



Review Article

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Cervical Spondylotic Myelopathy: Natural Course and the Value of Diagnostic Techniques –WFNS Spine Committee Recommendations

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Objective: This study presents the results of a systematic literature review conducted to determine most up-to-date information on the natural outcome of cervical spondylotic myelopathy (CSM) and the most reliable diagnostic techniques.

Methods: A literature search was performed for articles published during the last 10 years.

Results: The natural course of patients with cervical stenosis and signs of myelopathy is quite variable. In patients with no symptoms, but significant stenosis, the risk of developing myelopathy with cervical stenosis is approximately 3% per year. Myelopathic signs are useful for the clinical diagnosis of CSM. However, they are not highly sensitive and may be absent in approximately one-fifth of patients with myelopathy. The electrophysiological tests to be used in CSM patients are motor evoked potential (MEP), spinal cord evoked potential, somatosensory evoked potential, and electromyography (EMG). The differential diagnosis of CSM from other neurological conditions can be accomplished by those tests. MEP and EMG monitoring are useful to reduce C5 root palsy during CSM surgery. Notable spinal cord T2 hyperintensity on cervical magnetic resonance imaging (MRI) is correlated with a worse outcome, whereas lighter signal changes may predict better outcomes. T1 hypointensity should be considered a sign of more advanced disease.

Conclusion: The natural course of CSM is quite variable. Signal changes on MRI and some electrophysiological tests are valuable adjuncts to diagnosis.

Keywords: Cervical spondylotic myelopathy, Electrophysiology, Myelopathic signs, MR signal intensity, Intraoperative monitoring, Magnetic resonance imaging



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INTRODUCTION

Cervical spondylotic myelopathy (CSM) is the most common cause of spinal cord dysfunction. It is the result of static or dynamic repeated compression of the spinal cord. This review

paper will present current knowledge on its natural course and the value of diagnostic techniques. This study is a summary of the consensus meeting of the World Federation of Neurosurgical Societies Spine Committee.

CLINICAL PRESENTATION OF CSM

The diagnosis of CSM is based on specific symptoms, physical signs, and imaging findings. Clinical symptoms of CSM are summarized in Table 1.¹ Neck pain, arm pain, limited motion of neck, diminished function of hands (clumsiness or difficulty with buttoning buttons, using keys, or changes in hand writing), wasting of the intrinsic muscles, spasticity, walking difficulty which can be tested by “heel-to-toe tandem walking,” “heel-walking,” or “toe-walking.”

Myelopathic signs can be defined as hyperreflexia (grade 3 or 4) or provocative signs (clonus [> 3 beats], Babinski's sign, Hoffmann sign, inverted brachioradialis reflex).²

Gibson et al.³ have examined the prevalence of myelopathic signs in cervical myelopathy. They have compared CSM patients with control group for sensitivity and specificity of those clinical finding. Hoffman's sign had 59% sensitivity and 84% specificity. Inverted brachioradialis reflex had 51% sensitivity and 81% specificity. Babinski sign and clonus had 13% sensitivity and 100% specificity. Hyperreflexia had 72% sensitivity and 43% specificity.

Although the physical signs on neurologic examination are well known, the symptoms are vague. The myelopathy signs (Hoffman's sign, hyperreflexia, inverted brachioradialis reflex, Babinski, and clonus) are important for the diagnosis.² However, it has been reported that these signs are absent in 21% of cervical myelopathy patients.⁴

An adequate decompression is expected to revert these myelopathy signs to normal. Acharya et al.² have examined those signs in severe CSM cases (mean Nurick score ≥ 3). They have found that 38% of patients have still one sign at the end of 1 year.

Table 1. Typical clinical symptoms and signs observed in cervical spondylotic myelopathy patients

Symptoms	Signs
Weakness	Myelopathic signs
Impairment of gait	Hyperreflexia
Numbness of hands	Inverted brachioradialis reflex
Spasticity	Hoffmann's sign
Incontinence	Ankle clonus
Paresthesias	Babinski sign
Neck pain	Motor deficits
Arm pain	Romberg sign
	Lhermitte's sign
	Thenar atrophy

The most resolved sign was inverted brachioradialis reflex, Babinski, and clonus with only 5% had positive signs. Hoffman did not resolve much, 38% of the patients still had a positive test at the end of 1 year. Although triceps and biceps changed to normal in all patients, patella reflex (10%) and Achilles (14%) were still hyperactive. The maximum recovery was seen in the first 6 months after surgery. After 6 months, a plateau was seen.²

1. Scores Defining the Severity of the Disease

There are multiple classifications and measurements of disease severity. The Nurick classification system for myelopathy⁵ is the oldest classification first proposed in 1972 (Table 2).

Japanese Orthopaedic Association (JOA) scale for CSM was introduced by Hukuda et al.⁶ in 1985. It consists of a total of 17 points. In 1991, Benzel et al.⁷ have modified Japanese Orthopaedic Association Scoring System (mJOA) and this scoring system has been the most widely used system (Table 3). It has total of 20 points.

Since the Nurick grade and mJOA scores assess different modes of functionality, in 11.8% of patients there was disagreement. The correlation of Nurick grade mJOA was best in patients with moderate myelopathy than in those with mild or severe ones.

In conclusions, we should continue to incorporate both Nurick scale and mJOA score in evaluation of patients with CSM till there is a more comprehensive scoring system that shows all aspects of function in a patient.⁸

A study by Tetreault et al.⁹ has reviewed 91 articles commenting on the predictive value of clinical factors (16 excellent, 38 good, 37 poor papers). Most important outcome predictors were preoperative severity and duration of symptoms. This review also reported many other valuable predictors including signs, symptoms, comorbidities and smoking status.

Table 2. Nurick grades for myelopathy (1972)²³

Grade	Signs and symptoms
0	Signs or symptoms of root involvement but without evidence of spinal cord disease
1	Signs of spinal cord disease but no difficulty in walking
2	Slight difficulty in walking which did not prevent full-time employment
3	Difficulty in walking which prevented full-time employment or the ability to do all housework, but which was not so severe as to require someone else's help to walk
4	Able to walk only with someone else's help or with the aid of a frame
5	Chair bound or bedridden

Table 3. Modified Japanese Orthopaedic Association scoring system

Criterion	Content	Point	
Motor	Upper extremities	Unable to move hands	0
		Unable to eat with a spoon but able to move hands	1
		Unable to button shirt but able to eat with a spoon	2
		Able to button shirt with great difficulty	3
		Able to button shirt with slight difficulty	4
		No dysfunction	5
	Lower extremities	Complete loss of motor & 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 (cane or crutch)	3
		Able to walk up- &/or downstairs w/aid of a handrail	4
		Moderate-to-significant lack of stability but able to walk up- &/or downstairs without handrail	5
		Mild lack of stability but able to walk unaided with smooth reciprocation	6
		No dysfunction	7
Sensory	Upper extremities	Complete loss of hand sensation	0
		Severe sensory loss or pain	1
		Mild sensory loss	2
		No sensory loss	3
Sphincter dysfunction	Unable to micturate voluntarily	0	
	Marked difficulty in micturition	1	
	Mild-to-moderate difficulty in micturition	2	
	Normal micturition	3	
Total		18	

NATURAL COURSE OF CSM

Natural course of the CSM is still not well known. There are mainly 3 symptom complexes: Neck pain, radiculopathy, myelopathy. A combination of those are very common, and it is not clear if we should call the disease CSM in case there is no myelopathy. Patients usually experience long and constant periods of disease with a series of new episodes during which they experience new symptoms and signs.¹ A steady progression of symptoms is not common. Instead, myelopathic disease has silent periods of time with intermittent periods of rapid decline in neurological function.¹⁰

Natural history of CSM can be reported on different stages of the disease:

1. Moderate to Severe CSM Patients (mJOA Scores Less Than 13)

There is a consensus that patients with severe progressive

myelopathy need a surgical treatment.¹¹ However, what is the best option for patients with very subtle signs of myelopathy, or no myelopathy is not well known.

Clarke and Robinson¹² have reported 120 patients with CSM. They have treated 26 of them conservatively. They showed that almost 75% of patients had symptom progression episodes with subsequent stability. A slow deterioration happened in 20% of them. In 5%, after initial symptoms and signs, they had a long stable period. Approximately 50% of the conservatively managed patients improved.¹²

Although many authors have reported that CSM has a progressive course over time,^{11,13} there are contrary reports. One of them has been reported by Lees and Turner.¹⁰ They have described patients with CSM (n = 44) and patients with spondylosis without myelopathy (n = 51). Some of the patients with CSM (n = 28) were managed conservatively and 17 of them have improvement over time.

2. Mild CSM Patients

The CSM patients with mJOA scores between 13–17 can be considered as mild CSM. Those patients with mild CSM have no limitations on daily activities. Hence, it is controversial as to whether surgical intervention is optimal treatment. Sumi et al.¹⁴ have followed 60 patients with mild CSM with conservative treatment, and found that the outcomes of mild CSM without surgical treatment is fairly good with a tolerance rate of 70%.

