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Intraoperative Neuromonitoring Is Associated with Superior Neurological and Pain Outcomes After Single-Level Anterior Cervical Discectomy and Fusion: A Retrospective Cohort Study

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Research Article

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Intraoperative Neuromonitoring Is Associated with Superior Neurological and Pain Outcomes After Single-Level Anterior Cervical Discectomy and Fusion: A Retrospective Cohort Study

Running title: Intraoperative Neuromonitoring in ACDF

Abstract

Background: The value of intraoperative neuromonitoring (IONM) during anterior cervical discectomy and fusion (ACDF) remains debated, and evidence linking IONM to clinical outcomes—rather than to signal detection alone—is limited.

Methods: In this single-center retrospective cohort study, consecutive patients who underwent single-level ACDF for degenerative cervical radiculopathy or myelopathy between January 2020 and December 2024 were categorized into an IONM group and a non-IONM group according to surgeon preference and equipment availability. Neurological outcomes (Japanese Orthopaedic Association [JOA] score, 0–17; visual analogue scale [VAS] for pain, 0–10) were compared between groups after excluding patients with intraoperative alerts or neurological deterioration. The diagnostic performance of IONM was characterized using a four-category alert adjudication.

Results: Of 495 patients with complete 6-month follow-up, 238 underwent IONM and 257 did not. In the IONM group, 23 patients (9.7%) experienced intraoperative alerts, concentrated at the decompression checkpoint (16/23, 69.6%). IONM yielded a sensitivity of 66.7%, specificity of 91.1%, positive predictive value of 8.7%, and a negative predictive value of 99.5%. Among event-free patients (214 IONM vs. 248 non-IONM), the IONM group showed significantly better outcomes at the immediate postoperative assessment (JOA 14.50 vs. 12.19, $P<0.001$; VAS 2.47 vs. 4.48, $P<0.001$) and at 6 months (JOA 16.00 vs. 13.52, $P<0.001$; VAS 2.00 vs. 3.48, $P<0.001$). The incidence of neurological deterioration was lower in the IONM group (3/238, 1.26% vs. 9/257, 3.50%). Somatosensory (SSEP) and motor evoked potential (MEP) amplitudes increased significantly after decompression ($P<0.001$), corroborating the clinical improvement.

Conclusions: IONM during single-level ACDF was associated with superior immediate and 6-month neurological and pain outcomes, a strong negative predictive value for ruling out neurological injury, and alerts concentrated at the decompression stage. These findings support the clinical utility of IONM in ACDF while underscoring the need for judicious interpretation of alerts given their low positive predictive value.

Keywords: intraoperative neuromonitoring; anterior cervical discectomy and fusion; somatosensory evoked potentials; motor evoked potentials; neurological outcomes

Introduction

Anterior cervical discectomy and fusion (ACDF) is one of the most widely performed procedures for degenerative cervical radiculopathy and myelopathy that have failed conservative management [1]. Although the procedure is generally safe, perioperative neurological injury—including C5 nerve root palsy and new or worsening myelopathy or radiculopathy—remains a clinically important and potentially devastating complication [2]. The reported incidence of new neurological deficit after cervical surgery varies, and the consequences for patients can be substantial and often permanent.

Intraoperative neuromonitoring (IONM), comprising somatosensory evoked potentials (SSEPs) and transcranial motor evoked potentials (TcMEPs), has been proposed as a means of detecting impending neural injury in real time, thereby allowing the surgeon to intervene before irreversible damage occurs [3,4]. In deformity and complex posterior cervical surgery, multimodal IONM has become relatively well established [5]. However, for routine single-level ACDF—a shorter, lower-risk procedure—the role of IONM remains controversial. Routine monitoring adds time and cost [6,7], and its alerts are frequently reported to have a low positive predictive value, raising concerns about false-positive alarms and unnecessary surgical responses [8].

Critically, much of the existing literature has focused on the diagnostic accuracy of IONM (i.e., whether an alert predicts a deficit) rather than on whether the use of IONM actually translates into better clinical outcomes for patients [9,10]. Few studies have combined an assessment of IONM diagnostic performance with a direct comparison of neurological and pain outcomes between monitored and unmonitored patients undergoing the same procedure. Moreover, the intraoperative timing of alerts and the electrophysiological changes that accompany adequate decompression remain incompletely characterized in the ACDF setting.

The aim of this study was therefore to evaluate, in a large retrospective cohort, (1) the association between IONM use and immediate and 6-month neurological (JOA) and pain (VAS) outcomes after single-level ACDF, and (2) the diagnostic performance and

intraoperative characteristics of IONM alerts, including their distribution across surgical checkpoints and their relationship to electrophysiological improvement after decompression.

Methods

Study design and patients

This single-center retrospective cohort study included consecutive patients who underwent single-level ACDF for degenerative cervical radiculopathy and/or cervical myelopathy at Ruijin Hospital, Shanghai Jiao Tong University School of Medicine, between January 2020 and December 2024. Patients were categorized into an IONM group and a non-IONM group according to the attending surgeon's preference and the intraoperative availability of neuromonitoring equipment. The study protocol was reviewed and approved by the Institutional Review Board of Ruijin Hospital. The requirement for informed consent was waived by the IRB given the retrospective nature of the study. All procedures were performed in accordance with the Declaration of Helsinki.

