Neurophysiologie Clinique / Clinical Neurophysiology 54 (2024) 103022

Contents lists available at ScienceDirect

Neurophysiologie Clinique

journal homepage: www.elsevier.com/locate/neucli

Original article

# Transcranial MEPs predict clinical outcome during minimally invasive dorsal decompression for cervical spondylotic myelopathy

Fares Komboz [a], Fabian Kück [b], Silvia Hernández-Durán [a], Ingo Fiss [a], Xenia Hautmann [a], Dorothee Mielke, Prof. [a,c], Veit Rohde, Prof. [a], Tammam Abboud [a,*]

[a] Department of Neurosurgery, University Medical Center Göttingen, Robert-Koch-Straße 40 37075 Göttingen, Germany
[b] Department of Medical Statistics, University Medical Center Göttingen, Robert-Koch-Straße 40 37075 Göttingen, Germany
[c] Department of Neurosurgery, University Hospital Augsburg, Stenglinstr. 2, 86156 Augsburg, Germany

ARTICLE INFO

*Keywords:*
Cervical spondylotic myelopathy
Intraoperative monitoring
Motor evoked potentials
Surgical decompression
Threshold criterion
Threshold level

ABSTRACT

*Objectives:* Motor evoked potential (MEP) monitoring is a reliable method for real-time assessment of corticospinal tract integrity. However, the potential benefits of MEP monitoring during degenerative spine surgery remain controversial. This study aims to determine the role of MEP monitoring during surgery for cervical spondylotic myelopathy (CSM) in prediction of prognosis.
*Methods:* Transcranial electrical stimulation was performed to elicit MEPs during dorsal decompression for the treatment of CSM. MEP-threshold levels were assessed separately at the beginning and end of the surgery in upper extremity muscles corresponding to nerve roots at the level of/distal to the decompression site. Clinical outcome was measured using the modified Japanese Orthopedic Association score (mJOA).
*Results:* The study included 47 patients. 31 patients (66 %) showed improvements in neurological function at discharge. A measurable improvement in the majority of tested muscles, or in at least one muscle group, in a given patient highly correlated with mJOA score increase at discharge ($p < 0.001$) with an odds ratio of 10.3 (CI:2.6–34.4) and 11.4 (CI:2.8–41.3), respectively. Conversely, MEP deterioration was not associated with worse clinical outcome, nor was it predictive of failure to recover.
*Conclusion:* MEP improvement during CSM surgery seems to be highly predictive of early postoperative neurological recovery and could indicate subclinically enhanced signal conduction. This highlights the potential of MEP monitoring as an intraoperative, real-time predictive tool for clinical recovery after decompression in patients with CSM.

## Introduction

Intraoperative neuromonitoring (IONM), particularly the use of motor evoked potentials (MEPs), has become an indispensable tool in the realm of modern cranial and spinal neurosurgery, heralded for its capacity to assess the integrity of the corticospinal tract with remarkable precision in real-time [16,28]. This capability is crucial, as it aids in the prevention and prediction of postoperative motor deficits, thereby enhancing surgical outcomes [5,9,10,16]. While the efficacy of MEP monitoring has been extensively documented and validated within the scope of tumor resections in both the brain and spinal cord [3,11], its application and added value in the context of degenerative spinal surgeries, such as those addressing cervical spondylotic myelopathy (CSM), remain subjects of ongoing debate and investigation.

The discussion around the utility of MEP, in comparison to somatosensory evoked potentials (SSEP) during spinal surgeries, brings to light the potential advantages of MEP in the early detection and prevention of motor tract injuries, particularly in surgeries involving the cervical spine [13,25,27]. This is of paramount importance in the treatment of CSM, a condition characterized by the narrowing of the spinal canal due to degenerative changes in the cervical spine, leading to a spectrum of neurological impairments. As the most prevalent cause of spinal cord dysfunction in the elderly, CSM presents a significant clinical challenge, with surgical decompression through anterior or posterior approaches being the cornerstone of treatment [15,22]. The efficacy of such interventions in not only halting disease progression but also in facilitating neurological recovery has been increasingly recognized [6].

Given this backdrop, the current study introduces a novel threshold

* Corresponding author.
*E-mail address:* tammamabboud@gmail.com (T. Abboud).

https://doi.org/10.1016/j.neucli.2024.103022
Received 21 July 2024; Accepted 16 October 2024
Available online 5 November 2024

criterion for the interpretation of intraoperative MEPs, aimed at enhancing the predictive accuracy of postoperative motor outcomes. This criterion evaluates the minimum current intensity required to evoke a discernible muscle action potential, a parameter that has shown promise in predicting motor deficits following the surgical resection of brain tumors [1,3]. By extending this approach to the context of CSM, we hypothesize that improvements in MEP thresholds during surgical decompression could serve as reliable indicators of postoperative neurological improvement. This prospective study seeks to test this hypothesis and explore the potential correlation between intraoperative MEP improvements and neurological outcomes following dorsal decompression in CSM, contributing valuable insights to the field and potentially informing clinical practice.

## Methods

### *Study design*

We conducted a prospective observational study at our department between June 2018 and July 2021. Inclusion criteria were age $\geq$ 18, CSM with indication for surgical dorsal decompression and no contraindication for transcranial electrical stimulation. Informed consent was obtained from all the patients preoperatively. Assessment upon admission included magnetic resonance imaging (MRI), computerized tomography (CT), and the modified Japanese Orthopedic Association score (mJOAS) (see Methods §5). Intraoperative transcranial electrical stimulation (TES) was performed to elicit MEPs during surgery. Postoperative assessment included mJOAS at discharge. The study was approved by the local ethics committee of the university medical center under application number [hidden for review].

