eDepartment of Neurosurgery, University Hospital Salzburg, Paracelsus Medical University Salzburg, Austria

Key Words

Magnetic Resonance • Diffusion Tensor Imaging • Spinal Cord Lesions

Abstract

Background/Aims: Magnetic Resonance Diffusion Tensor Imaging (MR-DTI) enables *in vivo* visualization of spinal cord white matter integrity and may provide complementary diagnostic information beyond conventional MRI. Despite its potential, clinical application in spinal cord pathology remains limited due to technical challenges. This study aimed to assess the feasibility and clinical value of MR-DTI for evaluating various spinal cord lesions. **Methods:** We retrospectively analyzed 55 consecutive patients with spinal cord lesions who underwent MR-DTI between September 2012 and January 2022. Imaging was performed on a Philips Achieva 3.0 T scanner using 16 non-collinear diffusion directions (b-value 500–800 s/mm²). Clinical severity was classified according to the American Spinal Injury Association Impairment Scale (AIS). Demographic, etiologic, and lesion-level data were evaluated descriptively. **Results:** The cohort comprised 38 men and 17 women (mean age 57.7 ± 15.9 years). Lesions were cervical in 55%, thoracic in 40%, and mixed in 5%. Etiologies included traumatic (n = 24), compressive (n = 24), ischemic (n = 20), and inflammatory (n = 7) causes, with overlaps across categories. AIS grades were A = 13, B = 7, C = 8, D = 14. Fiber-tracking revealed rarefaction or disconnection of tracts at the lesion level in 16 patients. **Conclusion:** MR-DTI of the spinal cord is feasible in a clinical setting and provides valuable structural information not visible on conventional MRI. Visualization of tract disruption supports its potential as a complementary diagnostic and prognostic tool. Standardized quantitative protocols and multicenter validation are warranted to establish MR-DTI as part of routine spinal cord imaging.

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Introduction

Diffusion tensor imaging (DTI) is a noninvasive magnetic resonance imaging (MRI) technology that can provide *in vivo* assessment of spinal cord white matter tract integrity (1). Magnetic resonance diffusion tensor imaging (MR-DTI) can be used to visualize neural pathways within normal-appearing white matter fibers, also called fiber tracking or tractography. DTI is significantly more powerful in visualizing disruption of microstructures than standard MRI sequences and has been shown to be capable of providing complementary or additional information to MRI in several spinal cord pathologies such as multiple sclerosis, acute and chronic spinal cord injury, amyotrophic lateral sclerosis, cord compression, myelitis, syringomyelia, and spinal cord tumors and spinal cord injuries (2-5). MR-DTI is a technically challenging but rapidly evolving diagnostic method. However, despite its importance in the assessment of brain lesions, such as space-occupying tumors, clinical application of DTI in spinal cord lesions remained underutilized primarily due to technical limitations. Application of DTI to the human spinal cord remains technically demanding because of the small cross section of the cord and constant pulsatile cord motion due to respiration and cerebrospinal fluid movement (2). Development and application of this imaging modality potentially improve our understanding of the nature and evolution of structural damage through detecting subtle changes of spinal cord tracts (6). Therefore, the aim of this study was to evaluate the feasibility and clinical applicability of MR-DTI tractography in a real-world cohort of patients with diverse spinal cord lesions over a ten-year period.

Materials and Methods

This retrospective single centre analysis of MR-DTI investigations was done on consecutive patients with spinal cord lesions between September 2012 to January 2022. MR-DTI has been included in the routine examination of patients with SCI at our centre since 2012. All investigations were performed with a *Philips Achieva 3.0 Tesla MRI scanner (single shot spin-echo echo planar imaging, 16 non-collinear diffusion gradient directions, voxel size 2 mm x 2 mm x 2 mm, minimum TE, b-value 500 and/or 800 s/mm²)*. The extent of motor and sensory impairment was classified using the International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI). Diffusion tensor datasets were processed using the vendor-provided diffusion analysis software integrated into the Philips Achieva workstation. Deterministic fiber tracking was performed using standard diffusion tensor tractography algorithms. Regions of interest (ROIs) were manually placed at the level of the spinal cord lesion and in adjacent normal-appearing cord segments to reconstruct longitudinal white matter tracts. Tracking was performed using fractional anisotropy thresholds and angular deviation constraints recommended by the software defaults for spinal cord imaging. Tracts affected by severe susceptibility or motion artifacts were excluded from analysis. Fiber rarefaction or discontinuity at the lesion level was visually assessed by experienced neuroradiologists.