Patients were eligible if they met all of the following criteria: age ≥18 years; degenerative cervical radiculopathy and/or cervical myelopathy confirmed by clinical and imaging findings; failure of standardized conservative treatment; single-level ACDF; and complete preoperative, intraoperative, and postoperative follow-up data. Patients were excluded if they had: ossification of the posterior longitudinal ligament (OPLL); ossification of the ligamentum flavum; developmental cervical canal stenosis or other major non-degenerative cervical disorders; prior major cerebrovascular events; peripheral neuropathy or motor neuron disease; diabetes mellitus or other chronic systemic disease judged likely to impair peripheral nerve function; documented heavy alcohol or tobacco abuse; previous cervical surgery; or multilevel ACDF or combined anterior–posterior procedures.

Baseline variables included age, sex, body mass index (BMI), diagnosis subtype, symptom type, symptom duration, operative level, and preoperative neurological status. Table 1 presents the key baseline characteristics.

Surgical procedure

All patients underwent standard single-level ACDF via a Smith–Robinson approach by spine surgeons experienced in anterior cervical surgery. After exposure of the target level, discectomy, neural decompression, endplate preparation, interbody graft/cage insertion, and anterior plating or stand-alone fixation were performed according to surgeon preference and implant strategy. Operative level, decompression method, implant type, use of plating, estimated blood loss, total operative time, and key procedural times were recorded.

Intraoperative neuromonitoring

IONM was performed using a Medtronic NIM-ECLIPSE E4 system. SSEPs were elicited by stimulation of the median and ulnar nerves (20 mA, 4.7 Hz) for the upper extremities and the posterior tibial nerve (40 mA, 4.7 Hz) for the lower extremities, with band-pass filtering at 30–300 Hz. TcMEPs were elicited by transcranial electrical stimulation (pulse width 100 μs, inter-stimulus interval 4 ms, intensity up to 250 V) and recorded from the deltoid, thenar, and abductor hallucis muscles (band-pass 30–1500 Hz).

Monitoring checkpoints were defined as follows: T0, after induction and final positioning, before incision; T1, after exposure and before discectomy; T2, after disc removal/decompression; T3, after cage/graft insertion and final fixation; and T4, at skin closure. SSEP amplitudes were measured at T0, T2, and T4, and TcMEP amplitudes at T0 and T4.

Alert criteria and adjudication

SSEP deterioration was defined according to conventional warning criteria as a >50% amplitude decrease and/or >10% latency increase relative to baseline, particularly when sustained and reproducible. For patients with unstable baseline waveforms, recent pre-change traces rather than only the initial trace were used for contextual interpretation, in keeping with the updated ASNM position statement [11]. TcMEP alerts were defined as any of the following after exclusion of technical or anesthetic confounders: disappearance of previously reproducible responses; marked persistent amplitude reduction; or a clinically relevant increase in stimulation threshold. Signal deterioration was interpreted

in the full intraoperative context, because warning significance depends on reversibility, timing, anesthesia, blood pressure, temperature, and the monitored pathway.

Alerts were classified as: true positive (sustained signal change with a corresponding postoperative deficit); false positive (signal change without a plausible surgical/physiological correlate and without a postoperative deficit); false negative (no relevant alert despite a postoperative deficit in a monitored pathway); and true negative (no alert and no deficit).

Outcome measures

Neurological function was assessed with the Japanese Orthopaedic Association (JOA) scoring system (range 0–17), and pain was assessed with a visual analogue scale (VAS; range 0–10). JOA and VAS scores were assessed preoperatively, immediately postoperatively, and at 6 months. Neurological deterioration was defined as a postoperative decrease in JOA score and/or increase in VAS score relative to the preoperative baseline, with either criterion being sufficient for classification. The JOA recovery (improvement) rate was calculated using the Hirabayashi formula: (postoperative JOA − preoperative JOA)/(17 − preoperative JOA) × 100%. An "excellent" outcome was prespecified as a recovery rate ≥75%.

Neurophysiological improvement was prespecified as any improvement observed after decompression and maintained at the final recording, including: SSEP amplitude increase ≥20%; SSEP latency decrease ≥10%; or TcMEP threshold decrease ≥20%.

Statistical analysis

Continuous variables are presented as mean ± standard deviation (SD) and were compared between groups using the two-sample t test; within-group longitudinal comparisons used the paired t test. Categorical variables are presented as counts (percentages) and were compared using the chi-square test. Operative time is presented as median (interquartile range) and was compared using the Mann–Whitney U test. The diagnostic performance of IONM was summarized using sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV), derived from the 2 × 2 contingency table with postoperative neurological deterioration as the reference standard.

The ability of SEP-derived variables to predict an excellent JOA outcome was assessed using receiver operating characteristic (ROC) analysis. Independent predictors of an excellent outcome were evaluated using Firth penalized logistic regression to account for quasi-complete separation [12], with results presented as odds ratios (ORs) with 95% confidence intervals (CIs). Statistical analyses were performed using GraphPad Prism, and a two-sided P value <0.05 was considered statistically significant.

Results

Baseline characteristics

A total of 792 patients were screened, of whom 495 (62.5%) completed the 6-month follow-up and were included in the analysis (297 were lost to follow-up). Of these, 238 patients comprised the IONM group and 257 the non-IONM group. The two groups were well balanced in key baseline characteristics (**Table 1**): there were no significant differences in sex (P=0.968), age (57.6±12.3 vs. 58.4±11.6 years, P=0.480), operative level (P=0.530), operative time (median 120 vs. 120 min, P=0.548), or diagnosis subtype (P=0.949).

