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ORIGINAL ARTICLE

Predictive factors for neurological deterioration after surgical decompression for thoracic ossified yellow ligament

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Abstract
Purpose To investigate the rate and predictive factors of post-operative neurological deterioration in ossified yellow ligament (OYL) surgery.
Methods A retrospective review was conducted for all patients with thoracic OYL causing myelopathy requiring surgical decompression from January 1998 to December 2012. Clinical parameters under study included clinical presentation, distribution of OYL, pre-operative walking score, pre- and post-operative neurological status, status of intra-operative neurophysiological monitoring, and modified Japanese Orthopaedic Association (mJOA) score. Any complications were also recorded. All outcomes were measured at post-operative 1 week and at 2 years.
Results A total of 26 patients were included in this study. Most patients (92.3%) had Frankel grade D pre-operatively. The rate of neurological deterioration was 15.4% and was correlated with the presence of dural tear, extra-dural hematoma and spinal cord injury. Pre-operative walking score was prognostic of patients' walking ability in the post-operative period. Intra-operative monitoring of Somatosensory Evoked Potentials (SSEP) was found to be useful for monitoring spinal cord injury in OYL surgery, with a positive predictive value of 100% and a negative predictive value of 92.3%. The false negative rate of a SSEP signal drop was only 7.7%
Conclusions This is the first study exploring risk factors for post-operative neurological deterioration after surgery for thoracic OYL. The rate of neurological deficit is not small and prognostic factors for poor outcome include poor pre-operative walking score, presence of intra-operative dural tear, extra-dural hematoma and spinal cord injury, and intra-operative drop of SSEP signal.

Keywords Ossified yellow ligament · Surgery · Neurological deterioration

Introduction

Ossified yellow ligament (OYL), also known as ossified ligamentum flavum (OLF), is a common cause of thoracic myelopathy [1–4]. Aizawa et al. [3] reported that up to 75% of thoracic myelopathies are caused by OYL. The development of OYL is a result of endochondral ossification of the ligamentum flavum [5] (Fig. 1), which causes subsequent compressive myelopathy. Many possible factors have been described in the literature as the cause of endochondral ossification in OYL such as mechanical stress [5], overproduction of bone morphogenetic proteins (BMPs) 2, 4 and 7 and transforming growth factor-ß (TGF-ß) [6]. Patients with OYL also have a higher prevalence of obesity, diabetes mellitus, hyperinsulinism and impaired glucose tolerance [7].

This condition appears to be more common in Asian populations as evidenced by the majority of OYL studies published from the region [3, 8–13]. In one population-based study, the overall prevalence was reported to be 3.8% within a southern Chinese population [11]. Yet,

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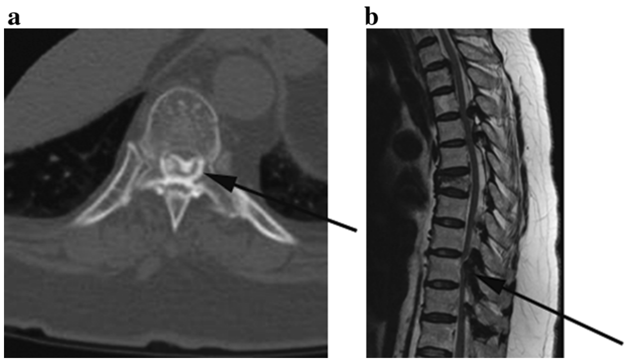

Fig. 1 Axial CT scan (**a**) and sagittal MRI (**b**) showing an example of OYL with dural ossification. Note the 'comma sign' as showed by the *arrow*. Intra-operatively, there was severe dural ossification with the dura merging with the OYL. Patch repair with fascia and fat was performed after decompression

despite these epidemiological studies, there is limited clinical information regarding post-operative outcomes and complications [2, 3, 8]. Despite not being discussed in the literature, many surgical complications are well known to surgeons with regards to thoracic OYL surgery, including epidural hematoma, dural tear and spinal cord injury. Dural ossification increases the chance of dural tear during laminectomy [14]. In a series of 110 patients undergoing multilevel laminectomies with no posterolateral fusion by Epstein [15], 10 patients developed dural tears and all 10 (100%) had corresponding levels of OYL. Three patients (30%) had ossification extending to and through the dura in the lumbar levels. Thus OYL operations are high risk for dural tear, especially when associated with dural adhesions [15]. A study by Kawaguchi et al. [13] examined the variables affecting postsurgical prognosis for thoracic OYL in a Japanese population. However, the neurological outcome was only studied as a collective Japanese Orthopaedic Association (JOA) score without further analyzing the specific subtype of neurological outcome, such as motor or sensory improvement and walking ability.

