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RESEARCH

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Leverage of applying diffusion tensor imaging (DTI) indices in assessment of cervical spondylotic myelopathy

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Abstract

Background Cervical spondylotic myelopathy (CSM) is the most prevalent form of dysfunction in the cervical cord. For best results, CSM must be identified and treated quickly, before spinal cord injury develops. We aimed at determining the diagnostic value of quantitative and qualitative diffusion tensor imaging (DTI) indices in the assessment of CSM. Thirty patients were included in this prospective study with clinically suspected CSM of both sexes. This study aimed at determining the diagnostic value of quantitative and qualitative DTI indices in early assessment of CSM and subsequently early and proper management decision rendering better clinical outcome.

Results This prospective study included 30 patients: with clinically suspected CSM with a mean age of 51.88 ± 10.28 years. Patients with CSM were graded to 3 grades, mild (No. = 17), moderate (No. = 13) and severe (No. = 0) according to the modified Japanese orthopedic association (mJOA) grading system. Correlation test was performed between mJOA grades of severity with fractional anisotropy (FA), apparent diffusion coefficient (ADC) and T2 cord signal. We found a negative correlation between ADC and FA with Spearman's rho value of − 0.612 and "*P* value 0.000" (*P* value < 0.05), a positive correlation between FA with mJOA clinical score with Spearman's rho value of − 0.504 & "*P* value 0.036" (*P* value < 0.05) and a negative correlation between ADC and mJOA clinical score with Spearman's rho value of 0.385 and *P* value 0.005 (*P* value < 0.05), and no significant correlation was found between mJOA clinical score and T2 hyperintense signal with Spearman's rho value of − 0.304 and "*P* value 0.102" (*P* value < 0.05). Qualitative maps grading by 3D tractography images were done, and 18 patients in the study (60%) showed homogenous intact fiber tracts (grade I), 9 patients (30%) showed reduction or alteration of anisotropy or mixed colors intensity (grade II), and 3 patients (10%) showed fiber tract disruption or displaced cord (grade III). Three DTI parameters (other than FA and ADC) were measured, and two of them show significant difference between their measures in the stenotic and non-stenotic portions of the spinal cord—RA (*P* value = 0.00) and RD (*P* value = 0.00).

Conclusions We concluded that DTI is a crucial tool for early diagnosis and grading of CSM (cervical spondylosis myelopathy)—quantitatively and qualitatively—hence, it should be routinely integrated with conventional cervical spine MRI in case of clinically or radiologically suspected cervical cord compression, as the FA parameter together with the clinical assessment formulates the management plan decision for the CSM whether surgical or non-surgical and depicts the need for early surgical decision rendering better clinical outcome compared to that based on T2 hyperintense cord signal.

Keywords Diffusion tensor imaging, Myelopathy, Cervical spondylotic myelopathy, CSM, DTI

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Background

Cervical spondylotic myelopathy (CSM) is the most prevalent form of dysfunction in the cervical cord. It is a degenerative, chronic cord condition that damages the cervical cord [1]. It has been demonstrated to be the 1ry cause of cervical myelopathy in adults 55-year-old or older [2]. For best results, CSM must be identified and treated quickly, before spinal cord injury develops. Therefore, an increased awareness of this illness is necessary [3]. As the magnetic resonance imaging (MRI) of the cervical spine is the best diagnostic tool used to ensure the clinical diagnosis and offers anatomical details of the underlying disease processes, it is advised when CSM is suspected. Furthermore, cervical spine MRI is incredibly helpful for identifying pathologic alterations in the cord, vertebra, disc, ligament and facet joints [4]. Hyperintense T2 signal is a sign of compressive cord myelopathy but manifests late [5]. Diffusion tensor imaging (DTI) is a noninvasive advanced MRI technique that allows white matter tracts visualization by evaluating the diffusion of water molecules, thus enabling the quantitative assessment of the stability of tissue microstructure [6].

The aim of this study was to determine the diagnostic value of quantitative and qualitative diffusion tensor imaging (DTI) indices in early assessment of cervical spondylotic myelopathy and subsequently early and proper management decision rendering better clinical outcome.

Methods

In this prospective study, thirty patients were included according to the inclusion criteria. Patients with clinically suspected cervical spondylotic myelopathy of both sexes were referred from the neurosurgical clinic to the magnetic resonance imaging unit at our radiology department in the period from August 2022 to May 2023. Conventional MRI and DTI were performed for all the patients included in this study. The study was approved by the ethical committee of the faculty of medicine, Minia University (Approval No. 350:7/2022, Date: 14 July 2022) (Figs. 1, 2, 3).

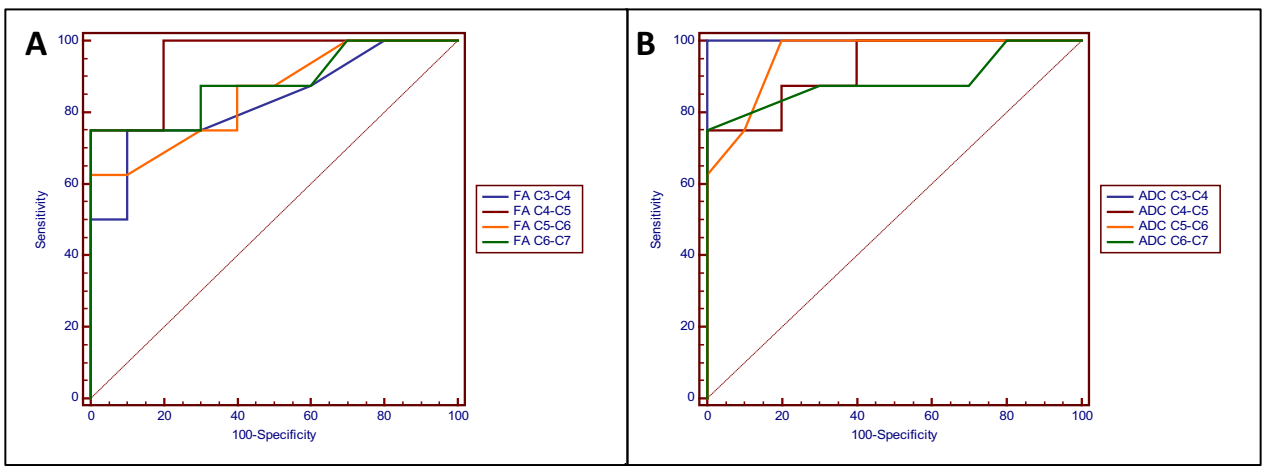


Fig. 1 **A** ROC curve of FA and **B** ROC curve of ADC at different cervical levels

(See figure on next page.)

Fig. 2 A 53-year-old male patient complaining of neck and shoulder pain with mJOA score = 14 (Moderate grade). Conventional MRI: **A** Sagittal T2WI, **B** Sagittal T1WI, **C**, **D** Axial T2WI at CV6/7 disc level, Sagittal DTI: **E** ADC map, **F** FA grayscale map, **G** FA color map, **H** 3D tractography. **A**, **B** Sagittal T2WI, **A** Sagittal T1WI, **B** showing straightening of cervical curve with uni-level diffuse disc bulge with central protruded component opposite CV6/7 encroaching upon sub-arachnoid space; the condition is augmented by hypertrophied ligamentum flavum with 2^{ry} canal stenosis. This disc level is seen severely compressing the related portion of the cervical cord (3rd degree), with type I T2 hyperintense cord signal (white arrow) measuring about 10 mm in size, no abnormal cord signal at T1WI (compressive cord myelopathy grade II). **C**, **D** axial T2WI at CV6/7 disc level showing diffuse disc bulge with central protruded component indenting the subarachnoid space and compressing the related cord with T2 hyperintense signal (Grade II). **E** Sagittal ADC map showing high ADC value at site of cord myelopathy CV6/7 (represented by arrow) = 1.42×10^{-3} mm^2/s compared to 0.8×10^{-3} mm^2/s at non-compressive site. **F** Sagittal FA grayscale map showing low FA value at site of cord myelopathy (CV6/7) = 0.43 (moderate FA grade) compared to 0.63 at non-compressive site. **G** FA color map showing faint green color intensity of FA map at CV6/7 disc level. **H** 3D tractography showing homogenous color of the cervical cord and intact fiber tracts (grade I)