In a systematic review, 20% to 62% of patients with symptomatic myelopathy were found to worsen if not managed surgically.^{13,15}

Those patients with pure radiculopathy with no sensory or motor deficits do have nerve root compression mostly recover with conservative treatment (85% resolve in 4 weeks).¹⁶ Pure radiculopathy with sensory and motor changes have also great tendency to recover (75%–90%). Best results are reported with soft disc herniations and shorter history. However, in case of hard spondylotic changes, longer history, those patients do have moderate results. Return of muscle power is better with soft disc (60%) in comparison to hard disc herniation (40%).

Matsumoto et al.¹⁷ has reported a series with mild CSM in which 35% of patients had progression of symptoms during conservative management.

Kadanka et al.¹⁸ have reported that most of the patients with mild myelopathy (80%) will improve with or without surgery. Shimomura et al.¹⁹ have reported 80% of patients were stable during a 3-year follow-up. Murphy et al.²⁰ have reported that in the case of conservative management, subjective self-assessment and general health can worsen by the time.

In most analyses, approximately 20% of patients who had conservative treatment initially, had to go a surgical treatment during follow-up.

3. Patients With Myelopathy Signs but No Symptoms

Significant cord compression may present on magnetic resonance imaging (MRI) without any symptoms in approximately 5% of patients.²¹ Some authors use the term “nonmyelopathic spondylotic cervical cord compression” (NMSCCC) in this condition.²²

Wilson et al.²³ have searched the predictors of deterioration in patients who had no myelopathy but radiological findings of cervical stenosis. They found that the incidence of myelopathy development at 1-year follow-up is 8%, and at 4 years, it is 23%.

4. Patients With No Symptoms Having Significant Stenosis (Premyelopathic)

If the patient has no symptoms and on examination no signs

of myelopathy, it is widely accepted to follow-up them. However, minor trauma may cause worsening of such patients.

Matsunaga et al.²⁴ have reported 323 ossification of the posterior longitudinal ligament (OPLL) patients with significant cervical stenosis but having no symptoms. They found that during 17.6-year average follow-up time only 17% developed myelopathy. In general, there are 2 studies examining the rate of progression to myelopathy in patients with significant canal stenosis having no symptoms.^{24,25} So, the risk of developing myelopathy with cervical stenosis can be estimated as approximately 3% per year (range, 1% to 5%).²⁶

In conclusion, the clinical course of cervical myelopathy is quite variable. In the majority of patients with mild symptoms, conservative management may result in stability or improvement of symptoms.^{12,13,15} Predicting the clinical course of a single patient remains difficult, though some evidence suggests that patients in younger ages and patients with mild symptoms are more likely to improve.²⁷

DIAGNOSTIC TESTS FOR CSM

In this session, we will discuss the value of electrophysiological tests and imaging techniques for CSM.

1. Value of Electrophysiology

Electrophysiological tests help for localizing diagnosis of a lesion, they do not give etiologic diagnosis. Such as they can tell the lesion is in anterior horn cells, they cannot tell it is amyotrophic lateral sclerosis (ALS). Most common electrophysiological tests used for cervical spinal cord and radicular syndromes are somatosensory evoked potential (SEP), motor evoked potential (MEP), electromyography (EMG), and nerve conduction study (NCS). They usefully provide additional information to clinical and neuroimaging findings in assessing the spinal cord injury severity. They were also found useful in follow-up evaluation after surgical treatment and rehabilitation. In CSM, they are expected to help in differential diagnosis and provide early signs in patients with mild symptoms.

1) Somatosensory evoked potential

SEP reflects the dorsal column function. Segmental cervical cord dysfunction can be shown by an abnormal spinal N13 response, and the P14 potential indicates a dorsal column dysfunction. These 2 peaks are reflections of the spinal cord function.

2) *Motor evoked potential*

Magnetic or electrical motor cortex stimulation and recording from distal muscles are procedure to elicit MEP. Other than central motor conduction time (CMCT), recruitment curve for MEP and silent period provide more information on the functional status of the cord.²⁸

3) *EMG and NCS* are sensitive tests for cervical radiculopathy, useful to differentiate peripheral nerve disorders that can cause clinical symptoms similar to CSM.

Cutaneous silent period (CSP) and contact heat evoked potentials (CHEPs) may be added to the list although not considered as routine tests. CSP has been reported to have a high sensitivity for detecting CSM.²⁹ CHEPs have shown the highest sensitivity (approximately 95%) to disclose at-level impairments in CSM patients.³⁰

4) *Electrophysiology in differential diagnosis of CSM from other neurologic diseases*

Differentiation of ALS, polyneuropathy, and radiculopathy is not easy with routine needle EMG and nerve conduction velocity studies. Root stimulation, triple stimulation MEP have been proposed for differentiation.³¹ In early phases of ALS, it is harder to diagnose the disease. Cervical root stimulation may allow a clear distinction between motor neuronopathy and demyelinating polyneuropathy.³²

5) *Electrophysiological tests in the prediction of outcomes of CSM*

In earlier studies, electrophysiological tests before surgery by evoked potentials have been reported as useful for outcome prediction after surgery.³³⁻³⁵ In cervical myelopathy after a decompressive surgery, De Mattei et al.³³ have first demonstrated a significant CMCT improvement by MEPs in 11 of 12 patients. Similar findings have been reported. In another study, preoperative MEPs were not found to give predictive information for clinical outcome, but the potentials have also improved after surgery.³⁶

Besides, in patients with mild CSM, a decompressive surgery was resulted with neurological improvement and increased thoracolumbar spinal cord CMCT.³⁴

The timing of surgery had also positive effects on potentials. Early surgery for CSM was found to produce a beneficial effect on MEPs. In a retrospective study, MEP changes were correlated with clinical findings.³⁵

SEPs also provide important preoperative information. In severe CSM patients, median SEP N9-N20 interval can predict

good functional outcome.³⁷ Besides, N13 abnormalities have predicted good surgical outcomes. SEPs have been found useful in outcome prediction in many studies.^{37,38}

6) *MEPs and CMCT measurement*

Earlier reports indicated that CMCT is a useful measurement to assess preoperative CSM severity.^{33,39} But, it is not well known whether an upper limb CMCT or lower limb CMCT prolongation is more valuable.

CMCT has been found to be useful,³³ or not useful³⁶ to assess CSM severity, or useful only in mild CSM.³⁴

Clinical findings, multimodal spinal cord evoked potentials (SCEPs), and surgical outcomes have been correlated in a study.³⁹ The results have shown that patients with prolonged CMCT-thoracic level (TL) had affection of lateral corticospinal tract, posterior funiculus and gray matter. In patients with severe myelopathy and prolonged CMCT-TL, the prognosis may be poor even after surgery.³⁹

In 34 patients operated with anterior decompressions ascending SCEP and descending SCEP recordings in addition to MRI, have been found useful in localization of the lesion segments of cervical myelopathy.⁴⁰ That has helped identification of clinically silent compressions and avoid surgical interventions.

SCEP can give accurate functional localization.⁴¹ In a retrospective study, SCEPs were found useful to learn the responsible level in multilevel OPLL.⁴²

7) *Electrophysiological tests versus magnetic resonance changes in prediction of outcome*

Patients with CSM with pathologic SEPs had also reduction in myelin water fraction (MWF) in 3 T magnetic resonance (MR).⁴³ MWF was also correlated with SEP latencies. The authors have commented that decreased myelin content in the spinal cord is together with impaired spinal cord conduction.

It was interesting to see that patients with significant cervical cord compression on MRI, but having no clinical myelopathy signs, risk of early progression into symptomatic CMS (< 1 year) was predicted by the presence of symptomatic radiculopathy and abnormal SEPs and MEPs.⁴⁴ However, hyperintense signal changes on MRI predicted the later (> 1 year) development of CSM.⁴⁴ In another report, the lower limbs CMCTs, but not the diameters of the spinal canal on MRI, were correlated with long-term outcomes. They concluded that electrophysiology is predicting outcomes better than MRI changes.⁴⁴ Transcranial motor cortex stimulation was found more valuable in determining the localization of the lesion than MRI.⁴⁵ Anteroposterior (AP)

diameter of the spinal cord, flattening at the lesion level and CMCT were well correlated.⁴⁶

MRI using diffusion tensor imaging (DTI) at the lesion level can provide a more sensitive information regarding spinal tract damage than the clinical and electrophysiological assessments.⁴⁷

8) Presymptomatic CSM evaluation

Bednarik et al.⁴⁸ have examined canal compression area, MR T2 hyperintensity, SEP, MEP, EMG findings in a group of 199 presymptomatic patients. Inclusion criteria were axial pain or radiculopathy, absence of any clinical signs attributed to cervical cord involvement. After 2-year follow-up, 45 patients (22.6%) have developed clinical signs of CSM. If there was a positive electrophysiology, time-to-CSM development was earlier (< 12 months). If there was an MRI hyperintensity, time-to-CSM development was later (> 12 months).⁴⁸ In conclusion, asymptomatic patients with abnormal SEPs and radiculopathy tend to progress to clinical myelopathy.^{25,48,49} Interestingly, the amount of compression at the AP diameter divided by transverse diameter has not affected the development of CSM.²⁵

9) Electrophysiological tests in monitoring of surgeries for CSM

Intraoperative electrophysiological monitoring has an important role in high-risk spinal cord injury surgery.