Overall, there is only limited information for neurologic outcomes and its predictors, and it is the authors' impression that patients with thoracic myelopathy secondary to OYL are at particular high risk for neurologic deterioration after surgery. Thus, the aim of this study was to evaluate our experience in management of thoracic myelopathy caused by OYL with specific reference to post-operative neurologic outcome and its associated factors.

Materials and methods

A retrospective review was conducted, assessing myelopathic patients with surgically treated thoracic OYL from January 1998 to December 2012 in a single center. Ethics was approved by the local institutional review board. Only patients with thoracic myelopathy caused by OYL were included. Other involved regions and spine pathologies including infection, tumors and previous reoperations were excluded.

Presentation

Clinical parameters including patient age, gender, mean time of presentation of symptoms to operation and presenting symptoms were collected. Spinal levels of OYL were assessed and classified into upper, middle and lower thoracic segments. The upper thoracic segment referred to T1–4, the middle thoracic segment referred to T5–8 and the lower thoracic segment referred to T8–12 [11]. The extensiveness of OYL was assessed by pre-operative CT scan and MRI.

Surgical technique

All patients were operated by three surgeons with more than 15 years of surgical experience. For all patients, after exposure of the posterior elements, a laminotomy is performed cranial and caudal to the compression level or at the "normal zone" before working towards the location of the OYL. The laminae over the OYL is thinned by a high-speed burr until it becomes "paper-thin". If a cleavage plane exists between the dura and OYL, a small dissector is used to peel off the thin remaining piece of OYL. If it is not possible to separate it from the dura, it can be left as a floating piece by detaching it from the remaining laminae and facet joint. If the dura is ossified and merged with the OYL, it is removed with the OYL by incising the dura mater while preserving the subarachnoid layer. Thereafter, a piece of fascia is harvested locally for patch repair of the dural defect. Usually if the facet capsule is also ossified, more of the facets will be removed, thus causing instability requiring instrumented fusion.

Neurological status

Patients were examined at initial (pre-operative), post-operative 1 week and 2 years for lower limb motor power, sensation, sphincter function and walking abilities. The walking ability is often affected in OYL patients and has significant impact on patients' activities of daily living. Thus, an objective criterion was needed to quantify the walking disability. The authors adopted a simple walking score grading scale for this study: score 0: cannot walk; score 1: unstable walking requiring aids for support; score 2: walking unaided with subjective instability; score 3: normal walking. Other objective assessments included the modified Japanese Orthopaedic Association (mJOA) score and the Frankel grading [16] for the initial and post-operative neurological status.

Neurophysiological monitoring

Intra-operative use of somatosensory evoked potentials (SSEP) for neurological monitoring was routinely performed by a neurophysiologist with at least 5 years of experience. Any additional motor evoked potential (MEP) monitoring performed was also recorded. Any amplitude drop of more than 50% from baseline was considered significant and recorded [17–19].

Outcome measures

Outcome measures included immediate (within 1 week post-operatively) and 2-year post-operative neurological recovery. Parameters under study included lower limb motor power, sensation, sphincter function and walking abilities, mJOA score, change in mJOA score, the presence of motor or sensory deficit and the presence of post-operative complications. Motor improvement was defined as muscle power improvement of at least 1 grade in at least 1 myotome of lower limbs by the MRC (Medical Research Council) grading [20]. Sensory improvement was defined as decrease in the area of numbness or decrease in severity of numbness within the same area of involvement. Neurological improvement was defined as either motor or sensory improvement. Any complications were also recorded.

Statistical analysis

Descriptive data were presented by means, ranges and standard deviation (SD). Statistical analysis was performed with Chi-squared test for discrete variables (pre- and post-operative neurological outcome) and analysis of variance (ANOVA) for multiple continuous variables (mJOA for upper, middle and lower thoracic OYL). Fisher's exact test was used if the variable numbers were less than five (neurological deterioration). Dependent *t* test was used to compare the means of two related groups (pre-operative and post-operative walking score, mJOA). A *p* value of <0.05 was considered significant. For analysis of SSEP with neurological outcome, a 2×2 table was used to calculate the sensitivity, specificity, positive predictive value and negative predictive value. Sensitivity (true positive rate) was defined as those patients who had significant intra-operative drop in SSEP signal and had neurological deterioration in the immediate post-operative period. Specificity (true negative rate) was defined as those who had no change in SSEP intra-operatively and did not have any neurological deterioration. Positive predictive value was calculated as the proportion of people with significant intra-operative signal drop who had spinal cord injury. Negative predictive value was calculated as the proportion of people without significant intra-operative signal drop who did not have spinal cord injury.