Ethical statement

This retrospective study was conducted in accordance with the principles of the Declaration of Helsinki. As this was a retrospective analysis of anonymized clinical and imaging data, the requirement for written informed consent was waived by the ethics committee.

Results

55 patients with spinal cord lesions were included. Mean age was 57.7 ± 15.9 years (range, 19–86); 38/55 (69%) were male and 17/55 (31%) female. Lesions involved the cervical cord in 30/55 (55%), the thoracic cord in 22/55 (40%), and were unspecified in 3/55 (5%) (Supplementary file 1). Etiologies were traumatic 24, compressive 24, ischemic 20, and inflammatory 7. Because etiologies were not mutually exclusive, these totals exceed

Fig. 1. 41 y.o. male with spinal cord infarction C4-Th1 after embolization of a spinal arteriovenous malformation. Patient had tetraparesis AIS D. Tibial SSEP and MEP from lower limbs and left arm were absent. MEPs from the right arm were delayed. MR DTI shows rarefied fiber tracts at the level of injury.

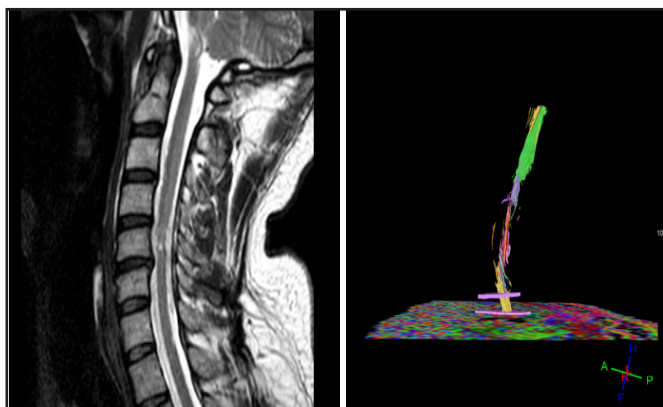


Fig. 2. 48 y.o. male with compressive myelopathy following disc herniation at level Th10/Th11. Patient had paraparesis AIS C. SSEP and MEP from upper limbs were normal and were absent from lower limbs. MR DTI shows discontinuation of fiber tracts at the level of injury.

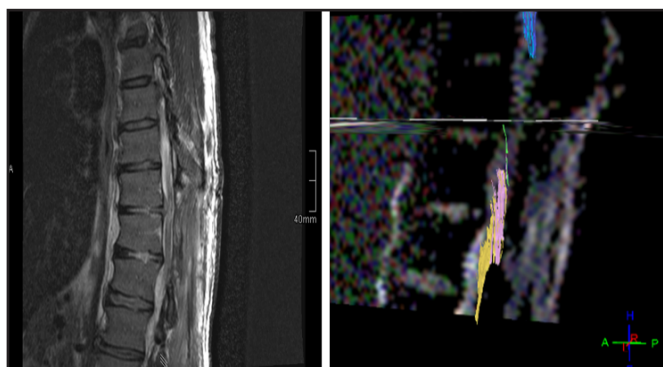


Fig. 3. 65 y.o. male with compressive myelopathy C3-C7 following epidural abscess and spinal stabilization and cage implantation at C5 and C6. Patient had tetraparesis AIS D. Tibial SSEPs were delayed, MEPs were not tested. In MR DTI susceptibility artefacts due to vertebral cage implants caused significant geometric distortion.

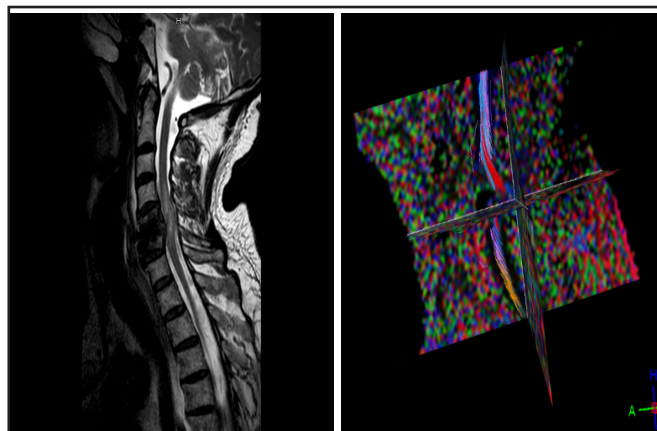


Fig. 4. 19 y.o. male with psychogenic paraparesis after stair fall. SSEPs and MEPs were normal. MRI DTI shows intact fiber tracks.