(1) SEP monitoring

SEPs provide effective information to evaluate the functional integrity of the spinal cord.⁵⁰ SEPs can be obtained very simply, they are noninvasive, they do not have much interference with inhaled anesthetics. The main disadvantage of SEP is that it reflects the posterior pathways not the anterior motor pathways. However, in a series with 462 patients with intraoperative SEP monitoring, only one patient had no intraoperative SEP changes, but developed a partial central cord syndrome.⁵¹

(2) MEP monitoring

The shortcomings of SEPs can be answered by employing MEPs. MEP intraoperative recording techniques are as below:

- (a) Cranial electrical stimulation and recording from the intradiscal electrodes⁵² is not used anymore. With this method, it was possible to localize the conduction block at spinal cord level, but it was an invasive technique.
- (b) Cranial or spinal (orthodromic, antidromic) electrical stimulation and recording from very thin epidural electrodes.⁵³ In this technique, direct (D) waves may be elicited. This technique allows a more reliable functional local-

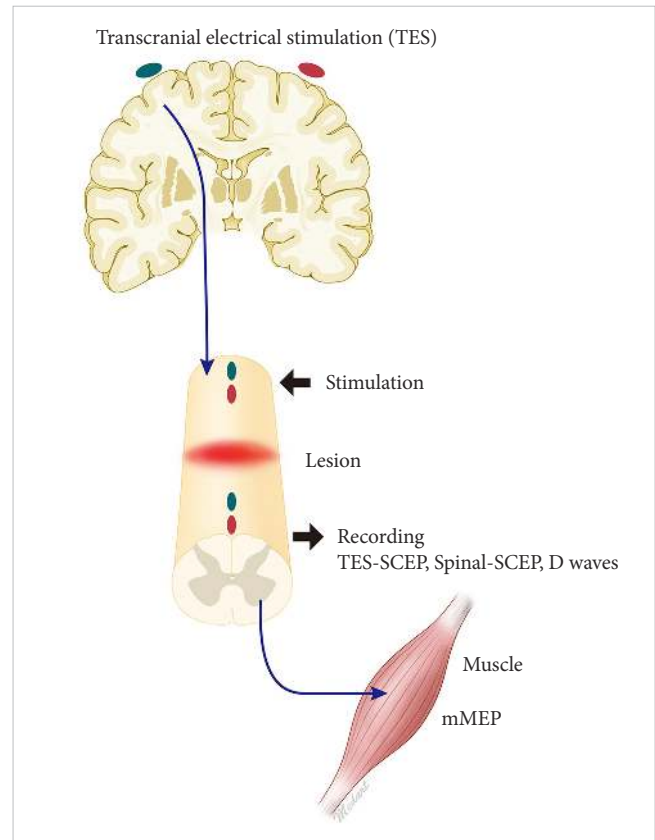


Fig. 1. Techniques to record motor evoked potentials (MEPs) during surgery. Transcranial electrical stimulation (TES) results a volley on descending tracts mostly via corticospinal tract. Recording from the spinal cord is called TES spinal cord evoked potential (TES-SCEP). If the stimulation is applied to rostral spinal cord via epidural electrodes, it is called Spinal-SCEP. D waves can be recorded with both of these techniques. If the potentials are recorded from distal muscles, it is called myogenic MEP (mMEP).

ization. It also correlates with functional outcomes.⁵³

- (c) Cranial electrical stimulation and recording from muscles.⁵⁴ This can be done with constant-voltage stimulators using a short train of stimuli in anesthetized patients.⁵⁴ Some authors call those potentials myogenic MEP. Instead of halogenated volatile anesthetic agents, total intravenous anesthesia should be preferred for MEP monitoring (Fig. 1).

10) Prediction of intraoperative neurological worsening by MEPs

In a study with 427 patients MEPs were found very sensitive for showing motor tract function during cervical surgery.⁵⁵ The authors strongly recommend to use MEPS during surgery of patients with CSM, especially on those with OPLL.⁵⁵ However, the literature is full with controversial results. For prediction of

intraoperative neurological worsening MEPs were found sensitive,⁵⁵ not sensitive especially for segmental paralysis. MEPs had unnecessary alerts in 18.4% of 1,445 patients who did not have any deficits after surgery.⁵⁶

Traynelis et al.⁵⁷ have reported 720 patients using different approaches of cervical spine without monitoring. A postoperative neurological deficit was reported in only 3 patients (0.4%). Two of them had myelopathy, but 1 had radiculopathy only. In all 3 patients, postoperative deficits completely resolved without any treatment. They commented that monitoring during decompression for symptomatic cervical disease is not necessary.⁵⁷ The surgeons operating on such patients without monitoring could well reduce the costs of surgery without risking patient safety.

Haghighi et al.⁵⁸ have reported the results of MEP and SEP monitoring in 100 patients and found that MEPs are more sensitive for detecting myelopathy and this is correlated well with abnormal MR images.

A systematic review searching the utility of intraoperative monitoring in CSM has concluded similar results for anterior cervical surgery.⁵⁹ MEP and SEP monitoring may be sensitive for diagnosis of neurological injury during such surgeries, however intraoperative MEP/SEP worsening is not specific.⁵⁹ Such changes may happen without clinical worsening and it does not always prevent neurological injury.^{29,59}

Ajiboye et al.⁶⁰ have monitored 2,627 cases during surgery for anterior cervical discectomy and fusion (ACDF). Neurological injuries occurred in 0.23% and 0.27% of patients with and without monitoring. The usage of intraoperative monitoring for ACDFs has dropped from 22.8% in 2007 to 4.3% in 2014. They have concluded that the utility of routine intraoperative monitoring for ACDFs is questionable.

Positive changes in MEP during monitoring may reflect a functional improvement 1 month after surgery in CSM patients.⁶¹ However, the neuropathic pain and long-term functional outcomes are not affected. Improvement of MEPs during surgery may reflect better outcomes of motor power.

11) C5 root monitoring

During cervical posterior decompression, especially patients with CSM at the C4–5 levels are susceptible to C5 injury.⁶² EMG and MEP monitoring during cervical laminoplasty has decreased C5 root palsy.^{62,63} Myogenic MEP recordings from deltoid and biceps and spontaneous EMG are more sensitive than any other electrophysiologic tests.⁶³

Bose et al.⁶³ have reported in a retrospective study who un-

derwent anterior cervical decompression MEPs were more sensitive to C5 deficits in comparison to spontaneous EMG activity alone, since the false-negative findings during EMG activity only are more often.

Oya et al.⁶⁴ have examined 131 cases during cervical laminoplasty with multimodality potentials. C5 palsy after surgery was in 3 patients. Incidence of C5 palsy (2.2%) and other neurologic deficits while using multimodality potentials were relatively low. MEPs elicited from deltoids or biceps had 100% sensitivity for predicting a postoperative deficit. SEPs were not helpful in predicting postoperative deficits. They have commented that SEP monitoring is not useful, MEP monitoring is not useful for lower extremity power, but it is useful for C5 palsy.⁶⁴

Ando et al.⁶⁵ have examined the efficacy of MEP to prevent deltoid weakness in 278 patients operated with laminoplasty technique. 7 patients (2.5%) developed deltoid weakness (2 acute, 5 delayed onsets). Persistent monitoring alerts occurred in 2 patients with acute-onset. In 1 patient deltoid weakness was prevented by foraminotomy. No alerts in delayed onset palsies. MEPs by cortical stimulation and recording from deltoid muscle is valuable in detecting early onset C5 nerve palsy.⁶⁵

In conclusion, electrophysiological tests are useful for differential diagnosis of other neurological disorders from CSM. MEP and SEP are valuable tests to predict outcomes of CSM surgery. But no evidence that they are more valuable than clinical parameters. The use of MEP/SEP monitoring may be considered as a sensitive technique to diagnose potential neurological injury during surgery for CSM. However, intraoperative MEP/SEP worsening is not specific, and it does not show clinical worsening in every incidence. Intraoperative MEP/SEP changes do not necessarily prevent neurological injury and improve the outcomes. MEP by recording from deltoid muscle is valuable in detecting C5 nerve palsy. The value of monitoring during ACDF surgery and lower extremity function are questionable.

2. Value of Canal Diameters in Computed Tomography and MRI

The main component of the CSM is the narrowing of the spinal canal. It results from a combination of intervertebral disc herniation, osteophytes and OPLL.⁶⁶ However, the mere presence of cord compression on MRI is inadequate for the diagnosis of CSM as it can be demonstrated in approximately 5% of asymptomatic patients,²¹ lending the diagnosis of NMSCC.²² Specificity of cord compression seen on MRI is limited for the diagnosis of CSM.⁶⁷ This session assesses the impact of canal diameters on clinical outcomes in patients with CSM. Twenty-

four key articles published in the last 10 years were reviewed.