Results

A total of 26 patients (16 males and 10 females) were included in the study. The mean age was 58 years (range 38–84 years, SD 12.4 years). The mean time of symptom presentation to operation was 9.3 months (range from 0.5 to 48 months, SD 13.0 months). All patients underwent decompression surgery, and instrumented fusion was performed if intra-operative destabilization was evidenced after decompression. Instrumented fusion was performed in 5 out of the 26 patients due to iatrogenic instability to clear the OYL lesion with lateral separation.

Presentation

All patients presented with bilateral lower limb numbness. Seventeen patients (65.4%) had bilateral lower limb weakness and 1 patient (3.8%) had sphincter disturbance at initial presentation. Majority (92.3%) of patients were Frankel grade D (Fig. 2) at presentation. There were 7 spinal levels (21.2%) of OYL found in the upper thoracic segment, 6 (18.2%) in the middle thoracic segment and 20 (60.6%) in the lower thoracic segment. A total of 12 patients (46.2%) had single-level disease, 7 patients (26.9%) had OYL affecting 2 levels and 7 patients (26.9%) had OYL affecting 3 levels or more.

Neurological status

Regarding the pre-operative walking score, 7 patients (26.9%) had score of 0, 12 patients (46.2%) had score of 1 and 7 patients (26.9%) had score of 2. Post-operatively at 2-year follow-up, 4 patients (15.4%) had walking score of

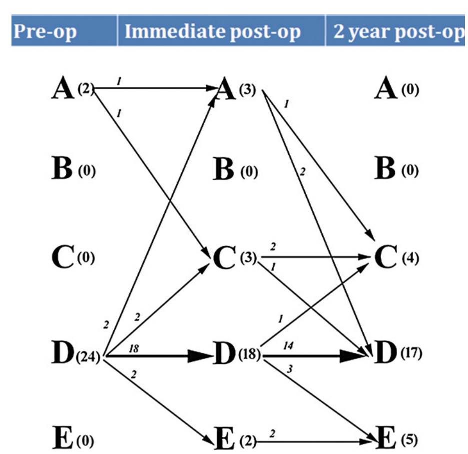

Fig. 2 Frankel grade distribution in our series. Number of patients in each grade is *highlighted by parenthesis*. Majority were Frankel grade D on presentation and most improved after operation

Table 1 Summary of the neurological status

Category	Immediate post-operative (%)	2 year post-operative (%)	*p* values
Motor improvement	11 patients (42.3%)	14 patients (53.8%)	<0.001
Sensory improvement	19 patients (73.1%)	24 patients (92.3%)	0.065
Sphincter function	The only 1 patient presented with sphincter disturbance had control of sphincter function immediately after operation		N/A
Walking ability improvement	8 patients (30.8%)	16 patients (61.5%)	0.099
Neurological improvement	21 patients (80.8%)	24 patients (92.3%)	0.031
Residual motor deficit	15 patients (57.7%) (6 less severe)	10 patients (38.5%) (4 less severe)	0.014
Residual sensory deficit	19 patients (73.1%) (16 less severe)	14 patients (53.8%) (12 less severe)	1.000

0, 11 patients (42.3%) had score of 1 and 11 patients (42.3%) had score of 3.

Majority of patients had significant motor, sensory and neurological improvements in the immediate (within 1 week post-operatively) post-operative period, and further improved in the 2-year post-operative period. Similar improvements were seen for sphincter function and walking abilities (Table 1).

Patients with OYL at the upper thoracic segment had the least improvement in the mean post-operative mJOA score, followed by the lower thoracic segment. The middle thoracic segment had the largest improvement in the mJOA score (Table 2). Multiple levels of OYL had the least improvement in mJOA score, followed by single-level and 2-level involvement. In patients who had pre-operative walking score of 0, 71.4% (5/7) had score of 1 at 2-year follow-up; whereas in patients who had pre-operative walking score of 2, 85.7% (6/7) had score of 3 at 2-year follow-up. This suggested that patients with higher walking ability pre-operatively were more likely to have a better walking ability post-operatively.