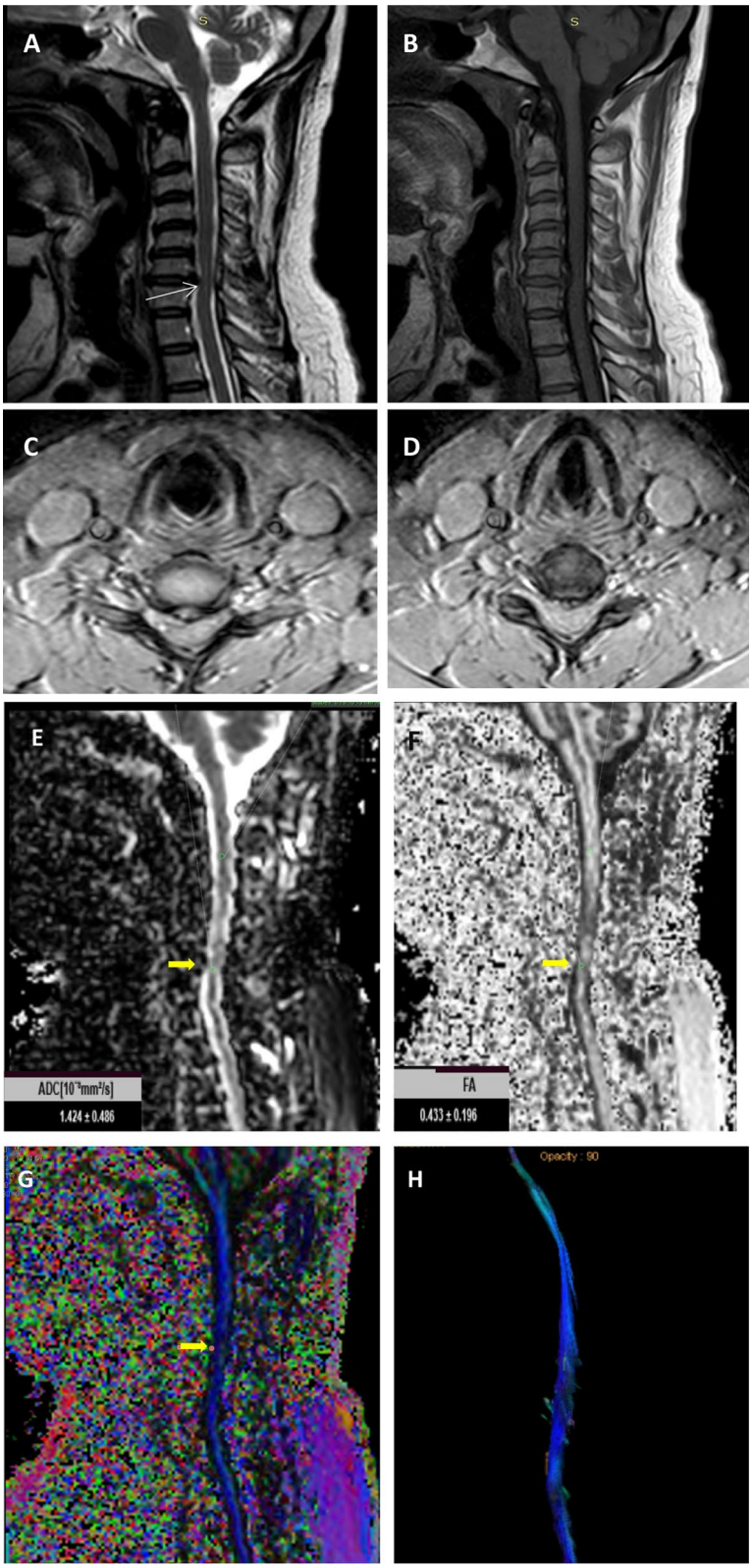


Fig. 2 (See legend on previous page.)

Patient selection

- **Inclusion criteria**
- Patient with cervical disc prolapse with:
  - Typical clinical manifestations and signs of cervical spondylotic myelopathy (CSM) according to the modified Japanese orthopedic association (mJOA) system (Table 1).
  - MRI findings consistent with cervical cord compression (2^{nd} and 3^{rd} degrees are those involved in our study) (Table 2)
- **Exclusion criteria**
  - Patient with other neurological diseases, other than disc prolapse as 1^{ry} or 2^{ry} neoplastic cord lesions, trauma, infectious and inflammatory process, neurodegenerative disorders.
  - Patients with MRI contraindication, e.g., implanted magnetizing device, patients with fixation of vertebrae by screws hindering the diffusion sequence by the metal artifacts, pacemaker, claustrophobia.
- Refusal to participate in this study.

Each patient included in this study was subjected to:

1. Full history taking.
2. A written consent to participate in this study.
3. Clinical examination.
4. Cervical MRI examination:
   - Conventional MRI
   - Diffusion tensor imaging (DTI)

MR Imaging technique

Cervical MRI examination was acquired on a closed 1.5 Tesla MRI system (Ingenia–Philips medical system), using standard cervical spine coil. Patients were scanned while lying face down, headfirst. During the scan, patients were advised to stop moving. The clinical grading system was compared to the final quantitative radiological findings.

Image acquisition

- Conventional MRI acquisition:

The protocol of MRI examination of the cervical spine and cord-based standard on conventional MRI protocol by Farshad-Amacker et al. [7]:

1. **Axial T2WI**: with repetition time /echo time (TR/TE) = 331/4.6 ms, acquisition matrix 176 × 222, field of view (FOV) = 200 × 200 mm^2, slices number 15, slice thickness 3.5 mm. slice gap = 15, flip angle = 25°, time of acquisition (TA) = 3:57
2. **Sagittal T2WI**: with repetition time /echo time (TR/TE) = 2179/100 ms, acquisition matrix 200 × 226, filed of view (FOV) = 221 × 100 mm^2, slices number 15, slice thickness 3 mm. slice gap 15, flip angle = 90°, time of acquisition (TA) = 2:23
3. **Sagittal T1WI**: with repetition time/ echo time (TR/TE) = 589/8.2 ms, acquisition matrix 168 × 219, filed of view (FOV) = 220 × 150 mm^2, slices number 15, slice thickness 3 mm, slice gap 15, flip angle 90°, time of acquisition (TA) = 3:33

- DTI acquisition:

4. **Sagittal diffusion tensor imaging (DTI)**: with diffusion with b = 800s/mm^2 with another measurement with no diffusion gradient (b = 0 s/mm^2) with repetition time / echo time (TR/TE) = 3121/99 ms, acquisition matrix 92 × 88, filed of view (FOV) = 224 × 224 mm2, b value 800 s/ mm2 slices number 40, slice thickness 2 mm, slice gap 0 percent, flip angle 90°, time of acquisition (TA) = 6:33.3

(See figure on next page.)

Fig. 3 A 50-year-old male patient complaining of neck pain with mJOA score = 17 (Mild grade). Conventional MRI: **A** Sagittal T2WI, **B** Sagittal T1WI, **C**, **D** Axial T2WI at CV5/6 disc level, Sagittal DTI: **E** ADC map, **F** FA grayscale map, **G** FA color map, **H** 3D tractography. **A**, **B** Sagittal T2WI (**A**) and Sagittal T1WI (**B**) showing straightening of cervical curve with uni-level bulky diffuse osteophytic disc complex bulge more inclined to left side at CV5/6 disc level, encroaching upon the sub arachnoid space narrowing of left neural exit foramen, the condition is augmented with mildly hypertrophied ligamentum flavum with mild 2^{ry} canal stenosis at CV5/6. This disc level is seen indenting the related portion of the cervical cord (2nd degree), with no abnormal cord signal at T2WI and T1WI (Grade I). **C**, **D** axial T2WI at CV5/6 disc level showing bulky diffuse osteophytic disc complex bulge more inclined to left side that is seen indenting the subarachnoid space and compressing the related cord with no abnormal cord signal at T2WI and T1WI (Grade I). **E** Sagittal ADC map showing: ADC value at CV5/6 disc level (represented by arrow) = 1.2×10^{-3} mm^2/s compared to 0.99×10^{-3} mm^2/s at non-compressive site. **F** Sagittal FA grayscale map showing: low FA value at CV5/6 disc level = 0.57 (mild grade) compared to 0.7 at non-compressive site. **G** FA color map showing subtle indention of cord at FA color map with faint green color at site of cord myelopathy (CV5/6). **H** 3D tractography showing homogenous color of the cervical cord and intact fiber tracts (grade I)

