Check for updates

Diffusion Tensor Imaging and Fiber Tractography Reveal Significant Microstructural Changes of Cervical Nerve Roots in Patients with Cervical Spondylotic Radiculopathy

Kang-Ning Liang[1], Ping-Yong Feng[2], Xu-Ran Feng[2], Hao Cheng[2]

■ OBJECTIVE: **To delineate the fractional anisotropy (FA) and apparent diffusion coefficient (ADC) values of patients with cervical spondylotic radiculopathy by diffusion tensor imaging and fiber bundle tracing.**

■ METHODS: **Thirty patients with cervical spondylotic radiculopathy and 24 healthy volunteers were assessed using the International Standards for Neurological Classification of Spinal Cord Injury scale. All subjects underwent conventional sagittal T1- and T2-weighted imaging and horizontal 3-dimensional T2 driven equilibrium radiofrequency reset pulse and diffusion tensor imaging scan. The ADC and FA values were measured in the cervical nerve at most stenotic segment and heterolateral nonstenotic segment of patients.**

■ RESULTS: **Fiber tractography revealed thinned and sparse nerve roots and disruption of the fiber bundles in patients with cervical spondylotic radiculopathy. The FA values of C5—C8 in healthy volunteers or heterolateral nonstenotic nerve of patients with cervical spondylotic radiculopathy were significantly greater than those of the stenotic cervical segments of patients with cervical spondylotic radiculopathy (both $P < 0.01$). Furthermore, the ADC values of C5—C8 in healthy volunteers or heterolateral nonstenotic nerve of patients with cervical spondylotic radiculopathy were significantly lower than those of the stenotic cervical segments of cervical spondylotic radiculopathy patients (both $P < 0.01$).**

■ CONCLUSIONS: **Fiber tractography is capable of delineating microstructural changes of cervical nerve roots and cervical spondylotic radiculopathy exhibits significant changes in FA and ADC values.**

INTRODUCTION

Cervical spondylosis is the most important cause of cervical spine disorders, affecting more than 60% of the population older than 40 years of age.[1] Thickening and calcification of the posterior longitudinal ligament may eventually lead to segmental compression of the spinal cord, and the nerve root type is the most common of cervical diseases.

Conventional magnetic resonance imaging (MRI) such as T1- or T2-weighted imaging cannot selectively visualize peripheral nerves or quantify the severity of nerve injury.[2] Notable changes on MRI, such as increased signal intensity of the spinal cord on T2-weighted imaging, typically occur late in cervical spondylosis. Magnetic resonance functional imaging can be used to delineate fine changes in the nerves themselves, allowing earlier diagnosis of cervical spondylotic radiculopathy. Diffusion tensor imaging (DTI) and fiber tracing imaging are currently the only noninvasive imaging methods for displaying white matter fibers in vivo.

In recent years, DTI and fiber bundle tracking have been used in peripheral nerve imaging, such as sciatic nerve, median nerve, and ulnar nerve. An early study[3] on patients with cervical spondylotic

Key words
■ Apparent diffusion coefficient (ADC)
■ Cervical spondylotic radiculopathy
■ Diffusion tensor imaging
■ Fiber tractography
■ Fractional anisotropy (FA)
■ International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI) scale
■ Nerve roots

Abbreviations and Acronyms
3D: 3-Dimensional
ADC: Apparent diffusion coefficient
DRIVE: Driven equilibrium radiofrequency reset pulse
DTI: Diffusion tensor imaging
FA: Fractional anisotropy
ISNCSCI: International Standards for Neurological Classification of Spinal Cord Injury
JOA: Japanese Orthopaedic Association
MRI: Magnetic resonance imaging
ROI: Region of interest

From the [1]Department of Medical Imaging, Shanghai Corps Hospital of the Chinese People's Armed Police Force, Shanghai; and [2]Department of Medical Imaging, The Second Hospital of Hebei Medical University, Shijiazhuang, China

To whom correspondence should be addressed: Ping-Yong Feng, B.M. [E-mail: xjfpy@163.com]

Citation: World Neurosurg. (2019) 126:e57-e64.
https://doi.org/10.1016/j.wneu.2019.01.154

Journal homepage: ***www.journals.elsevier.com/world-neurosurgery***

Available online: ***www.sciencedirect.com***

myelopathy by DTI demonstrated significant differences in fractional anisotropy (FA) values and apparent diffusion coefficient (ADC) values between the compressed cord and normal spinal cord. Tokas et al.[4] recently have studied 21 patients with cervical spondylotic radiculopathy by DTI and found that stenotic segments had significantly lower FA values and greater ADC values versus nonstenotic segments. Maki et al.[5] studied 26 patients with cervical compressive myelopathy and found that FA was a good predictive indicator of surgical outcome in terms of Japanese Orthopaedic Association (JOA) scores. A recent systemic review suggested that DTI is associated with preoperative severity and postoperative outcomes in patients with cervical compressive myelopathy.[6]

In the current study, we delineated the FA and ADC values of patients with cervical spondylotic radiculopathy by DTI and fiber bundle tracing and further investigated the relationship between FA or ADC values and the International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI) scores of these patients.