The mean mJOA score was 7.0 ± 1.4 pre-operatively, whereas it was 8.5 ± 2.2 post-operatively ($p < 0.05$). There was a significant difference between the pre- and post-operative walking score ($p < 0.01$) according to the dependent t test. Associations between the presence of neurological deterioration, age and duration of symptoms were tested. Due to the mean age of 58 years, patients were stratified into <60 years and ≥60 years for analysis. Fisher's exact test was $p = 1$ when testing associations between the presence of neurological deterioration and age. A cut-off of 12 months was used for studying the duration of symptoms and a p value of 0.54 was generated for associations between neurological deterioration and duration of symptoms. Hence, no association between the neurological outcome after operation, age and symptom duration was detected.

Neurophysiological monitoring

The role of intra-operative neurophysiological monitoring was also investigated. SSEP monitoring was performed for 22 patients (Table 3). However, MEP monitoring was only performed for 2 patients and thus was not used for statistical analysis. One patient who had no change in MEP intra-operatively did not have any neurological deterioration (true negative). The other patient had complete disappearance of both SSEP and MEP intra-operatively and had neurological deterioration in the immediate post-operative period (true positive).

The absence of any significant intra-operative drop of SSEP predicted 2-year sensory improvement ($p = 0.048$). The false negative rate of a drop in SSEP signal was 7.7%. Failure to detect any signal pre-operatively was not associated with poor neurological outcome. In our series, SSEP monitoring for spinal cord injury in OYL surgery had a sensitivity of 50%, specificity of 100%, positive predictive value of 100% and negative predictive value of 92.3%.

Risk factors for post-operative neurological deterioration

Four patients (15.4%) had immediate neurological deterioration post-operatively. Neurological deterioration was associated with the presence of post-operative complications, namely dural tear, extra-dural hematoma and spinal cord injury ($p = 0.01$). In our series, there were in total five patients (19.2%) with post-operative complications and these included two dural tears, one wound infection, one extra-dural hematoma and one spinal cord injury. Only three (dural tear, extra-dural hematoma and spinal cord injury) of these five patients (60%) had immediate post-operative neurological deterioration. All of the patients with complications nevertheless had residual symptoms at post-operative 2 years (2 had residual motor

Table 2 Mean mJOA score changes at different levels of OYL

Region of OYL	Pre-operative mJOA	2 years post-operative mJOA	Mean mJOA change	*p* values
Upper thoracic	7	7.3	0.3	0.02
Middle thoracic	7.7	10.0	2.3	<0.05
Lower thoracic	6.9	8.5	1.6	0.06

mJOA modified Japanese Orthopaedic Association, *OYL* ossified yellow ligament

Table 3 Intra-operative SSEP monitoring for spinal cord injury (22 out of 26)

	Unrecordable pre-op	Intra-op significant drop	Intra-op no significant drop
No neurological deterioration	7	0	12
Neurological deterioration	1	1	1

p value = 0.22

deficit, 4 had residual sensory deficit). All were Frankel grade D (Fig. 2) at 2-year follow-up. No statistical significant relationship could be drawn between the presence of complications and residual neurological symptoms at 2-year follow-up ($p = 0.10$). All of the patients who experienced immediate neurological deterioration had residual symptoms at post-operative 2 years (50% patients had less severe than pre-operative status, but both of them were still Frankel grade D).

Discussion

This is the first study to analyze the incidence and possible risk factors of post-operative neurological deterioration and complications after surgical decompression for thoracic OYL. Results show that neurological deterioration was significantly associated with the presence of complications. Pre-operative walking score showed good prediction of post-operative functional outcome and intra-operative SSEP monitoring was a useful tool to monitor spinal cord injury in OYL surgery.

In our series, all patients have bilateral lower limb numbness on presentation. Consistent with Guo et al. [11], our study showed that the lower thoracic spine (T9-12) was most commonly affected (60.6%). This may be due to less anatomic protection from the rib cage, and thus more prone to degeneration because of high tensile forces present in the posterior column. Further study should be carried out to verify this.