The early studies assessing the canal diameters were based on radiographs.^{68,69} They assessed the size of the cervical spinal canal using the developmental segmental sagittal diameter (DSSD). This was measured from the vertebral body posterior surface to the closest point on the spinolaminar line at the level of the pedicle.⁶⁸ DSSD less than 10 mm was predicted to cause myelopathy.⁶⁸ However, variations in magnification and distance from the X-ray source to film can confound such measurements.⁶⁹ The Torg-Pavlov ratio – the ratio between the canal diameter and the vertebral body width was used to overcome this limitation. Torg-Pavlov ratio < 0.8 was used as an indicator of spinal canal stenosis.⁶⁹ However, this ratio had a low positive predictive value due to false positives arising from errors of patient positioning.⁷⁰

With the advent of computed tomography (CT) and MRI, the use of plain radiography for assessing the spinal canal fell out of favor.⁷¹ The MRI had benefit of being able to measure the soft tissue components (herniated disc and hypertrophied ligamentum flavum) contributing to canal stenosis.⁶⁶ Earlier MRI based techniques relied mainly on qualitative or semiquantitative data such as percentage of flattening, cross-sectional cord shape, shape of the cord on midsagittal T1- and T2-weighted imaging (T2WI).^{14,19,72} Over time however, they became more quantitative and thus less influenced by subjective bias. Currently AP diameter, transverse area (TA), and compression ratio (CR) are the measurements of choice in evaluating spondylotic cord compression.^{48,66}

1) Semiquantitative scales

As the degree of segmental pathologic changes and cord compression exist on a spectrum, the need for assessment of the severity of these processes resulted in the development of grading systems. Muhle et al.⁷³ graded cervical stenosis on a 4-point scale as follows.

Grade 0: no obliteration of anterior or posterior subarachnoid space

Grade 1: partial obliteration of the anterior or posterior subarachnoid space

Grade 2: complete obliteration of the anterior or posterior subarachnoid space

Grade 3: cervical cord compression or displacement

Kang et al.⁷⁴ modified Muhle's grading to include signal intensity (SI) changes on T2WI. Their proposed classification was as follows:

Grade 0: absence of spinal canal stenosis

Grade 1: subarachnoid space obliteration exceeding 50%

Grade 2: presence of spinal cord deformity

Grade 3: presence of spinal cord SI change

The grade of stenosis in study of Kang et al.⁷⁴ was found to have a positive correlation with neurologic deterioration and with the percent of patients who had undergone surgery. Park et al.⁷⁵ validated Kang classification and found it to correlate with clinical manifestations of CSM.

Nagata et al.⁷⁶ used sagittal T1 weighted MRI for assessing the severity of the latter. They have divided cervical cord compression on MRI into 3 classes:

Class 1: slight compression, cord width decrease by $< 1/3$

Class 2: moderate compression, cord width decrease by $> 1/3$

Class 3: severe compression, cord width decrease by $> 2/3$

2) Quantitative measurements

While grading systems allow for a calibrated estimation of disease severity, they are only semiquantitative, and hence not free from bias. To develop more quantitative methods, MRI based measurements of cord and canal dimensions were investigated. A good correlation of 2 variables measured on CT myelography – TA of the spinal cord, CR with the degree of pathologic changes have been reported in cadavers.⁴⁸

(1) Compression ratio

The CR is defined as the ratio between the AP diameter and the transverse diameter of the cord on axial imaging.²² A CR < 0.436 is associated with an unfavorable prognosis. The CR is a more objective measure of cord compression, but is not without limitations. It fails to be useful in cases with circumferential cord compression. Another shortcoming is that since the cord is not rectangular in shape the CR may overestimate sagittal compression when compression is measured laterally.⁴⁸ In a systematic review, no excellent quality studies were found correlating CR with postoperative outcomes.⁷⁷

(2) Cross-sectional area of the spinal cord

The other variable is cross-sectional area of the spinal cord (CSA) measured on axial images. The CSA has been validated by multiple studies as a marker of severity of myelopathy, post-surgical recovery, and pathological cord changes.^{22,48,78,79} The cord loses its function when its CSA is $< 45 \text{ mm}^2$ (also known as CSA_{critical}) and surgery on patients with a CSA lower than this value was shown to have worse functional outcomes in spite of adequate morphological decompression.⁷⁸ CSA on MRI correlates with recovery ratio, but not with postoperative functional

score assessed by JOA/mJOA Scores (Level of evidence: 2).⁷⁷ A more recent systematic review reported that patients with greater CSA had better neurological outcomes after surgery.⁸⁰

(3) Maximum canal compromise/Maximum spinal cord compression

Another commonly employed tool for assessing the severity of cervical stenosis is called “maximum canal compromise” (MCC). Its equivalent for assessing cord compression is known as “maximum spinal cord compression” (MSCC). They are first described for spinal cord injury,⁸¹ then now commonly used to evaluate CSM.⁶⁶ The MCC is the ratio of the AP diameter of the spinal canal at the region of interest to the AP diameter of the spinal canal at the average of the normal sites above and below it.⁸¹ The MSCC is a tool for assessing cord compression that is derived in the same manner

$$\text{Canal Compromise} = \left[1 - \frac{D_i}{(D_a + D_b)/2} \right] \times 100$$

$$\text{Cord Compression} = \left[1 - \frac{d_i}{(d_a + d_b)/2} \right] \times 100$$

While MSCC/MCC eliminates the need for standardization of measurements across patient populations, they are not free from limitations. The variation in cord size within the cervical spine is not well quantified. Therefore, any estimate of the diameter of a segment that is derived by interpolation from the segments above and below it has doubtful accuracy.⁶⁶ Their inability to pick up lateral stenosis as the assessment is carried out in the midsagittal plane, is another limitation.⁶⁶

Nouri et al.⁶⁶ have found a good correlation between worse outcomes (mJOA < 16) at 6 months and MCC/MSCC. Arvin et al.⁸² have also found a correlation between MSCC and 6 months and 1-year postoperative mJOA recovery rate, walking test times.

(4) Canal diameter

The AP diameter of the canal is another measure of the de-

gree of canal compromise. It is the distance between the most posterior point on the posterior aspect of the vertebral body and the nearest point on the spinolaminar line. It has been shown to be able to differentiate between patients with normal anatomy, NMSCCC, and CSM,²² but no significant association with prognosis has been demonstrated (Table 4).^{77,83,84}

(5) Occupation rate

The proportion of the spinal canal occupied by the cord measured as the ratio between the AP diameters of the cord and the canal in the midsagittal plane is occupation rate of the spinal cord.²¹ The authors have found that the border value for the occupation rate in asymptomatic persons is at 72.3%. So, they proposed an occupation rate > 75% as a cutoff for developmental cervical stenosis.

3. Value of Signal Intensity Changes in MRI

CSM is known to lead to T1 and T2 signal changes on cervical MRI.⁸⁵ T1, T2 changes and histology are associated with spinal cord compression and constriction. Those signal changes have been attributed to myelomalacia and cord gliosis secondary to a long-standing compressive effect.⁸⁶ Al-Mefty et al.⁸⁷ have speculated high signal T2 shall be related to edema, inflammation, gliosis, and myelomalacia. On the other hand, low signal T1 can be related to cystic necrosis and syrinx. Signal changes in gray matter may indicate temporal progression of CSM. Though the anatomical translation of T1/T2 signal changes is established, its effect on outcome is still under study.⁸⁸

Several grading systems for SI changes have been proposed according to the extent, SI types, axial appearance or combination of those. SI can be assessed both qualitatively (presence vs absence) and quantitatively (SI ratio),⁷⁹ sagittal extents, TA.^{66,89} Most of them contain T2 changes, some also include T1. No grading system is yet accepted as the increase (Fig. 2).

High signal in T2: A simple and most widely used grading of

Table 4. Correlation between canal diameter (CD) and outcomes

Study	Assessed	Strength of association	p-value
Kovalova et al. ²²	Ability to differentiate between patients without compression and those with NMSCCC*	OR = 32.495	< 0.001
	Ability to differentiate between patients with NMSCCC and CSM†	OR = 9.158	< 0.001
Oshima et al. ⁸³	Risk of conversion to surgery in CSM patients with SI change	CPHR = 2.26	0.17
Yoshimatsu et al. ⁸⁴	Correlation between CD and improvement of myelopathy in patients with CSM	Beta = 0.085	0.761

OR, odds ratio; NMSCCC, nonmyelopathic spondylotic cervical cord compression; CSM, cervical spondylotic myelopathy; SI, signal intensity; CPHR, Cox proportional hazard ratio.

*CD_{disc} < 9.9 mm. †CD_{disc} < 8.3 mm.

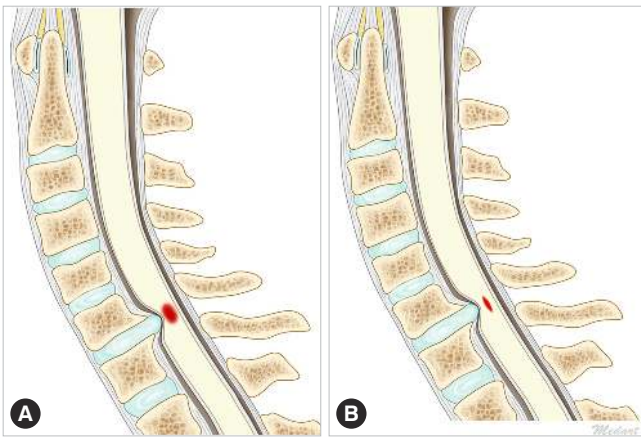


Fig. 2. High signal in T2-weighted magnetic resonance images has been graded by Chen et al.⁹⁰: Grade 0 is no increase of signal. (A) Grade 1 is faint, fuzzy bordered intensity increase. (B) Grade 2 is intense, well-defined bordered intensity increase.