SUBJECTS AND METHODS

Subjects

This prospective study enrolled 30 patients with cervical spondylotic radiculopathy who sought surgical treatment between March 2015 and January 2016 at Hebei province. This study was approved by The Institutional Review Board of Ethics Committee of The Second Hospital of Hebei Medical University. All participants received written and oral information before giving written consent, and the study was performed in accordance with the Helsinki II declaration. Patients were included 1) if they met the diagnostic criteria of cervical spondylotic radiculopathy by the Third National Congress on Cervical Spondylosis,[7] 2) if they exhibited symptoms and signs of cervical nerve root compression, and 3) if MRI demonstrated foraminal stenosis with unilateral posterolateral prolapse or protrusion to the intervertebral foramen of the intervertebral disc of C4—C5, C5—C6, C6—C7, or C7—T1. Patients were considered to have acute cervical spondylotic radiculopathy if they were within 1 month of onset or their symptoms were aggravated within 1 month. In addition, 24 healthy volunteers who showed normal findings of the cervical spine on MRI were included.

Neurologic Assessment

Patients received a comprehensive clinical assessment of C5 to C8 function using the ISNCSCI scale at admission.[8]

MR Data Acquisition

Imaging was performed with a 3.0 T MRI scanner (Achieva; Philips, Best, The Netherlands) operated with a 16-channel head and neck coil. The subject was placed supine and the scanner was positioned at C5. All subjects underwent conventional sagittal T1-weighted imaging and T2-weighted imaging, and horizontal 3-dimensional (3D) T2 driven equilibrium radiofrequency reset pulse (DRIVE) and DTI scan. The 3D T2 DRIVE scan covered the vertebrae from C5 to C8 with the following parameters: repetition time = 1573 milliseconds, echo time = 100 milliseconds, field of view = 140 × 140, and slice thickness 2 mm. DTI scan used the same central line, scan extent, and slice thickness as 3D T2 DRIVE with the following parameters: repetition time = 2420 milliseconds, echo time = 69 milliseconds, dispersion sensitivity coefficient b = 800 mm^2/s, orientation dispersion index 32, and the number of excitations 4; fat suppression was spectral presaturation with inversion recovery strong. Presaturation band was placed in front of the vertebral body during MRI scan to eliminate artifacts of the vertebral body, abdominal fat, and bowel.

The 3D T2 DRIVE and DTI images were connected in parallel. Using 3D T2 DRIVE images as the anatomical basis, we manually segmented the region of interest (ROI) 4 mm^2 in size in the course of the nerve roots from C5 to C8. The ROI was copied onto DTI scans, and the FA value of the ROI was measured twice and averaged. The ADC value of the ROI was determined using the same method. The ADC and FA values were measured in the cervical nerve at most stenotic segment and heterolateral nonstenotic of patients with cervical spondylotic radiculopathy and the counterparts at C5—C8 nerve in healthy volunteers.

Fiber Tracking

The Diffusion Registration software (Philips Achieva, Shanghai, China) package was used for diffusion correction at the Philips Extended MR WorkSpace R2.6.4.3 workstation (Philips). In the entry zones of the intervertebral foramen of the cervical spine, 2 ROIs of approximately 50 voxels were defined, and fiber tracking was performed. Multiple ROIs were defined using the interactive mode and the Freehand ROI mode was chosen. The tracking angle threshold was set at 25°, the FA threshold was 0.15, and the shortest fiber length was 10 mm.

Statistical Analysis

Data were expressed in $\bar{X} \pm S$ and analyzed using SPSS17.0 statistical software (SPSS Inc., Chicago, Illinois, USA). A paired t test was used to compare FA and ADC values of the cervical nerve at most stenotic segment and heterolateral nonstenotic of cervical spondylotic radiculopathy patients. Reliability in interobserver FA and ADC values were assessed using independent t test. The independent t test was used to compare FA and ADC values of the cervical nerve at stenotic segments of cervical spondylotic radiculopathy patients and C5—C8 segments of healthy volunteers, and in stenotic segments of patients with acute and chronic cervical spondylotic radiculopathy. A Spearman rank correlation analysis was performed to delineate the relationships between FA or ADC values and ISNCSCI scores. The statistical significance was set at $P < 0.05$.

RESULTS

Demographic and Baseline Characteristics of the Study Population

Thirty patients with cervical disc herniation were included. Patient demographic and baseline characteristics are shown in Table 1. They included 14 male and 16 female patients and their mean age was 49.06 ± 9.06 years (range 25—62 years). Thirty-one nerve roots were involved including 8 (25.8%) at C5, 17 (54.8%) at C6, 5 (16.1%) at C7, and 1 (3.2%) at C8. One patient had cervical spondylotic radiculopathy in 2 segments (C5 and C6). The nerve roots were involved on the left side in 11 (35.5%) cases and on the right side in 20 (64.5%) cases. The duration of cervical spondylotic

Table 1. Demographic and Baseline Characteristics of the Study Patients with Cervical Spondylotic Radiculopathy ($n = 30$)

	All	Acute	Chronic
Age, years			
Mean (SD)	49.06 (9.06)	48.4 (6.0)	49.3 (9.9)
Range	25.62	43.60	25.62
Male sex, *n* (%)	14 (46.7)	5 (71.4)	9 (37.5)
n (%) of involved segments	31 (100)*	7 (22.6)	24 (77.4)
Laterality, *n* (%)			
Left	11 (35.5)	1 (14.3)	10 (41.7)
Right	20 (64.5)	6 (85.7)	14 (58.3)
Involved segments, *n* (%)			
C5	8 (25.8)	1 (14.3)	7 (29.2)
C6	17 (54.8)	4 (57.1)	13 (54.2)
C7	5 (16.1)	2 (28.6)	3 (12.5)
C8	1 (3.2)	0 (0)	1 (4.2)
ISNCSC score			
Mean (SD)	7.5 (1.1)	6.9 (0.4)	7.7 (1.2)

SD, standard deviation; ISNCSC, International Standards for Neurological Classification of Spinal Cord Injury.
*One patient had radiculopathy in 2 segments of the cervical spine.

radiculopathy from onset to seeking medical attention ranged from 2 weeks to 10 years. Cervical spondylotic radiculopathy was acute (<1 month) in 7 nerve roots and chronic in 24 nerve roots. The mean ISNCSCI score was 7.52 ± 1.12 for all patients. The mean ISNCSCI score was significantly lower in patients with acute radiculopathy (6.9 ± 2.06) than patients with chronic radiculopathy (7.7 ± 2.06) ($P < 0.01$).