Intraoperative alert characteristics

Among the 238 IONM patients, 23 (9.7%) experienced intraoperative alerts: 12 transient, 9 sustained single-modality, and 2 sustained dual-modality (**Table 2, Figure 1**). Alerts were concentrated at the T2 decompression checkpoint (16/23, 69.6%), followed by T1 (4/23), T3 (2/23), and T4 (1/23). All T1-stage alerts were transient, whereas both sustained dual-modality alerts occurred at T2.

Diagnostic performance of IONM

In the IONM group, postoperative neurological deterioration occurred in 3 patients (1.26%). The relationship between alerts and deterioration is shown in **Table 3**: True positive, 2; False positive, 21; False negative, 1; and True negative, 214. IONM therefore demonstrated a sensitivity of 66.7% (2/3), specificity of 91.1% (214/235), PPV of 8.7% (2/23), and NPV of 99.5% (214/215) (**Figure 2**).

Neurological and pain outcomes

After excluding the 23 alert patients and the 1 false-negative patient from the IONM group (True negative patients), and the 9 patients with neurological deterioration from the non-IONM group, 214 IONM and 248 non-IONM patients were compared (**Table 4, Figures 3**). Preoperative JOA (10.50 ± 1.74 vs. 10.57 ± 1.75) and VAS (7.90 ± 1.40 vs. 7.86 ± 1.35) scores were comparable (P>0.05). The IONM group showed significantly better outcomes at the immediate postoperative assessment (JOA 14.50 ± 1.11 vs. 12.19 ± 1.40, P<0.001; VAS 2.47 ± 1.14 vs. 4.48 ± 1.12, P<0.001) and at 6 months (JOA 16.00 ± 0.83 vs. 13.52 ± 1.12, P<0.001; VAS 2.00 ± 0.83 vs. 3.48 ± 1.12, P<0.001). Within each group, JOA increased and VAS decreased significantly over time (all P<0.001), confirming that surgery itself was effective; the magnitude of improvement was greater in the IONM group. Further VAS relief from the immediate assessment to 6 months was not significant in either group (IONM P=0.121; non-IONM P=0.058), indicating that the major pain relief occurred in the immediate postoperative period.

Outcomes among patients with neurological deterioration

The incidence of neurological deterioration was lower in the IONM group (3/238, 1.26%) than in the non-IONM group (9/257, 3.50%). Among these 12 patients, both groups exhibited a similar trajectory of an immediate postoperative JOA decrease and VAS increase (surgical stress), followed by JOA recovery and VAS relief at 6 months (**Table 5**, **Figures 4**). However, the IONM group showed significantly better recovery: immediate postoperative JOA was higher (8.8 vs. 7.4, P=0.016), 6-month JOA was higher (14.3 vs. 12.2, P=0.009), and 6-month VAS was lower (1.7 vs. 2.8, P=0.014). The magnitude of VAS relief from the immediate assessment to 6 months was also greater in the IONM group (−78.3% vs. −64.2%, P=0.031), indicating more complete pain resolution.

Intraoperative electrophysiological changes

In the 214 event-free IONM patients, SSEP amplitudes (upper and lower extremity) increased significantly from T0 (before decompression) to T2 (after decompression) (P<0.001), indicating immediate relief of sensory pathway compression (**Figure 5**). No significant change occurred from T2 to T4 (closure), suggesting that the post-decompression phase, including cage insertion, did not further alter sensory conduction.

TcMEP amplitudes recorded from the deltoid, thenar, and abductor hallucis muscles increased significantly from T0 to T4 (P<0.001) (**Figure 6**), indicating improved motor conduction. These electrophysiological improvements were consistent with the observed clinical JOA and VAS improvements.

Predictive value of SEP improvement for excellent outcome

The predictive value of SEP amplitude improvement for an excellent JOA outcome (recovery rate≥75%) was limited (**Figure 7**). The change in lower-extremity SEP amplitude (ΔLSEP, T4−T0) showed a borderline area under the ROC curve (AUC) of 0.720 (P=0.056), and the LSEP ratio (T4/T0) showed an AUC of 0.705 (P=0.075), both trending toward significance. In contrast, upper-extremity SEP (ΔUSEP) showed no predictive value (AUC 0.485). On Firth logistic regression (**Figure 8**), only disease duration showed a borderline association with excellent outcome (OR 0.88, 95% CI 0.76–1.02, P=0.096), with longer disease duration tending to predict a lower likelihood of an excellent outcome. ΔLSEP showed a positive but non-significant association (OR 6.53, 95% CI 0.50–85.69, P=0.153), consistent with the ROC analysis. Disc calcification/osteophyte and T2 hyperintensity were associated with wide confidence intervals consistent with quasi-complete separation and were considered unreliable; age, myelopathy type, blood loss, and body temperature showed no predictive value.

Discussion

In this retrospective cohort of 495 patients undergoing single-level ACDF, the use of IONM was associated with significantly better immediate and 6-month neurological (JOA) and pain (VAS) outcomes, a numerically lower incidence of neurological deterioration, and an NPV of 99.5% for ruling out postoperative neurological injury. Alerts were concentrated at the decompression checkpoint, and intraoperative SSEP and MEP amplitude improvements after decompression corroborated the clinical benefit. Together, these findings provide a coherent—diagnostic, functional, and electrophysiological—evidence base supporting the clinical utility of IONM in ACDF.