the number of patients. AIS grading was available in 42/55 (76%). In 16 patients, Fiber tracking showed rarefaction or disconnection of fibres at the level of injury (see *figures 1-4*). Among graded patients, the distribution was AIS A 13/42 (31.0%), AIS B 7/42 (16.7%), AIS C 8/42 (19.0%), and AIS D 14/42 (33.3%). Patients with complete injuries (AIS A) were younger on average than those with milder deficits: mean ages (years) were AIS A 47.6 ± 16.1 , B 60.1 ± 14.1 , C 59.6 ± 12.4 , and D 69.0 ± 11.0 .

Discussion

In this retrospective study, we assessed the feasibility and clinical utility of magnetic resonance diffusion tensor imaging (MR-DTI) for the evaluation of various spinal cord lesions. Among 55 patients with traumatic, ischemic, and inflammatory spinal cord pathologies, tractography demonstrated rarefaction or disruption of spinal cord white-matter tracts in a substantial proportion of cases. These findings indicate that MR-DTI can provide complementary diagnostic information beyond conventional MRI, allowing visualization of microstructural damage and potentially distinguishing true lesions from functional disorders. The present cohort included patients with heterogeneous spinal cord lesion etiologies, including traumatic, compressive, ischemic, and inflammatory causes. This heterogeneity reflects the real-world clinical environment in which MR-DTI may be applied and was intentionally retained because the primary objective of the study was to assess feasibility of tractography in routine clinical imaging rather than disease-specific diagnostic performance. Demonstrating successful acquisition across different pathological conditions supports the general applicability of MR-DTI in clinical spinal cord evaluation.

Our study supports prior evidence suggesting that MR-DTI of the spinal cord is a feasible and clinically valuable method for visualizing microstructural damage in patients with spinal cord lesions. Despite the technical challenges associated with small cord size, motion artifacts, and susceptibility effects, we were able to obtain diagnostically useful tractography images in the majority of patients over a ten-year period. The fact that tract disruption or attenuation could be detected in more than half of the cases underlines the potential role of DTI as a complementary diagnostic tool alongside conventional MRI. When compared with previous studies, our findings align with those reported by Facon et al. (20) and Cheran et al. (19), who also demonstrated decreased fractional anisotropy (FA) in affected regions of the spinal cord and correlations with neurological impairment. In our cohort, lesion distribution was predominantly cervical and thoracic, similar to the regional patterns described in studies on compressive and ischemic myelopathies (4, 9, 18). Although our dataset did not include quantitative DTI parameters such as FA or apparent diffusion coefficient (ADC), the high rate of successful fiber tracking provides indirect evidence of the technique's applicability in routine clinical imaging, even outside highly specialized research environments.

Currently, MRI is the main imaging modality for the radiographic evaluation of spinal cord parenchyma, which allows for the visualization of injury characteristics such as hemorrhage and compression. However, conventional MRI is not useful in the evaluation of integrity of white matter tracts that characterize the condition of the spinal cord. Consequently, the utility of anatomic MRI as a prognostic tool is limited during the acute phase of injury since the extent of injury to white matter tracts is a major determinant of the functional capacity of patients following spinal cord injury (7). There are also discrepancies between MRI findings and clinical presentations. The compressed cervical cord in patients of the spondylotic myelopathy for example, could be normal on conventional MRI when it is at the earlier stage or even if patients had severe symptoms (8). Therefore, it is necessary to take developed MR techniques such as DTI to detect the intramedullary spine lesions. To verify the usefulness of DTI compared with routine MRI and to clarify the relationship between motor and sensory impairments and DTI parameters, Chang et al. performed routine MRI and DTI on 10 patients with chronic cervical spinal cord injury and on 10 controls. They found that abnormal cervical levels detected on routine MRI were not correlated with clinical

findings, but fractional anisotropy (FA) parameter of DTI was correlated with motor function (9). DTI parameters might reflect the post-pathological status of spinal cord parenchyma at the epicenter and distal parts during the chronic stage, while showing good consistency with locomotor performance (10). A systematic review by Zaninovich et al. found that fractional anisotropy (FA) and apparent diffusion coefficient (ADC) are the most common DTI metrics used in different studies (1). Wang et al. found that all their 42 patients with spinal cord compression had increased ADC and decreased FA values at the lesion level compared to the 49 normal controls (4). The FA, with values ranging from 0 to 1, is a numerical measure of relative white matter integrity and measures the degree of anisotropy while the ADC, is the mathematical average of diffusivities along the three principal axes for each voxel and is an expression of the magnitude of the diffusion (7). Changes in these metrics reflect changes in tissue integrity.