### *Anesthesia*

All procedures were performed under general intravenous anesthesia according to local standards [4]. The same protocol was followed for all patients, using identical drugs at weight-adjusted doses. Anesthesia was induced and maintained with propofol. Analgesia was started with sufentanil, and continued with remifentanil. Invasive blood pressure monitoring was performed to maintain a stable mean arterial pressure during all procedures. Body temperature was also monitored throughout.

### *Surgical treatment*

In 2015, bilateral osteoligamentous decompression via unilateral (partial) hemilaminectomy (OLD) was described as an alternative technique for the surgical management of CSM [21]. In the sitting position with the head fixed in the Mayfield clamp, partial hemilaminectomy was performed using a high-speed diamond drill. Under a microscope, the base of the spinous process was removed, beginning at the medial edge of the hemilamina and ending near the contralateral medial part of the facet joint, thereby thinning the inner contralateral hemilamina. Bilateral undercutting of the laminae above and below was performed. The yellow ligament was removed using a Kerrison rongeur until the contralateral dorsal nerve root was exposed (Fig. 1). Several levels can be treated by using this approach [12].

### *Technical setup and MEP recording*

IONM was performed by a dedicated neurophysiology technician who routinely monitors neurosurgical procedures at our department. MEP monitoring was initiated before head fixation. Corkscrew-like electrodes were placed subcutaneously at C3 and C4 according to the international 10–20 electroencephalography system. Bilateral stimulation was performed in all the patients. To record MEPs, subdermal needle electrodes were inserted bilaterally in the deltoid, biceps, triceps, and abductor pollicis brevis muscles of all patients. For stimulation and recording, we used ISIS and NeuroExplorer softwares (Inomed Medizintechnik GmbH, Emmendingen, Germany). TES was applied via constant-current stimulation (anodal 5-train-stimulation, 2 ms interstimulus interval, 220 mA upper intensity limit). The threshold level of a specific muscle was defined as the lowest current intensity (in mA) required to achieve a muscle action potential of at least 50 μV. Multiple stimulations were performed to determine each threshold level, with the values adjusted in increments or decrements of 1 mA. Threshold levels were determined for each connected muscle corresponding to the cervical nerve root exiting the spinal canal, at and below the level of decompression. This was performed once before surgery began, every 5


**Fig. 1.** a. Patient positioning: The head is fixed in the Mayfield skull clamp, then the patient is placed in the sitting position. An X-ray guided vertical incision is used for surgical decompression, b. 3D- reconstruction of a postoperative computed tomography of a patient who underwent a right-sided bilateral osteoligamentous decompression.

min throughout the intervention, and at the end of the intervention. The percentage change in threshold level was evaluated for each muscle. Fig. 2 depicts an example of determining the threshold level of the biceps muscle (C6) at the beginning and end of the surgery.

The maximum number of muscles evaluated per patient was eight, corresponding to the deltoid, biceps, triceps, and abductor pollicis brevis muscles bilaterally, if the surgical decompression was performed at the level of C4/5 or higher. The minimum number of muscles evaluated was two, corresponding to the abductor pollicis brevis muscles, if the surgical decompression occurred at the level of C6/7.

### Outcome measures

*MEP changes of a given muscle:* A permanent decrease in the threshold level of MEP recorded from a certain muscle between the start and end of surgery was considered an improvement, whereas a permanent increase in the threshold level of recorded MEP between the start and end of surgery was considered a deterioration.

*General improvement of MEP:* A general improvement was defined in such cases where muscles, from which improved MEP were recorded, outnumbered the muscles where MEP deterioration was recorded.

*mJOAS:* For clinical assessment, we measured the modified Japanese Orthopedic Association score [17] preoperatively and at discharge. After OLD surgery, patients were discharged between the third and fifth day after surgery (POD 3–5), which was also the day where the postoperative mJOAS was evaluated. Postoperative improvement was defined as an increase $\geq 1$ point.

### Statistical analysis

All data were analyzed using SPSS Statistics 26 (IBM SPSS Statistics, Chicago, IL, USA), Microsoft Excel (2013, Microsoft Inc., Seattle, Washington, USA), and SigmaPlot (v12.5, Systat Software Inc., Erkrath, Germany). Age and mJOAS are presented as mean ±standard deviation (SD). The MEP threshold level distribution over the tested muscles was assessed using mixed linear models with the side and tested muscles as fixed factors and a random intercept for each patient. The dependent variable was either the log-transformed MEP threshold level at the start or end of surgery, or the log-transformed ratio of these two MEP threshold levels. The mJOAS differences preoperatively and at discharge were compared using the exact sign test. Non-normally distributed data are presented as median and interquartile range (IQR). The association between the threshold level variation and mJOAS variation was investigated using Fisher's exact test. The significance level was set at a two-tailed $p \leq 0.05$. Owing to the exploratory nature of the study, no adjustment for multiple testing was applied.

## Results

### Patient demographics and clinical data

All surgery candidates provided signed informed consent. Forty-seven patients, 34 males (72.3 %) and 13 females (27.7 %), were included in this study. The mean age was 69.9 ± 10.1 years. OLD was performed over one segment in 16 patients (34.0 %), over two segments in 21 patients (44.7 %), and over three or more segments in 10 patients (21.3 %). The C3-C4 segment was decompressed in 21 patients (44.7 %), C4-C5 and the C5-C6 segments in 30 patients each (63.8 %), and the C6–7 segment in 13 patients (27.7 %).

