Accuracy of diffusion tensor imaging for diagnosing cervical spondylotic myelopathy in patients showing spinal cord compression but otherwise unremarkable conventional MRI findings

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Directed by Professor Sungjun Kim

The Master's Thesis
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This certifies that the Master's Thesis of Seungbo Lee is approved.

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ABSTRACT

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Objective: To assess performance of diffusion tensor imaging (DTI) for diagnosis of cervical spondylotic myelopathy (CSM) in patients who show deformed spinal cord but otherwise unremarkable conventional magnetic resonance imaging (MRI) findings and to assess the correlation between the degree of central canal stenosis (CCS) and DTI parameters.

Materials and Methods: CCS severity was graded from sagittal T2-weighted images in 64 patients with cervical spondylosis. DTI parameters (mean diffusivity [MD], longitudinal diffusivity [LD], radial diffusivity [RD] and fractional anisotropy [FA]) were measured at the most stenotic level. Correlations between the degree of CCS and the DTI parameters were assessed. The performances of MD, FA, MD∩FA (considered positive when both the MD and FA results were positive), LD∩FA, and RD∩FA were evaluated and compared in patients showing compressed spinal cord without a signal change for distinguishing whether the patient clinically has CSM (n = 4) or not (n = 29).

Results: FA and RD values were negatively (r = −0.545) and positively (r = 0.399) correlated respectively with the degree of CCS ($p < 0.001$). Sensitivity, specificity, positive predictive value and negative predictive values in patients (n=33) showing compressed spinal cord without a signal change were best in LD∩FA. The calculations (percentages) were: 100, 44.8, 20, and 100 for MD; 100, 27.5, 16, and 100 for FA; 100, 58.6, 25, and 100 for MD∩FA; 100, 68.9, 30.8 and 100 for LD∩FA; and 75, 68.9, 25, and 95.2.for RD∩FA.

Conclusion: FA combined with MD, LD, and RD was a useful means to distinguish patients with and without CSM.

Key words: Cervical spondylotic myelopathy, magnetic resonance imaging, diffusion tensor imaging, mean diffusivity, longitudinal diffusivity, radial diffusivity, fractional anisotropy

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I. INTRODUCTION

Cervical spondylotic myelopathy (CSM) is the most common spinal cord disorder in patients > 55 years.[1] Although CSM is diagnosed primarily based on clinical manifestations, magnetic resonance imaging (MRI) has been a useful diagnostic tool, as it depicts increased signal intensity on T2-weighted images (T2WI). However, this finding is not seen in every patient with clinical signs of CSM.[2-5] Additionally, individual tolerance to a compressed spinal cord may vary according to the patient;[6] hence, MRI findings can be confusing due to the frequent disconnect between the degree of central canal stenosis and clinical symptoms.[7-9]

Thus, another MRI approach using diffusion tensor imaging (DTI) has been proposed to assess CSM.[10-20] The DTI parameters investigated to assess CSM include mean diffusivity (MD), longitudinal diffusivity (LD), radial diffusivity (RD), and fractional anisotropy (FA). Previous studies have reported that MD values increase and FA values decrease in the compressed cord. [11, 15, 16, 18] Additionally, LD (corresponding to the largest eigenvalue) and RD (corresponding to the average of the two smallest eigenvalues) are believed to reflect the degree of axonal and myelin damage, respectively. [21-24] Available evidence suggests that diminished FA is more sensitive for detecting a cord injury than hyperintensity depicted on T2WI [25] because there are patients whose spinal cords are sufficiently compressed to cause CSM but do not show a definite signal change on conventional MRI. However, no study has been conducted to assess the performance of diffusion tensor imaging (DTI) parameters and their combinations for evaluation of presence of cervical spondylotic myelopathy (CSM) in a patient group that shows deformed spinal cord without a signal change on conventional MRI. Such patients would not be confidently interpreted as having CSM on conventional MRI. [5, 26] We hypothesized that DTI parameters would be beneficial for this purpose. Therefore, we assessed the diagnostic performance of DTI parameters and their combinations for diagnosing CSM, particularly in patients showing spinal cord compression but without a spinal cord signal change on conventional MRI. We also assessed the correlation between the degree of central canal stenosis and DTI parameters.

II. MATERIALS AND METHODS

1. Patients

The institutional review board approved this retrospective study based on the HIPPA standard and written informed consent was waived. However, all patients signed informed consent as part of their research hospital visits. Consecutive 64 patients (36 males and 28 females; mean age, 53.6 ± 12.8 years; range, 25–80 years) who underwent C-spine MRI after signing comprehensive informed consent for this study using conventional and diffusion-weighted sequences to assess cervical spondylosis were collected as study subjects from February 2013 to September 2014.

Patients with at least one CSM symptom and at least two physical examinations for CSM were considered to have CSM. [27] The CSM symptoms included gait disturbance, lower extremity weakness, and bladder/bowel impairment. The CSM physical examinations included evaluations of spastic gait, the finger-escape sign, the grip-and-release test, and the Hoffmann and Babinski signs.

2. MRI Protocol

Imaging was performed on a 1.5 T MR scanner (MAGNETOM Avanto, Siemens Healthcare, Erlangen, Germany). Conventional MRI pulse sequences included sagittal T2-, sagittal T1-, and axial T2-weighted fast spin echo sequences (Table 1).

