

Multimodal Intraoperative Neurophysiological Monitoring in Pediatric Spinal Surgery: A Single-Center Ambispective Study

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Research Article

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Abstract

Background

Neurological injury remains a major concern during pediatric spinal surgery because of the complexity of spinal pathologies and the vulnerability of the developing spinal cord. Multimodal intraoperative neurophysiological monitoring (IONM) facilitates real-time assessment of neural pathway integrity and may help prevent postoperative neurological deficits. This study evaluated the diagnostic performance and clinical utility of multimodal IONM in pediatric spinal surgery.

Methods

We performed an ambispective observational study of pediatric patients (0–18 years) who underwent spinal surgery with multimodal IONM at a tertiary neurosurgical center between January 2022 and December 2025. Monitoring modalities included transcranial motor evoked potentials (TcMEPs), somatosensory evoked potentials (SSEPs), electromyography (EMG), D-wave monitoring, and bulbocavernosus reflex assessment when indicated. Significant IONM alerts were defined as a $\geq 50\%$ reduction or complete loss of TcMEP amplitude and a $\geq 50\%$ reduction in SSEP amplitude and/or $\geq 10\%$ increase in SSEP latency from baseline. Neurological assessment was done immediately after surgery and at 3-month follow-up. Primary outcome was the occurrence of a new postoperative neurological deficit. Secondary outcomes included IONM alert incidence and recovery, postoperative neurological outcomes, and the diagnostic accuracy of individual IONM modalities

Results

Sixty-four patients were included (mean age, 95 months; 53.1% male), comprising spinal dysraphism (n = 44), spinal tumors (n = 14), atlantoaxial instability (n = 5), and spinal deformity (n = 1). Significant intraoperative IONM alerts occurred in 31 patients (48.4%), with signal recovery following response protocol initiation in 21 patients (67.7%). Persistent alerts were observed in 10 patients (32.3%). Three patients (4.7%) developed new postoperative neurological deficits, of whom only one (1.6%) had persistent deficit at 3 months. TcMEPs and EMG demonstrated 100% sensitivity and 100% negative predictive value for detecting post operative neurological deficits, while SSEPs achieved 100% sensitivity, specificity, positive predictive value, and negative predictive value. The proportion of patients with motor deficits decreased from 76.6% preoperatively to 60.9% at follow-up, with similar improvement in sensory deficits. **p = 0.031** for motor deficits: Preoperative motor dysfunction reduced significantly from 76.6% (49/64) to 60.9% (39/64) at the 3-month follow-up. **p = 0.248** for sensory deficits and **p = 0.453** for bowel/bladder involvement: Sensory symptoms decreased from 59.4% to 50.0% and sphincter dysfunction decreased from 56.3% to 50.0%, though neither reached statistical significance. **p = 0.009** for diagnostic risk, **p = 0.002** for persistent alerts, and **p = 0.317** for overall neurological outcome change: Spinal tumors had a significantly higher incidence of alerts (35.5% vs 9.1%)¹ and unresolved alerts

(42.9%) compared to other pathologies ², while overall recovery rates from immediate post-op to 3 months showed non-significant improvement ³.

Conclusion

Multimodal IONM demonstrated high diagnostic performance and was associated with favorable neurological outcomes in pediatric spinal surgery. Early identification of intraoperative neurophysiological changes enabled timely rescue interventions and may have contributed to minimizing postoperative neurological deficits. Larger multicenter studies with longer follow-up are warranted to validate these findings and further define the role of multimodal IONM in pediatric spinal surgery.

INTRODUCTION

Pediatric spinal surgery encompasses a wide range of procedures performed for spinal dysraphism, spinal deformities, intradural and intramedullary tumors, craniovertebral junction anomalies, trauma and infections. Despite advances in surgical techniques, these procedures continue to carry a significant risk of intraoperative neurological injury because of the proximity of neural structures, the need for complex spinal manipulation, and the unique anatomical and physiological characteristics of the developing nervous system. Even minor spinal cord or nerve root injury may result in permanent motor, sensory, or sphincter dysfunction, with profound lifelong physical, psychological, and socioeconomic consequences for affected children and their families. [1, 2]

Traditionally, the prevention of neurological injury relied on meticulous surgical technique, anatomical knowledge, and postoperative neurological examination. However, these methods do not provide real-time assessment of spinal cord function during surgery, potentially delaying recognition of neurological compromise until irreversible injury has occurred.[3, 4] The introduction of intraoperative neurophysiological monitoring (IONM) has transformed pediatric spinal surgery by enabling continuous functional assessment of neural pathways throughout the operative procedure, allowing early detection of impending neurological injury and facilitating timely corrective interventions.[5, 6]