### Intraoperative MEP

The MEP could be successfully elicited in all 47 patients and recorded from a cumulative total of 179 muscles corresponding to the cervical nerve roots exiting the spinal canal at and below the decompression level. The median measured MEP threshold level was 62 mA (IQR = 40) at the beginning and 60 mA (IQR = 43) at the end of the surgery. Muscle- and side-specific median MEP threshold levels at the beginning and end of surgery are presented in Table 1. Mixed linear models were fitted to examine the effect of side and tested muscles on mean MEP threshold levels (see Tables 2 and 3 in the Appendix for details). Neither the MEP threshold levels at the beginning and end of the surgery, nor the changes in MEP threshold levels differed significantly between the two sides. However, there were significant differences between the tested muscle groups, as biceps and thenar MEP threshold levels were significantly lower than those in the deltoid and triceps at the beginning and end of surgery.

**Table 1**
Median MEP threshold levels at the beginning and at the end of CSM surgery for each muscle in mA.

| | | Mean MEP threshold levels (mA) | | | |
|---|---|---|---|---|---|
| | | Surgery start | | Surgery end | |
| | | Median | IQR | Median | IQR |
| Deltoid | Left | 65 | 52 | 66 | 43.5 |
| | Right | 67.5 | 40.75 | 70 | 41 |
| Biceps | Left | 55 | 35 | 52.5 | 36.75 |
| | Right | 58.5 | 33.25 | 60 | 31.5 |
| Triceps | Left | 65 | 45 | 65 | 40 |
| | Right | 70 | 47 | 70 | 55 |
| Thenar | Left | 60 | 42 | 60 | 47 |
| | Right | 60 | 39 | 60 | 41 |

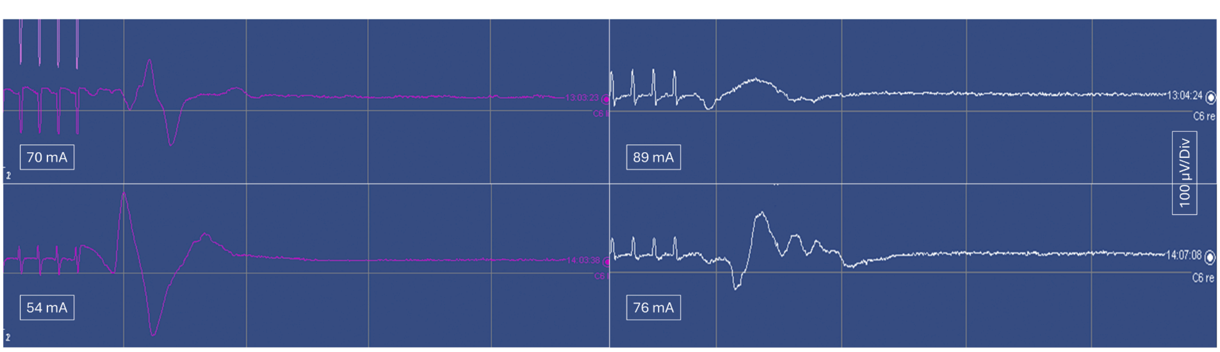


**Fig. 2.** Example of determining of threshold level of the biceps muscle (C6) at the beginning (top) and at the end (bottom) of the surgery. Left: A muscle action potential from the left muscle was elicited with 70 mA at the beginning of the surgery, and with 54 mA after decompression, corresponding to a 23 % decrease in threshold level. Right: A muscle action potential from the right muscle was elicited with 89 mA at the beginning of the surgery, and with 76 mA after decompression, corresponding to a 15 % decrease in threshld level.

**Table 2**
Results of linear mixed models for MEP at surgery start, MEP at surgery end and the ratio of MEP at surgery end and MEP at surgery start. Note that the dependent variables were log-transformed so that the exponentiated regression coefficient exp(β) corresponds to the ratio of means.

| Dependent variable | Independent variable | exp (β) | 95 % CI | p-value |
|---|---|---|---|---|
| **MEP at surgery start** | **Intercept** | 62.82 | (55.23, 71.45) | *<0.001* |
| | **side** | | | |
| | left | 0.98 | (0.94, 1.03) | 0.496 |
| | right | 1.00 | Reference | |
| | **root** | | | *<0.001* |
| | C5 | 1.14 | (1.06, 1.21) | *<0.001* |
| | C6 | 1.01 | (0.94, 1.08) | 0.810 |
| | C7 | 1.19 | (1.11, 1.27) | *<0.001* |
| | C8 | 1.00 | Reference | |
| **MEP at surgery end** | **Intercept** | 63.66 | (56.07, 72.28) | *<0.001* |
| | **side** | | | |
| | left | 0.99 | (0.94, 1.03) | 0.554 |
| | right | 1.00 | Reference | |
| | **root** | | | *<0.001* |
| | C5 | 1.08 | (1.01, 1.16) | *0.017* |
| | C6 | 0.95 | (0.89, 1.02) | 0.142 |
| | C7 | 1.11 | (1.04, 1.19) | *0.003* |
| | C8 | 1.00 | Reference | |
| **Ratio MEP at surgery end/MEP at surgery start** | **Intercept** | 1.01 | (0.98, 1.05) | 0.470 |
| | **side** | | | |
| | left | 1.00 | (0.98, 1.03) | 0.845 |
| | right | 1.00 | Reference | |
| | **root** | | | *<0.001* |
| | C5 | 0.95 | (0.92, 0.98) | *0.003* |
| | C6 | 0.94 | (0.91, 0.98) | *0.001* |
| | C7 | 0.93 | (0.90, 0.97) | *<0.001* |
| | C8 | 1.00 | Reference | |