Table 1. Imaging parameters for the conventional pulse sequences

Imaging parameters	Sagittal T1-weighted FSE	Sagittal T2-weighted FSE	Axial T2-weighted FSE
Repetition time (msec)	450	4000	3500
Echo time (msec)	8.6	106	112
Bandwidth (Hz/pixel)	199	150	130
Echo train length	3	17	17
Flip angle (°)	145	170	170
No. of slices	17	17	36
Section thickness, gap (mm)	3, 0.3	3, 0.3	4, 0.4
Matrix size	286×448	358×512	173×384
Field of view (mm)	291×320	500×500	149×199
Imaging time	1 min, 4 sec	2 min, 12 sec	1 min, 06 sec

TR, repetition time; TE, echo time; ETL, echo train length; FSE, fast spin echo

Additionally, DTI was performed in the sagittal plane using a novel pulse sequence of two-dimensional (2D) single-shot interleaved multi-section inner volume diffusion-weighted echo-planar imaging (ss-IMIV-DWEPI). [28] The 2D ss-IMIV-DWEPI sequence allows effective interleaved multi-section DTI with less susceptibility to magnetic distortion, which improves image quality attributable to restricted field of view. [14] The 2D ss-IMIV-DWEPI imaging parameters were: TR = 3200 ms, TE = 74 ms, imaging matrix = 128 × 40, voxel size = 1.5 × 1.5 × 2.0 mm^3, section thickness = 2mm, b value = 0, 500 s/mm^2, echo train length = 20, receiver bandwidth = 1562 Hz/pixel, and 10 interleaved sections. Diffusion weighted gradients were applied in 12 noncollinear directions. Total scanning time for the DTI acquisition was 5 min 36 sec.

3. Image and Data Analysis

The degree of central canal stenosis was graded on conventional sagittal T2WI MRI by a musculoskeletal radiologist (C.S.Y.) with 23 years of experience in spinal imaging interpretation based on the following criteria proposed by Kang et al.: Grade 0, normal; grade 1, obliteration of > 50% of the subarachnoid space without any cord deformity sign; grade 2, central canal stenosis with a spinal cord deformity but without a spinal cord signal change; and grade 3, spinal cord hyperintensity at the compressed level (Fig. 1). [29]

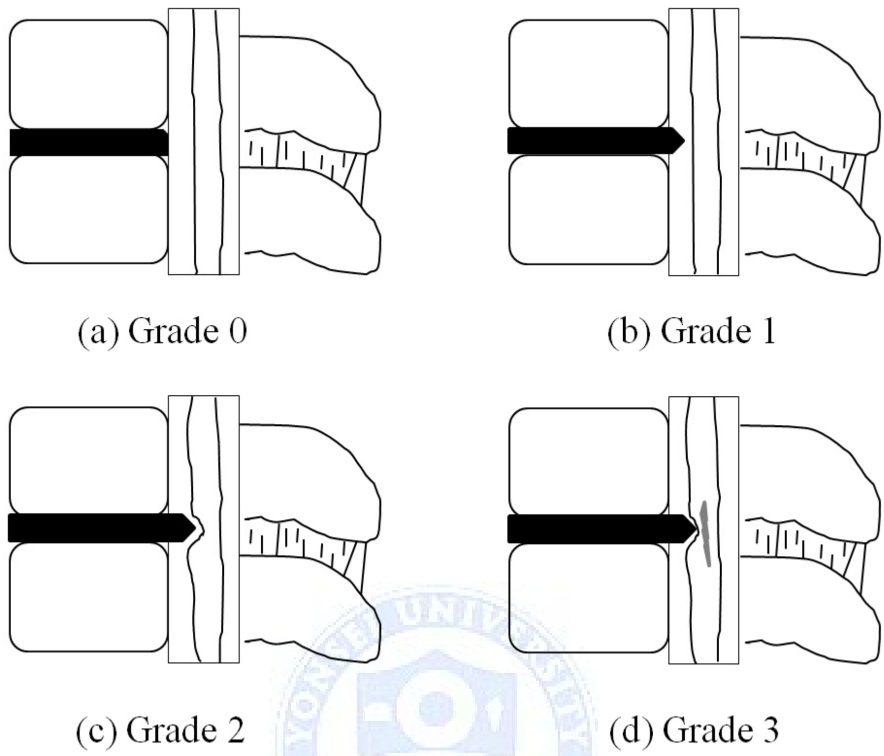

Fig. 1. Schematic diagrams of the cervical canal stenosis grading system

(A) Grade 0, normal.

(B) Grade 1, obliteration of > 50% of the subarachnoid space without any cord deformity sign.

(C) Grade 2, central canal stenosis with a spinal cord deformity; cord is deformed but no signal change is noted in the spinal cord.

(D) Grade 3, increased spinal cord signal intensity near the compressed level on T2-weighted images.

Only grade 3 is generally regarded as CSM on MRI in clinical practice. [26] The most stenotic level and the grade were recorded for all patients. The most stenotic level was also recorded for cases in which all levels were grade 0. To designate the most stenotic level for these patients graded as 0, two musculoskeletal radiologists (C.S.Y. and Y.H.L. with 23 and 6 years of experience in spinal imaging interpretation, respectively) viewed the images in consensus as a separate review session after comprehensively assessing obliteration of the subarachnoid space and ligamentum flavum thickness. The number of patients in each grade was recorded, and the sex composition and mean age ± standard deviation were assessed.