Several DTI metrics and combinations have demonstrated significant correlations with clinical function both in animal and clinical studies (11-14). The findings from preclinical animal models showed that DTI parameters have correlation with function and histology, which highlights the potential predicting value of DTI in the form a noninvasive diagnostic method for spinal cord injuries. Parallel and following to many animal studies, clinical studies started evaluating MR-DTI parameters for predicting of the outcome of patients with spinal injuries. Shanmuganathan et al., for example using DTI parameters for predicting one-year outcome in 16 patients with cervical spinal cord injury and 15 controls, found that among all DTI measures, axial diffusivity most strongly correlated with both motor and Spinal Cord Independence Measure (SCIM III) (15). In a group of pediatric cervical and thoracic spinal cord injury, statistically significant decreases in FA and tract density were found in addition to increase in ADC values and length of fiber tracts comparing to control subjects. The tractography visually showed that the white matter tracts of the SCI patients had overall less abundant and less organized structure compared with control cases (16, 17). Using 1.5 Tesla MR-DTI to identify the correlations of DTI indices between healthy volunteers and patients with cervical spondylotic myelopathy, Chen et al. found the ADC value of the cervical spinal cord and lumbosacral enlargement showing significant increase in patients' group, while the FA significantly decreased (18). Investigating correlations between American Spinal Injury Association (ASIA) clinical injury motor scores in 25 traumatic cervical cord injury patients and MR-DTI parameters, Cheran et al. observed a significant reduction in FA and longitudinal diffusivity at the whole cord level in the injured group (19). Facon et al. evaluated the diagnostic accuracy of ADC, FA, and fiber tracking in both acute and slowly progressive spinal cord compressions using a 1.5-T MR scanner and found a significant difference in the FA values between volunteers and patients. In their study, FA had the highest sensitivity and specificity in the detection of acute spinal cord abnormalities (20).

DTI provides unique quantitative information pertaining to structural and orientation features of central nervous system tissue. It enables the visualization of tissue structure at a microscopic scale through capitalizing on the diffusion properties of water molecules within an axon. Furthermore, measurements of anisotropy and diffusivity with DTI enable the detection of subtle changes that cannot be detected using conventional MR techniques (2). Although DTI has been successfully applied in brain research for decades, several main difficulties have stopped its extended utilization in spinal cord imaging. These difficulties lie in the characteristics of the cord itself and not diffusion tensor methodology. The spinal cord is only 12 mm in diameter on average, surrounded by flowing CSF, is adjacent to structures that are moving due to respiration and swallowing and is adjacent to a large bony structure, the spinal column. For DTI to be used in a clinical setting as a mean of assessing the integrity of white matter tracts and to determine the spatial extent of the damage, reference DTI measures from each region of the healthy spinal cord are required. It is important to know whether DTI indices are consistent across cervical, thoracic, and lumbar regions of the healthy cord. Knowledge of the consistency of these measurements along the healthy cord will determine whether changes in these indices at any level can be characterized relative to

values obtained from any regions along the healthy cord.

From a clinical perspective, DTI may help in several scenarios. In ischemic or inflammatory lesions, where conventional MRI may reveal only subtle or delayed changes, diffusion anisotropy and tract continuity can provide early markers of axonal injury. In compressive myelopathies, MR-DTI could aid in differentiating reversible cord compression from irreversible myelomalacia. Furthermore, in traumatic spinal cord injury, DTI metrics have been shown to correlate with functional scales such as the AIS or SCIM III (15), suggesting a possible prognostic role. Our observation that younger patients more frequently presented with complete lesions (AIS A), while older patients tended to have milder grades, may reflect age-related vulnerability and regenerative potential—findings consistent with demographic trends reported in other series. The feasibility of MR-DTI in our single-center cohort is particularly encouraging given that the scans were acquired using a 3.0 Tesla system integrated into routine clinical protocols, without dedicated research sequences. This underlines the practical potential for translation of MR-DTI into everyday neuroradiological workups for spinal cord disease.