*Clinical outcome*

At discharge, 31 patients (66.0 %) showed clinical improvement (mJOAS increase), whereas 16 patients (34.0 %) did not (mJOAS unchanged). Detailed patient mJOAS variations are listed in Table 4. An exact sign test showed a significant difference when comparing the mJOAS preoperatively (median =13.5, IQR =2.75, mean 12.48 ± 2.80) and postoperatively (median =14, IQR =2.75, mean 13.38 ± 2.94; $p < 0.001$), indicating a postoperative clinical improvement at discharge (Fig. 3). Postoperative neurological deterioration was not observed.

*MEP general improvement*

In 28 patients (59.6 %), the number of muscles in which MEP improved was greater than that of muscles showing MEP deterioration, indicating general improvement. Fisher's exact test showed a significant association between general MEP improvement and mJOAS increase at discharge ($p = 0.001$). Further contingency analysis showed an odds ratio (OR) = 10.3 (2.6–34.4), a sensitivity of 0.77 (0.60–0.89), a specificity of 0.75 (0.51–0.90), a positive predictive value (PPV) of 0.86 (0.69–0.94) and a negative predictive value (NPV) of 0.63 (0.41–0.81), indicating a significant correlation between general MEP threshold improvement and mJOAS increase at discharge (Fig. 4).

**Table 3**
Pairwise comparisons for root from the linear mixed models of Table 2.

| Dependent variable | Contrast | Estimated percentage difference | 95 % CI | p-value |
|---|---|---|---|---|
| **MEP at surgery start** | **C5 – C6** | 12.6 | (5.6, 20.2) | *<0.001* |
| | **C5 – C7** | −4.3 | (−10.6, 2.4) | 0.200 |
| | **C5 – C8** | 13.5 | (6.2, 21.4) | *<0.001* |
| | **C6 – C7** | −15.0 | (−20.6, −9.1) | *<0.001* |
| | **C6 – C8** | 0.8 | (−5.7, 7.8) | 0.810 |
| | **C7 – C8** | 18.6 | (10.7, 27.3) | *<0.001* |
| **MEP at surgery end** | **C5 – C6** | 13.7 | (6.7, 21.0) | *<0.001* |
| | **C5 – C7** | −2.3 | (−8.5, 4.4) | 0.493 |
| | **C5 – C8** | 8.2 | (1.4, 15.5) | *0.017* |
| | **C6 – C7** | −14.0 | (−19.5, −8.2) | *<0.001* |
| | **C6 – C8** | −4.8 | (−10.8, 1.7) | 0.142 |
| | **C7 – C8** | 10.7 | (3.5, 18.6) | *0.003* |
| **Ratio MEP at surgery end/MEP at surgery start** | **C5 – C6** | 0.9 | (−2.2, 4.1) | 0.562 |
| | **C5 – C7** | 2.0 | (−1.3, 5.4) | 0.229 |
| | **C5 – C8** | −4.7 | (−7.7, −1.6) | *0.003* |
| | **C6 – C7** | 1.1 | (−2.2, 4.4) | 0.515 |
| | **C6 – C8** | −5.5 | (−8.6, −2.5) | *0.001* |
| | **C7 – C8** | −6.6 | (−9.7, −3.4) | *<0.001* |

*Any MEP improvement*

Improvement in at least one MEP threshold level was observed in 31 patients (66.0 %). Fisher's exact test was used to assess the relationship between any MEP improvement and mJOAS increase. There was a statistically significant association between these two variables ($p < 0.001$). Further contingency analysis showed an OR =11.4 (2.8–41.3), a sensitivity of 0.84 (0.67–0.93), a specificity of 0.69 (0.44–0.86), PPV =0.84 (0.67–0.93) and NPV =0.69 (0.44–0.86). Therefore, intraoperative improvement of at least one MEP threshold level was highly correlated with clinical improvement at discharge (Fig. 4).

*MEP deterioration*

Deterioration of at least one MEP threshold level was observed in 26 (55.3 %) patients. As none of the patients exhibited new postoperative deficits, the relationship between MEP threshold variation and clinical deterioration could not be evaluated. Instead, we sought to look for a possible relationship between any MEP threshold increase (MEP deterioration) and the lack of clinical improvement at discharge (unchanged mJOAS). Fisher's exact test showed no statistically significant association between the two variables ($p = 1$). Further contingency analysis showed OR =0.94 (0.28–2.97), a sensitivity =0.55 (0.38–0–71), a specificity =0.44 (0.23–0.67), PPV =0.65 (0.46–0.81) and NPV =0.33 (0.17–0.55). Thus, there seemed to be no relationship between MEP deterioration and clinical status at discharge (Fig. 4).