The rate of neurological deterioration was 15.4% and correlated with the presence of complications, namely dural tear, extra-dural hematoma and spinal cord injury. A multivariate analysis for all spine surgery in 2012 [21] suggested that revision surgery, advanced age, and degenerative disease were significant risk factors for dural tears. Although that study was based on all spine surgeries and not specific to OYL causing thoracic myelopathy, it is important to stress that surgeons should be more alert during surgery to avoid dural tear when the above risk factors are present. Dural adhesions in OYL are common and thus, the decompression should be performed cautiously. Adhesions occur as a result of chronic and severe compressions and thus dural tears not only indicate a surgical complication, it also suggests that the neural tissue has been compromised for a prolonged period of time. Dural ossification (Fig. 1) is a further extreme from adhesions and this further increases the risk of dural tear in laminectomy [15]. Thus, pre-operative identification of this is very important using CT imaging. In the bone window of axial CT scans, 2 radiological hallmarks of dural ossification in OYL can be identified as described by Muthukumar [22]. The 'comma sign' is characterized by ossification of one-half of the circumference of the dura and the 'tram track sign' consists of a hyperdense bony excrescence with a hypodense centre. Two methods are commonly employed intra-operatively to decrease the chance of dural tear in dural ossification. In the first method (slitting the dura), the dura mater is incised using a knife blade and nerve stripper to visualize the spinal cord. If possible, the arachnoid layer is preserved to avoid CSF leak. The void between the ossification and the spinal cord is utilized to excise the entire ossification. Small dural defects are directly sutured while large defects required patch repair. In the second method (floating the dura), the entire ossification is thinned as much as possible using a high-speed burr. The dura is dissociated from the ossification to cause it to bulge naturally. Sun et al. [23] compared 33 patients who underwent surgery with either method and found no significant differences between them in terms of post-operative mJOA score. The risk of dural tear may be decreased with the above methods and the risk can be predicted in pre-operative imaging. Nevertheless, the presence of these dural changes indicate a more technically demanding surgery and higher risk of neurological complications. This relationship between dural tears and poor neurological outcomes is also relevant to ossification of the posterior longitudinal ligament (OPLL) in the thoracic spine.

Similarly to OYL, direct decompression through the ossified ligament is high risk for dural tear, cerebrospinal fluid leakage and neurologic deficit [24]. However, unlike OYL, indirect decompression through a posterior approach is possible allowing for a less risky surgical option.

In addition to dural tear as an important risk factor for neurological complications, a previous report has also shown that for combined OYL and OPLL surgery, >70% occupancy ratio of the OYL to spinal canal, intraoperative bleeding >800 mL, and mean arterial pressure <81 mmHg are important risk parameters [25]. In our study, the neurological deterioration was not predicted by age, duration of symptoms and pre-operative mJOA score. Regarding the surgical outcomes from previous studies, patients with lower pre-operative mJOA have a lower post-operative mJOA score [8], which is consistent with our study. We found that the pre-operative walking score, described in this study, showed prognostic value in determining future walking status. Spastic gait is the most disturbing symptom affecting a patient's daily function and the authors believe that the walking score can reflect the patient's functional activities. Furthermore, it is an easy-to-use score which the authors suggest for clinicians to routinely use. Since a higher pre-operative walking score predicts higher post-operative walking score, earlier surgery may be able to gain a more satisfactory outcome. However, this concept can only be validated with prospective studies.

As described in our surgical approach, our patients underwent surgery via conventional open posterior approach with adequate laminectomy to expose the normal tissues cranial and caudal to the OYL before thinning and attempted excision. However, there are other alternatives to the surgical technique described in the literature. Baba et al. [26] reported a series of 9 patients undergoing microendoscopic posterior decompression for thoracic OYL with planned floating technique. Yet, this technique lacks versatility as compared to an open approach. The indications are narrow and may be only applicable to single-level round OYL and without comma and tram track signs. In addition, the learning curve is steeper for microendoscopic posterior decompression. Nevertheless, the fundamental objective of OYL surgery is to achieve adequate exposure to visualize and remove the OYL while having enough flexibility in the surgical field to deal with complications such as dural tear. Avoidance of neurological deterioration is of utmost importance in these high risk surgeries. An additional technique described for more severe and extensive OYL is segmental en bloc resection of the posterior wall of the thoracic canal. Although a technically demanding procedure, it has been shown to be a safe and effective alternative [27].