T2 SI has been proposed by Chen et al.⁹⁰: Grade 0 is no increase of signal. Grade 1 is faint, fuzzy bordered intensity increase. Grade 2 is intense, well-defined bordered intensity increase.

There is a significant correlation between the degree of compression (axial area of spinal cord) and high signal in T2WI.^{91,92} Sagittal extent and area of T2 hyperintensity have also been found significant predictors of surgical outcome at 6 months.⁸⁹

Approximately one-third of the CSM patients have T2 hyper-signal.⁶⁷ Pyramidal signs correlated with SI changes on T1 and T2WI.⁹¹ Also, Hoffmann sign was related to a greater degree of signal change (T1 and T2).⁹²

Dynamic factors have been investigated and found to have a role in high signals in T2WI. Increased segmental range of motion is a risk factor for T2 signal changes in CSM, and segmental hyperextension is correlated with higher hyperintensity on T2.⁸⁵

Cervical cord available space was examined in a prospective study using flexion and extension dynamic MR images.⁹³ The space was found very narrow on extension, T2 intensity was found more pronounced on flexion. The authors have commented that despite reduced canal diameter in extension, higher rate of signal changes in flexion occurs because of expansion effect.⁹³

1) High signal in T2 and outcomes

This change in intensity is known to be associated with more severe disease and a worse prognosis.^{48,82,89,94} There was a significant correlation of SI change and presence of clinical myelopa-

thy and a correlation of SI ratio with recovery rate.⁶⁷ A correlation of worse outcomes at 6 months and 12 months with presence of hypointensity on T1-weighted imaging (T1WI), hyperintensity on T2WI, area on T2WI, sagittal extent on T2WI were reported.^{82,92} However, there was no significant correlation between the SI change and severity of clinical symptoms⁷⁹ or deterioration of myelopathy,¹⁴ or exacerbation of CSM in patients managed conservatively.⁸⁴ Instead, in a retrospective study, Oshima et al.⁸³ have found that among patients with clinically mild CSM with SI change on MRI, only 44% had neurologic deterioration or undergone surgery over the course of 10 years. They suggest that the presence of SI change in otherwise mild CSM may not necessarily warrant an operative intervention.

In a meta-analysis investigating high signal changes in T2WI and outcomes,⁹⁵ multisegmental and sharp increase in T2 signal changes have been found to end with poorer outcomes (Class II evidence). If the T2WI signal changes are regressing after surgery, better postoperative outcomes should be expected (Class II evidence).⁹⁵ Higher preoperative signal change ratio correlates with worse clinical outcome.⁹⁶

In a retrospective study including 197 patients,⁹⁷ T2 SI has been graded according to Chen et al.⁹⁰ Grade 2 signal changes on T2 were associated with lower rates of cure. T1 hypointensity was also related with lower rates of cure.⁹⁷

Mastronardi et al.⁹⁸ have reported disappearance rates of the T2WI after surgery. They have found 52% had regressed after decompressive surgery, of which 17.4% regressed in the immediate postoperative MRI. That means T2 signal changes tend to be reversible.

On the other hand, T2 high signal changes may also be found in asymptomatic canal stenosis. Kato et al.²¹ have investigated 1,211 healthy volunteers. Sixty-four volunteers had significant radiological compression, 28 volunteers (2.3%) presented T2 signal changes. In conclusion, T2 signal changes do not necessarily translate into clinical disease.

T2WI signal hyperintensity is not specific and can reflect reversible or irreversible structural changes. We know that patients may have both weak and strong T2WI signal hyperintensity parts (Table 5).^{66,99}

2) Low signal in T1

Low-intensity signal on T1WI is considered as a sign of advanced disease or significant neural tissue loss.^{66,77,87,90,99} Hypo-signal in T1 rarely appears without increase in T2 signal.

Low-intensity signal on preop T1WI correlates with poor postoperative neurological outcome.⁴¹ In a prospective study by

Table 5. Correlation between MRI signal changes and their correlations with histopathology. Adapted from Nouri et al.⁶⁶

Imaging type	MRI characteristics	Possible pathological correlation	Structural change
T2WI	Weak signal hyperintensity (without clear border)	Edema; Wallerian degeneration; demyelination; ischemia; gliosis	Reversible
	Strong signal hyperintensity (with sharp, clear border)	Potential cavitation; neural tissue loss; myelomalacia; necrosis; gray matter changes	Largely irreversible
T1WI	Remarkable presence of signal hypointensity; appearing dark, focal, faint	Cavitation; neural tissue loss; myelomalacia; necrosis; spongiform changes in gray matter	Largely irreversible

MRI, magnetic resonance imaging; T2WI, T2-weighted imaging; T1WI, T1-weighted imaging.

Salem et al.¹⁰⁰ 93 patients operated by either anterior or posterior approach and 12 months of follow-up, signal changes in the T1 cervical MRI have been found to predict worse outcome after surgery.

In conclusion, high SI on T2WI alone cannot be considered as a predictor of worse outcome.⁹⁹ However, if there is T2WI strong signal hyperintensity with sharp, clear border, if there are long high-intensity segments on T2WI, low SI segments on T1WI or combined T1 and T2 SI changes, if T2WI high intensity after surgery persists, those can be considered as negative predictors of surgical outcome. Those patients have more severe histological changes and worse recovery after surgery.

4. New Imaging Techniques for CSM

Conventional MRI can only give the structural information of spinal cord. However, advanced techniques such as DTI, MWF, magnetization transfer (MT), MR spectroscopy (MRS), and functional MRI (fMRI) can provide additional information about spinal cord metabolism and structure.¹⁰¹ Ischemia due to direct compression of vessels, as well as impaired microcirculation, free radical-mediated cell injury, glutamatergic toxicity, and apoptosis are the changes which may be reflected by new imaging techniques.¹⁰¹⁻¹⁰⁵

1) Dynamic MRI

Dynamic MRI (dMRI) can find more spinal cord compression than static MRI.⁷³ In a report using extension MRI it was found that compression levels were quite more with extension MRI in comparison to the static MRI.¹⁰⁶

2) Fiber tracking

MR DTI and spinal cord fiber tracking are useful tools for CSM imaging. It was reported that when compression of the spinal cord white matter increases, the mean apparent diffusion coefficient (ADC) has decreased.¹⁰⁷ A slightly elevated fractional anisotropy (FA) at the compression level was found.

At the compression site, almost half of the CSM patients (46%) are having normal to decreased ADC, or normal to elevated FA.¹⁰⁸ Clinical studies have clearly documented that an increase in ADC and decrease in FA are signs of the late stages of chronic spinal cord compression.¹⁰⁵ The reason of these pathological changes are the elevation of ADC after an increase in extracellular water and suppression of FA due to absence of directional organization inside the cord.¹⁰⁹

A recent study has also shown that if the FA before surgery is high at the site of compression these patients are having better functional recovery.¹¹⁰ That means FA at the compression site is a biomarker for determining good surgical candidates.

3) MR spectroscopy

Although MRS provides important information about cellular biochemistry and neural function, studies examining MRS changes in CSM patients are very few.

N-acetyl aspartate (NAA), choline, lactate, and creatine (Cr) are some metabolites examined. NAA is an indicator of axonal integrity and it was found mostly in axons and neurons. Lactate is an indicator of metabolic dysfunction after central nervous system injury. The NAA/Cr ratio is decreased in CSM patients which reflects increased neuronal injury to these patients.¹¹¹ In about 1/3 of CSM patients an abnormal lactate signal was found.¹⁰¹

On the other hand, there are many limitations to MRS study. Since the spinal cord is smaller in volume, adjacent tissues can contaminate the results. Patient movement during scan acquisition can also affect MRS and DTI. Cardiac pulsations and the respiratory movements also cause physiological movements of the spinal cord, so the suppression of those movements by cardiac gating, special radiofrequency coils are necessary to enhance the quality of MRS and DTI in the spinal cord.

Future applications of DTI and MRS can be speculated.¹¹² Some of them are inhibition, such as the cell apoptosis inhibition with antibody, neurotrophin release via genetically altered fibroblasts and repairing injured plasma membranes by dietary

therapy. Some noninvasive modalities would be necessary to understand the efficacy of these therapies.

There it comes new MR technologies to have more information about spinal cord function. Some of those techniques are; chemical exchange saturation transfer imaging, dynamic susceptibility contrast perfusion MRI, MT imaging (MTI), dynamic contrast-enhanced perfusion MRI, arterial spin labeling, and spinal cord fMRI. Especially MTI, which has the ability to quantify myelin integrity was found useful for detecting changes of multiple sclerosis and ALS patients.

RECOMMENDATIONS

1. Recommendations for Clinical Presentation of CSM

- Myelopathic signs (hyperreflexia, inverted brachioradialis reflex, Hoffmann sign, Babinski, and clonus) are an integral component of clinical diagnosis of cervical myelopathy. However, they are not very sensitive and may be absent in about 20% of myelopathic patients.
- Individual myelopathic signs taken alone cannot diagnose cervical myelopathy in all patients but at least one is present in severe myelopathy.
- Clinical diagnosis of CSM relies heavily on characteristic symptoms and signs elicited during history and physical exam which prompt further investigation with cervical spine imaging.
- In severe myelopathic patients, after laminoplasty, major recovery in myelopathic signs occurs during the first 6 months and there after it plateaus.
- In patients with myelopathic signs, if there are no alternative explanations, a combination of clinical symptoms and imaging studies must form the basis of our treatment decisions. The absence of myelopathic signs does not preclude the diagnosis of CSM nor its successful surgical treatment.