The acquired DTI dataset was processed pixel-by-pixel by using custom-made DTI processing software written in Interactive Data Language ver. 8.3 (ITT Visual Information Solutions, Boulder, CO, USA). First, three eigenvalues (λ1, λ2, and λ3) and the eigenvectors were calculated. Longitudinal diffusivity (LD) and radial diffusivity (RD) were defined in equations from the directional diffusivity values obtained:

$$LD = \lambda 1$$

$$RD = (\lambda 2 + \lambda 3) / 2$$

Mean diffusivity (MD) was calculated as:

$$MD = (\lambda 1 + \lambda 2 + \lambda 3)/3 = (ADCx+ADCy+ADCz)/3$$

The MD value was considered analogous to the apparent diffusion coefficient (ADC) value. [30]

The degree of anisotropy was determined by FA,[31] which was calculated with the following equation:

$$FA = \sqrt{3\left[\left(\lambda1 - MD\right)^2 + \left(\lambda2 - MD\right)^2 + \left(\lambda3 - MD\right)^2\right]} \; / \; \sqrt{2\left(\lambda1^2 + \lambda2^2 + \lambda3^2\right)}$$

FA values from 0 (completely isotropic) to 1 (completely anisotropic) indicate the degree of structural anisotropy. [14]

Pixel-based FA map and principal eigenvector RGB map images were automatically produced by the software. The blue color represents the principal eigenvector aligned along the head-foot direction. The MD, LD, RD, and FA values were measured at the most stenotic level, which was recorded in the stenosis grading session stated above by drawing oval regions of interest (ROI) twice on the FA map images as large as possible by a third-year resident trainee (S.L.) and a musculoskeletal radiologist (S.K.) with 11 years of experience with spinal imaging interpretation in consensus using the customized program stated above (Fig. 2).

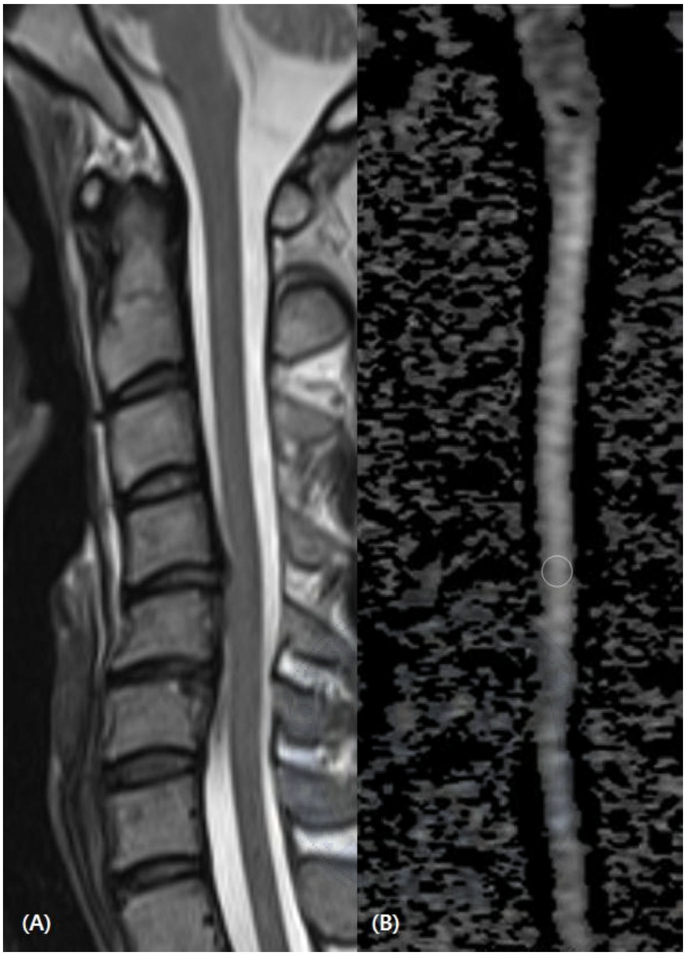

Fig. 2. Representative image used for the diffusion tensor imaging parameter measurements.

The gray-tone fractional anisotropy (FA) map was automatically produced by the software, and FA and mean diffusivity values were measured at the most severe stenosis level by drawing an oval region of interest on the FA map (B) not to include regions outside the spinal cord, such as adjacent anatomical structures, and cord morphology compared with the T2-weighted images (A) as a reference.

ROIs (mean, 29.71 ± 0.67 mm^2; range, 28.69–30.78 mm^2) with their mean area ± standard deviation (SD) were drawn on the FA map but did not include regions outside of the spinal cord, such as adjacent anatomical structures, and cord morphology was compared with the T2WIs as a reference. FA values and eigenvalues were automatically presented for each ROI in the software. FA, LD ($\times 10^{-3} mm^2/sec$), and RD ($\times 10^{-3} mm^2/sec$) values were recorded as presented. Mean diffusivity ($\times 10^{-3} mm^2/sec$) values were calculated using the eigenvalues with the aforementioned equation and were recorded.