Modern multimodal IONM combines several complementary monitoring techniques to assess different components of the nervous system. Transcranial motor evoked potentials (TcMEPs) evaluate the functional integrity of corticospinal motor pathways, whereas somatosensory evoked potentials (SSEPs) monitor dorsal column sensory pathways. Electromyography (EMG), including both free-running and triggered EMG, provides continuous assessment of nerve root function and assists in the safe placement of spinal instrumentation. Additional modalities such as D-wave monitoring and bulbocavernosus reflex (BCR) assessment offer additional information regarding descending motor tract integrity and sacral cord function respectively. [6, 7] The combined use of these modalities has been shown to improve the sensitivity of detecting intraoperative neural compromise compared with single-modality monitoring.

Although multimodal IONM is now considered standard practice for many complex spinal procedures, its clinical utility in pediatric neurosurgery continues to evolve. Variability in monitoring protocols, alert criteria, anesthetic techniques, and interpretation of neurophysiological changes may influence its diagnostic performance. [6–10] Furthermore, false-positive and false-negative alerts continue to pose clinical challenges. Most published evidence has focused on pediatric scoliosis surgery or individual spinal pathologies, whereas data evaluating multimodal IONM across the broader spectrum of pediatric spinal disorders—including spinal dysraphism, intramedullary tumors, craniovertebral junction anomalies and other complex spinal pathologies—remain limited. Data from low- and middle-income countries are particularly scarce, despite increasing adoption of IONM in specialized pediatric neurosurgical centers. [6, 10–13]

To address this gap, we conducted an ambispective observational study to evaluate the diagnostic performance and clinical utility of multimodal intraoperative neurophysiological monitoring in pediatric spinal surgery at a tertiary care neurosurgical center. Specifically, we assessed the incidence and recovery of intraoperative IONM alerts, the predictive accuracy of individual monitoring modalities for postoperative neurological deficits, and the neurological outcomes.

METHODOLOGY

Study Design and Setting

This ambispective observational study was conducted in the Department of Neurosurgery, King George's Medical University (KGMU), Lucknow, India. The retrospective cohort comprised pediatric patients who underwent spinal surgery with multimodal intraoperative neurophysiological monitoring (IONM) between January 2022 and April 2024, whereas the prospective cohort included consecutive eligible patients undergoing surgery between May 2024 and December 2025. Clinical, operative, anesthetic, neurophysiological, and follow-up data were collected using a standardized data collection protocol.

Ethical Considerations

The study was approved by the Institutional Ethics Committee of King George's Medical University, Lucknow (Reference code: XVI-PGTSC-IIA/P67; Date: 5/8/23) & (Reference code: XXXIII-PGTSC-IIA/P6; Date: 15/4/25). The retrospective component was conducted after approval for review of hospital medical records whereas written informed consent was obtained from the parents or legally authorized guardians of prospectively enrolled patients. The study was conducted in accordance with the ethical principles of the Declaration of Helsinki and the STROBE guidelines for reporting observational studies.

Data Collection and Management

Demographic, Clinical, radiological, anesthetic, operative, neurophysiological, and postoperative outcome data for prospectively enrolled patients were recorded contemporaneously using standardized case record forms. For the retrospective cohort, data were extracted from the departmental Neuro-Patient Management System (NPMS) database and cross-verified with operative records, anesthesia charts, inpatient case files, and the hospital electronic medical records wherever required to ensure data accuracy and completeness. All collected data were anonymized and entered into a secure study database for analysis. Data quality was maintained through periodic verification; consistency checks and validation against source documents prior to statistical analysis.

Patient Selection

All consecutive pediatric patients (0–18 years) undergoing spinal surgery with multimodal intraoperative neurophysiological monitoring (IONM) during the study period were screened for eligibility. Patients meeting the predefined inclusion and exclusion criteria were enrolled. Consecutive enrolment was adopted to minimize selection bias.

Flow chart 1: patient selection

Inclusion Criteria

Patients fulfilling all of the following criteria were included:

- Age ≤ 18 years.
- Undergoing spinal surgery requiring multimodal intraoperative neurophysiological monitoring.
- Availability of complete perioperative clinical, operative, anesthetic and neurophysiological monitoring data.
- Completion of the planned postoperative neurological assessment.