The strong NPV (99.5%) is among the most clinically relevant findings. It indicates that an uneventful (silent) monitoring session reliably excludes neurological injury, which is

valuable for intraoperative decision-making and for postoperative counseling. It is important, however, to interpret this in light of the low event rate: with only 3 neurological deteriorations in the IONM group, the NPV is expected to be high, and the wide confidence intervals inherent to small event counts temper the precision of the sensitivity and PPV estimates. The low PPV (8.7%) is consistent with the broader IONM literature [8,9] and reflects the inherent imbalance between the many alerts prompted by non-pathological signal fluctuations and the few true injuries. This underscores that IONM alerts should be interpreted in their full intraoperative context—with attention to modality, persistence, timing, and physiological confounders—rather than prompting reflexive intervention.

The observation that alerts clustered at the T2 decompression checkpoint (69.6%) is clinically intuitive: neural decompression is the step of greatest mechanical stress on the cord and nerve roots, and it is the moment at which both true injury and transient signal perturbation are most likely to occur. The finding that all T1 (exposure) alerts were transient, whereas both sustained dual-modality alerts occurred at T2, reinforces the notion that the decompression phase is the highest-risk window and the most informative time point for monitoring. This timing pattern has direct practical implications for where surgical vigilance—and monitoring attention—should be concentrated.

A distinctive contribution of this study is the demonstration that the IONM group not only showed a lower incidence of deterioration but also recovered better among the minority who did deteriorate. Among the 12 deterioration patients, the IONM group achieved significantly higher 6-month JOA and lower VAS scores, and a greater magnitude of pain relief. This is mechanistically plausible: real-time monitoring allows earlier recognition and correction of impending injury, thereby limiting the severity of any damage that does occur. This "damage-mitigation" role is a frequently overlooked benefit of IONM that extends beyond simple detection, and it aligns with reports of the prognostic value of IONM in cervical procedures [10,13].

The electrophysiological data reinforce the clinical findings at the pathway level: decompression produced significant improvements in both sensory (SSEP) and motor (MEP) conduction, whereas the subsequent steps (cage insertion through closure)

produced no further change. These data provide objective, mechanism-level evidence that the surgical decompression itself—rather than nonspecific perioperative factors—drives the observed functional recovery, and they validate the physiological basis for the monitoring strategy used. The significant improvements in both SSEP and MEP amplitudes are consistent with the known correlation between evoked potential changes and clinical outcomes in cervical myelopathy [14].

Several limitations must be acknowledged. First, the retrospective, non-randomized design—with grouping determined by surgeon preference and equipment availability—introduces potential selection bias that cannot be fully eliminated by statistical adjustment. Second, the loss to follow-up rate was substantial (297/792, 37.5%), which may introduce attrition bias if patients with poorer outcomes were less likely to return. Third, postoperative complications other than neurological deterioration (e.g., C5 palsy specifically, dysphagia, cerebrospinal fluid leakage, hematoma, infection, and reoperation) were not systematically collected, and the safety assessment therefore rests on functional scores rather than a dedicated complication registry [2,15,16]. Fourth, the number of neurological deterioration events was small (12 across both groups), limiting statistical power for subgroup and predictive analyses; the subgroup analyses involving three patients in particular should be regarded as exploratory. Fifth, the SEP predictive analyses showed only borderline significance, and the wide confidence intervals for several regression coefficients reflect the sparse-event setting [17]. Finally, the single-center design may limit generalizability, and the economic implications of routine monitoring remain contested [6,18,19].

Conclusions

Intraoperative neuromonitoring during single-level ACDF was associated with superior immediate and 6-month neurological and pain outcomes, a high negative predictive value for excluding neurological injury, and alerts concentrated at the decompression stage. The electrophysiological improvements after decompression corroborated the clinical findings. These results support the clinical value of IONM in ACDF while highlighting the need for context-sensitive interpretation of alerts given their low positive predictive value. Prospective, multicenter studies with systematic complication collection are

warranted to confirm these findings and to define the optimal criteria for routine versus selective IONM use in ACDF.

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Table 1. Characteristics of the patients

Variable	Non-IONM group (n=257)	IONM group (n=238)	P value
Sex, n (%)			
Male	154 (59.9)	144 (60.5)	0.968
Female	103 (40.1)	94 (39.5)	
Age (years), mean ± SD	57.6 ± 12.3	58.4 ± 11.6	0.480
Surgical level, n (%)			
C3/4	60 (23.3)	64 (26.9)	0.530
C4/5	105 (40.9)	86 (36.1)	
C5/6	92 (35.8)	88 (37.0)	
Operative time (min), median (IQR)	120 (90–130)	120 (90–125)	0.548
Diagnosis, n (%)			
Cervical radiculopathy	167 (65.0)	154 (64.7)	0.949
Cervical myelopathy	90 (35.0)	84 (35.3)	

Table 2. Monitoring characteristics of the 23 alert patients

Alert characteristic	n (%)
Alert type	
Transient	12 (52.2)
Sustained single-modality	9 (39.1)
Sustained dual-modality	2 (8.7)
Alert checkpoint	
T1 (after exposure)	4 (17.4)
T2 (after decompression)	16 (69.6)
T3 (after cage insertion)	2 (8.7)
T4 (skin closure)	1 (4.3)