4. Statistical Analysis

All continuous values are presented in mean ± SD with ranges. Spearman's rank correlation coefficient analysis was used to assess the correlations between the DTI parameters and the degree of stenosis using a conventional MRI grading system. Student's t-test was used to compare the spinal cord DTI parameter values between patients with and without CSM. Furthermore, to assess the CSM diagnostic performance in the subgroup of patients showing spinal cord compression but without a signal change on T2WI, we obtained the cut-off value from a receiver operating characteristic (ROC) curve analysis of the DTI parameters to assess how many patients in this category could be correctly diagnosed. Sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) were calculated for MD and FA based on the ideal cut-off values obtained from the ROC curve analysis. We additionally adopted parameter combinations of MD∩FA, LD∩FA, and RD∩FA to determine the overall diagnostic performance of FA considering diffusivity and the eigenvalues. The MD∩FA, LD∩FA, and RD∩FA parameter combinations were considered positive when both the MD and FA, both the LD and FA, and both the RD and FA results were positive respectively based on the ideal cut-off values for FA, MD, LD, and RD. Sensitivity, specificity, PPV, and NPV of MD∩FA, LD∩FA and RD∩FA were also obtained. SPSS ver. 20.0 (SPSS Inc., Chicago, IL, USA) was used for the statistical analyses, including Student's t-test, Spearman's rank correlation and ROC curve analyses. Sensitivity, specificity, PPV, and NPV were compared among MD, FA, MD∩FA, LD∩FA, and RD∩FA using multiple comparison and post-hoc analyses with least square means. The multiple comparisons with least square means were performed using SAS ver. 9.2 (SAS Institute, Cary, NC, USA). P-values < 0.05 were considered significant.

III. RESULTS

Among the 64 patients (36 males and 28 females; mean age, 53.6 ± 12.8 years; range, 25–80 years) enrolled, 14 patients had CSM according to the patient's symptoms and a physical examination. The most stenotic levels were C3–4 in seven patients, C4–5 in 21 patients, C5–6 in 24 patients, and C6–7 patients in 12 patients on sagittal T2WI.

According to the conventional MRI grading criteria, four patients (one male and three females; mean age, 40 ± 15.1 years; range, 25–54 years) were grade 0, 16 patients (eight males and eight females; mean age, 49.8 ± 11.5 years; range, 38–74 years) were grade 1, 33 patients (16 males and 17 females; mean age, 56.5 ± 13.5 years; range, 34–80 years) were grade 2, and 11 patients (11 males; mean age, 55.4 ± 7.5 years; range, 43–70 years) were grade 3.

In the correlation assessment between the DTI parameters and the degree of stenosis, the FA values were negatively correlated with the degree of central canal stenosis (rho = −0.545, $p < 0.001$). RD was positively correlated with the degree of central canal stenosis (rho = 0.399, $p < 0.001$). However, MD (rho = 0.156, $p < 0.217$) and LD (rho = −0.149, $p < 0.238$, respectively) were not significantly correlated with the degree of central canal stenosis (Fig. 3).

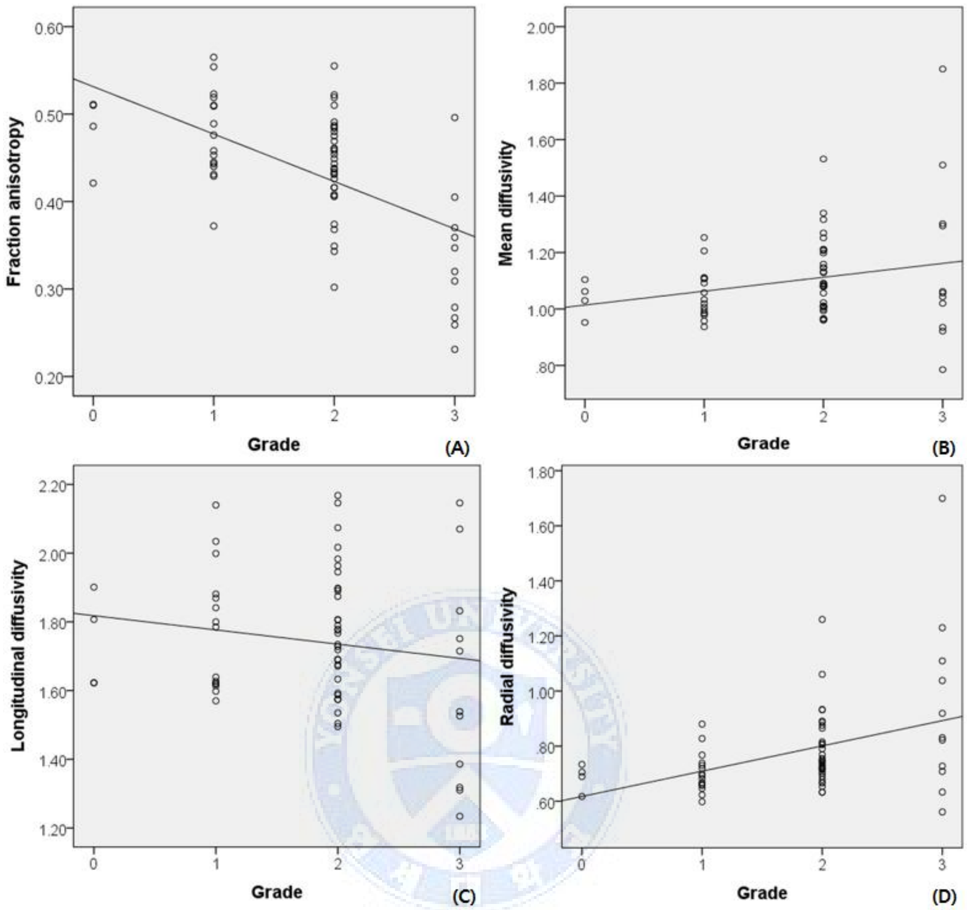

Fig. 3. Correlations between the degree of central canal stenosis and the diffusion tensor imaging (DTI) parameters.