Our study highlights specifically the use of SSEP as intra-operative neurophysiological monitoring for neurological deterioration. False negative rates are shown to be low. In our series, only one patient who had no significant intra-operative drop of SSEP signal experienced neurological deterioration post-operatively, giving a false negative rate of 7.7% (1 out of 13). In OYL surgery, SSEP for intra-operative spinal cord injury monitoring has a sensitivity of 50%, specificity of 100%, positive predictive value of 100% and negative predictive value of 92.3%. Previous studies of intra-operative SSEP monitoring proposed sensitivities ranging from 0% [28] to 100% [29–31] and specificitities ranging from 27% [32] to 100% [9] for detecting intra-operative spinal cord injury. The positive predictive value ranged from 15% [33] to 100% [9]. and the negative predictive value was 100% in one study [31]. One previous study suggested a false-negative rate of 9% in SSEP monitoring which was similar to our results [28]. These studies, however, were based on all spinal operations collectively and none of them assessed the usage of SSEP specifically in thoracic myelopathy caused by OYL. A relatively low sensitivity with a high specificity of SSEP should alert the surgeons to identify the cause of the spinal cord injury whenever there is a significant drop in SSEP during OYL surgery. The false negative rate for SSEP monitoring in OYL surgery is relatively low. Thus, our findings suggest that SSEP is useful for monitoring in OYL surgery and the false negative rate is no worse than other spinal surgeries.

As only two subjects received intra-operative MEP monitoring, we could not draw any conclusion regarding its role in OYL surgery. However, it was interesting to look into the outcomes of the two subjects who did have MEP monitoring. One patient had both SSEP and MEP monitoring intra-operatively. There was no signal drop and there was no neurological deterioration post-operatively. The other patient had complete disappearance of both SSEP and MEP intra-operatively and had neurological deterioration in the immediate post-operative period. A recent multicenter study [34] showed that the sensitivity, specificity and false positive rates for MEP alone are 82%, 94% and 6.4%, respectively. The authors in that study suggested that the most accurate modality combination is MEP and Br-SCEP (cord evoked potential after stimulation to the brain) with sensitivity of 90%, specificity of 94% and false positive rate of 6.1%. The accuracy of predicting neurological deficit using MEP combined with SSEP requires further study.

Nevertheless, there are some limitations to this study including its small sample size and retrospective design. Due to the study design, some of the important pre-operative parameters including pre-operative proprioception test and ankle clonus were not retrievable. Previous studies suggested that big toe proprioception impairment [13] and ankle clonus [35] were associated with poorer surgical outcome but unfortunately this information could not be retrieved for analysis in this study. The predictability of a pre-operative prone test (duration at which patient is able to lie in prone position before symptom deterioration) for post-operative outcomes should also be tested. Due to the small number of cases with instrumented fusion, further analysis was not performed, but this should be addressed in future work. Nevertheless, all operating surgeons were very experienced and hence, the inter-operator variations were reduced to a minimum. For neuromonitoring, only drops in signal amplitude regarding intra-operative SSEP monitoring were recorded while increases in latency and MEP monitoring are also pertinent and should be studied. Although it is now routine to perform both MEP and SSEP monitoring, for some of the historical cases presented in this study, performing MEP was not routine. Hence, the predictive factors proposed require further validation in a prospective manner.

Conclusions

This study specifically addresses the issue of neurologic outcome after surgery for thoracic myelopathy caused by OYL. Study results show that the complication rate for OYL surgery is not low and post-operative neurological outcome in the presence of non-neurological complications is poor. Pre-operative walking score, intra-operative dural tear, hematoma formation and drop in SSEP signal are potential predictive risk factors that warrant future attention. This is also the first series to investigate the accuracy of SSEP to detect intra-operative spinal cord injury for OYL surgery. All patients are suggested to have intra-operative SSEP monitoring despite the small false negative rate.

Compliance with ethical standards

Conflict of interest None of the authors has any potential conflict of interest.