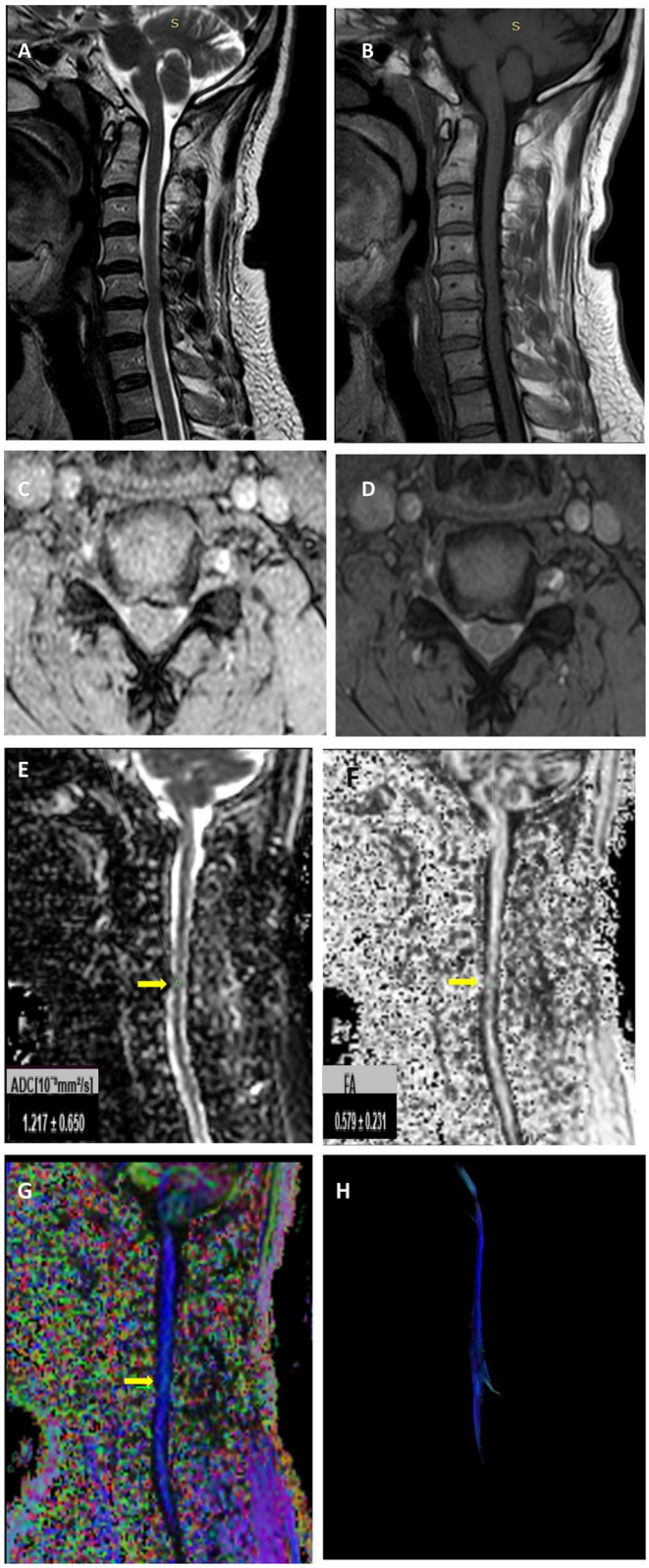


Fig. 3 (See legend on previous page.)

Table 1 Clinician's clinical score of the modified Japanese orthopedic association (mJOA) system

Evaluation description	Point
1. Motor function of upper limbs:	
Inability to move hands	0
Inability to eat with spoon but able to move hands	1
Inability to button shirt but able to eat with spoon	2
Able to button shirt with great difficulty	3
Able to button shirt with slight difficulty	4
No dysfunction	5
2. The lower extremity dysfunction score:	
Complete loss of motor and sensory function	0
Sensory preservation without ability to move legs	1
Able to move legs, but unable to walk	2
Able to walk on flat floor with a walking aid	3
Able to walk up and /or down stairs with hand rail	4
Moderate to significant lack of stability, but able to walk up and/or down without hand rail	5
Mild lack of stability but walks with smooth reciprocation unaided	6
No dysfunction	7
3. Sensory dysfunction score of the upper extremities:	
Complete motor and sensory function loss	0
Severe sensory loss of pain	1
Mild sensory loss	2
No sensory loss	3
4. Sphincter dysfunction score:	
Unable to micturate voluntarily	0
Marked difficulty with micturition	1
Mild to moderate difficulty with micturition	2
Normal micturition	3

It is an 18-point scale that assesses the upper extremities motor function (5 points), lower extremities motor function (7 points), sensation and micturition each (3 points). A total score of 18 indicates that there are no neurological abnormalities, while a score below that suggests a greater level of functional impairment and disability. The severity of myelopathy is graded as *mild* if the score is ≥ 15, *moderate* if the score 12–14 or *severe* if the score is < 12

Table 2 Cord compression degrees

0	No subarachnoid space compression
1	Minimal degree of compression of subarachnoid space
2	Mild compression of spinal cord
3	Severe spinal cord compression or cord atrophy

Images post-processing

Acquired diffusion tensor imaging (DTI) images were transferred to (Philips IntelliSpace Portal V9.0) workstation for post-processing and analysis. Post-processing of DTI images was performed using the Fiber-Track package software (Philips, Best, The Netherlands). DTI metrics were obtained from sagittal images using regions of interest (ROIs) placed at stenotic and non-stenotic segments. The ROI was positioned with attention to prevent partial volume effect from the surrounding structures like CSF, necrosis, hemorrhage, calcification and bone. Sizes of the ROIs drown were similar at stenotic and non-stenotic segments, ranging from 60 to 65 mm^2 independent to difference in cross-sectional area of stenotic and non-stenotic segments of the cord. Several measurements were assessed and then the mean values were analyzed:

- **In uni-level compression**: at site of compression, above the level of compression and below level of compression (above and below as control levels).
- **In multilevel compression**: at site of compression and opposite C2/3 disc level (C2/3 as control level).

Image analysis

Two reviewers (with 10 and 12 years of experience in interpreting neuroradiology MR images) interpreted all the images independently.

Conventional MRI

Conventional MRI was interpreted for full assessment of the degenerative state regarding the following:

MRI findings of CSM:

- Alignment (normal, kyphosis or scoliosis and for spondylolisthesis)
  - *Assessed by* a drawn line from posteroinferior aspect of the C2 vertebral body, to the posteroinferior aspect of the C7 vertebral body, and no portion of the C3-6 vertebral body should cross this line.
  - As for spondylolisthesis which is anterior or posterior displacement of vertebra over the other, it was assessed based on the measurement of the separation between the posterior margins of the normal and abnormal vertebral bodies, which is measured by a drawn line perpendicular to the superior endplate of the vertebrae just below the level of listhesis [8].

- Disc pathology (hydration signal, herniation type, level, direction of herniation)
    - *Type of herniated disc* whether bulge, protrusion, extrusion or sequestration.
    - *Disc level* whether uni or multilevel.
    - *Direction of cord compression* whether mid sagittal, lateral or diffuse.
- Ligamentous pathology (of ligamentous flavum "LF" posteriorly and posterior longitudinal ligament "PLL" anteriorly).
    - *Method for assessment on sagittal T1WI and T2WI,* presence of anterior effacement of CSF and spinal cord compression that is contiguous across multiple levels.
    - Hypertrophy, ossification or calcification of LF and PLL (it is difficult to discriminate between them on MRI)
    - Calcification of ossified PLL continuous (extending beyond one vertebral body), may be segmental, mixed (continuous and segmental), circumscribed-nodular (present behind inter vertebral disc).
- Canal stenosis (bony 1ry or soft tissue 2ry).
    - *Method for assessment* with use of T2WI, the presence of visible CSF anterior and posterior to cervical cord with delineation of the canal borders.
- Cervical cord compression
    - *The method used for assessment* of cord compression in our study was the qualitative sagittal method which is based on appearance.
    - According to this technique, the cord compression is divided to four degrees (Table 2): 2nd and 3rd degrees are those involved in our study.
    - The cervical cord was also assessed for presence or absence of abnormal high-intensity cord signal on T2WI.

If present:

- *Size of cord signal* measured as largest diameter in sagittal T2WI.
- *High T2 signal characteristic* Type I: faint hyperintense, diffuse, its borders not circumscribed. Type II: sharp, strong hyperintense, clear borders based on A. Nouri et al. [9].
- *T2 cord signal grading system* according to Wang et al. [10]:
    - *Grade I*: no abnormal cord signal at T1WI and T2WI
    - *Grade II*: hyperintense T2WI signal but normal signal intensity at T1WI
    - *Grade III*: hyperintense T2WI signal and hypointense T1WI signal.

DTI interpretation

1. *Quantitative maps (DTI metrics)*: multiple measures at stenotic and non-stenotic level obtained and mean value analyzed.

- *Apparent diffusion coefficient (ADC)*: measured as mm^2/s.
- *Fractional anisotropy (FA)*: values ranging from 0 (for isotropic diffusion) to 1 (diffusion anisotropy). Score of FA was measured as:
    - Mild: < 0.7 to ≥ 0.5
    - Moderate: < 0.5 to ≥ 0.3
    - Severe: < 0.3.
- *Other DTI metrics* were measured for cervical myelopathy assessment including radial diffusivity (RD), axial diffusivity (AD) and relative anisotropy (RA).