(A), Fractional anisotropy values were negatively correlated with the degree of central canal stenosis (rho = −0.545, $p < 0.001$).

(B), Mean diffusivity was not correlated with the degree of central canal stenosis (rho = 0.156, $p < 0.217$).

(C), Longitudinal diffusivity was not correlated with the degree of central canal stenosis (rho = −0.149, $p < 0.238$).

(D), Radial diffusivity was positively correlated with the degree of central canal stenosis (rho = 0.399, $p < 0.001$).

*Diffusivity units are 1×10^{-3} mm^2/sec.

Mean FA values were significantly different ($p < 0.001$) between patients with CSM (0.36 ± 0.08; range, 0.23–0.50) and those without CSM (0.46 ± 0.06; range, 0.30–0.57). Mean MD, LD, and RD values in patients with CSM were 1.16 ± 0.27 (range, 0.79–1.85), 1.68 ± 0.26 (range, 1.23–2.15), and 0.90 ± 0.30 (range, 0.56–1.70) respectively in units of 10^{-3} mm^2/sec. Mean MD, LD, and RD values in patients without CSM were 1.09 ± 0.12 (range, 0.93–1.53), 1.76 ± 0.19 (range, 1.32–2.17), and 0.74 ± 0.12 (range, 0.60–1.26) in units of 10^{-3} mm^2/sec. No between-group differences were observed among mean MD (p=0.318), LD (p=0.227), and RD (p=0.082) values (Fig. 4).

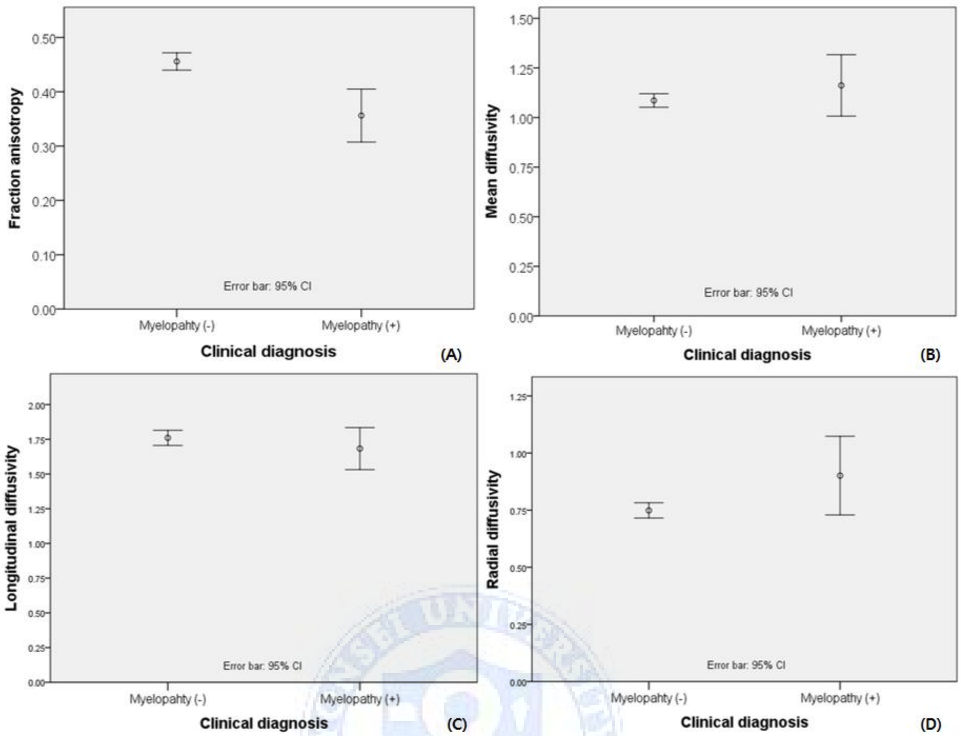

Fig. 4. Statistical comparison of the diffusion tensor imaging values of patients with and without cervical spondylotic myelopathy (CSM).

(A), Mean fractional anisotropy values were lower ($p < 0.001$) in patients with CSM (0.36 ± 0.08; range, 0.23–0.50) than in those without CSM (0.46 ± 0.06; range, 0.30–0.57).

(B), Mean diffusivity values were not different ($P = 0.318$) between patients with CSM (1.16 ± 0.27; range, 0.79–1.85) and those without CSM (1.09 ± 0.12; range, 0.93–1.53).

(C), Mean longitudinal diffusivity values were not different ($P = 0.227$) between patients with CSM (1.68 ± 0.26; range, 1.23–2.15) and those without CSM (1.76 ± 0.19; range, 1.32–2.17).

(D), Mean radial diffusivity values were not different (P = 0.082) between patients with CSM (0.90 ± 0.30; range, 0.56–1.70) and those without CSM (0.74 ± 0.12; range, 0.60–1.26).

*Diffusivity units are 1×10^{-3} mm^2/sec.