Table 3. Alert performance (IONM group, n=238)

	Neurological deterioration (+)	Neurological deterioration (−)	Total
Alerts (+)	2 (true positive)	21 (false positive)	23
Alerts (−)	1 (false negative)	214 (true negative)	215
Total	3	235	238

Table 4. JOA and VAS scores of the two groups (event-free cohort)

Time point	IONM (n=214)		Non-IONM (n=248)	
	JOA	VAS	JOA	VAS
Preoperative	10.50 ± 1.74	7.90 ± 1.40	10.57 ± 1.75	7.86 ± 1.35
postoperative	14.50 ± 1.11	2.47 ± 1.14	12.19 ± 1.40	4.48 ± 1.12
6 months	16.00 ± 0.83	2.00 ± 0.83	13.52 ± 1.12	3.48 ± 1.12

Table 5 The JOA and VAS scores of neurological deterioration patients

	INOM Group(n=3)		Non-INOM Group(n=9)	
	JOA	VAS	JOA	VAS
Preop	11.5 ± 1.1	6.3 ± 1.0	10.6 ± 1.8	6.4 ± 1.1
Postop	8.8 ± 0.8	7.7 ± 0.5	7.4 ± 0.9	7.8 ± 0.7
Postop (6 mo)	14.3 ± 0.8	1.7 ± 0.5	12.2 ± 1.4	2.8 ± 0.7

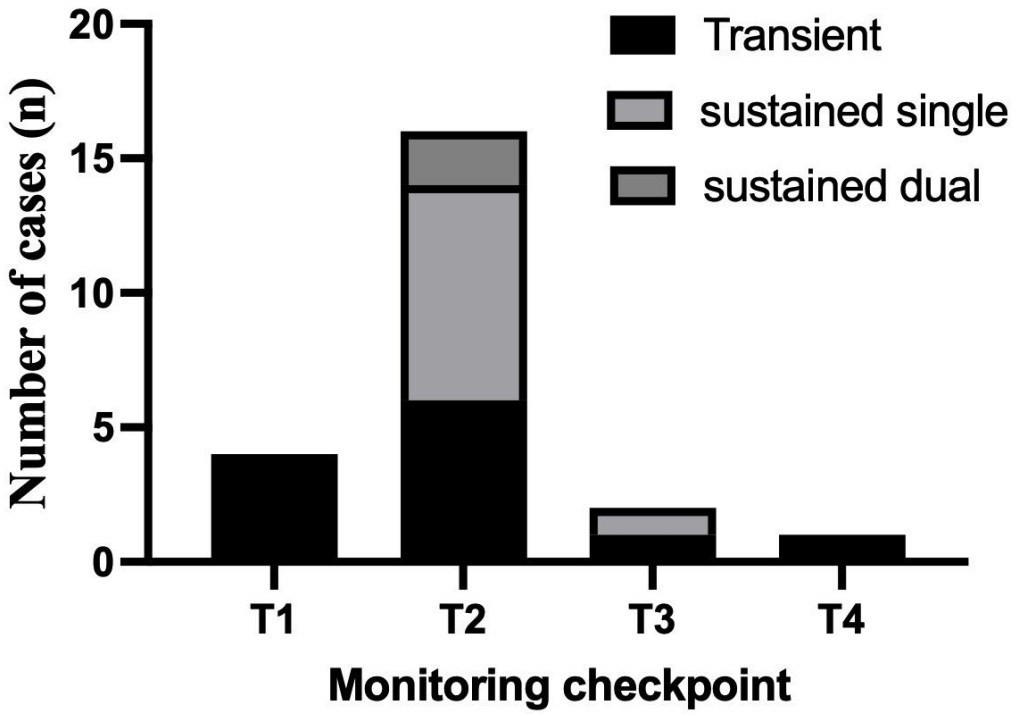


Figure 1. Distribution of alert types across monitoring checkpoints among the 23 alert patients.