2. *Qualitative maps*:

- *FA color map*: Interpreted for color abnormalities as the normal color appears as a homogenous blue color, changes of color intensity or mixed colors are considered abnormal.
- *3D tractography*: 3D white matter tracts were generated using the principal diffusion direction method typically using FA threshold value of 0.20 and angle threshold of 30°, sample/voxel length = 1 (machine default settings). By the tool provided by IntelliSpace workstation, multiple ROIs were drowned along visualized cord area and then tractogram tool allows extrac-

tion of tracts. Images of tractography were divided into three grades according to "Wang et al. [10]:

- Grade I: homogenous color and normal tract fibers at site of compression.
- Grade II: abnormal cord signal and distortion of tracts at the site of compression corresponding to T2.
- Grade III: distorted spinal cord with interruption of its fibers at compression site corresponding to T2.

Results

This prospective study included 30 patients: with clinically suspected CSM with a mean age of 51.88 ± 10.28 years. The majority of patients (53.3%) were males and 46.7% were females. The most frequent neurological clinical presentations were neck pain and numbness of upper limb (UL) and/or lower limb (LL) seen in 19 patients accounting for 62%. Patients with CSM had undergone MRI of the cervical spine from craniocervical junction down to C7 vertebral level with the diffusion tensor imaging (DTI) protocol. In uni-level compression, the DTI metrics were measured at the site of compression, also above and below the affected level as control levels as well. In multilevel compression, DTI metrics were measured at site of compression and opposite C2/3 disc level—as control level (Figs. 4, 5, 6, 7).

Diffusion tensor imaging (DTI) data

In this study the DTI metrics were measured at the stenotic and non-stenotic segments, it was found that the mean FA value was significantly lower at stenotic segments (0.52 ± 0.11) versus (0.69 ± 0.17) at non-stenotic segments with significant *P* value = 0.00. And the mean ADC value was significantly higher 1.32 ± 0.49 in the stenotic segments versus 0.86 ± 0.27 in non-stenotic segments with significant *P* value = 0.00 ($P < 0.05$) (Tables 3 and 4). Stenotic segments showed decreases in FA value and increased ADC value.

Correlation test was performed between mJOA grades of severity with FA, ADC and T2 cord signal (Table 5). We found a negative correlation between ADC and FA with Spearman's rho value of −0.612 and "*P* value 0.000" (*P* value < 0.05), a positive correlation between FA with mJOA clinical score with Spearman's rho value of −0.504 and "*P* value 0.036" (*P* value < 0.05) and a negative correlation between ADC and mJOA clinical score with Spearman's rho value of 0.385 and *P* value 0.005 (*P* value < 0.05), and no significant correlation was found between mJOA clinical score and T2 hyperintense signal with Spearman's rho value of −0.304 and "*P* value 0.102" (*P* value < 0.05).

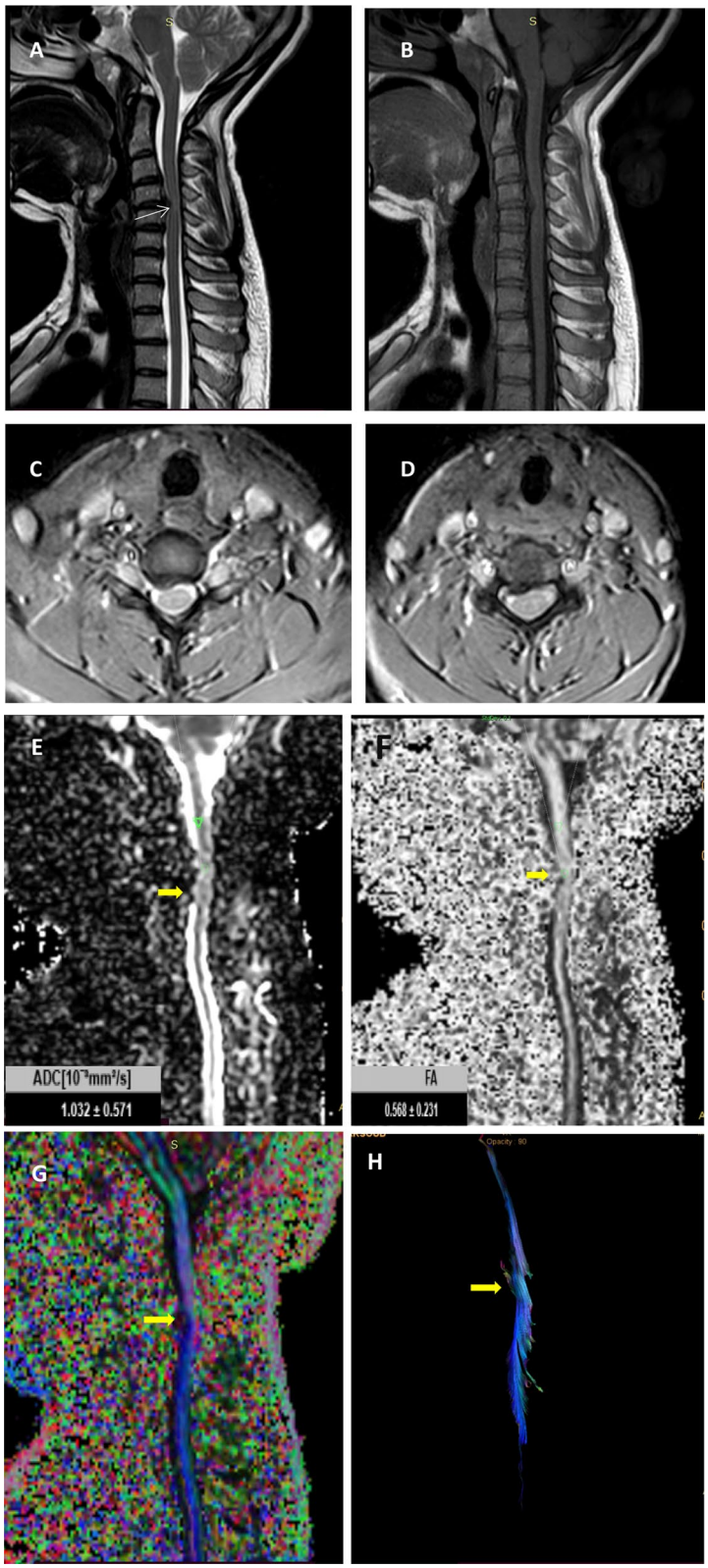
All 14 patients with T2 abnormal cord signal showed abnormal DTI metrics (FA and ADC values); of 16 patients without T2 cord signal, 13 patients showed abnormal FA values (81.25%), while only 9 patients showed abnormal ADC values (56.25%) (Table 6).

Comparison between different severity grading systems by FA and T2 with clinical grading system by mJOA. It was found that grading by FA showed statistical significance ($P = 0.01$), while grading by T2 is not statistically significant *P* value ($P = 0.135$) (Tables 7 and 8).

The overall sensitivity in identifying cervical cord early affection was through DTI metrics abnormalities (FA (83.9%) and ADC (76.8%), rather than with T2WI cord signal (26.8%). The sensitivity, specificity, PPV, NPV and

(See figure on next page.)

Fig. 4 A 37-year-old female patient complaining of neck & shoulder pain with mJOA score = 16 (Mild grade). Conventional MRI: **A** Sagittal T2WI, **B** Sagittal T1WI **C**, **D** Axial T2WI at CV4/5 disc level, Sagittal DTI: **E** ADC map, **F** FA grayscale map **G** FA color map, **H** 3D tractography. **A**, **B** Sagittal T2WI **A** and sagittal T1WI **B** showing straightening of cervical curve with multilevel central and right para central disc protrusion opposite CV3/4 through CV5/6 more notably at CV4/5 encroaching upon sub arachnoid space; the condition is augmented by hypertrophied ligamentum flavum with 2^{ry} canal stenosis more at CV4/5 level. This disc level is seen severely compressing the related portion of the cervical cord (3rd degree), with type I T2 hyperintense cord signal (white arrow) measuring about 7 mm in size, no abnormal cord signal at T1WI (compressive cord myelopathy grade II). **C**, **D** Axial T2WI at CV4/5 disc level showing central and right para central disc protrusion seen indenting the subarachnoid space and compressing the related cord with T2 hyperintense signal (Grade II). **E** Sagittal ADC map showing high ADC value at site of cord myelopathy CV4/5 (represented by arrow) = 1.02×10^{-3} mm^2/s compared to 0.94×10^{-3} mm^2/s at non-compressive site. **F** Sagittal FA grayscale map showing low FA value at site of cord myelopathy (CV4/5) 0.56 (mild FA grade) compared to 0.8 at non-compressive site. **G** Sagittal FA color map showing indention of cord at FA color map with abnormal faint green color at site of cord myelopathy (CV4/5). **H** 3D tractography showing mixed color intensity at site of cord myelopathy (grade II)



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total diagnostic accuracy of FA, ADC and T2 hyperintense signal were described in (Table 9).