**Table 4**
Patient list with pre- and post-operative modified Japanese Orthopedic Association score (mJOAS) measured preoperatively and at discharge. Postoperative improvement was defined as an increase ≥ 1 point. The right part of table 4 specifies in which category of the mJOA score the point gain was observed: upper limb motor function (UL motor), lower limb motor function/gait (LL motor), sensory function (sens.), sphincter function (sph.). Note that, at discharge, no improvement of the latter function was observed.

| Patient Nr. | Age | Sex | Preoperative mJOAS | Postoperative mJOAS | UL motor | LL motor | Sens. | Sph. |
|---|---|---|---|---|---|---|---|---|
| **1** | 82 | M | 15 | 16 | | 1 | | |
| **2** | 75 | M | 11 | 11 | | | | |
| **3** | 51 | M | 15 | 16 | | | 1 | |
| **4** | 56 | M | 15 | 15 | | | | |
| **5** | 74 | F | 12 | 13 | | 1 | | |
| **6** | 73 | M | 14 | 16 | | 2 | | |
| **7** | 71 | M | 14 | 15 | | 1 | | |
| **8** | 83 | M | 4 | 5 | 1 | | | |
| **9** | 68 | M | 5 | 5 | | | | |
| **10** | 62 | M | 13 | 13 | | | | |
| **11** | 76 | M | 11 | 13 | 1 | 1 | | |
| **12** | 78 | M | 15 | 16 | | 1 | | |
| **13** | 76 | M | 10 | 12 | 1 | 1 | | |
| **14** | 74 | M | 14 | 15 | | 1 | | |
| **15** | 72 | F | 14 | 16 | | 2 | | |
| **16** | 65 | M | 12 | 12 | | | | |
| **17** | 84 | F | 15 | 16 | | | 1 | |
| **18** | 67 | M | 11 | 11 | | | | |
| **19** | 55 | M | 9 | 11 | 1 | 1 | | |
| **20** | 76 | M | 10 | 12 | 1 | 1 | | |
| **21** | 47 | F | 14 | 16 | 1 | 1 | | |
| **22** | 54 | M | 13 | 13 | | | | |
| **23** | 56 | M | 8 | 8 | | | | |
| **24** | 73 | M | 15 | 17 | | 2 | | |
| **25** | 44 | M | 16 | 17 | | | 1 | |
| **26** | 70 | M | 14 | 16 | | 2 | | |
| **27** | 80 | F | 14 | 14 | | | | |
| **28** | 81 | M | 15 | 16 | | | 1 | |
| **29** | 71 | M | 11 | 11 | | | | |
| **30** | 76 | M | 14 | 15 | | | 1 | |
| **31** | 76 | M | 13 | 15 | | 1 | 1 | |
| **32** | 74 | M | 14 | 16 | | 1 | 1 | |
| **33** | 85 | F | 5 | 6 | 1 | | | |
| **34** | 67 | F | 13 | 13 | | | | |
| **35** | 61 | M | 14 | 15 | | 1 | | |
| **36** | 59 | F | 13 | 15 | | 1 | 1 | |
| **37** | 54 | F | 14 | 14 | | | | |
| **38** | 77 | F | 13 | 14 | | 1 | | |
| **39** | 68 | M | 14 | 15 | | | 1 | |
| **40** | 71 | F | 14 | 15 | | 1 | | |
| **41** | 81 | M | 9 | 10 | | 1 | | |
| **42** | 78 | M | 16 | 16 | | | | |
| **43** | 73 | M | 13 | 13 | | | | |
| **44** | 63 | M | 14 | 14 | | | | |
| **45** | 78 | M | 11 | 13 | | | 1 | |
| **46** | 82 | F | 13 | 13 | | | | |
| **47** | 69 | F | 14 | 14 | | | | |

## Discussion

This research elucidates the significant role of intraoperative MEP in predicting neurological recovery post-surgically in patients undergoing decompression for CSM. Specifically, a decrease in the threshold required to elicit MEPs during surgery is identified as a robust predictor of improved neurological function postoperatively. Notably, the presence of measurable enhancements in MEPs across a majority of the muscle groups tested within individual patients was found to strongly forecast an increased mJOAS at the time of discharge, with a PPV of 0.86.

Historically, the integration of electrophysiological monitoring within the realm of vascular, oncological and orthopedic spine surgery has been well-documented since the 1990s [8,14,18,24]. However, this pilot study distinguishes itself as a pioneering effort in the academic field by specifically exploring the efficacy and utility of MEP monitoring throughout the operative decompression process for CSM. Given the historical paucity of reliable indicators for gauging adequate decompression of the spinal canal, this study introduces a novel perspective, suggesting the substantial benefits of leveraging intraoperative MEPs as a predictive measure for neurological rehabilitation in the context of CSM surgeries.

The findings from this study are congruent with existing literature that establishes a connection between MEP enhancement and functional recuperation across a spectrum of conditions leading to neurological deficits. This includes analogous insights from the domain of acute ischemic stroke treatment, where MEP improvement during mechanical endovascular procedures was associated with significant improvements in neurological function [26]. Furthermore, the application of transcranial magnetic stimulation to the motor cortex for eliciting MEP shortly after a stroke has been validated as a reliable prognostic tool for motor and overall functional recovery [7].

Through these observations, this study contributes significantly to the broader understanding of MEP as a valuable intraoperative tool, not only in the realm of spine surgery but also in the wider context of neurological recovery, providing a foundation for future research and clinical practice in the treatment of CSM and potentially other neurological impairments.