Thirty-three patients showing compressed spinal cord without a signal change on T2WI were included in the subgroup to assess diagnostic performance of the DTI parameters and their combinations. Among them, four patients had CSM (Fig. 5), and the remaining 29 did not. The ideal MD, LD, RD, and FA cut-off values in this subgroup were: > 1.079 × 10−3, > 1.719 × 10−3, and > 0.749 × 10−3 mm2/sec and ≤ 0.475, respectively. Sensitivity, specificity, PPV, and NPV of MD, FA, MD∩FA, LD∩FA, and RD∩FA are summarized in Table 2.

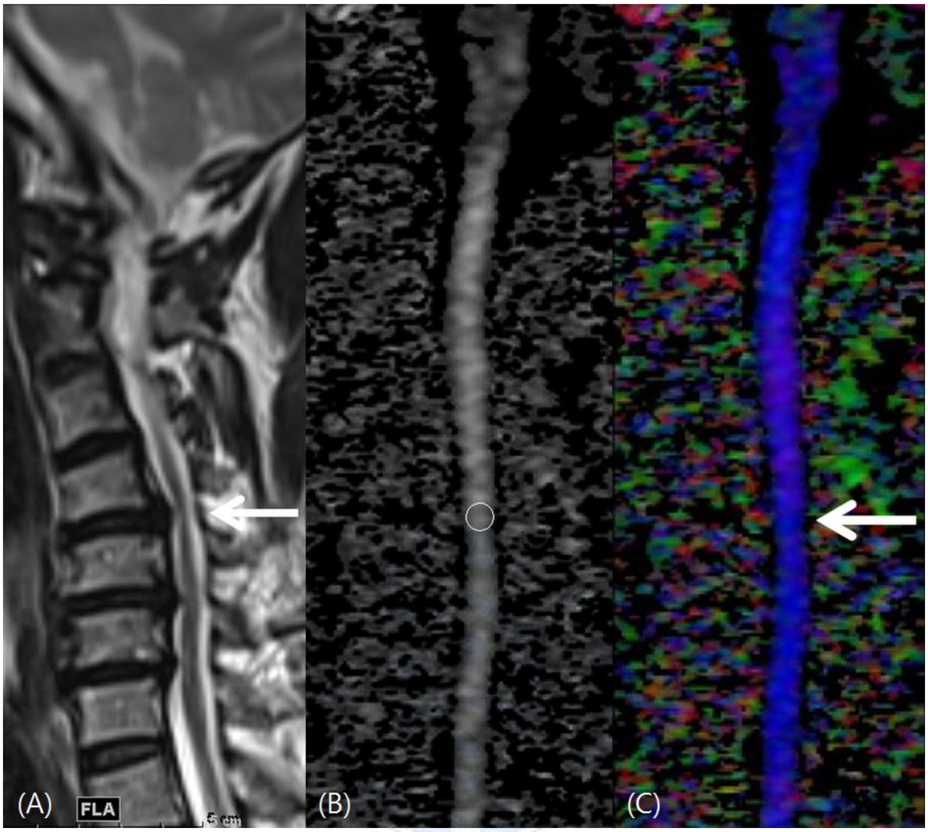

Fig. 5. Cervical spondylotic myelopathy (CSM) detected using diffusion tensor imaging (DTI) parameters in a patient whose T2-weighted image was designated as grade 2 stenosis.

An off-center sagittal T2-weighted image (A) of the patient showed a deformed spinal cord without definite signal change at the C4–5 disc level, which was the most stenotic level; thus being designated as grade 2. The DTI parameters were measured at the level on the mid-sagittal gray-tone fractional anisotropy (FA) map (B). The FA, mean diffusivity, longitudinal diffusivity, and radial diffusivity values of this patient were 0.349, 1.198 × 10^{-3} mm^2/sec, 1.728 × 10^{-3} mm^2/sec, and 0.933 × 10^{-3} mm^2/sec, respectively. All values were compatible with CSM considering the cut-off value of each parameter. A color-coded map (C) based on the principal eigenvalues in the sagittal plane revealed subtle dark color, suggesting changes in the eigenvalues at the most stenotic level. Blue color represents the principal eigenvector aligned along the head-foot direction.

Table 2 Diagnostic Performance of Each Parameter and their Combinations Determined through Receiver Operating Characteristic Curve in Patients with a Grade 2 Stenosis.

Parameter	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)
MD	100% (4/4; –)	44.8% (13/29; 26.7–62.9)	20.0% (4/20; 2.4–37.5)	100% (13/13; –)
FA	100% (4/4; –)	27.6% (8/29; 11.3–43.9)	16.0% (4/25; 1.6–30.4)	100% (8/8; –)
MD∩FA*	100% (4/4; –)	58.6% (17/29; 40.7–76.5)	25.0% (4/16; 3.8–46.2)	100% (17/17; –)
LD∩FA†	100% (4/4; –)	68.9% (20/29; 52.1–85.8)	30.8% (4/13; 5.7–55.9)	100% (20/20; –)
RD∩FA‡	75.0% (3/4; 32.6–100%)	68.9% (20/29; 52.1–85.8)	25.0% (3/12; 1–49.5)	95.2% (20/21; –)

Numbers in parenthesis are the counts used for the calculations and their 95% confidence intervals.

FA, fractional anisotropy; MD, mean diffusivity; LD, longitudinal diffusivity; RD, radial diffusivity; PPV, positive predictive value; NPV, negative predictive value

MD∩FA* means positive in both MD and FA based on the ideal cut-off value for each parameter.