Qualitative maps

Qualitative maps grading by 3D tractography images was done, and we found that 18 patients (60%) showed homogenous intact fiber tracts (grade I), 9 patients (30%) showed reduction or alteration of anisotropy or mixed colors intensity (grade II), and 3 patients (10%) showed fiber tract disruption or displaced cord (grade III) (Table 10).

Other DTI metrics including relative anisotropy (RA), axial diffusivity (AD) and radial diffusivity (RD) were measured at stenotic and non-stenotic segments.

It was found that mean RA value at stenotic segments was 0.51 ± 0.08 compared with 0.77 ± 0.33 at non-stenotic segments. The mean AD value at stenotic segments was 1.94 ± 0.35 compared with 1.80 ± 0.47 at non-stenotic segments, and the mean RD at stenotic segments was 0.73 ± 0.24 when compared with 0.48 ± 0.21 at non-stenotic segments. At the stenotic segments, the RA value was significantly lower than non-stenotic with P value significant = 0.00 ($P < 0.05$), the AD value was higher than non-stenotic with P value non-significant = 0.338 ($P > 0.05$), and the RD value was significantly higher than non-stenotic with P value significant = 0.00 ($P < 0.05$) (Tables 11, 12, 13).

Inter-rater reliability

The percent agreement was excellent between readers of DTI images; the inter-reader reliability was calculated at 96% and 95% for measurement of DTI parameter (FA and ADC values) and for assessment of T2 hyperintense cord signal, respectively (Table 14).

Discussion

Cervical spondylosis has a wide range of changes to the spinal cord, myelopathy is one of them. Before the advent of diffusion tensor imaging (DTI), T2WI was the sole way to detect intrinsic cord abnormalities but it has a minimal role in assessing the cord microstructure changes. So, the advent of new techniques like DTI was necessary [5].

In this prospective study that included 30 patients, conventional MRI examination was performed for assessment of cervical spondylotic myelopathy (CSM) through evaluation of the cervical discs, ligamentous pathology, spinal canal stenosis and cervical cord. Image processing with DTI technique was done, where ROI areas were drawn on the spinal cord of the cervical spine in different levels (affected and non-affected) with generation of DTI parametric. This technique was based on Hassan et al. study [11].

The aim of this study was to determine the diagnostic value of quantitative and qualitative diffusion tensor imaging (DTI) indices in early assessment of cervical spondylotic myelopathy with subsequently early and proper management decision rendering better clinical outcome.

Each patient is considered as self-control, to avoid CSF partial volume effect, and due to relative stability of the upper cervical region and lack of disc lesion at this site, we obtained a normal metrics value for each patient at CV2/CV3 level to be used as internal reference especially in multilevel compression to reduce metrics variability of different ages and sex according to Hassan et al. [12] and Berberat et al. [13]. In the case of uni-level compression, we measured two controls one above and one below and considered the mean value of the two measurements. This method was used by Khedr and Settein [14] in their

(See figure on next page.)

Fig. 5 A 65-year-old female patient complaining of severe neck pain with motor disability with mJOA score = 12 (Moderate grade). Conventional MRI: **A** Sagittal T2WI, **B** Sagittal T1WI **C** Axial T2WI at CV3/4 level **D** Axial T2WI at CV4/5 level, Sagittal DTI: **E** ADC map **F** FA map **G** FA color map **H** 3D tractography **A**, **B** Sagittal T2WI (**A**) and Sagittal T1WI (**B**) showing multilevel disc bulge at CV3/4 through CV5/6 disc levels were CV3/4 shows bulky diffuse disc bulge, CV4/5 diffuse disc bulge with centrally protruded component and CV5/6 diffuse disc bulge, encroaching upon the sub arachnoid space with narrowing of both neural exit foramen the condition is augmented by hypertrophied PLL with 2^{ry} canal stenosis. Those disc levels seen mildly compressing the related portion of the cervical cord (2nd degree), with no abnormal cord signal at T2WI & T1WI (Grade I). **C**, **D** axial T2WI at CV3/4 (**C**) showing bulky diffuse disc bulge and at CV4/5 level (**D**) showing diffuse disc bulge those disc levels indenting the subarachnoid space and compressing the related cord with no abnormal cord signal at T2WI and T1WI (Grade I). **E** Sagittal ADC map showing: high ADC value at CV4/5 disc level (represented by arrow) = 1.6×10^{-3} mm^2/s compared to 0.6×10^{-3} mm^2/s at non-stenotic segments. **F** Sagittal FA grayscale map showing: low FA value at CV4/5 disc level = 0.47 (moderate grade) compared to 0.7 at non-stenotic segments. **G** FA color map showing indention of cord at FA color map with abnormal faint green color at CV4/5 level. **H** 3D tractography showing homogenous color and intact fiber tracts (grade I)

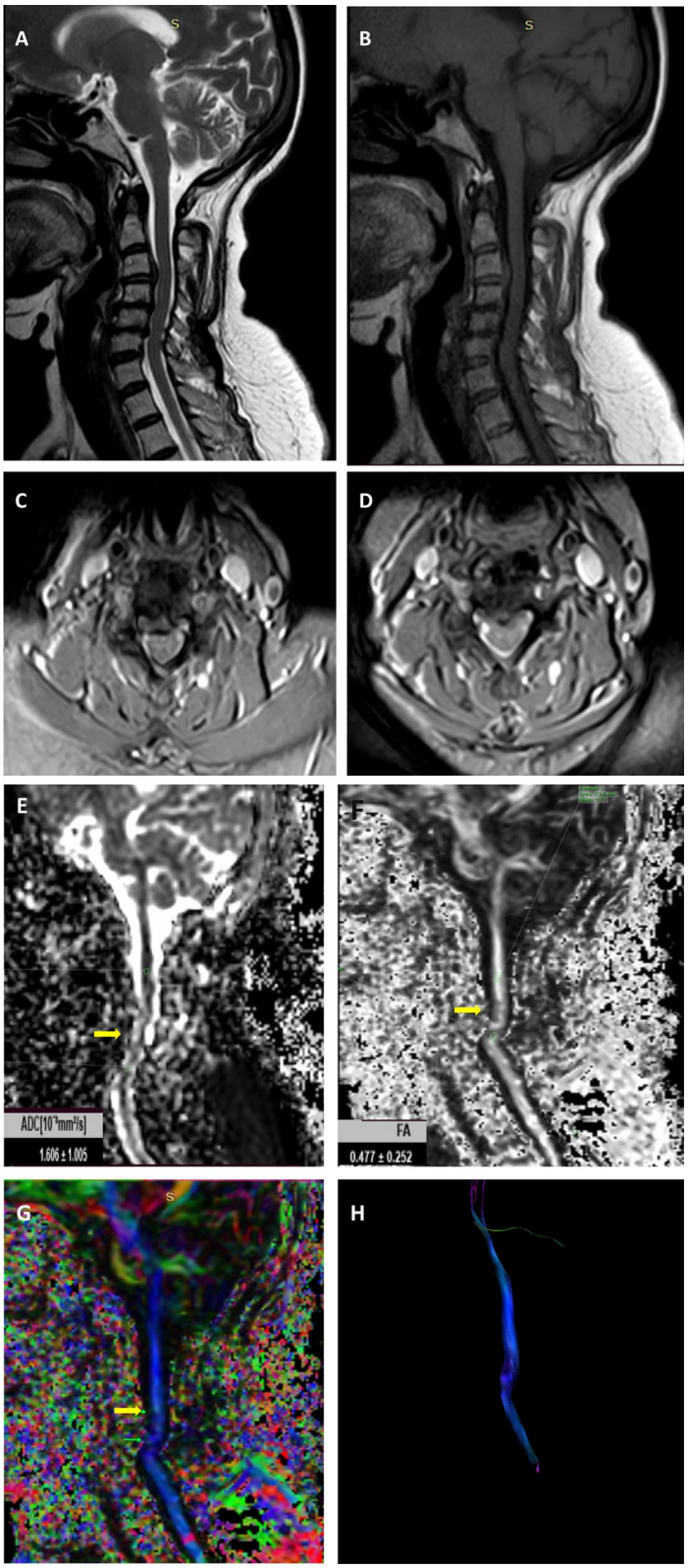

Fig. 5 (See legend on previous page.)

study, where he considered all cases as self-control by using two measurements, above and below the stenotic level.

The current study inferred that the mean FA value of stenotic segments was (0.52 ± 0.11) which was significantly lower than the mean FA value (0.69 ± 0.17) in non-stenotic segments. Regarding the ADC value at the stenotic segment, it was significantly increased, with a mean value of (1.32 ± 0.49) as compared to (0.86 ± 0.27) at non-stenotic segments. Similar results have been reported by Nischal et al. [15] in their study who detected significantly lower mean FA (0.5009 ± 0.087) in the stenotic segments compared with non-stenotic segments (0.6557 ± 0.104) and the significantly higher mean ADC value (1.1965 ± 0.311) compared with non-stenotic segments (0.9370 ± 0.284).