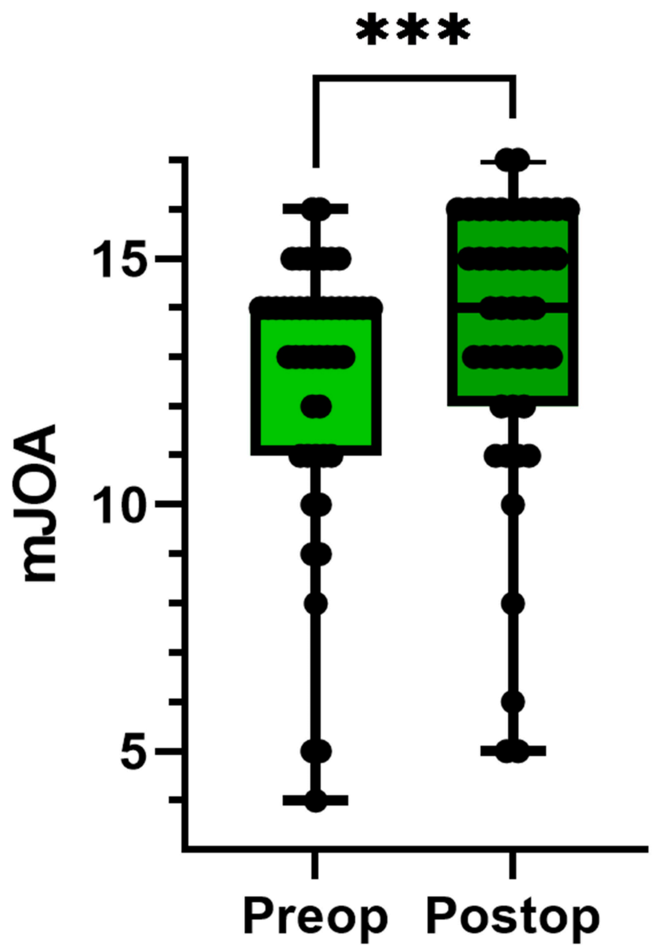


**Fig. 3.** Modified Japanese Orthopedic Association score (mJOAS) before surgery and at discharge. A significant score increase was observed at discharge ($p \leq 0.001$). (Sign test: *** $\leq 0.001$).

*MEP deterioration*

Intriguingly, the phenomenon of intraoperative MEP deterioration, characterized by an increase in the threshold required for elicitation, did not exhibit a direct correlation with adverse clinical outcomes or a prognostication of failure to recover within our study. Typically, in the context of neurosurgical interventions, MEP deterioration that is not attributable to direct surgical trauma to the corticospinal tract is often a consequence of the loss of cerebrospinal fluid subsequent to durotomy [2]. However, this particular causal factor is not relevant in the surgical treatment of CSM.

Additionally, another common contributory factor to MEP deterioration in spinal surgery is the utilization of the prone position, which can lead to suboptimal patient positioning [23]. This positioning factor was not applicable in our study series, eliminating it as a potential cause for the observed MEP changes. A plausible explanation for the MEP changes detected in our patient cohort could be linked to the phenomenon known as "fading MEP". This term, originally introduced by Lyon et al. [20], describes a scenario where the rate at which MEP threshold levels increase is inversely related to the duration of anesthesia. Despite this association, the degree of threshold elevation observed in our study did not preclude the discernment of MEP improvements attributed to the decompressive surgical intervention. This suggests that, while "fading MEP" might influence the MEP threshold levels, it does not negate the potential for observing MEP enhancements that signify successful surgical outcomes.