In addition, 24 healthy subjects were included. There were 10 male and 14 female patients, with a mean age of 33.3 ± 8.1 years (range 25–52 years). Their mean ISNCSCI score was 9.

DTI Characteristics of the Study Population

The mean values of FA and ADC of healthy subjects are shown in Table 2. Independent t test showed good agreement between the mean values of FA and ADC measured by the 2 observers. The P values of mean FA by independent t test for compressed nerve roots and contralateral nerve roots in patients with cervical spondylotic radiculopathy and healthy volunteers were 0.721, 0.911, and 0.825, respectively. The P values of mean ADC by independent t test for compressed nerve roots and contralateral nerve roots in patients with cervical spondylotic radiculopathy and healthy volunteers were 0.538, 0.816, and 0.864, respectively.

Representative T2-weighted images are shown in Figure 1A of normal intervertebral disc of the cervical spine (C5–C6) in a healthy volunteer. Fiber tractography showed the natural course of C6 nerve roots and even distribution of the fiber bundles in the normal subject (Figure 1B–C). The FA values of C5–C8 segments in healthy volunteers were 0.45 ± 0.04 and the FA values of healthy volunteers aged <40 years (0.46 ± 0.04) were comparable with those aged >40 years (0.45 ± 0.04) ($P = 0.22$). Furthermore, the ADC values of C5–C8 segments in healthy volunteers were $1.16 \pm 0.12 \times 10^{-3}$ mm^2/s. The ADC values of healthy volunteers aged <40 years ($1.16 \pm 0.12 \times 10^{-3}$ mm^2/s) were comparable with those aged >40 years ($1.18 \pm 0.14 \times 10^{-3}$ mm^2/s) ($P = 0.31$).

Representative T2-weighted images are shown in Figure 2A and Figure 3A of prolapsed intervertebral disc in 2 female patients with cervical spondylotic radiculopathy. Fiber tractography revealed thinned and sparse nerve roots and disruption of the fiber bundles (Figure 2B–C and Figure 3B–C). The FA values of heterolateral nonstenotic cervical nerve (0.45 ± 0.04) were significantly greater than those of the stenotic cervical segments of patients with cervical spondylotic radiculopathy (0.40 ± 0.04) (paired t-test, $P < 0.01$) (Figure 4A). The FA values of C5–C8 segments in healthy volunteers (0.45 ± 0.04) were significantly greater than those of the stenotic cervical segments of patients with cervical spondylotic radiculopathy (0.40 ± 0.04) (independent t test, $P < 0.01$) (Figure 4B). No statistically significant difference was found in the FA values of stenotic cervical segments of patients with acute cervical spondylotic radiculopathy (0.38 ± 0.04) and those with chronic cervical spondylotic radiculopathy (0.40 ± 0.03) (Independent t test, $P = 0.26$) (Figure 4C). Furthermore, the ADC values of heterolateral nonstenotic cervical nerve ($1.18 \pm 0.11 \times 10^{-3}$ mm^2/s) were significantly lower than those of the stenotic cervical segments of patients with cervical spondylotic radiculopathy ($1.30 \pm 0.13 \times 10^{-3}$ mm^2/s) (paired t test, $P < 0.01$) (Figure 5A). The ADC values of C5–C8 segments in healthy volunteers ($1.16 \pm 0.12 \times 10^{-3}$ mm^2/s) were significantly lower than those of the

Table 2. The Mean FA Values and ADC Values of Nerve Roots from C5 to C8 in Healthy Volunteers

Cervical Segments	ADC	FA
C5 (left, right)	1.17 ± 0.12 (1.18 ± 0.12, 1.17 ± 0.12)	0.45 ± 0.04 (0.45 ± 0.05, 0.45 ± 0.03)
C6 (left, right)	1.17 ± 0.11 (1.17 ± 0.12, 1.17 ± 0.12)	0.45 ± 0.04 (0.45 ± 0.05, 0.45 ± 0.04)
C7 (left, right)	1.15 ± 0.12 (1.16 ± 0.13, 1.15 ± 0.12)	0.45 ± 0.05 (0.46 ± 0.04, 0.45 ± 0.05)
C8 (left, right)	1.15 ± 0.14 (1.14 ± 0.13, 1.16 ± 0.15)	0.46 ± 0.04 (0.46 ± 0.04, 0.46v0.04)
C5–C8 (left, right)	1.16 ± 0.12 (1.16 ± 0.12, 1.16 ± 0.13)	0.45 ± 0.04 (0.46 ± 0.05, 0.45 ± 0.04)

FA, fractional anisotropy; ADC, apparent diffusion coefficient.