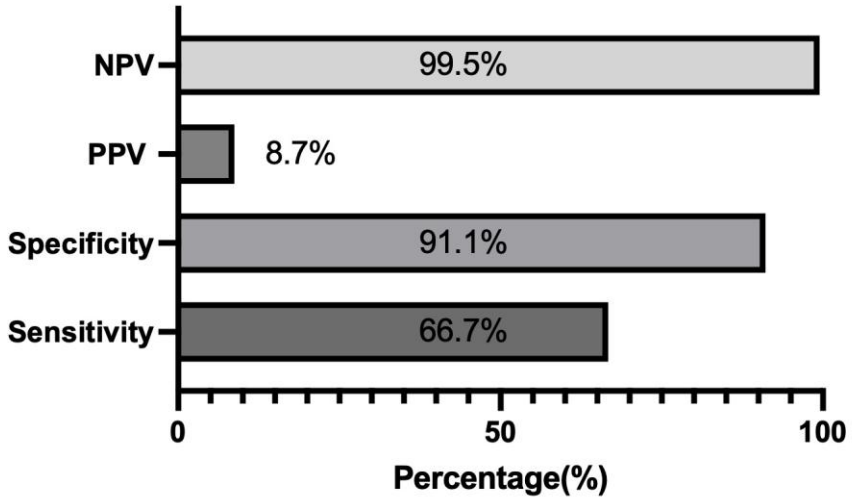
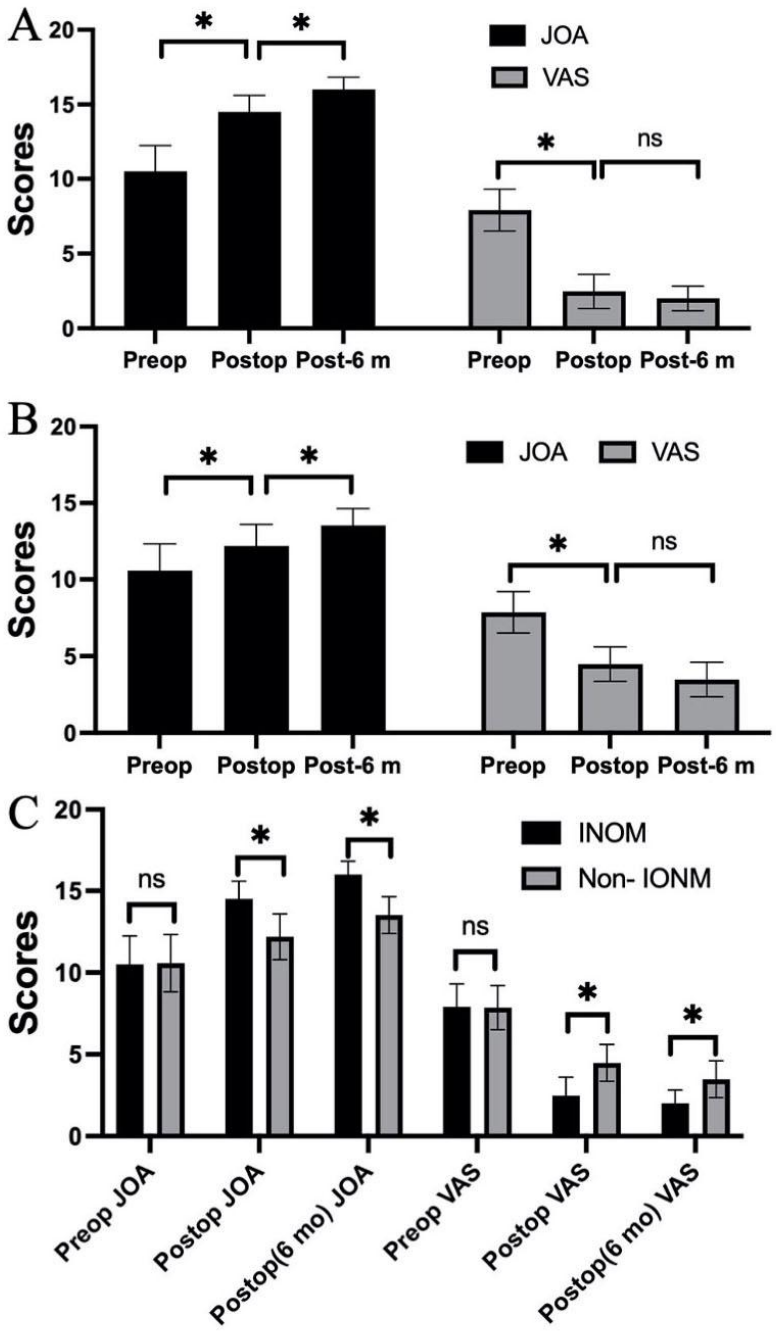
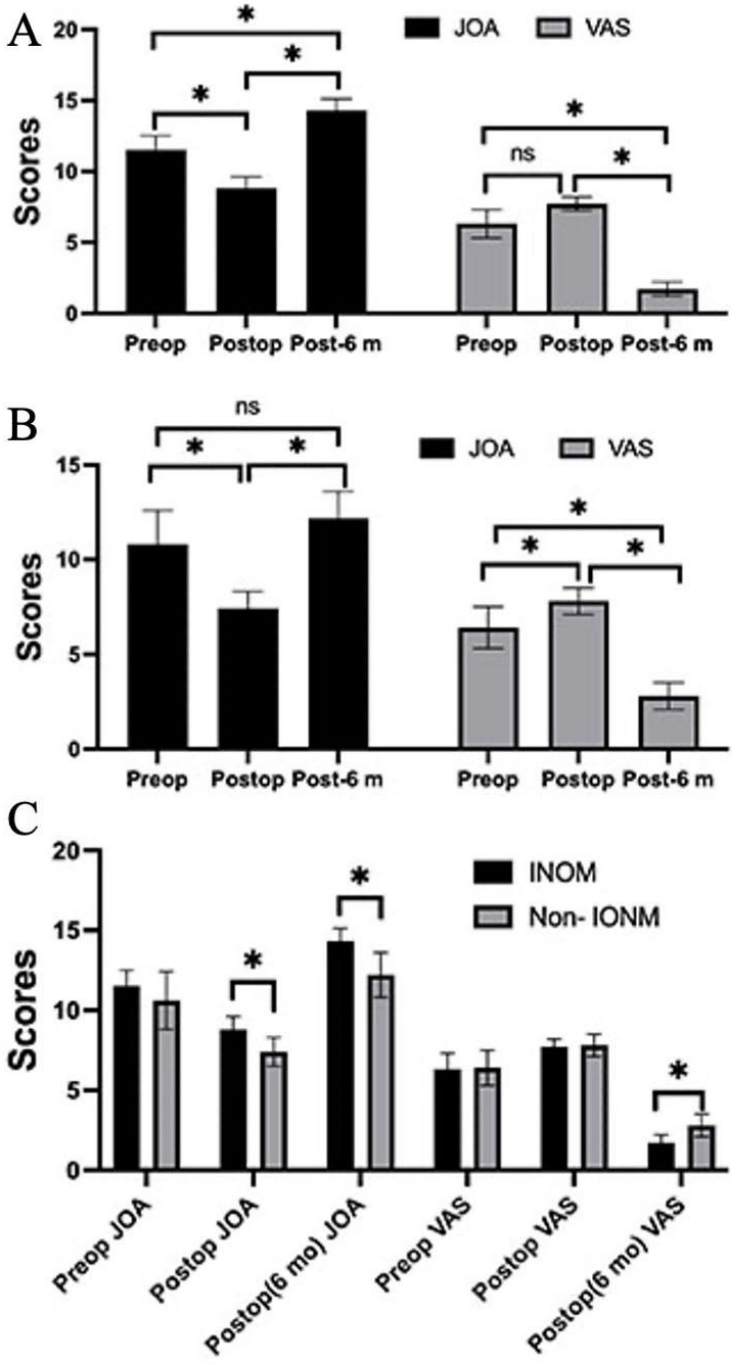