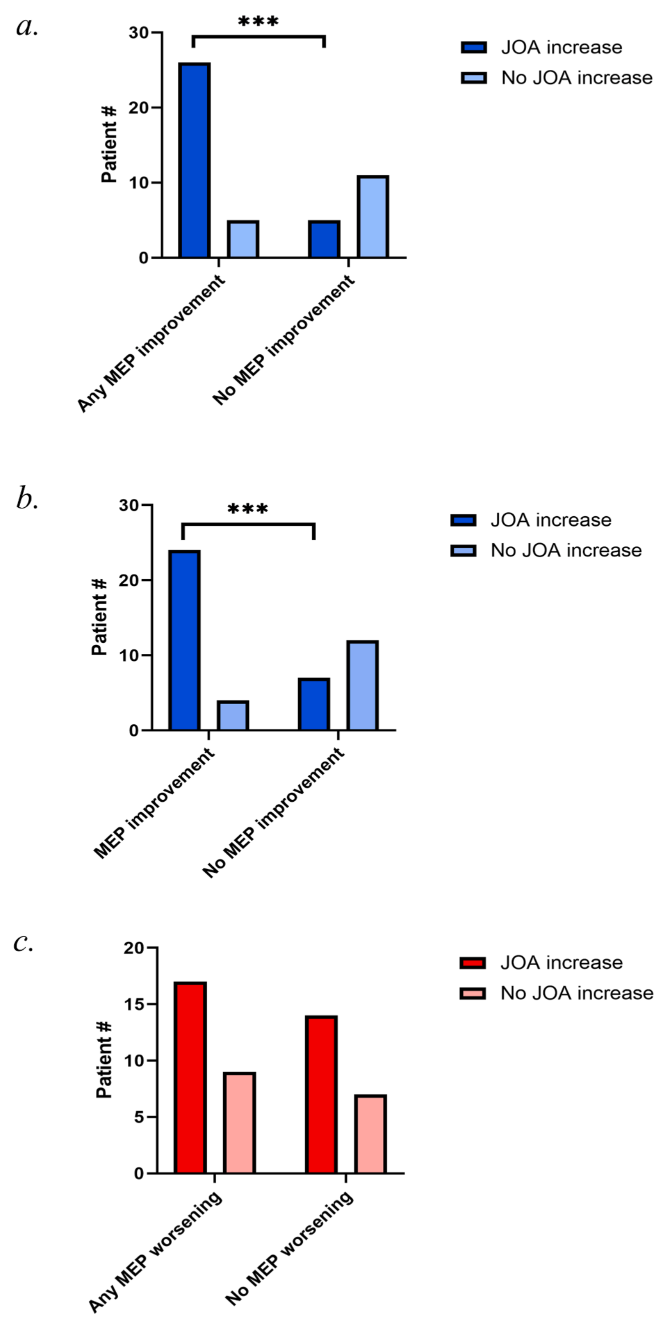


**Fig. 4.** Relationship between clinical improvement at discharge assessed via the modified Japanese Orthopedic Association (mJOAS and intraoperative motor evoked potential (MEP) variation of patients with cervical spondylotic myelopathy. (a): MEP improvement in the majority of tested muscles. (b): observed MEP improvement in at least 1 tested muscle. (c): observed MEP deterioration in at least 1 tested muscle (Fisher's exact tests: *** $\leq 0.001$). Significant association was observed between intraoperative MEP threshold level improvement and clinical improvement at discharge ($p \leq 0.001$).

*Extent of surgical decompression*

The current literature lacks substantial evidence linking the extent of surgical decompression in CSM treatment with postoperative neurological improvement. However, utilizing intraoperative MEP for assessing the motor pathways may offer a real-time biomarker for evaluating spinal canal decompression and its correlation with functional recovery. This promising area warrants further exploration in future research.

*Obstacles to MEP recording in spine surgery*

While MEP recording holds significant promise for prognostic assessment in CSM surgery, its application is met with skepticism by some practitioners. The challenges stem from the inherent instability of IONM recordings in spine surgeries, where phenomena like signal loss are not uncommon [9,11,19]. Factors contributing to these issues include the patient's prone positioning, the extended duration of surgical procedures, and the opening of the dural sac during surgeries for intradural tumors. Despite these hurdles, we were able to obtain multiple MEP signals from each patient, ensuring an adequate dataset for thorough signal analysis and assessment.

*C5 nerve root palsy*

Postoperative nerve root palsy, particularly affecting the C5 nerve root, has often been reported following cervical decompression surgery, with recent meta-analyses indicating a C5 palsy incidence of approximately 5–7 %. Posterior approaches have been associated with a higher risk compared to anterior approaches [29,30,31]. However, the posterior approaches described in these studies primarily involved foraminotomy, laminoplasty, and laminectomy with fusion. Notabley, in our series, we used hemilaminectomy with contralateral decompression using the undercutting technique in the sitting position and observed no cases of postoperative nerve palsy.

## Limitations

A substantial limitation of this study was the lack of long-term clinical data, which could not be obtained as most patients did not present for follow-up. However, clinically significant symptom variations were already observed at discharge, leading to the aforementioned results, which were statistically significant. Similarly, postoperative MRI controls could have provided insights to the radiographic improvement of myelopathy; this also could not be performed in our center. In addition, MEP could not be recorded from all connected muscles, likely due to the sitting position.

## Conclusion

MEP monitoring could constitute an intraoperative real-time predictive tool for clinical recovery during CSM surgery. As MEP improvement significantly correlates with early postoperative clinical recovery, this electrophysiological variation might correspond to an early subclinical substrate of enhanced signal conduction, thereby honing the controversial potential of IONM in spine surgery. Further multicenter evidence is needed regarding the true potential of this method.

## Declaration of competing interest

None to declare.


## Acknowledgements

None.