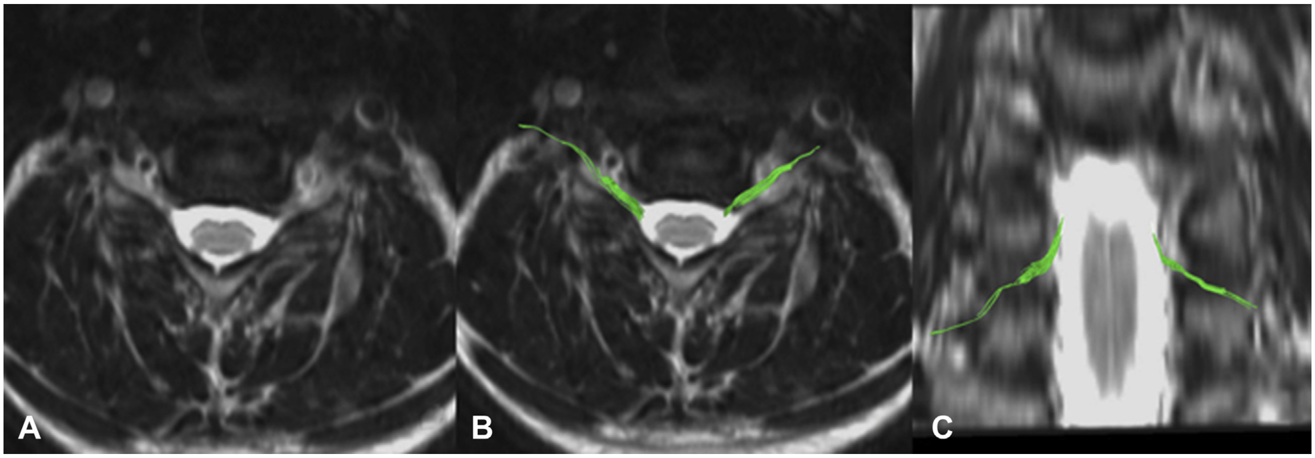

Figure 1. T2-weighted imaging reveals normal intervertebral disc of C5–C6 in a 26-year-old healthy volunteer (**A**). Fiber tractography shows that in the axial plane, the course of C6 nerve root is normal and the fiber bundles are evenly distributed (**B**) and in the coronal plane, the C6 nerve root runs naturally (**C**). The *green line* is the normal volunteer's bilateral neck 6 nerve fiber bundles displayed by Fiber tractography technology.

stenotic cervical segments of patients with cervical spondylotic radiculopathy (independent t test, $P < 0.01$) ($1.30 \pm 0.13 \times 10^{-3}$ mm^2/s) (Figure 5B). No statistically significant difference was found in the ADC values of stenotic cervical segments of patients with acute cervical spondylotic radiculopathy ($1.33 \pm 0.08 \times 10^{-3}$ mm^2/s) and those with chronic cervical spondylotic radiculopathy ($1.29 \pm 0.14 \times 10^{-3}$ mm^2/s) (independent t test, $P = 0.46$) (Figure 5C).

FA and ADC Values and ISNCSCI Scores

Pearson correlation analysis showed that the FA values of stenotic cervical segments of patients with cervical spondylotic radiculopathy did not correlate with ISNCSCI scores ($r = 0.115$, $P = 0.539$) (Figure 6A). No significant correlation was observed between the FA values of stenotic cervical segments and ISNCSCI scores of patients with acute cervical spondylotic radiculopathy ($r = -0.644$, $P = 0.119$) (Figure 6B) or those with chronic cervical spondylotic radiculopathy ($r = 0.126$, $P = 0.557$) (Figure 6C). Furthermore, the ADC values of stenotic cervical segments of patients with cervical spondylotic radiculopathy did not correlate with ISNCSCI scores ($r = 1.140$, $P = 0.452$) (Figure 7A). There was no significant correlation between the ADC values of stenotic cervical segments and ISNCSCI scores of patients with acute cervical

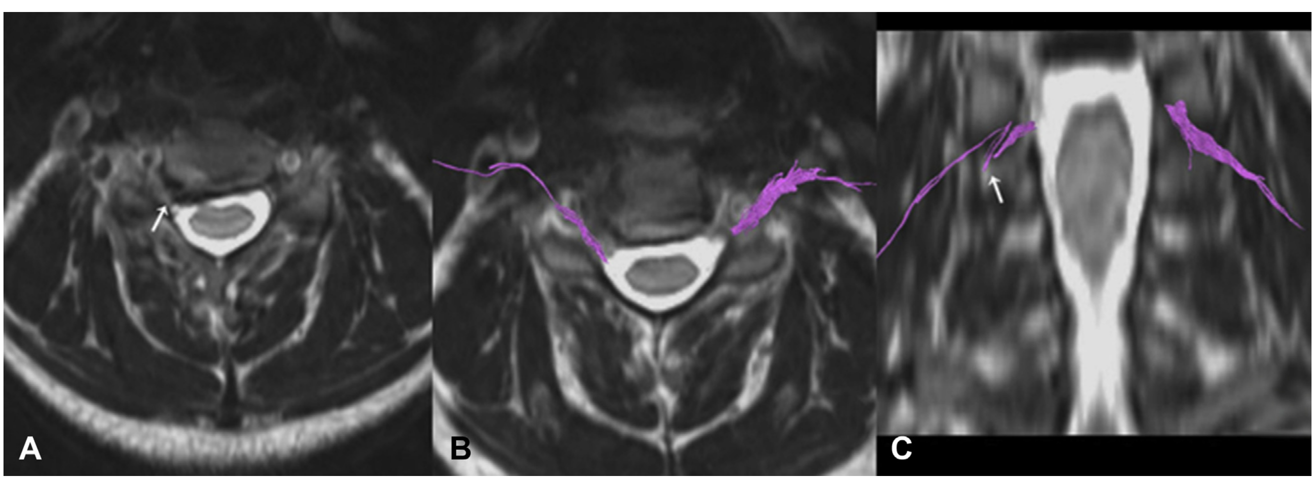

Figure 2. (**A**) Axial T2-weighted imaging reveals posterolateral prolapse of the intervertebral disc of C4–C5 on the right side in a 32-year-old female patient with right-hand pain for more than 1 year that was worsened with activity. Fiber tractography shows that in the axial plane, the C5 nerve root is thin and sparse (**B**) and (**C**) in the coronal plane and the fiber bundles of the right C5 nerve root are mostly disrupted. The *purple line* is the nerve neck type of cervical spondylosis patients with fiber tractography technology. *Arrows* indicate nerve root type cervical spondylosis.