References

1. Mohindra S, Chhabra R, Mukherjee KK, Gupta SK, Vaiphei K, Khosla VK (2006) Spinal compression due to ossified yellow ligament: a short series of 5 patients and literature review. Surgical neurology 65:377–384. doi:10.1016/j.surneu.2005.10.026 **(discussion 384)**
2. Mohindra S, Gupta R, Chhabra R, Gupta SK (2011) Compressive myelopathy due to ossified yellow ligament among South Asians: analysis of surgical outcome. Acta Neurochir 153:581–587. doi:10.1007/s00701-010-0904-2
3. Aizawa T, Sato T, Sasaki H, Matsumoto F, Morozumi N, Kusakabe T, Itoi E, Kokubun S (2007) Results of surgical treatment for thoracic myelopathy: minimum 2-year follow-up study in 132 patients. J Neurosurg Spine 7:13–20. doi:10.3171/spi-07/07/013
4. Payer M, Bruder E, Fischer JA, Benini A (2000) Thoracic myelopathy due to enlarged ossified yellow ligaments. Case report and review of the literature. J Neurosurg 92:105–108
5. Yoshida M (2006) Pathology of Ossification of the Ligamentum Flavum
6. Hayashi K, Ishidou Y, Yonemori K, Nagamine T, Origuchi N, Maeda S, Imamura T, Kato M, Yoshida H, Sampath TK, ten Dijke P, Sakou T (1997) Expression and localization of bone morphogenetic proteins (BMPs) and BMP receptors in ossification of the ligamentum flavum. Bone 21:23–30
7. Takeuchi Y, Matsumoto T, Takuwa Y, Hoshino Y, Kurokawa T, Shibuya N, Ogata E (1989) High incidence of obesity and elevated serum immunoreactive insulin level in patients with paravertebral ligamentous ossification: A relationship to the development of ectopic ossification. J Bone Miner Metab 7:17–21
8. Aizawa T, Sato T, Sasaki H, Kusakabe T, Morozumi N, Kokubun S (2006) Thoracic myelopathy caused by ossification of the ligamentum flavum: clinical features and surgical results in the Japanese population. J Neurosurg Spine 5:514–519. doi:10.3171/spi.2006.5.6.514
9. Khan MH, Smith PN, Balzer JR, Crammond D, Welch WC, Gerszten P, Sclabassi RJ, Kang JD, Donaldson WF (2006) Intraoperative somatosensory evoked potential monitoring during cervical spine corpectomy surgery: experience with 508 cases. Spine 31:E105–E113. doi:10.1097/01.brs.0000200163.71909.1f
10. Kang KC, Lee CS, Shin SK, Park SJ, Chung CH, Chung SS (2011) Ossification of the ligamentum flavum of the thoracic spine in the Korean population. J Neurosurg Spine 14:513–519. doi:10.3171/2010.11.spine10405
11. Guo JJ, Luk KD, Karppinen J, Yang H, Cheung KM (2010) Prevalence, distribution, and morphology of ossification of the ligamentum flavum: a population study of one thousand seven hundred thirty-six magnetic resonance imaging scans. Spine 35:51–56. doi:10.1097/BRS.0b013e3181b3f779
12. Miyakoshi N, Shimada Y, Suzuki T, Hongo M, Kasukawa Y, Okada K, Itoi E (2003) Factors related to long-term outcome after decompressive surgery for ossification of the ligamentum flavum of the thoracic spine. J Neurosurg 99:251–256
13. Kawaguchi Y, Yasuda T, Seki S, Nakano M, Kanamori M, Sumi S, Kimura T (2013) Variables affecting postsurgical prognosis of thoracic myelopathy caused by ossification of the ligamentum flavum. Spine J Off J North Am Spine Soc 13:1095–1107. doi:10.1016/j.spinee.2013.03.001
14. Sun X, Sun C, Liu X, Liu Z, Qi Q, Guo Z, Leng H, Chen Z (2012) The frequency and treatment of dural tears and cerebrospinal fluid leakage in 266 patients with thoracic myelopathy caused by ossification of the ligamentum flavum. Spine 37:E702–E707. doi:10.1097/BRS.0b013e31824586a8
15. Epstein NE (2007) The frequency and etiology of intraoperative dural tears in 110 predominantly geriatric patients undergoing multilevel laminectomy with noninstrumented fusions. J Spinal Disord Techn 20:380–386. doi:10.1097/BSD.0b013e31802dabd2
16. Frankel HL, Hancock DO, Hyslop G, Melzak J, Michaelis LS, Ungar GH, Vernon JD, Walsh JJ (1969) The value of postural reduction in the initial management of closed injuries of the spine with paraplegia and tetraplegia. I. Paraplegia 7:179–192. doi:10.1038/sc.1969.30
17. Forbes HJ, Allen PW, Waller CS, Jones SJ, Edgar MA, Webb PJ, Ransford AO (1991) Spinal cord monitoring in scoliosis surgery. Experience with 1168 cases. J Bone Joint Surg Br 73:487–491