This retrospective single-center study lacked a healthy control group and standardized quantitative DTI metrics (e.g., FA, ADC), limiting direct comparison with previous reports and preventing correlation analyses with clinical scores. The inclusion of heterogeneous etiologies (traumatic, ischemic, inflammatory, compressive) enhances generalizability but adds variability in lesion characteristics. Motion and susceptibility artifacts may have reduced tract quality in some cases. Due to the retrospective design, longitudinal outcomes were unavailable, and occasional mixed etiologies complicated pathophysiologic classification. Future prospective studies with standardized MR-DTI protocols, quantitative metrics, and motion-correction methods are needed to improve reproducibility and clinical applicability. A further limitation of this study is the absence of standardized quantitative DTI metrics such as fractional anisotropy (FA) and apparent diffusion coefficient (ADC). While tractography allowed visualization of fiber disruption at the lesion level, the lack of quantitative measurements limits direct comparison with previously published studies that have demonstrated correlations between FA, ADC, and neurological outcomes. Quantitative DTI parameters have been reported to reflect microstructural integrity and to correlate with functional scores in spinal cord injury. Therefore, our findings should primarily be interpreted as demonstrating the technical and clinical feasibility of spinal cord MR-DTI, rather than providing quantitative biomarkers of disease severity. Future prospective studies should incorporate standardized acquisition and post-processing pipelines to enable reliable measurement of FA, ADC, and related indices.

MR-DTI of the spinal cord is feasible in clinical practice and provides valuable structural information beyond conventional MRI. Visualization of tract disruption offers complementary diagnostic insights, aiding differentiation between structural and functional deficits. Quantitative DTI parameters, such as FA and ADC, show promise as biomarkers for lesion severity and recovery. Standardized acquisition protocols and multicenter validation will be essential for wider clinical adoption and integration into prognostic assessment and rehabilitation planning.

Abbreviations

MR: Magnetic Resonance; DTI: Diffusion Tensor Imaging

Acknowledgements

Mahdi Safdarian performed data analysis and drafted the manuscript. Stefan Leis contributed to patient recruitment, data collection. Fritz Klausner, and Mark Mc Coy did imaging analysis. Eugen Trinka conceived and designed the study, provided critical revision

of the manuscript for important intellectual content and supervised the study. All authors reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

This retrospective study was conducted in accordance with the principles of the Declaration of Helsinki. As this was a retrospective analysis of anonymized clinical and imaging data, the requirement for written informed consent was waived by the ethics committee.

Disclosure Statement

Eugen Trinkla reports personal fees from EVER Pharma, Marinus, Argenix, Arvelle/Angelini, Medtronic, Bial – Portela & C^a, S.A., NewBridge, GL Pharma, GlaxoSmithKline, Hikma, Boehringer Ingelheim, LivaNova, Eisai, UCB, Biogen, Genzyme Sanofi, GW Pharmaceuticals, and Actavis outside the submitted work; his institution received grants from Biogen, UCB Pharma, Eisai, Red Bull, Merck, Bayer, the European Union, FWF Österreichischer Fond zur Wissenschaftsförderung, Bundesministerium für Wissenschaft und Forschung, and Jubiläumsfond der Österreichischen Nationalbank outside the submitted work. Other authors declare no Disclosure Statement. No artificial intelligence (AI) tools were used in the preparation, writing, data analysis, or figure generation of this manuscript. All work was conducted and written entirely by the authors.