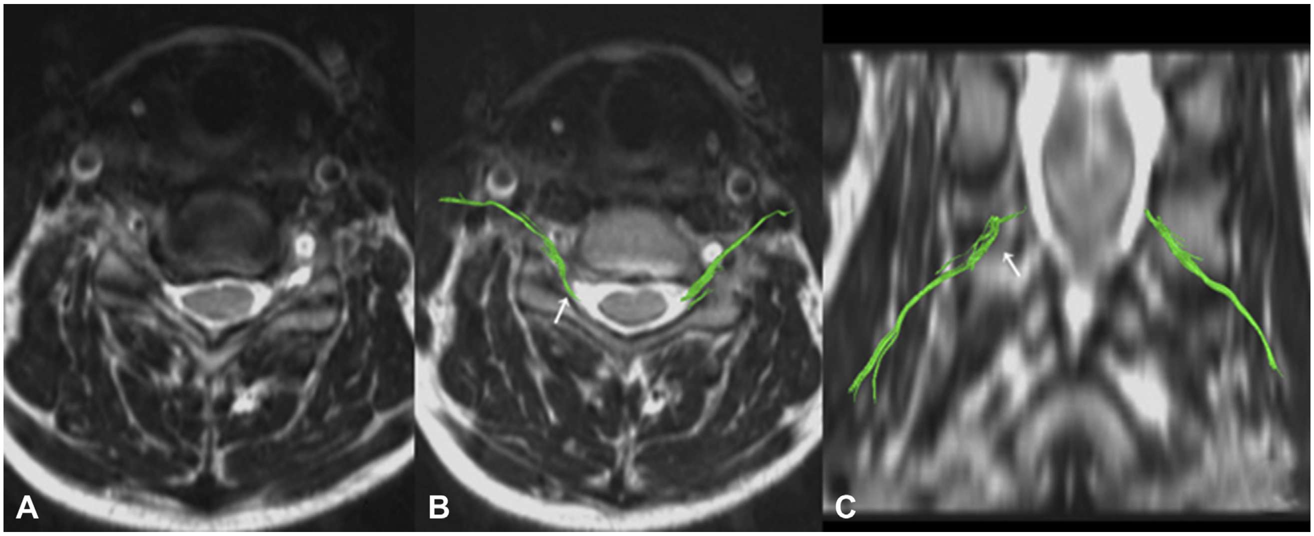

Figure 3. Axial T2-weighted imaging reveals posterolateral prolapse of the intervertebral disc of C5–C6 on the right side in a 38-year-old female patient with numbness of the right hand for 2 weeks (**A**). Fiber tractography shows that in the axial plane, the C5 nerve root is displaced laterally (**B**) and (**C**) in the coronal plane and the fiber bundles of the right C5 nerve root are loosened and run a tortuous course. The *green line* is the normal volunteer's bilateral neck 6 nerve fiber bundles displayed by fiber tractography technology. *Arrows* indicate nerve root type cervical spondylosis.

spondylotic radiculopathy (r = −0.374, P = 0.408) (**Figure 7B**) or those with chronic cervical spondylotic radiculopathy (r = 0.226, P = 0.288) (**Figure 7C**).

DISCUSSION

In the current study, we demonstrated that the stenotic segments of patients with cervical spondylotic radiculopathy had significantly lower FA values and noticeably greater ADC values compared with nonstenotic segments of these patients and normal cervical spine of healthy volunteers, suggesting that changes in DTI parameters may aid early diagnosis of cervical spondylotic radiculopathy.

Conventional MRI cannot effectively visualize peripheral nerves or track fiber bundles whereas DTI can track fiber bundles noninvasively and quantify severity of nerve root injury.[2,9-11] Apart from revealing significant changes in the stenotic segments of patients with cervical spondylotic radiculopathy, fiber tractography showed that the fiber bundles of involved cervical nerve roots ran a tortuous course and were loosened or disrupted, providing a structural basis for the changes in DTI parameters. Our demonstration of significant reduction in the FA values of the stenotic segments of cervical spondylotic radiculopathy is consistent with