18. Jones SJ, Edgar MA, Ransford AO, Thomas NP (1983) A system for the electrophysiological monitoring of the spinal cord during operations for scoliosis. J Bone Joint Surg Br 65:134–139
19. Ney JP, van der Goes DN (2012) Evidence-based guideline update: Intraoperative spinal monitoring with somatosensory and transcranial electrical motor evoked potentials. Report of the therapeutics and technology assessment subcommittee of the american academy of neurology and the american clinical neurophysiology society. Neurology 79:292. doi:10.1212/WNL.0b013e3182637c24 **(author replies 292–294)**
20. Council MR (1976) Aids to examination of the peripheral nervous system. Memorandum no 45 London: Her Majesty's Stationary Office
21. Baker GA, Cizik AM, Bransford RJ, Bellabarba C, Konodi MA, Chapman JR, Lee MJ (2012) Risk factors for unintended durotomy during spine surgery: a multivariate analysis. Spine J Off J North Am Spine Soc 12:121–126. doi:10.1016/j.spinee.2012.01.012
22. Muthukumar N (2009) Dural ossification in ossification of the ligamentum flavum: a preliminary report. Spine 34:2654–2661. doi:10.1097/BRS.0b013e3181b541c9
23. Sun J, Zhang C, Ning G, Li Y, Li Y, Wang P, Feng S (2014) Surgical strategies for ossified ligamentum flavum associated with dural ossification in thoracic spinal stenosis. J Clin Neurosci Off J Neurosurg Soc Australasia 21:2102–2106. doi:10.1016/j.jocn.2014.02.027
24. Xu N, Yu M, Liu X, Sun C, Chen Z, Liu Z (2015) A systematic review of complications in thoracic spine surgery for ossification of the posterior longitudinal ligament. Eur Spine J Off Publ Eur Spine Soc Eur Spinal Deform Soc Eur Sect Cerv Spine Res Soc. doi:10.1007/s00586-015-4097-5
25. Wang H, Ma L, Xue R, Yang D, Wang T, Wang Y, Yang S, Ding W (2016) The incidence and risk factors of postoperative neurological deterioration after posterior decompression with or without instrumented fusion for thoracic myelopathy. Medicine 95:e5519. doi:10.1097/md.0000000000005519
26. Baba S, Oshima Y, Iwahori T, Takano Y, Inanami H, Koga H (2016) Microendoscopic posterior decompression for the treatment of thoracic myelopathy caused by ossification of the ligamentum flavum: a technical report. Eur Spine J Off Publ Eur Spine Soc Eur Spinal Deform Soc Eur Sect Cerv Spine Res Soc 25:1912–1919. doi:10.1007/s00586-015-4158-9
27. Wang T, Yin C, Wang D, Li S, Chen X (2017) Surgical technique for decompression of severe thoracic myelopathy due to tuberous ossification of ligamentum flavum. Clin Spine Surg 30:E7-e12. doi:10.1097/bsd.0000000000000213
28. Deutsch H, Arginteanu M, Manhart K, Perin N, Camins M, Moore F, Steinberger AA, Weisz DJ (2000) Somatosensory evoked potential monitoring in anterior thoracic vertebrectomy. J Neurosurg 92:155–161
29. Papastefanou SL, Henderson LM, Smith NJ, Hamilton A, Webb JK (2000) Surface electrode somatosensory-evoked potentials in spinal surgery: implications for indications and practice. Spine 25:2467–2472
30. Stechison MT, Panagis SG, Reinhart SS (1995) Somatosensory evoked potential. Monitoring during spinal surgery. Acta Neurochirurgica 135:56–61
31. Leung YL, Grevitt M, Henderson L, Smith J (2005) Cord monitoring changes and segmental vessel ligation in the "at risk" cord during anterior spinal deformity surgery. Spine 30:1870–1874
32. May DM, Jones SJ, Crockard HA (1996) Somatosensory evoked potential monitoring in cervical surgery: identification of pre- and intraoperative risk factors associated with neurological deterioration. J Neurosurg 85:566–573. doi:10.3171/jns.1996.85.4.0566
33. Manninen PH (1998) Monitoring evoked potentials during spinal surgery in one institution. Canadian J Anaesthesia = J canadien d'anesthesie 45:460–465. doi:10.1007/bf03012582
34. Ito Z, Matsuyama Y, Ando M, Kawabata S, Kanchiku T, Kida K, Fujiwara Y, Yamada K, Yamamoto N, Kobayashi S, Saito T, Wada K, Satomi K, Shinomiya K, Tani T (2016) What is the best multimodality combination for intraoperative spinal cord monitoring of motor function? A Multicenter study by the monitoring committee of the Japanese Society for spine surgery and related research. Global Spine J 6:234–241. doi:10.1055/s-0035-1559582
35. He S, Hussain N, Li S, Hou T (2005) Clinical and prognostic analysis of ossified ligamentum flavum in a Chinese population. J Neurosurg Spine 3:348–354. doi:10.3171/spi.2005.3.5.0348