The optimum myelopathy onset cutoff values have been proposed for FA and ADC in our study according to the ROC curve derived from the total FA and ADC values at different cervical levels, The proposed cutoff for the FA value was lower than 0.6, and the ADC value was higher than 0.89×10^{-3} mm^2/s at CV4/5 level, most affected level (35.71%) in our study. This finding was harmonious with Nischal et al. study [15] where the cutoff for the FA value was low (0.46), and the ADC value was high (1.29) at C5/6 level, the most affected level in his study. The proposed cutoff values may act as a valuable tool to indicate myelopathy onset in conjunction with clinical scores to determine the need for operative interference.

Of interest was that in the current study, the relationship between DTI measurements and mJOA (modified Japanese orthopedic association) scores were assessed to determine whether FA or ADC were valuable predictors of disease severity or not. Modified Japanese orthopedic association (mJOA) is a worldwide used score to classify the severity of CSM as three grades mild, moderate and severe grades, with a score ranging from 1 to 18. On correlation of FA, ADC and T2 hyperintense cord signal with the mJOA, it was found that there is a positive correlation between FA and mJOA score with significant *P* value of 0.036 that coincided with the study conducted by Liu et al. [16] who also reported that FA value showed a positive linear correlation with mJOA score.

The ADC value at stenotic segments showed a negative correlation with mJOA clinical scoring as well as with FA values, with significant *P* value of (0.005) and (0.000), respectively; this was in agreement with Nischal et al. [15] who found a strong negative correlation between the mean ADC value and mJOA score as well as FA values at stenotic segments.

Something to be considered is that in the current study, there was no significant correlation between mJOA score and T2 hyperintense cord signal at the stenotic level. This result was in concordance with the study conducted by Budzik et al. [17] who reported that in their study, where the high signal intensity of the spinal cord probably represents a broad spectrum of cord lesions from reversible lesions (edema) to more severe lesions (demyelination or cavitation), so it's not correlated with disease severity.

We evaluated the accuracy of DTI metrics (FA and ADC) in cervical cord myelopathy quantitative assessment and compared it with that of T2 hyperintense signal and found that FA sensitivity was (83.9%) and ADC was (76.8%) which was significantly higher than the sensitivity of T2 hyperintense signal (26.8%). This was approved by the previous study of Kara et al. [4] who reported that FA sensitivity was higher (87.5%) when compared with ADC (75%).

(See figure on next page.)

Fig. 6 A 42-year-old female patient complaining of neck pain & motor disability with mJOA score = 14 (Moderate grade). Conventional MRI: **A** Sagittal T2WI and **B** Sagittal T1WI **C** Axial T2WI at CV4/5 level **D** Axial T2WI at CV5/6 level, Sagittal DTI: **E** ADC map, **F** FA grayscale map **G** FA color map and **H** 3D tractography. **A**, **B** sagittal T2WI (**A**) and sagittal T1WI (**B**) showing straightening of cervical curve with multilevel bulky diffuse osteophytic disc complex bulge at CV4/5 through CV6/7 disc levels with central protruded component at those levels, encroaching upon the related portion of the sub arachnoid space with narrowing of both neural exit foramen; the condition is augmented by hypertrophied PLL with 2ry canal stenosis. Those disc levels are seen indenting the related portion of the cervical cord (2nd degree), more at CV4/5 with type II T2 hyperintense cord signal (white arrow) measuring about 11.5 mm in size, no abnormal cord signal at T1WI (compressive cord myelopathy grade II). **C**, **D** Axial T2WI at CV4/5 (**C**) and at CV5/6 (**D**) showing bulky diffuse osteophytic disc complex bulge with central disc protrusion at those disc levels encroaching upon the subarachnoid space and indenting the related portion of the cord with abnormal high T2 cord at CV4/5 level (Grade II). **E** Sagittal ADC map showing a higher ADC value at site of cord myelopathy CV4/5 (represented by arrow) = 1.16×10^{-3} mm^2/s compared to 1×10^{-3} mm^2/s at non-compressive site. **F** Sagittal FA grayscale map showing a lower FA value at site of cord myelopathy (CV4/5) 0.52 (mild FA grade) compared to 0.74 at non-compressive site. **G** FA color map showing subtle indention of cord at CV4/5 disc level with faint green color intensity. **H** 3D tractography showing mixed color intensities at site of cord myelopathy (grade II)

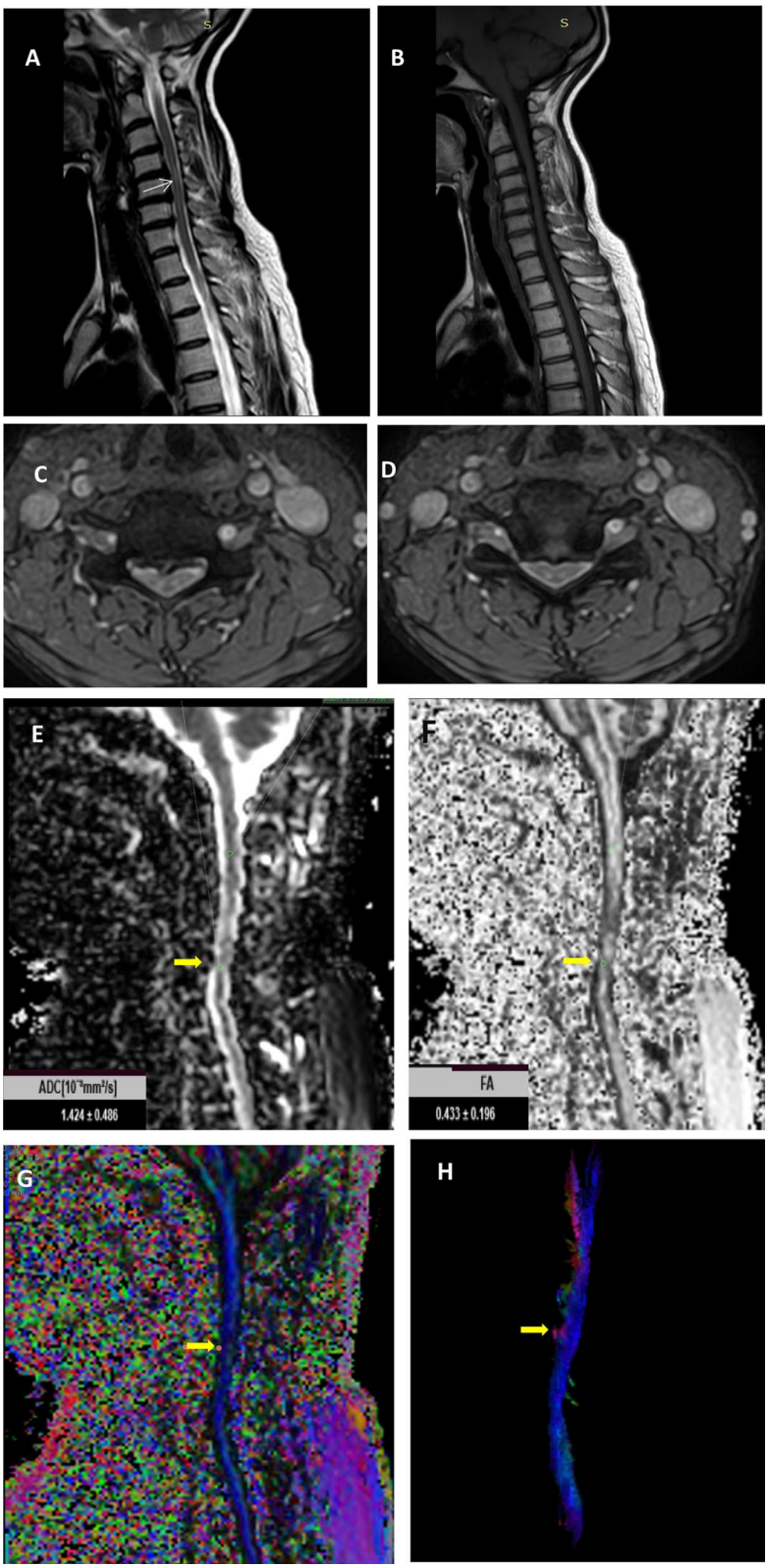

Fig. 6 (See legend on previous page.)

Considering that management outcomes differ for patients with mild, moderate and severe neurological impairment, it is essential to distinguish between them [12]. It's worth mentioning that this study confers a clear evidence that FA grading is such a sensitive tool in grading CSM severity preceding the sensitivity of T2 grading, allowing for depiction of early stage myelopathy even before appearance of T2 cord signal and thus early surgical interference and better clinical outcome with discrimination between mild, moderate and severe degrees. That was in proximity to the study conducted by Nischal et al. [15] who stated that the FA grading is more sensitive than T2 grading. This evidence will give the fundamental core in the management plan, where the FA grade along with the clinical assessment by mJOA will formulate the management plan decision whether surgical or not. In addition, this will render better clinical outcome for the early diagnosed myelopathy management.