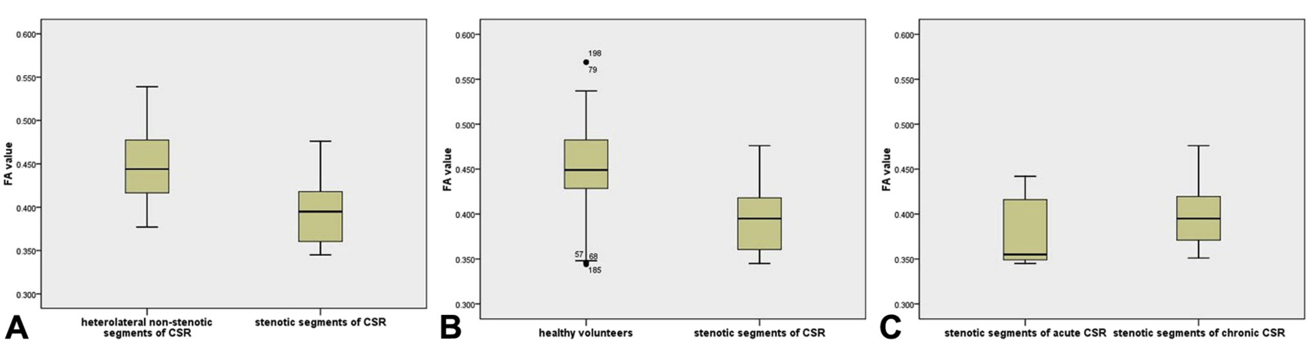

Figure 4. (**A**) The fractional anisotropy (FA) values of heterolateral nonstenotic cervical nerve and stenotic segments of patients with cervical spondylotic radiculopathy (paired *t* test, $P < 0.01$). (**B**) The FA values of C5–C8 segments of healthy volunteers and stenotic segments of patients with cervical spondylotic radiculopathy (independent *t* test, $P < 0.01$). (**C**) The FA values of stenotic segments of patients with acute and chronic cervical spondylotic radiculopathy (independent *t* test, $P = 0.26$).

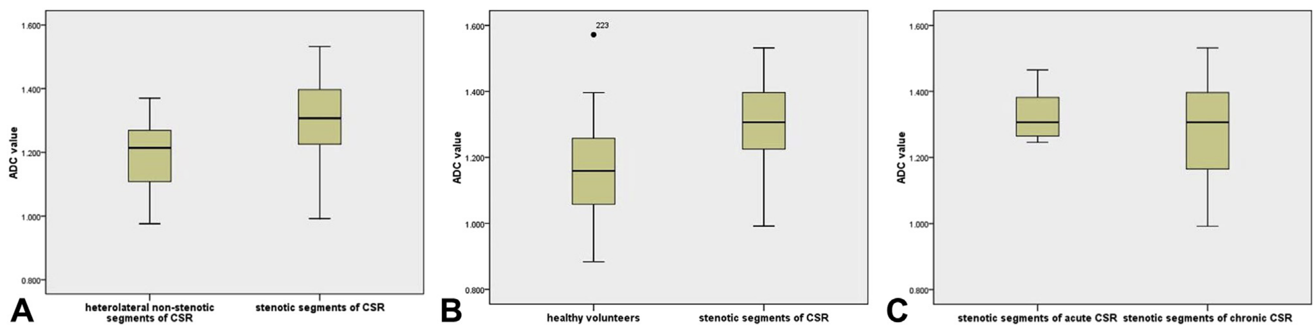

Figure 5. (**A**) The apparent diffusion coefficient (ADC) values of heterolateral nonstenotic cervical nerve and stenotic segments of patients with cervical spondylotic radiculopathy (paired *t* test, $P < 0.01$). (**B**) The ADC values of C5–C8 segments of healthy volunteers and stenotic segments of patients with cervical spondylotic radiculopathy (independent *t* test, $P < 0.01$). (**C**) The ADC values of stenotic segments of patients with acute and chronic cervical spondylotic radiculopathy (independent *t* test, $P = 0.46$).

previous reports.[4] Reduction in FA values is believed to be due to decrease in the density of fiber bundles as a result of nerve root compression, leading to Wallerian degeneration, demyelination, and axonal injury. We also observed thinning and loosening of fiber bundles in the involved cervical roots. These structural changes slow down diffusion of water molecules, especially horizontal diffusion, leading to increase in ADC values and reduction in FA values.[12,13] Neurologic impairment in cervical spondylotic radiculopathy is mainly due to chronic cord compression and impaired blood supply at the level of stenosis, leading to neural degeneration in the gray and white matter. The time course of stenosis and emergence of clinical symptoms is currently unknown but is probably protracted as the disease may be clinically silent for many years. DTI and fiber tractography may uncover early subtle changes by delineating changes in DTI parameters and lead to an early diagnosis of cervical spondylotic radiculopathy.

In the current study, we compared nonstenotic segments of patients with cervical spondylotic radiculopathy and normal cervical segments of healthy volunteers with stenotic segments of patients with cervical spondylotic radiculopathy. Consistent with an earlier study, there was no difference in FA and ADC values between normal segments of healthy subjects and nonstenotic segments of patients with cervical spondylotic radiculopathy.[14] In addition, we found no significant difference in FA and ADC values of C5–C8 segments between healthy volunteers aged <40 years and those aged >40 years. This is different from the study by Hori et al.,[15] who found that FA values decreased and ADC values increased with age. In addition, we found no difference in FA and ADC values of acute and chronic cervical spondylotic radiculopathy. We do not know whether this is due to similar changes caused by acute and chronic cervical and nerve root compression in patients with cervical spondylotic radiculopathy or some other unknown causes, as current data from humans