2. Recommendations for Natural Course of CSM

- Natural course of patients with cervical stenosis and signs of myelopathy greatly vary.
- Progression of the disease is possible, but prediction of those patients is not well known. Some patients may remain static for lengthy periods, and some patients with severe disability can improve without treatment.
- For patients with no symptoms but having significant stenosis (premyelopathic), risk of developing myelopathy with cervical stenosis is approximately 3% per year.

3. Recommendations for Value of Electrophysiology

- Electrophysiological tests to be used in CSM patients are (in order of benefits): MEP, SCEP, SEP, and EMG.
- Routine electrophysiological tests are useful in differential diagnosis of CSM from other neurological conditions. However, especially during the early course of the disease differential diagnosis is very difficult, specific tests are necessary and mild forms of ALS and polyneuropathy may not be differentiated easily.
- Although MEP and SEP have been found as valuable tests to predict outcomes of CSM surgery, there is no evidence that they are more valuable than clinical parameters.
- Electrophysiological tests may have better outcome predictions than MR changes.
- Electrophysiological tests are not very useful in monitoring lower extremity power, and the value of monitoring during ACDF surgery is questionable.
- EMG and MEP monitoring have been found to be useful to decrease C5 root palsy during CSM surgery.
- Intraoperative MEP/SEP worsening is not specific, and it does not show clinical worsening in every incidence. Intraoperative MEP/SEP changes do not necessarily prevent neurological injury and improve the outcomes.

4. Recommendations for Value of Canal Diameters in CT and MRI

- In spite of conflicting evidence, MRI morphometric analysis of the spine has a significant role in evaluation and prognostication of CSM and it should be included in the preoperative workup.
- Among the many variables assessed using MRI – compression ratio, maximum canal compromise, and transverse area are most importantly correlated with functional outcomes following surgery in patients with CSM. Each parameter has its own strengths and limitations, therefore a combined assessment of MR parameters has a greater predictive yield.

5. Recommendations for Value of Signal Intensity Changes in MRI

- Spinal cord T2 hyperintensity on cervical MRI may be correlated with a worse outcome in CSM.
- Patients with lighter signal changes in T2 on cervical MRI should not be excluded from surgical treatment of CSM.
- More studies are needed to validate proposed grading systems, or to create new ones.

- T1 hyposignal should be considered as a sign of more advanced disease, with worse outcome.
- More studies are needed to assess the effect of sagittal and axial extension of T1 signal changes on outcome.

6. Recommendations for New Imaging Techniques for CSM

- Diffusion MRI, MR Spectroscopy, and dMRI may be a part of MR examinations for CSM protocol apart from conventional MRI. We suggest their usage for outcome studies.
- With data pooling of clinical and imaging findings, we will be able to prognosticate better and identify patients earlier before the changes and permanent damage sets in.

CONFLICT OF INTEREST

The authors have nothing to disclose.

REFERENCES

1. Lebl DR, Hughes A, Cammisa FP Jr, et al. Cervical spondylotic myelopathy: pathophysiology, clinical presentation, and treatment. *HSS J* 2011;7:170-8.
2. Acharya S, Srivastava A, Virmani S, et al. Resolution of physical signs and recovery in severe cervical spondylotic myelopathy after cervical laminoplasty. *Spine (Phila Pa 1976)* 2010;35:E1083-7.
3. Gibson J, Nouri A, Krueger B, et al. Degenerative cervical myelopathy: a clinical review. *Yale J Biol Med* 2018;91:43-8.
4. Rhee JM, Heflin JA, Hamasaki T, et al. Prevalence of physical signs in cervical myelopathy: a prospective, controlled study. *Spine (Phila Pa 1976)* 2009;34:890-5.
5. Nurick S. The pathogenesis of the spinal cord disorder associated with cervical spondylosis. *Brain* 1972;95:87-100.
6. Hukuda S, Mochizuki T, Ogata M, et al. Operations for cervical spondylotic myelopathy. A comparison of the results of anterior and posterior procedures. *J Bone Joint Surg Br* 1985;67:609-15.
7. Benzel EC, Lancon J, Kesterson L, et al. Cervical laminectomy and dentate ligament section for cervical spondylotic myelopathy. *J Spinal Disord* 1991;4:286-95.
8. Revanappa KK, Rajshekhkar V. Comparison of Nurick grading system and modified Japanese Orthopaedic Association scoring system in evaluation of patients with cervical spondylotic myelopathy. *Eur Spine J* 2011;20:1545-51.
9. Tetreault LA, Karpova A, Fehlings MG. Predictors of outcome in patients with degenerative cervical spondylotic myelopathy undergoing surgical treatment: results of a systematic review. *Eur Spine J* 2015;24 Suppl 2:236-51.
10. Lees F, Turner JW. Natural history and prognosis of cervical spondylosis. *Br Med J* 1963;2:1607-10.
11. Yarbrough CK, Murphy RK, Ray WZ, et al. The natural history and clinical presentation of cervical spondylotic myelopathy. *Adv Orthop* 2012;2012:480643.
12. Clarke E, Robinson PK. Cervical myelopathy: a complication of cervical spondylosis. *Brain* 1956;79:483-510.
13. Tetreault LA, Karadimas S, Wilson JR, et al. The natural history of degenerative cervical myelopathy and the rate of hospitalization following spinal cord injury: an updated systematic review. *Global Spine J* 2017;7(3 Suppl):28S-34S.
14. Sumi M, Miyamoto H, Suzuki T, et al. Prospective cohort study of mild cervical spondylotic myelopathy without surgical treatment. *J Neurosurg Spine* 2012;16:8-14.
15. Karadimas SK, Erwin WM, Ely CG, et al. Pathophysiology and natural history of cervical spondylotic myelopathy. *Spine (Phila Pa 1976)* 2013;38(22 Suppl 1):S21-36.
16. Holly LT, Matz PG, Anderson PA, et al. Clinical prognostic indicators of surgical outcome in cervical spondylotic myelopathy. *J Neurosurg Spine* 2009;11:112-8.
17. Matsumoto M, Chiba K, Ishikawa M, et al. Relationships between outcomes of conservative treatment and magnetic resonance imaging findings in patients with mild cervical myelopathy caused by soft disc herniations. *Spine (Phila Pa 1976)* 2001;26:1592-8.
18. Kadanka Z, Mares M, Bednarík J, et al. Predictive factors for mild forms of spondylotic cervical myelopathy treated conservatively or surgically. *Eur J Neurol* 2005;12:16-24.
19. Shimomura T, Sumi M, Nishida K, et al. Prognostic factors for deterioration of patients with cervical spondylotic myelopathy after nonsurgical treatment. *Spine (Phila Pa 1976)* 2007;32:2474-9.
20. Murphy R, Moledina I, McEvoy L, et al. The natural history of cervical myelopathy. *European Spine J* 2009;19:517.
21. Kato F, Yukawa Y, Suda K, et al. Normal morphology, age-related changes and abnormal findings of the cervical spine. Part II: Magnetic resonance imaging of over 1,200 asymptomatic subjects. *Eur Spine J* 2012;21:1499-507.
22. Kovalova I, Kerkovsky M, Kadanka Z, et al. Prevalence and imaging characteristics of nonmyelopathic and myelopathic spondylotic cervical cord compression. *Spine (Phila Pa 1976)* 2016;41:1908-16.
23. Wilson JR, Barry S, Fischer DJ, et al. Frequency, timing, and predictors of neurological dysfunction in the nonmy-