References

- 1 Zaninovich OA, Avila MJ, Kay M, Becker JL, Hurlbert RJ, Martirosyan NL. The role of diffusion tensor imaging in the diagnosis, prognosis, and assessment of recovery and treatment of spinal cord injury: a systematic review. *Neurosurg Focus*. 2019;46:E7.
- 2 Bosma R, Stroman PW. Diffusion tensor imaging in the human spinal cord: development, limitations, and clinical applications. *Crit Rev Biomed Eng*. 2012;40:1–20.
- 3 Fujiiyoshi K, Konomi T, Yamada M, Hikishima K, Tsuji O, Komaki Y, et al. Diffusion tensor imaging and tractography of the spinal cord: from experimental studies to clinical application. *Exp Neurol*. 2013;242:74–82.
- 4 Wang W, Qin W, Hao N, Wang Y, Zong G. Diffusion tensor imaging in spinal cord compression. *Acta Radiol*. 2012;53:921–928.
- 5 Guleria S, Gupta RK, Saksena S, Chandra A, Srivastava RN, Husain M, et al. Retrograde Wallerian degeneration of cranial corticospinal tracts in cervical spinal cord injury patients using diffusion tensor imaging. *J Neurosci Res*. 2008;86:2271–2280.
- 6 Clark CA, Werring DJ. Diffusion tensor imaging in spinal cord: methods and applications - a review. *NMR Biomed*. 2002;15:578–586.
- 7 Kaushal M, Shabani S, Budde M, Kurpad S. Diffusion tensor imaging in acute spinal cord injury: a review of animal and human studies. *J Neurotrauma*. 2019;36:2279–2286.
- 8 Song T, Chen WJ, Yang B, Zhao HP, Huang JW, Cai MJ, et al. Diffusion tensor imaging in the cervical spinal cord. *Eur Spine J*. 2011;20:422–428.
- 9 Chang Y, Jung TD, Yoo DS, Hyun JK. Diffusion tensor imaging and fiber tractography of patients with cervical spinal cord injury. *J Neurotrauma*. 2010;27:2033–2040.
- 10 Zhao C, Rao JS, Pei XJ, Lei JF, Wang ZJ, Zhao W, et al. Diffusion tensor imaging of spinal cord parenchyma lesion in rat with chronic spinal cord injury. *Magn Reson Imaging*. 2018;47:25–32.
- 11 Zheng W, Xu F, Chen H, Wang N, Xiao W, Liang Y, et al. Time course of diffusion tensor imaging metrics in the chronic spinal cord compression rat model. *Acta Radiol*. 2019;60:653–662.
- 12 Chen B, Tan Q, Zhao W, Yang Q, Zhang H, Gao F, et al. Diffusion tensor imaging and electrophysiology as robust assays to evaluate the severity of acute spinal cord injury in rats. *BMC Neurol*. 2020;20:236.
- 13 Wang-Leandro A, Hobert MK, Kramer S, Rohn K, Stein VM, Tipold A. The role of diffusion tensor imaging as an objective tool for the assessment of motor function recovery after paraplegia in a naturally-occurring large animal model of spinal cord injury. *J Transl Med*. 2018;16:258.

- 14 Patel SP, Smith TD, VanRooyen JL, Powell D, Cox DH, Sullivan PG, et al. Serial diffusion tensor imaging *in vivo* predicts long-term functional recovery and histopathology in rats following different severities of spinal cord injury. *J Neurotrauma*. 2016;33:917–928.
- 15 Shanmuganathan K, Zhuo J, Chen HH, Aarabi B, Adams J, Miller C, et al. Diffusion tensor imaging parameter obtained during acute blunt cervical spinal cord injury in predicting long-term outcome. *J Neurotrauma*. 2017;34:2964–2971.
- 16 Alizadeh M, Fisher J, Saksena S, Sultan Y, Conklin CJ, Middleton DM, et al. Reduced field of view diffusion tensor imaging and fiber tractography of the pediatric cervical and thoracic spinal cord injury. *J Neurotrauma*. 2018;35:452–460.
- 17 Alizadeh M, Intintolo A, Middleton DM, Conklin CJ, Faro SH, Mulcahey MJ, et al. Reduced FOV diffusion tensor MR imaging and fiber tractography of pediatric cervical spinal cord injury. *Spinal Cord*. 2017;55:314–320.
- 18 Chen X, Kong C, Feng S, Guan H, Yu Z, Cui L, et al. Magnetic resonance diffusion tensor imaging of cervical spinal cord and lumbosacral enlargement in patients with cervical spondylotic myelopathy. *J Magn Reson Imaging*. 2016;43:1484–1491.
- 19 Cheran S, Shanmuganathan K, Zhuo J, Mirvis SE, Aarabi B, Alexander MT, et al. Correlation of MR diffusion tensor imaging parameters with ASIA motor scores in hemorrhagic and nonhemorrhagic acute spinal cord injury. *J Neurotrauma*. 2011;28:1881–1892.
- 20 Facon D, Ozanne A, Fillard P, Lepeintre JF, Tournoux-Facon C, Ducreux D. MR diffusion tensor imaging and fiber tracking in spinal cord compression. *AJNR Am J Neuroradiol*. 2005;26:1587–1594.