LD∩FA† means positive in both LD and FA based on the ideal cut-off value for each parameter.

RD∩FA‡ means positive in both RD and FA based on the ideal cut-off value for each parameter.

Specificity was significantly different ($p < 0.001$) among the DTI parameters and their combinations in multiple comparisons indicating at least one of the comparisons was significant, whereas sensitivity ($p = 0.317$), PPV ($p = 0.328$), and NPV ($p = 0.210$) were not significantly different. Significant differences were observed between FA and MD∩FA ($p = 0.003$), FA and LD∩FA ($p < 0.001$), FA and RD∩FA ($p < 0.001$), MD and LD∩FA ($p = 0.024$) and MD and RD∩FA ($p = 0.024$) in a post-hoc analysis of specificity between the parameters and their combinations. No significant differences were observed in the other comparisons.

IV. DISCUSSION

Our study focused on the diagnostic performance of DTI parameters and their combinations to distinguish whether the patient clinically has CSM or not in a subgroup of patients with spinal cord compression but otherwise unremarkable conventional MRI findings. We were inspired by studies in which ADC and FA of patients without a spinal cord signal change on conventional MRI were different between CSM and non-CSM groups. [12, 13, 16] Although four studies have reported variable performance of DTI parameters to distinguish between various symptom groups, which were different from those in our study, no study has used an approach similar to ours. [10, 11, 18] Among these studies, two used the sagittal plane for DTI. [10, 11] One study reported sensitivity, specificity, PPV, and NPV of DTI parameters as 78%, 61%, 75%, and 66% for FA and 80%, 53%, 73%, and 63% for ADC to distinguish symptomatic and asymptomatic patients. The reference values, which were obtained from asymptomatic volunteers, were 0.83 ± 0.11 for FA and 2.58 $\times 10^{-3}$ mm^2/sec for ADC. That study was different from ours, as they enrolled patients with central canal stenosis observed on radiography, computed tomography, or MRI. [10] In another study that used sagittal DTI, sensitivity and specificity were 76.3% and 100% in FA and 13.4% and 80% in ADC, respectively, to distinguish symptomatic and asymptomatic patients. In that study, the reference values obtained from asymptomatic volunteers were 0.745–0.751 for FA and 0.96–1.05 for ADC. [11] That study was also different from ours, as the thoracic spine and patients with a signal change on conventional MRI imaging were included. The remaining two studies used DTI in the axial rather than the sagittal plane. [18, 20] One of the two studies reported that sensitivity and specificity for distinguishing between groups of patients with and without clinically symptomatic myelopathy were 65.0% and 71.9% for FA and 70.0% and 75.0% for ADC, respectively when the spinal cord DTI parameters were measured at the most severely compressed level, as in our study. [18] Another study using DTI in the axial plane assessed the performance of DTI parameters other than FA and MD, as we did. Those authors divided the patients into two groups of < 15 (moderate or more neurologic impairment) and < 18 (symptomatic patients), respectively, using the modified Japanese Orthopedic Association score as the cut-off value to test the performance of DTI parameters to distinguish between the groups based on cut-off values. Sensitivity and specificity for the mean FA values measured at the most severely compressed level were 72% and 75% for distinguishing symptomatic and asymptomatic patients and were 81% and 92% between groups with moderate or more neurologic impairment and less impairment. Although that study also assessed RD performance, sensitivity and specificity of RD were not reported. [20] All of these aforementioned studies included patients with a spinal cord signal change on conventional MRI or were uncertain whether the patient group included such patients. Additionally, LD and RD were not considered to assess DTI performance. Although direct sensitivity and specificity comparisons of these studies with ours would be difficult due to the differences stated above, the FA and MD (which was considered ADC) values in our study showed relatively higher sensitivity than those of previous investigations. However, specificities in our study were lower than those in previous studies. We speculate that the lower FA and MD specificity could be attributed to our subgroup used to assess diagnostic performance that did not include patients with a spinal cord signal change on conventional MRI. In contrast, when we combined the FA results with those of MD, LD, and RD, specificity was comparable to those of the previous studies. Among the parameter combination, LD∩FA showed the best specificity (68.9%) and the best sensitivity (100%), but no significant difference in specificities was detected among the combinations (MD∩FA, LD∩FA, and RD∩FA). We believe that the combination of MD, LD, or RD with FA would enhance specificity of FA in a patient group with spinal cord compression that is not associated with a signal change on conventional MRI based on our data, although the reason should be further assessed with a pathological correlation using an animal model.

In the present study, the FA values were negatively correlated, and the RD values were positively correlated with the degree of central canal stenosis assessed at the most stenotic level. We speculate that a compressed cord injured in its directionally oriented axon structures and myelin probably leads to a relative increase in water diffusion in directions perpendicular to their long axis compared to that in an intact spinal cord. A diminished spinal cord FA value may reflect loss of directionally oriented membrane structures, increased extracellular edema, or both. [25] An experimental rat spinal cord study demonstrated that mechanical disruption, tearing of fibers and myelin sheaths, Wallerian degeneration, and demyelination diminish FA values. [32] Previous studies using the mice brain and optic nerve demonstrated that demyelination increases RD. [21, 22] Although one study revealed a correlation between ADC (MD in our study) and diffusivity on conventional MRI imaging or patient symptomatology,[19] no significant correlation between MD and LD with the degree of stenosis was found. One explanation could be greater inter-individual variability for MD, which is partly affected by age. Another study reported a negative correlation between age and MD values, but the association was insignificant between age and FA ($p = 0.234$). [33] Our study included a wide age range of patients (25–80 years). The LD (corresponding to the largest eigenvalue) value is the most critical factor for MD, which represents the mean of three eigenvalues. [20] Therefore, LD is expected to have large inter-individual variability.