- elopathic patient with cervical spinal cord compression, canal stenosis, and/or ossification of the posterior longitudinal ligament. *Spine (Phila Pa 1976)* 2013;38(22 Suppl 1):S37-54.
24. Matsunaga S, Sakou T, Taketomi E, et al. Clinical course of patients with ossification of the posterior longitudinal ligament: a minimum 10-year cohort study. *J Neurosurg* 2004; 100(3 Suppl Spine):245-8.
25. Bednarik J, Kadanka Z, Dusek L, et al. Presymptomatic spondylotic cervical cord compression. *Spine (Phila Pa 1976)* 2004;29:2260-9.
26. Fassett DR, Jeyamohan S, Harrop J. Asymptomatic cervical stenosis: to operate or not? *Semin Spine Surg* 2007;19:47-50.
27. Nakamura K, Kurokawa T, Hoshino Y, et al. Conservative treatment for cervical spondylotic myelopathy: achievement and sustainability of a level of "no disability". *J Spinal Disord* 1998;11:175-9.
28. Nicotra A, King NK, Catley M, et al. Evaluation of corticospinal excitability in cervical myelopathy, before and after surgery, with transcranial magnetic stimulation: a pilot study. *Eur Spine J* 2013;22:189-96.
29. Nardone R, Höller Y, Brigo F, et al. The contribution of neurophysiology in the diagnosis and management of cervical spondylotic myelopathy: a review. *Spinal Cord* 2016; 54:756-66.
30. Jutzeler CR, Ulrich A, Huber B, et al. Improved diagnosis of cervical spondylotic myelopathy with contact heat evoked potentials. *J Neurotrauma* 2017;34:2045-53.
31. Furtula J, Johnsen B, Frandsen J, et al. Upper motor neuron involvement in amyotrophic lateral sclerosis evaluated by triple stimulation technique and diffusion tensor MRI. *J Neurol* 2013;260:1535-44.
32. Veltsista D, Chroni E. Usefulness of cervical root magnetic stimulation in assessing proximal motor nerve conduction. *J Electromyogr Kinesiol* 2015;25:742-8.
33. De Mattei M, Paschero B, Sciarretta A, et al. Usefulness of motor evoked potentials in compressive myelopathy. *Electromyogr Clin Neurophysiol* 1993;33:205-16.
34. Chang CW, Lin SM. Measurement of motor conduction in the thoracolumbar cord. A possible predictor of surgical outcome in cervical spondylotic myelopathy. *Spine (Phila Pa 1976)* 1996;21:485-91.
35. Capone F, Tamburelli FC, Pilato F, et al. The role of motor-evoked potentials in the management of cervical spondylotic myelopathy. *Spine J* 2013;13:1077-9.
36. Jaskolski DJ, Laing RJ, Jarratt JA, et al. Pre- and postoperative motor conduction times, measured using magnetic stimulation, in patients with cervical spondylosis. *Br J Neurosurg* 1990;4:187-92.
37. Lyu RK, Tang LM, Chen CJ, et al. The use of evoked potentials for clinical correlation and surgical outcome in cervical spondylotic myelopathy with intramedullary high signal intensity on MRI. *J Neurol Neurosurg Psychiatry* 2004; 75:256-61.
38. Ma Y, Hu Y, Valentin N, et al. Time jitter of somatosensory evoked potentials in recovery from hypoxic-ischemic brain injury. *J Neurosci Methods* 2011;201:355-60.
39. Fujimoto K, Kanchiku T, Imajo Y, et al. Use of central motor conduction time and spinal cord evoked potentials in the electrophysiological assessment of compressive cervical myelopathy. *Spine (Phila Pa 1976)* 2017;42:895-902.
40. Tadokoro N, Tani T, Kida K, et al. Localization of the primary sites of involvement in the spinal sensory and motor pathways for multilevel MRI abnormalities in degenerative cervical myelopathy. *Spinal Cord* 2018;56:117-25.
41. Uchida K, Nakajima H, Takeura N, et al. Prognostic value of changes in spinal cord signal intensity on magnetic resonance imaging in patients with cervical compressive myelopathy. *Spine J* 2014;14:1601-10.
42. Azuma Y, Kato Y, Taguchi T. Etiology of cervical myelopathy induced by ossification of the posterior longitudinal ligament: determining the responsible level of OPLL myelopathy by correlating static compression and dynamic factors. *J Spinal Disord Tech* 2010;23:166-9.
43. Liu H, MacMillian EL, Jutzeler CR, et al. Assessing structure and function of myelin in cervical spondylotic myelopathy: Evidence of demyelination. *Neurology* 2017;89: 602-10.
44. Deftereos SN, Kechagias E, Ioakeimidou C, et al. Transcranial magnetic stimulation but not MRI predicts long-term clinical status in cervical spondylosis: a case series. *Spinal Cord* 2015;53 Suppl 1:S16-8.
45. Deftereos SN, Kechagias EA, Panagopoulos G, et al. Localisation of cervical spinal cord compression by TMS and MRI. *Funct Neurol* 2009;24:99-105.
46. Rikita T, Tanaka N, Nakanishi K, et al. The relationship between central motor conduction time and spinal cord compression in patients with cervical spondylotic myelopathy. *Spinal Cord* 2017;55:419-26.
47. Wen CY, Cui JL, Mak KC, et al. Diffusion tensor imaging of somatosensory tract in cervical spondylotic myelopathy

- and its link with electrophysiological evaluation. *Spine J* 2014;14:1493-500.
48. Bednarik J, Kadanka Z, Dusek L, et al. Presymptomatic spondylotic cervical myelopathy: an updated predictive model. *Eur Spine J* 2008;17:421-31.
 49. Kadanka Z, Bednarik J, Vohánka S, et al. Spondylotic cervical myelopathy: three aspects of the problem. *Suppl Clin Neurophysiol* 2000;53:409-18.
 50. Bouchard JA, Bohlman HH, Biro C. Intraoperative improvements of somatosensory evoked potentials: correlation to clinical outcome in surgery for cervical spondylitic myelopathy. *Spine (Phila Pa 1976)* 1996;21:589-94.
 51. Smith PN, Balzer JR, Khan MH, et al. Intraoperative somatosensory evoked potential monitoring during anterior cervical discectomy and fusion in nonmyelopathic patients—a review of 1,039 cases. *Spine J* 2007;7:83-7.
 52. Tani T, Ushida T, Yamamoto H. Surgical treatment guided by spinal cord evoked potentials for tetraparesis due to cervical spondylosis. *Paraplegia* 1995;33:354-8.
 53. Uchida K, Nakajima H, Sato R, et al. Multivariate analysis of the neurological outcome of surgery for cervical compressive myelopathy. *J Orthop Sci* 2005;10:564-73.
 54. Deletis V, Sala F. Intraoperative neurophysiological monitoring of the spinal cord during spinal cord and spine surgery: a review focus on the corticospinal tracts. *Clin Neurophysiol* 2008;119:248-64.
 55. Hilibrand AS, Schwartz DM, Sethuraman V, et al. Comparison of transcranial electric motor and somatosensory evoked potential monitoring during cervical spine surgery. *J Bone Joint Surg Am* 2004;86:1248-53.
 56. Lee JY, Hilibrand AS, Lim MR, et al. Characterization of neurophysiologic alerts during anterior cervical spine surgery. *Spine (Phila Pa 1976)* 2006;31:1916-22.
 57. Traynelis VC, Abode-Iyamah KO, Leick KM, et al. Cervical decompression and reconstruction without intraoperative neurophysiological monitoring. *J Neurosurg Spine* 2012;16:107-13.
 58. Haghighi SS, Mundis G, Zhang R, et al. Correlation between transcranial motor and somatosensory-evoked potential findings in cervical myelopathy or radiculopathy during cervical spine surgery. *Neurol Res* 2011;33:893-8.
 59. Resnick DK, Anderson PA, Kaiser MG, et al. Electrophysiological monitoring during surgery for cervical degenerative myelopathy and radiculopathy. *J Neurosurg Spine* 2009;11:245-52.
 60. Ajiboye RM, D'Oro A, Ashana AO, et al. Routine use of intraoperative neuromonitoring during ACDFs for the treatment of spondylotic myelopathy and radiculopathy is questionable: a review of 15,395 cases. *Spine (Phila Pa 1976)* 2017;42:14-9.
 61. Park MK, Lee SJ, Kim SB, et al. The effect of positive changes during intraoperative monitoring of the functional improvement in patients with cervical compressive myelopathy. *Clin Interv Aging* 2018;13:1211-8.
 62. Fan D, Schwartz DM, Vaccaro AR, et al. Intraoperative neurophysiologic detection of iatrogenic C5 nerve root injury during laminectomy for cervical compression myelopathy. *Spine (Phila Pa 1976)* 2002;27:2499-502.
 63. Bose B, Sestokas AK, Schwartz DM. Neurophysiological detection of iatrogenic C-5 nerve deficit during anterior cervical spinal surgery. *J Neurosurg Spine* 2007;6:381-5.
 64. Oya J, Burke JF, Vogel T, et al. The accuracy of multimodality intraoperative neuromonitoring to predict postoperative neurologic deficits following cervical laminoplasty. *World Neurosurg* 2017;106:17-25.
 65. Ando M, Tamaki T, Matsumoto T, et al. Can postoperative deltoid weakness after cervical laminoplasty be prevented by using intraoperative neurophysiological monitoring? *J Clin Monit Comput* 2019;33:123-32.
 66. Nouri A, Martin AR, Mikulis D, et al. Magnetic resonance imaging assessment of degenerative cervical myelopathy: a review of structural changes and measurement techniques. *Neurosurg Focus* 2016;40:E5.
 67. Harrop JS, Naroji S, Maltenfort M, et al. Cervical myelopathy: a clinical and radiographic evaluation and correlation to cervical spondylotic myelopathy. *Spine (Phila Pa 1976)* 2010;35:620-4.
 68. Edwards WC, LaRocca H. The developmental segmental sagittal diameter of the cervical spinal canal in patients with cervical spondylosis. *Spine (Phila Pa 1976)* 1983;8:20-7.
 69. Pavlov H, Torg JS, Robie B, et al. Cervical spinal stenosis: determination with vertebral body ratio method. *Radiology* 1987;164:771-5.
 70. Herzog RJ, Wiens JJ, Dillingham MF, et al. Normal cervical spine morphometry and cervical spinal stenosis in asymptomatic professional football players. Plain film radiography, multiplanar computed tomography, and magnetic resonance imaging. *Spine (Phila Pa 1976)* 1991;16(6 Suppl): S178-86.
 71. Sureka B, Mittal A, Mittal MK, et al. Morphometric analysis of cervical spinal canal diameter, transverse foramen, and pedicle width using computed tomography in Indian