## References


[1] Abboud T, Schaper M, Dührsen L, et al. A novel threshold criterion in transcranial motor evoked potentials during surgery for gliomas close to the motor pathway. J Neurosurg 2016;125(4):795–802.
[2] Abboud T, Huckhagel T, Stork JH, et al. Why does threshold level change in transcranial motor-evoked potentials during surgery for supratentorial lesions? J Neurosurg Anesthesiol 2017;29(4):393–9.
[3] Abboud T, Schwarz C, Westphal M, Martens T. A comparison between threshold criterion and amplitude criterion in transcranial motor evoked potentials during surgery for supratentorial lesions. J Neurosurg 2018;131(3):740–9.
[4] Abboud T, Hahn G, Just A, et al. An insight into electrical resistivity of white matter and brain tumors. Brain Stimul 2021;14(5):1307–16.
[5] Abboud T, Mader M, Komboz F, Martens T, Mielke D, Rohde V. False-positive results in transcranial motor evoked potentials for outcome prognostication during surgery for supratentorial lesions. Neurosurg Rev 2022;45(4):2869–75.
[6] Badhiwala JH, Ahuja CS, Akbar MA, et al. Degenerative cervical myelopathy - update and future directions. Nat Rev Neurol 2020;16(2):108–24.
[7] Bembenek JP, Kurczych K, Karli Nski M, Czlonkowska A. The prognostic value of motor-evoked potentials in motor recovery and functional outcome after stroke – a systematic review of the literature. Funct Neurol 2012;27(2):79–84.
[8] Burke D, Hicks R, Stephen J, Woodforth I, Crawford M. Assessment of corticospinal and somatosensory conduction simultaneously during scoliosis surgery. Electroencephalogr Clin Neurophysiol 1992;85(6):388–96.
[9] Eager M, Shimer A, Jahangiri FR, Shen F, Arlet V. Intraoperative neurophysiological monitoring (IONM): lessons learned from 32 case events in 2069 spine cases. Am J Electroneurodiagnostic Technol 2011;51(4):247–63.
[10] Guo L, Gelb AW. The use of motor evoked potential monitoring during cerebral aneurysm surgery to predict pure motor deficits due to subcortical ischemia. Clin Neurophysiol 2011;122(4):648–55.
[11] Guo L, Li Y, Han R, Gelb AW. The correlation between recordable meps and motor function during spinal surgery for resection of thoracic spinal cord tumor. J Neurosurg Anesthesiol 2018;30(1):39–43.
[12] Hernández-Durán S, Zafar N, Behme D, et al. Volumetric analysis of bilateral spinal canal decompression via hemilaminectomy versus laminoplasty in cervical spondylotic myelopathy. Acta Neurochir 2020;162(9):2069–74.
[13] Hilibrand AS, Schwartz DM, Sethuraman V, Vaccaro AR, Albert TJ. Comparison of transcranial electric motor and somatosensory evoked potential monitoring during cervical spine surgery. J Bone Surg Am 2004;86(6):1248–53.
[14] Jones SJ, Harrison R, Koh KF, Mendoza N, Crockard HA. Motor evoked potential monitoring during spinal surgery: responses of distal limb muscles to transcranial cortical stimulation with pulse trains. Electroencephalogr Clin Neurophysiol 1996; 100(5):375–83.
[15] Kalsi-Ryan S, Karadimas SK, Fehlings MG. Cervical spondylotic myelopathy: the clinical phenomenon and the current pathobiology of an increasingly prevalent and devastating disorder. Neuroscientist 2013;19(4):409–21.
[16] Kombos T, Picht T, Derdilopoulos A, Suess O. Impact of intraoperative neurophysiological monitoring on surgery of high-grade gliomas. J Clin Neurophysiol 2009;26(6):422–5.
[17] Kopjar B, Tetreault L, Kalsi-Ryan S, Fehlings M. Psychometric properties of the modified japanese orthopaedic association scale in patients with cervical spondylotic myelopathy. Spine 2015;40(1):E23–8.
[18] Kothbauer K, Deletis V, Epstein FJ. Motor-evoked potential monitoring for intramedullary spinal cord tumor surgery: correlation of clinical and neurophysiological data in a series of 100 consecutive procedures. Neurosurg. Focus 1998;4(5):E3.
[19] Langeloo DD, Journee HL, de Kleuver M, Grotenhuis JA. Criteria for transcranial electrical motor evoked potential monitoring during spinal deformity surgery A review and discussion of the literature. Neurophysiol Clin 2007;37(6):431–9.
[20] Lyon R, Feiner J, Lieberman JA. Progressive suppression of motor evoked potentials during general anesthesia: the phenomenon of "anesthetic fade". J Neurosurg Anesthesiol 2005;17(1):13–9.
[21] Mielke D, Rohde V. Bilateral spinal canal decompression via hemilaminectomy in cervical spondylotic myelopathy. Acta Neurochir 2015;157(10):1813–7.
[22] Nouri A, Tetreault L, Singh A, Karadimas SK, Fehlings MG. Degenerative cervical myelopathy: epidemiology, genetics, and pathogenesis. Spine 2015;40(12): E675–93.
[23] Rizkallah M, El Abiad R, Badr E, Ghanem I. Positional disappearance of motor evoked potentials is much more likely to occur in non-idiopathic scoliosis. J Child Orthop 2019;13(2):206–12.
[24] Sala F, Niimi Y, Krzan M, Berenstein A, Deletis V. Embolization of a spinal arteriovenous malformation: correlation between motor evoked potentials and angiographic findings: technical case report. Neurosurgery 1999;45(4):932.
[25] Schwartz DM, Auerbach JD, Dormans JP, et al. Neurophysiological detection of impending spinal cord injury during scoliosis surgery. J Bone Surg Am 2007;89 (11):2440–9.
[26] Shiban E, Wunderlich S, Kreiser K, et al. Predictive value of transcranial evoked potentials during mechanical endovascular therapy for acute ischaemic stroke: a feasibility study. J Neurol, Neurosurg Psychiatry 2016;87(6):598.
[27] Spielholz NI, Benjamin MV, Engler GL, Ransohoff J. Somatosensory evoked potentials during decompression and stabilization of the spine. Methods Findings Spine 1979;4(6):500–5.
[28] Talacchi A, Turazzi S, Locatelli F, et al. Surgical treatment of high-grade gliomas in motor areas. The impact of different supportive technologies: a 171-patient series. J Neurooncol 2010;100(3):417–26.
[29] Bydon M, Macki M, Kaloostian P, et al. Incidence and prognostic factors of C5 Palsy: a clinical Study of 1001 cases and review of the literature. Neurosurgery 2014;74(6):595–605.
[30] Shou F, Li Z, Wang H, et al. Prevalence of C5 nerve root palsy after cervical decompressive surgery: a meta-analysis. Eur Spine J 2015;24:2724–34.
[31] Wang T, Wang H, Liu S, Ding W. Incidence of C5 nerve root palsy after cervical surgery: a meta-analysis for last decade. Medicine 2017;96(45):8560.