Figure 2. Diagnostic performance of IONM (sensitivity 66.7%, specificity 91.1%, PPV 8.7%, NPV 99.5%).



Figures 3. Comparison of JOA and VAS scores between the IONM and non-IONM groups at each time point (event-free cohort), with within-group(A&B) and between-group comparisons (C).



Figures 4. JOA and VAS trajectories of patients with neurological deterioration (IONM n=3 vs. non-IONM n=9), with within-group(A&B) and between-group comparisons (C).

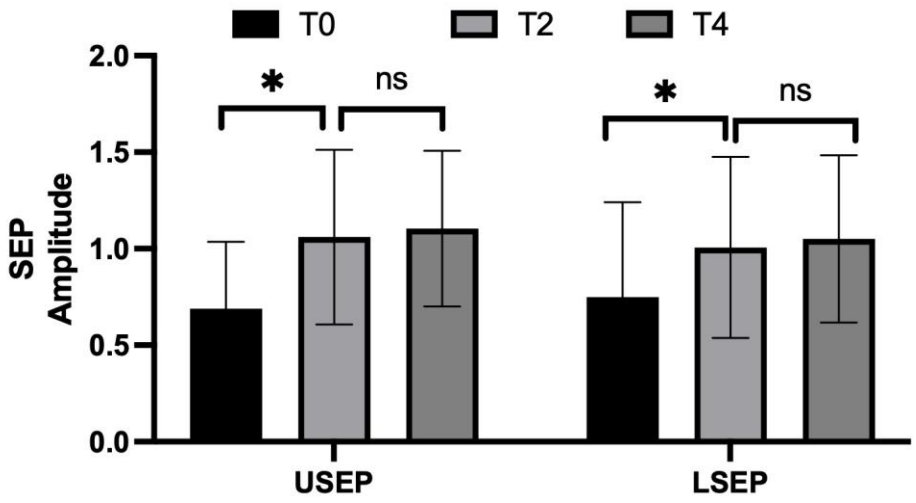


Figure 5. SSEP amplitude changes from T0 to T2 to T4 for upper (USEP) and lower (LSEP) extremity SSEPs.

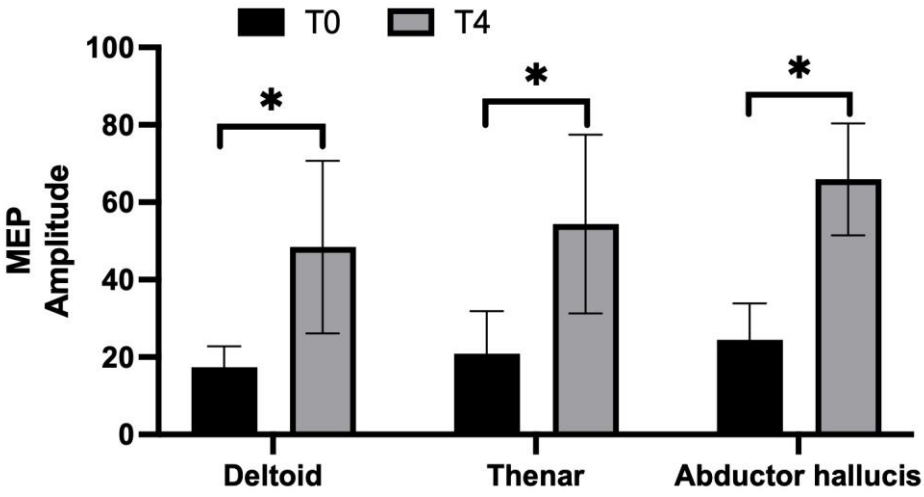


Figure 6. MEP amplitude changes from T0 to T4 for the deltoid, thenar, and abductor hallucis muscles.