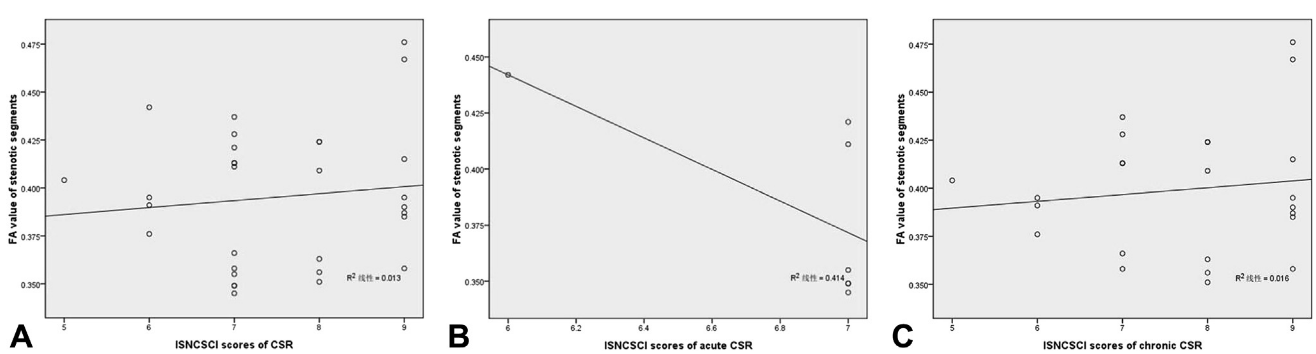

Figure 6. (**A**) Pearson correlation analysis shows no correlation between the fractional anisotropy (FA) values of stenotic cervical segments of patients with cervical spondylotic radiculopathy and International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI) scores ($r = 0.115$, $P = 0.539$). (**B**) There is also no significant correlation between the FA values of stenotic cervical segments and ISNCSCI scores of patients with acute cervical spondylotic radiculopathy ($r = -0.644$, $P = 0.119$) or (**C**) those with chronic cervical spondylotic radiculopathy ($r = 0.126$, $P = 0.557$).

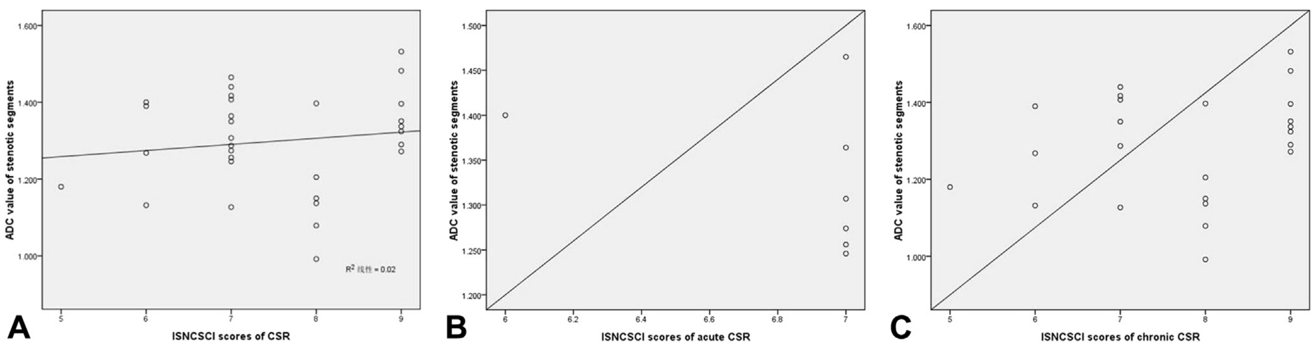

Figure 7. (**A**) Pearson correlation analysis shows no correlation between the apparent diffusion coefficient (ADC) values of stenotic cervical segments of patients with cervical spondylotic radiculopathy and International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI) scores ($r = 1.140$, $P = 0.452$). (**B**) There is no significant correlation between the ADC values of stenotic cervical segments and ISNCSCI scores of patients with acute cervical spondylotic radiculopathy ($r = -0.374$, $P = 0.408$) or (**C**) those with chronic cervical spondylotic radiculopathy ($r = 0.226$, $P = 0.288$).

are lacking. Liu et al.[16] found that FA values decreased and ADC values increased at postoperative day 51 in goat with chronic spinal compression. They speculated that acute aggravation of chronic spinal cord compression might lead to myelin sheath swelling and reduction in space between fiber bundles, with resultant increase in diffusion of water molecules.

We found no correlation between FA or ADC values and ISNCSCI scores of patients with cervical spondylotic radiculopathy, regardless of whether patients had acute or chronic cervical spondylotic radiculopathy. Several investigators found that the JOA scores correlated with FA and ADC values[17,18]; however, the JOA scale, unlike ISNCSCI, does not reflect severity of nerve compression at a particular spinal segment. Chen et al.[19] found no correlation between FA values and ISNCSCI scores of patients with cervical disc herniation whereas mean diffusivity, longitudinal diffusivity, and radial diffusivity positively correlated with ISNCSCI scores, indicating that DTI could detect microscopic structural changes due to nerve compression in the early stage of the disease. We speculate that the failure of the study to demonstrate correlation between FA and ADC values and ISNCSCI scores of patients with cervical spondylotic radiculopathy might be due to anastomosis of fine nerve fibers. Currently, it is believed[20] that anastomosis exists between cervical nerves and fine nerve fibers of different cervical segments, especially at C5—C6. Although anastomosis is physiological, it complicates sensation assessment as it causes overlapping of sensory symptoms and signs.

One of the limitations of the current study is the small size of the study population, especially the small number of patients with acute cervical spondylotic radiculopathy. In addition, the study only used the ISNCSC for neurologic assessment and did not use the JOA scale, the Roland—Morris Disability Questionnaire, and the visual analogue scale. We also did not delineate temporal dynamic changes of DTI parameters and only used the crude division of acute and chronic cervical spondylotic radiculopathy for characterizing changes in DTI parameters. No preoperative and postoperative characterization was done of the DTI parameters. It has been shown that FA values correlated with preoperative JOA scores[21] and postoperative neurologic recovery.[22] A prospective longitudinal study involving a larger sample size is warranted to definitely delineate changes in DTI parameters of patients with acute cervical spondylotic radiculopathy and their correlation with clinical outcome.