- population. *Neurol India* 2018;66:454-8.
72. Nagata K, Ohashi T, Abe J, et al. Cervical myelopathy in elderly patients: clinical results and MRI findings before and after decompression surgery. *Spinal Cord* 1996;34:220-6.
 73. Muhle C, Metzner J, Weinert D, et al. Classification system based on kinematic MR imaging in cervical spondylitic myelopathy. *AJNR Am J Neuroradiol* 1998;19:1763-71.
 74. Kang Y, Lee JW, Koh YH, et al. New MRI grading system for the cervical canal stenosis. *AJR Am J Roentgenol* 2011;197:W134-40.
 75. Park HJ, Kim SS, Chung EC, et al. Clinical correlation of a new practical MRI method for assessing cervical spinal canal compression. *AJR Am J Roentgenol* 2012;199:W197-201.
 76. Nagata K, Kiyonaga K, Ohashi T, et al. Clinical value of magnetic resonance imaging for cervical myelopathy. *Spine (Phila Pa 1976)* 1990;15:1088-96.
 77. Karpova A, Arun R, Cadotte DW, et al. Assessment of spinal cord compression by magnetic resonance imaging--can it predict surgical outcomes in degenerative compressive myelopathy? A systematic review. *Spine (Phila Pa 1976)* 2013;38:1409-21.
 78. Fukushima T, Ikata T, Taoka Y, et al. Magnetic resonance imaging study on spinal cord plasticity in patients with cervical compression myelopathy. *Spine (Phila Pa 1976)* 1991;16(10 Suppl):S534-8.
 79. Okada Y, Ikata T, Yamada H, et al. Magnetic resonance imaging study on the results of surgery for cervical compression myelopathy. *Spine (Phila Pa 1976)* 1993;18:2024-9.
 80. Waly FJ, Abduljabbar FH, Fortin M, et al. Preoperative computed tomography myelography parameters as predictors of outcome in patients with degenerative cervical myelopathy: results of a systematic review. *Global Spine J* 2017;7:521-8.
 81. Fehlings MG, Rao SC, Tator CH, et al. The optimal radiologic method for assessing spinal canal compromise and cord compression in patients with cervical spinal cord injury. Part II: Results of a multicenter study. *Spine (Phila Pa 1976)* 1999;24:605-13.
 82. Arvin B, Kalsi-Ryan S, Karpova A, et al. Postoperative magnetic resonance imaging can predict neurological recovery after surgery for cervical spondylotic myelopathy: a prospective study with blinded assessments. *Neurosurgery* 2011;69:362-8.
 83. Oshima Y, Seichi A, Takeshita K, et al. Natural course and prognostic factors in patients with mild cervical spondylotic myelopathy with increased signal intensity on T2-weighted magnetic resonance imaging. *Spine (Phila Pa 1976)* 2012;37:1909-13.
 84. Yoshimatsu H, Nagata K, Goto H, et al. Conservative treatment for cervical spondylotic myelopathy. prediction of treatment effects by multivariate analysis. *Spine J* 2001;1:269-73.
 85. Yu L, Zhang Z, Ding Q, et al. Relationship between signal changes on T2-weighted magnetic resonance images and cervical dynamics in cervical spondylotic myelopathy. *J Spinal Disord Tech* 2015;28:E365-7.
 86. Takahashi M, Sakamoto Y, Miyawaki M, et al. Increased MR signal intensity secondary to chronic cervical cord compression. *Neuroradiology* 1987;29:550-6.
 87. Al-Mefty O, Harkey LH, Middleton TH, et al. Myelopathic cervical spondylotic lesions demonstrated by magnetic resonance imaging. *J Neurosurg* 1988;68:217-22.
 88. Flanagan EP, Krecke KN, Marsh RW, et al. Specific pattern of gadolinium enhancement in spondylotic myelopathy. *Ann Neurol* 2014;76:54-65.
 89. Nouri A, Tetreault L, Zamorano JJ, et al. Role of magnetic resonance imaging in predicting surgical outcome in patients with cervical spondylotic myelopathy. *Spine (Phila Pa 1976)* 2015;40:171-8.
 90. Chen CJ, Lyu RK, Lee ST, et al. Intramedullary high signal intensity on T2-weighted MR images in cervical spondylotic myelopathy: prediction of prognosis with type of intensity. *Radiology* 2001;221:789-94.
 91. Karpova A, Arun R, Kalsi-Ryan S, et al. Do quantitative magnetic resonance imaging parameters correlate with the clinical presentation and functional outcomes after surgery in cervical spondylotic myelopathy? A prospective multicenter study. *Spine (Phila Pa 1976)* 2014;39:1488-97.
 92. Nouri A, Tetreault L, Dalzell K, et al. The relationship between preoperative clinical presentation and quantitative magnetic resonance imaging features in patients with degenerative cervical myelopathy. *Neurosurgery* 2017;80:121-8.
 93. Zhang L, Zeitoun D, Rangel A, et al. Preoperative evaluation of the cervical spondylotic myelopathy with flexion-extension magnetic resonance imaging: about a prospective study of fifty patients. *Spine (Phila Pa 1976)* 2011;36:E1134-9.
 94. Takahashi M, Yamashita Y, Sakamoto Y, et al. Chronic cervical cord compression: clinical significance of increased signal intensity on MR images. *Radiology* 1989;173:219-24.

95. Vedantam A, Rajshekhar V. Does the type of T2-weighted hyperintensity influence surgical outcome in patients with cervical spondylotic myelopathy? A review. *Eur Spine J* 2013;22:96-106.
96. Zhang JT, Meng FT, Wang S, et al. Predictors of surgical outcome in cervical spondylotic myelopathy: focusing on the quantitative signal intensity. *Eur Spine J* 2015;24:2941-5.
97. Vedantam A, Jonathan A, Rajshekhar V. Association of magnetic resonance imaging signal changes and outcome prediction after surgery for cervical spondylotic myelopathy. *J Neurosurg Spine* 2011;15:660-6.
98. Mastronardi L, Elsawaf A, Roperto R, et al. Prognostic relevance of the postoperative evolution of intramedullary spinal cord changes in signal intensity on magnetic resonance imaging after anterior decompression for cervical spondylotic myelopathy. *J Neurosurg Spine* 2007;7:615-22.
99. Tetreault LA, Dettori JR, Wilson JR, et al. Systematic review of magnetic resonance imaging characteristics that affect treatment decision making and predict clinical outcome in patients with cervical spondylotic myelopathy. *Spine (Phila Pa 1976)* 2013;38(22 Suppl 1):S89-110.
100. Salem HM, Salem KM, Burget F, et al. Cervical spondylotic myelopathy: the prediction of outcome following surgical intervention in 93 patients using T1- and T2-weighted MRI scans. *Eur Spine J* 2015;24:2930-5.
101. Martin AR, Aleksanderek I, Cohen-Adad J, et al. Translating state-of-the-art spinal cord MRI techniques to clinical use: A systematic review of clinical studies utilizing DTI, MT, MWF, MRS, and fMRI. *Neuroimage Clin* 2015;10:192-238.
102. Mummaneni PV, Kaiser MG, Matz PG, et al. Preoperative patient selection with magnetic resonance imaging, computed tomography, and electroencephalography: does the test predict outcome after cervical surgery? *J Neurosurg Spine* 2009;11:119-29.
103. Ellingson BM, Salamon N, Hardy AJ, et al. Prediction of Neurological Impairment in Cervical Spondylotic Myelopathy using a Combination of Diffusion MRI and Proton MR Spectroscopy. *PLoS One* 2015;10:e0139451.
104. Ellingson BM, Salamon N, Holly LT. Advances in MR imaging for cervical spondylotic myelopathy. *Eur Spine J* 2015; 24 Suppl 2:197-208.
105. Nilsson M, Lätt J, Ståhlberg F, et al. The importance of axonal undulation in diffusion MR measurements: a Monte Carlo simulation study. *NMR Biomed* 2012;25:795-805.
106. Kim CH, Chung CK, Kim KJ, et al. Cervical extension magnetic resonance imaging in evaluating cervical spondylotic myelopathy. *Acta Neurochir (Wien)* 2014;156:259-66.
107. Facon D, Ozanne A, Fillard P, et al. MR diffusion tensor imaging and fiber tracking in spinal cord compression. *AJNR Am J Neuroradiol* 2005;26:1587-94.
108. Mamata H, Jolesz FA, Maier SE. Apparent diffusion coefficient and fractional anisotropy in spinal cord: age and cervical spondylosis-related changes. *J Magn Reson Imaging* 2005;22:38-43.
109. Cheung MM, Li DT, Hui ES, et al. In vivo diffusion tensor imaging of chronic spinal cord compression in rat model. *Conf Proc IEEE Eng Med Biol Soc* 2009;2009:2715-8.
110. Jones JG, Cen SY, Lebel RM, et al. Diffusion tensor imaging correlates with the clinical assessment of disease severity in cervical spondylotic myelopathy and predicts outcome following surgery. *AJNR Am J Neuroradiol* 2013;34: 471-8.
111. Holly LT, Freitas B, McArthur DL, et al. Proton magnetic resonance spectroscopy to evaluate spinal cord axonal injury in cervical spondylotic myelopathy. *J Neurosurg Spine* 2009;10:194-200.
112. Kolcun JP, Chieng LO, Madhavan K, et al. The role of dynamic magnetic resonance imaging in cervical spondylotic myelopathy. *Asian Spine J* 2017;11:1008-15.