Interestingly, the specificity of FA in the current study was (84.4%), and that of ADC was (92.4%), while that of T2 hyperintense signal was the most specific (4.1%). That was incommensurate to the study conducted by Facon et al. [18] who reported that the FA parameters show higher sensitivity and specificity among the various DTI parameters for early detection of spinal cord subtle abnormalities.

The positive predictive values (PPV) for FA, ADC and T2 hyperintense signal were (82.5%), (97.7%) and (45.4%), respectively, and the negative predictive values (NPV) for FA, ADC and T2 hyperintense signal were (85.7%), (82.9%) and (61%), respectively, with total diagnostic accuracy of (84.2%) for FA, (87.4%) for ADC and (45.2%) for T2 hyperintense signal. The superiority of the FA value over the other DTI parameters and the T2 hyperintense cord signal was also reported by Nischal et al. [15] in their study which favors the diagnostic propriety of DTI over the conventional MRI and proving that DTI can be used as early diagnostic tool in CSM before T2 hyperintense signal appear.

That was in rapprochement to the previous study conducted by Vedantam et al. [19] who carried out one of the earliest studies on the application of DTI in CSM with thirty-six patients with spondylosis and discovered that areas of myelopathy had increased ADC values and decreased FA with sensitivity of 78% compared with 57% at T2WI. Likewise, the study conducted by Hassan et al. [12] proposed that the lower sensitivity of T2 signal change (26.8%) may be due to immediate presentation of patients after developing the clinical neurological symptoms before changes in cervical cord became apparent and may be due to varying degree of tolerance of spinal cord to compression making the T2 hyperintense signal appear.

We assessed grading by diffusion tensor tractography (DTT) images and found that majority of patients, 18 patients (60%) had homogenous intact fiber (grade I), 9 patients (30%) showed focal mixed colors intensity (grade II) and 3 patients (10%) showed fiber tract disruption (grade III). This was in agreement with Omar et al. [20] who assessed the diffusion tensor tractography (DTT) grading in all causes of myelopathy and found that 16 patients (32%) had grade I, 14 patients (24%) had grade II, and 20 patients (40%) had grade III.

It's worth mentioning that this is the first study to measure other DTI metrics—relative anisotropy (RA), axial diffusivity (AD) and radial diffusivity (RD)—at stenotic and non-stenotic segments and two of them show significant difference between their measures in the stenotic and non-stenotic portions of the spinal cord with RA (P value = 0.00) and RD (P value = 0.00).

Limitations in our study include that it needed to be applied on larger cohort of patients, with follow-up in terms of the diffusion tensor imaging (DTI) values and postoperative evaluation of DTI parameters.

(See figure on next page.)

Fig. 7 A 65-year-old male patient complaining of neck pain with mJOA score = 13 (Moderate grade). **A** Conventional MRI: Sagittal T2WI, **B** Sagittal T1WI **C** Axial T2WI at CV4/5 level **D** Axial T2WI at CV5/6 level, Sagittal DTI: **E** ADC map, **F** FA grayscale map **G** FA color map, **H** 3D tractography. **A**, **B** Sagittal T2WI **A** and sagittal T1WI **B** showing multilevel bulky diffuse osteophytic disc complex bulge at CV3/4 through CV6/7 more opposite CV4/5 disc level encroaching upon the sub arachnoid space with narrowing of both neural exit foramen the condition is augmented by hypertrophied ligamentum flavum with 2ry canal stenosis. Those disc levels are seen severely compressing the related portion of the cervical cord (3rd degree) more notably at CV4/5 were corresponding type I T2 hyperintense cord signal (white arrow) measuring about 8.5 mm in size, no abnormal cord signal at T1WI (compressive cord myelopathy grade II). **C**, **D** axial T2WI at CV4/5 (**C**) and at CV5/6 (**D**) Showing bulky diffuse osteophytic disc complex bulge with central disc protrusion of those disc levels indenting the subarachnoid space and compressing the related cord with abnormal high T2 cord opposite CV4/5 level (Grade II). **E** Sagittal ADC map showing high ADC value at site of cord myelopathy CV4/5 (represented by arrow) = 1.22×10^{-3} mm^2/s compared to 0.82×10^{-3} mm^2/s at non-compressive site. **F** Sagittal FA grayscale map showing low FA value at site of cord myelopathy (CV4/5) 0.48 (moderate FA) compared to 0.67 at non-compressive site. **G** FA color map showing indention of cord at FA color map with faint green color at site of cord myelopathy (CV4/5). **H** 3D tractography showing homogenous color of the cervical cord and intact fiber tracts (grade I)

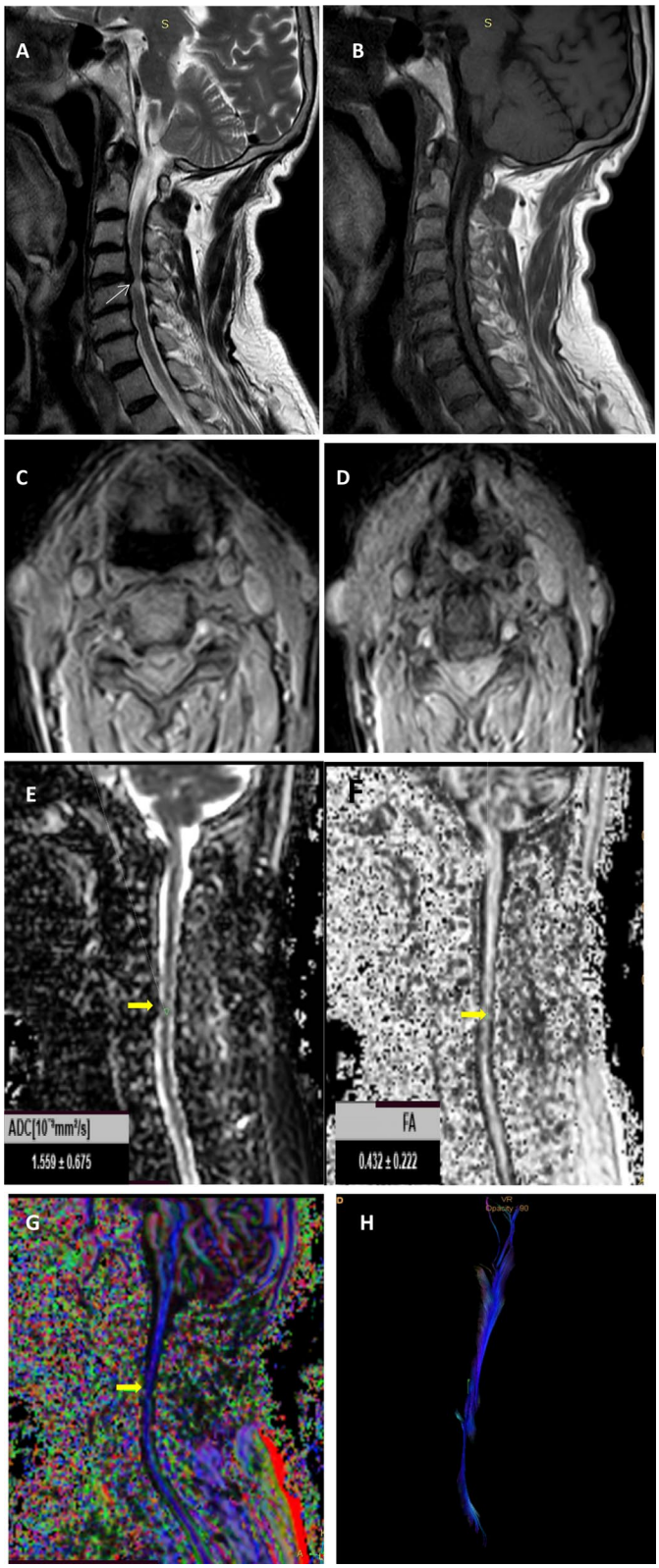

Fig. 7 (See legend on previous page.)