The mean FA value in patients with CSM was significantly lower than that in those without CSM, which was compatible with previous studies. [14-17] However, in our study, mean MD, LD, and RD values in patients with CSM were not different from those in patients without CSM, suggesting large inter-individual variability dependent on patient age. Decreased FA values are not always consistent with elevated MD values, as FA values decrease but MD values may not increase when neural tissue has damaged fibers but the damage is stabilized by gliosis in the surrounding tissue. [34-36]

Several limitations need to be addressed in our study. First, the ROI used covered the entire spinal cord and did not distinguish white matter from gray matter, as differentiating between them is difficult on sagittal plane images, particularly those of a in compressed spinal cord, and this may have caused some bias. Van Hecke et al. [37] performed a thresholding procedure (FA = 0.2) to distinguish white from gray matter on axial plane images. However, the thresholding procedure caused loss of severely degenerated white matter information.[15] After we balanced the advantages and disadvantages of different approaches, we used sagittal plane images to define a ROI that covered the entire spinal cord and focused on excluding the cerebrospinal fluid space as much as possible. Second, although many conditions, including cystic necrosis, syrinx, myelomalacia, and atrophy of a compressed spinal cord have been speculated to affect the change in DTI values,[38, 39] the exact causes for changes in each DTI parameter remain unclear because a pathological correlation was not possible in our study. Third, 100% sensitivity of the parameters and parameter combinations can be attributable to small number of subject counts, particularly to the fact that we have only four patients who presented with symptom of CSM, not demonstrating signal change on T2WI. Therefore, we believe that further study should be conducted with larger number of such patient group in our study. Finally, we could not evaluate the correlation between patient symptom severity and DTI parameters due to limited medical records from the retrospective nature of this study. However, this was not only due to limited medical records but also because the main purpose of this study was to assess DTI diagnostic performance for evaluating grade 2 lesions.

V. CONCLUSION

In conclusion, spinal cord FA values were negatively correlated with the degree of central canal stenosis, whereas RD was positively correlated with the degree of central canal stenosis. There was statistically significant reduction of FA values in clinically diagnosed CSM patients ($p<0.001$). Among the DTI parameters and their combinations, FA combined with MD, RD, or LD is expected to be used as a tool with reasonable diagnostic performance to distinguish patients with and without CSM among those who show spinal cord compression but otherwise unremarkable conventional MRI findings.

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ABSTRACT(IN KOREAN)

고식적 자기공명영상에서 척수 압박 소견만을 보이는
환자에서 확산텐서영상의 경추증성 척수증 진단수행도

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서론: 고식적 자기공명영상에서 척수 압박을 보이나 신호변화를 보이지 않는 환자에 대한 자기공명 확산텐서영상의 경추증성 척수증 진단수행도를 평가하고 척추관협착의 정도와 확산텐서영상의 지표들간의 상관관계를 평가하고자 하였다.

대상 및 방법: 64명의 경추증 환자에서 고식적 자기공명영상 T2강조 시상영상을 통하여 척추관협착의 중증도를 나누었다. 확산텐서영상의 지표들 (mean diffusivity [MD], longitudinal diffusivity [LD], radial diffusivity [RD] and fractional anisotropy [FA])을 가장 협착이 심한 척수 레벨에서 측정하였다. 척추관협착의 정도와 확산텐서영상의 지표들간의 상관관계를 평가하였다. 고식적 자기공명영상에서 척수 압박을 보이나 신호변화를 보이지 않는 환자에서 경추증성 척수증의 유무를 판단하는 MD, FA, MD∩FA (MD와 FA 모두 양성인 경우를 양성으로 간주), LD∩FA와 RD∩FA의 진단수행도 (민감도, 특이도, 양성예측

치, 음성예측치)를 얻고, 비교하였다.

결과: FA와 RD값들은 각각 척추관협착의 정도와 음 ($r = -0.545$) 과 양 ($r = 0.399$)의 상관관계를 보였다 ($p < 0.001$). 고식적 자기공명영상에서 척수 압박을 보이나 신호변화를 보이지 않는 환자에서 민감도, 특이도, 양성예측치와 음성예측치는 LD∩FA에서 가장 우수하였다.

민감도, 특이도, 양성예측치와 음성예측치 백분율은 다음과 같다 : MD는 100, 44.8, 20, 100; FA는 100, 27.5, 16, 100; MD∩FA는 100, 58.6, 25, 100; LD∩FA는 100, 68.9, 30.8, 100; RD∩FA는 75, 68.9, 25, 95.2.

결론: FA를 MD, LD 그리고 RD와 조합하는 것이 고식적 자기공명영상에서 척수 압박을 보이나 신호변화를 보이지 않는 환자에서 경추증성 척수증의 유무를 판단하는데 유용한 방법이다.

핵심되는 말: 경추증성 척수증, 자기공명영상, 확산텐서영상, mean diffusivity, longitudinal diffusivity, radial diffusivity, fractional anisotropy