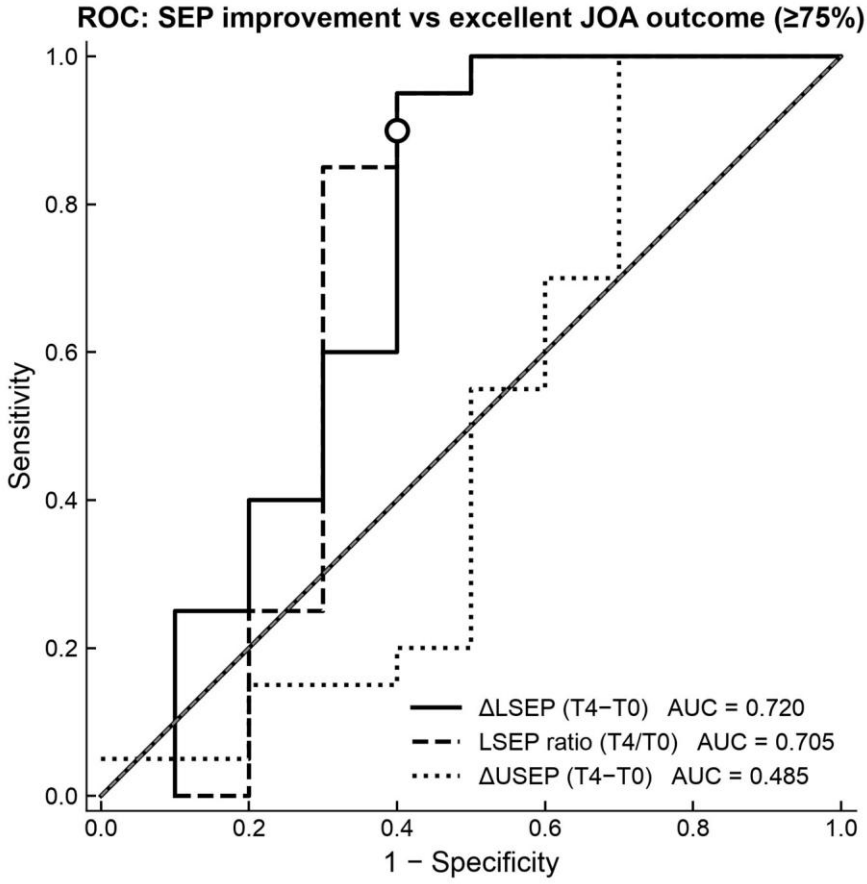


Figure 7. ROC curves of SEP-derived variables for predicting an excellent JOA outcome (recovery rate ≥75%).

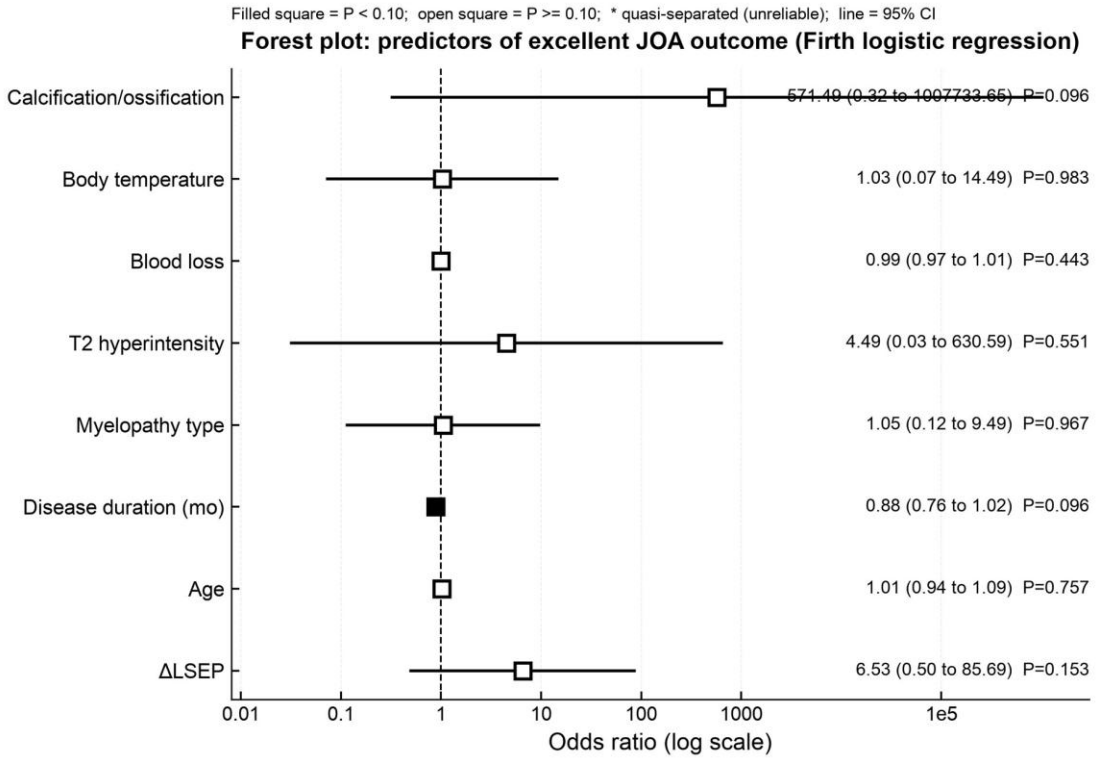


Figure 8. Forest plot of predictors of excellent JOA outcome (Firth logistic regression).