In conclusion, the current study used a 3.0-T MRI scanner for the first time to quantify the functional state of cervical nerve roots using DTI. We have found that fiber tractography is capable of delineating microstructural changes of cervical nerve roots and FA and ADC values exhibit significant changes in cervical spondylotic radiculopathy. Future studies are warranted to further delineate the relationship between DTI parameters and neurologic outcomes.

REFERENCES

1. Weis EB Jr. Abnormal magnetic-resonance scans of the cervical spine in asymptomatic subjects. *J Bone Joint Surg Am*. 1991;73:1113.
2. Todd NV. Cauda equina syndrome: is the current management of patients presenting to district general hospitals fit for purpose? A personal view based on a review of the literature and a medicolegal experience. *Bone Joint J*. 2015;97-B:1390-1394.
3. Song T, Chen WJ, Yang B, et al. Diffusion tensor imaging in the cervical spinal cord. *Eur Spine J*. 2011;20:422-428.
4. Toktas ZO, Tanrikulu B, Koban O, Kilic T, Konya D. Diffusion tensor imaging of cervical spinal cord: a quantitative diagnostic tool in cervical spondylotic myelopathy. *J Craniovertebr Junction Spine*. 2016;7:26-30.
5. Maki S, Koda M, Kitamura M, et al. Diffusion tensor imaging can predict surgical outcomes of patients with cervical compression myelopathy. *Eur Spine J*. 2017;26:2459-2466.
6. Rindler RS, Chokshi FH, Malcolm JG, et al. Spinal diffusion tensor imaging in evaluation of preoperative and postoperative severity of cervical spondylotic myelopathy: systematic review of literature. *World Neurosurg*. 2017;99:150-158.
7. Li ZC, Chen DY, Wu DS. The Third Session of the National Cervical Spondylosis Panel Summary. *Chinese J Surg*. 2008;46:1796-1799.
8. Committee Membership, Burns S, Biering-Sørensen F, Donovan W, et al. International standards for neurological classification of spinal

cord injury, revised 2011. *Top Spinal Cord Inj Rehabil*. 2012;18:85-99.

9. Eguchi Y, Ohtori S, Orita S, et al. Quantitative evaluation and visualization of lumbar foraminal nerve root entrapment by using diffusion tensor imaging: preliminary results. *AJNR Am J Neuroradiol*. 2011;32:1824-1829.

10. Budzik JF, Verclytte S, Lefebvre G, Monnet A, Forzy G, Cotten A. Assessment of reduced field of view in diffusion tensor imaging of the lumbar nerve roots at 3 T. *Eur Radiol*. 2013;23:1361-1366.

11. Dallaudière B, Lincot J, Hess A, et al. Clinical relevance of diffusion tensor imaging parameters in lumbar disco-radicular conflict. *Diagn Interv Imaging*. 2014;95:63-68.

12. Beaulieu C, Allen PS. Determinants of anisotropic water diffusion in nerves. *Magn Reson Med*. 1994;31:394-400.

13. Beaulieu C, Does MD, Snyder RE, Allen PS. Changes in water diffusion due to Wallerian degeneration in peripheral nerve. *Magn Reson Med*. 1996;36:627-631.

14. Facon D, Ozanne A, Fillard P, et al. MR diffusion tensor imaging and fiber tracking in spinal cord compression. *AJNR Am J Neuroradiol*. 2005;26:1587-1594.

15. Hori M, Okubo T, Aoki S, Kumagai H, Araki T. Line scan diffusion tensor MRI at low magnetic field strength: feasibility study of cervical spondylotic myelopathy in an early clinical stage. *J Magn Reson Imaging*. 2006;23:183-188.

16. Liu JC, Liu HJ, Xu YJ, Huang BY, Cui CX. Diffusion tensor imaging in spinal cord of goats under chronic compression complicated with acute compression. *Chinese J Med Imaging Technol*. 2011;27:222-226.

17. Eguchi Y, Oikawa Y, Suzuki M, et al. Diffusion tensor imaging of radiculopathy in patients with lumbar disc herniation: preliminary results. *Bone Joint J*. 2016;98-B:387-394.

18. Gao SJ, Yuan X, Jiang XY, et al. Correlation study of 3T-MR-DTI measurements and clinical symptoms of cervical spondylotic myelopathy. *Eur J Radiol*. 2013;82:1940-1945.

19. Chen YY, Lin XF, Zhang F, et al. Diffusion tensor imaging of symptomatic nerve roots in patients with cervical disc herniation. *Acad Radiol*. 2014;21:338-344.

20. Rui BF, An SF, Xia FQ, Wang Z, Zhang JL. Applied microanatomy of cervical nerve and its related structure. *Acta Acad Med Militaris Tertiae*. 2008;30:2296-2298.

21. Vedantam A, Rao A, Kurpad SN, et al. Diffusion tensor imaging correlates with short-term myelopathy outcome in patients with cervical spondylotic myelopathy. *World Neurosurg*. 2017;97:489-494.

22. Arima H, Sakamoto S, Naito K, et al. Prediction of the efficacy of surgical intervention in patients with cervical myelopathy by using diffusion tensor 3T-magnetic resonance imaging parameters. *J Craniovertebr Junction Spine*. 2015;6:120-124.

Conflict of interest statement: The authors declare that the article content was composed in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received 29 May 2018; accepted 17 January 2019

Citation: World Neurosurg. (2019) 126:e57-e64.
https://doi.org/10.1016/j.wneu.2019.01.154

Journal homepage: ***www.journals.elsevier.com/world-neurosurgery***

Available online: ***www.sciencedirect.com***