Table 3 Comparison between mean FA values at stenotic and non-stenotic segments in the studied group (No. = 30)

Variables	Mean	± SD	*P* value
Stenotic (FA)	0.52	0.11	0.000
Non-stenotic (FA)	0.69	0.17	

Table 4 Comparison between mean ADC values at stenotic and non-stenotic segments in the studied group (No. = 30)

Variables	Mean	± SD	*P* value
Stenotic (ADC)	1.32	0.49	0.000
Non-stenotic (ADC)	0.86	0.27	

Table 5 Correlation tests between mJOA scoring system, FA, ADC values and T2 hyperintense signal in the studied group (No. = 30)

	mJOA clinical scoring	
	Sp. Rho value	*P* value
Stenotic (FA)	0.504	0.036
Stenotic (ADC)	− 0.385	0.005
T2 hyperintense cord signal	− 0.304	0.102

Table 6 Comparison of FA and ADC in patients with and without high T2 cord signal abnormality in the studied group (No. = 30)

Variables	Presence of T2 cord signal (No. = 14)	Absence of T2 cord signal (No. = 16)	Total (No. = 30)
FA			
Positive	14 (100%)	13(81.25%)	27 (90%)
Negative	0 (0%)	3(18.7%)	3(10%)
ADC			
Positive	14 (100%)	9 (56.25%)	23(76.67%)
Negative	0 (0%)	7 (43.75%)	7(23.34%)

Table 7 Comparison between FA grading and mJOA grading using Chi-square test in the studied group (No. = 30)

mJOA grading	FA grading			*P* value
	Mild (No. = 15)	Moderate (No. = 15)	Total (No. = 30)	
Mild	12	5	17	0.01
	80%	33.3%	56.7%	
Moderate	3	10	13	
	20%	66.7%	43.3%	

Table 8 Comparison between T2 severity grading and mJOA grading using Chi-square test in the studied group (No. = 30)

mJOA grading	T2 severity grading			*P* value
	Grade I (No. = 16)	Grade II (No. = 14)	Total (No. = 30)	
Mild	11	6	17	0.135
	68.8%	42.9%	56.7%	
Moderate	5	8	13	
	31.3%	57.1%	43.3%	

Table 9 Comparison between sensitivity, specificity, PPV and NPV of FA, ADC and T2 hyperintense signal in the studied group (No. = 30)

Variable	FA	ADC	T2 hyperintense signal
Sensitivity	83.9	76.8	26.8
Specificity	84.4	92.4	94.1
PPV	82.5	97.7	45.1
NPV	85.7	82.9	61
Accuracy	84.2	87.4	45.2

Table 10 Frequencies of patients with different tractography grades in the studied group (No. = 30)

Variables	Grade I	Grade II	Grade III
No	18	9	3
Percent %	60%	30%	10%
Total	30		

Table 11 Comparison between RA values at stenotic and non-stenotic segments in the studied group (No. = 30)

Variables	Mean	± SD	*P* value
Stenotic (RA)	0.51	0.08	0.00
Non-stenotic (RA)	0.77	0.33	

Table 12 Comparison between AD values at stenotic and non-stenotic segments in the studied group (No. = 30)

Variables	Mean	± SD	*P* value
Stenotic (AD)	1.94	0.35	0.338
Non-stenotic (AD)	1.80	0.47	

Table 13 Comparison between RD values at stenotic and non-stenotic segments in the studied group (No. = 30)

Variables	Mean	± SD	*P* value
Stenotic (RD)	0.73	0.24	0.00
Non-stenotic (RD)	0.48	0.21	

Table 14 Interobserver reliability

	Agreement (%)	Kappa (95% CI)	*P* value
FA and ADC values	96	0.12–0.97	0.0001
T2 cord signal grade	95	0.89–0.97	0.0001

Our recommendations in future are application of the study on larger cohort of patients, with evaluation of other pathological conditions of the cord by different diffusion tensor imaging (DTI) parametrics to see their significance.

Conclusions

DTI (diffusion tensor imaging) is a crucial tool for early diagnosis and grading of CSM (cervical spondylosis myelopathy)—quantitatively and qualitatively. Hence, its integration into the routine cervical spine MR protocol is recommended, as the FA parameter together with the clinical assessment formulates the management plan decision for the CSM whether surgical or non-surgical and depicts the need for early surgical decision rendering better clinical outcome compared to that based on T2 hyperintense cord signal.

A prospective study for determining the capability of diffusion tensor imaging in early diagnosis of cervical spondylosis for early surgical decision is needed.

Abbreviations

CSM	Cervical spondylotic myelopathy
DTI	Diffusion tensor imaging
DTT	Diffusion tensor tractography
mJOA	Modified Japanese orthopedic association system
FA	Fractional anisotropy
ADC	Apparent diffusion coefficient
ROC	Receiver operating characteristic curve
PPV	Positive predictive value
NPV	Negative predictive value
RD	Radial diffusivity
RA	Relative anisotropy
AD	Axial diffusivity

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Author contributions

SMR and EAG carried out the manuscript preparation and editing, study concepts as well as the experimental studies and data analysis, design and literature research. AS and SG are the guarantors of integrity of the entire study and carried out the statistical analysis. MMN was responsible for the clinical studies and also shared in the statistical analysis. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and analyzed during the study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

This study was approved by the Research Ethics Committee (REC) under number 305 in 2018, Faculty of Dentistry, Minia University. Written and informed consent was obtained for all participants.

Consent for publication

All patients included in this research gave written informed consent to publish the data contained within this study according to our institution rules for ethics committee.

Competing interests

The authors declare that there is no conflict of interest.

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References

1. Dong F, Wu Y, Song P et al (2018) A preliminary study of 3.0-T magnetic resonance diffusion tensor imaging in cervical Spondylotic myelopathy. Eur Spine J 27:1839–1845
2. Kleinberg E (2010) Cervical spondylotic myelopathy. A review of the evidence. Orthopedic Clin 41(2):193–202
3. Bakhsheshian J, Mehta VA, Liu JC (2017) Current diagnosis and management of cervical Spondylotic myelopathy. Global Spine J 7(6):572–586
4. Kara B, Celik A, Karadereler S (2011) The role of DTI in early detection of cervical Spondylotic myelopathy. A preliminary study with 3-T MRI. Neuroradiology 8:609–616
5. Lee JB, Kim IS, Kwon JY et al (2019) Difference of dynamic morphometric changes between in patients with ossification of posterior longitudinal ligament and patients with cervical spondylosis. Assessment by cervical dynamic magnetic resonance imaging. World Neurosurg 123:566–573
6. Ozanne A, Kring T, Facon D et al (2007) MR diffusion tensor imaging and fiber tracking in spinal cord arteriovenous malformations: a preliminary study. AJNR 28(7):1271–1279
7. Farshad NA, Farshad M, Winklehner A et al (2015) MR imaging of degenerative disc disease. Eur J Radiol 84(9):1768–1776
8. Fehlings MG, Tetreault LA, Riew KD et al (2017) A clinical practice guideline for the management of patients with degenerative cervical myelopathy: recommendations for patients with mild, moderate, and severe disease and non-myelopathic patients with evidence of cord compression. Global Spine J 7(3_suppl):70S-83S
9. Nouri A, Martin AR, Mikulis D et al (2016) Magnetic resonance imaging assessment of degenerative cervical myelopathy. A review of structural changes and measurement techniques. Neurosurg Focus 40(6):E5

10. Wang K, Chen Z, Zhang F et al (2017) Evaluation of DTI parameter ratios and diffusion tensor tractography grading in the diagnosis and prognosis prediction of cervical spondylotic myelopathy. Spine 42(4):E202–E210
11. Hassan HG, Maarouf RA, Abo-Elela MA et al (2020) The role of diffusion tensor imaging (DTI) in spinal cord pathology. Ain Shams Med J 71(1):197–205
12. Hassan TA, Assad RE, Belal SA (2019) MR diffusion tensor imaging of the spinal cord. Can it help in early detection of cervical Spondylotic myelopathy and assessment of its severity? Egypt J Radiol Nuclear Med 50:1–9
13. Berberat J, Andereggen L, Gruber P et al (2023) A Diagnostic biomarker for cervical myelopathy based on dynamic MRI. Spine 48(15):1041–1046
14. Khedr DK, Settein M (2019) Effectiveness of diffusion tensor imaging in evaluation of spinal cord compression. In: European congress of radiology-ECR. 10.26044:C-2660
15. Nischal N, Tripathi S, Singh JP (2021) Quantitative evaluation of the diffusion tensor imaging matrix parameters and the subsequent correlation with the clinical assessment of disease severity in cervical spondylotic myelopathy. Asian Spine J 15(6):808–816
16. Liu Y, Kong C, Cui L et al (2017) Correlation between diffusion tensor imaging parameters and clinical assessments in patients with cervical spondylotic myelopathy with and without high signal intensity. Spinal Cord 55(12):1079–1083
17. Budzik JF, Balbi V, Le Thuc V et al (2011) Diffusion tensor imaging and fiber tracking in cervical Spondylotic myelopathy. Eur Radiol 21:426–433
18. Facon D, Ozanne A, Fillard P et al (2005) MR diffusion tensor imaging and fiber tracking in spinal cord compression. AJNR 26(6):1587–1594
19. Vedantam A, Rao A, Kurpad SN et al (2017) Diffusion tensor imaging correlates with short-term myelopathy outcome in patients with cervical Spondylotic myelopathy. World Neurosurg 97:489–494
20. Omar MK, Abd Allah AE et al (2021) The value of quantitative diffusion tensor imaging indices of spinal cord disorders. Egypt J Radiol Nuclear Med 52(1):1–9

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