Exclusion Criteria

Patients were excluded if they had:

- Incomplete demographic, operative, or neurophysiological monitoring records.
- Preoperative motor strength $\leq 1/5$ on the Medical Research Council (MRC) grading scale, precluding reliable interpretation of transcranial motor evoked potentials (TcMEPs).
- Missing postoperative neurological outcome data.
- Severely ill patients unsuitable for neuromonitoring.

Sample Size

This was a convenience sample including all consecutive eligible patients.

Since pediatric spinal surgeries requiring multimodal IONM are relatively uncommon, all eligible consecutive patients treated during the study period were included.

The sample size was calculated using as a convenience sampling including all consecutive eligible patients.

Preoperative Assessment

The following preoperative variables were recorded for all enrolled patients: demographic characteristics, clinical diagnosis, baseline neurological examination findings, preoperative motor strength graded according to the Medical Research Council (MRC) scale, and surgical details. In patients with intramedullary spinal cord tumors, functional neurological status was additionally assessed using the Modified McCormick Scale.

Anesthetic Protocol:

General anesthesia was administered according to the institutional neuroanaesthesia protocol optimized for multimodal intraoperative neurophysiological monitoring (IONM). Anesthesia was induced with intravenous propofol and a short-acting opioid, followed by maintenance using total intravenous anesthesia (TIVA). Propofol was administered either as a continuous infusion (approximately 100–200 µg/kg/min [6–12 mg/kg/h], titrated to clinical response) or by target-controlled infusion (TCI) with a target plasma concentration of 4–8 µg/mL, depending on patient age, physiological status, and concomitant opioid administration. A short-acting opioid (remifentanyl or fentanyl) was administered as a continuous infusion or intermittent boluses according to surgical requirements and haemodynamic responses.

Neuromuscular blocking agents were administered only to facilitate endotracheal intubation and were subsequently avoided or allowed to wear off completely before acquisition of transcranial motor evoked potentials (TcMEPs), thereby ensuring reliable assessment of corticospinal tract integrity. Volatile anaesthetic agents were avoided whenever feasible; when clinically required, they were maintained at <0.5 minimum alveolar concentration (MAC) to minimize suppression of evoked potentials.

The depth of anaesthesia was monitored using the Bispectral Index (BIS) and maintained between 40 and 60. Physiological variables known to influence neurophysiological recordings were carefully controlled throughout the procedure to ensure optimal signal quality and spinal cord perfusion. These included:

- Mean arterial pressure (MAP) $\geq$ 85 mmHg, with a target of 85–90 mmHg during significant IONM alerts.
- Normothermia (36–37°C).
- End-tidal carbon dioxide (35–40 mmHg).
- Peripheral oxygen saturation (SpO₂ >95%).

- Maintenance of adequate haemoglobin concentration.
- Normal electrolyte and acid–base balance.

Intraoperative Assessment and Neurophysiological Monitoring

Intraoperative data included operative characteristics (procedure performed, spinal levels involved, duration of surgery, estimated blood loss, and intraoperative complications) and neurophysiological monitoring findings. Multimodal intraoperative neurophysiological monitoring (IONM) was performed using the **NIM-Eclipse E4 Neurophysiological Monitoring System** (Medtronic Xomed Inc., Jacksonville, FL, USA). Monitoring was conducted throughout the procedure by an experienced multidisciplinary team comprising a neurophysiology technologist, consultant neuroanaesthesiologist, and operating neurosurgeon.

Sterile intramuscular needle electrodes were inserted into selected muscles according to the surgical pathology and spinal level involved. Common recording sites included the vastus medialis, tibialis anterior, gastrocnemius, abductor hallucis, and external anal sphincter muscles, while upper-limb muscles were monitored when clinically indicated. Baseline recordings were obtained after induction of anesthesia and before skin incision, followed by continuous monitoring throughout the surgical procedure.

The IONM modalities were selected according to the underlying pathology and included transcranial motor evoked potentials (TcMEPs), somatosensory evoked potentials (SSEPs), free-running electromyography (rEMG), triggered electromyography (tEMG), D-wave monitoring, and bulbocavernosus reflex (BCR) monitoring.

TcMEPs were elicited using transcranial electrical stimulation delivered through corkscrew scalp electrodes positioned at C1/C2 or C3/C4 according to the International 10–20 EEG system. Multipulse stimulation (5–7 square-wave pulses, pulse width 50–75 μ s) was applied with stimulus intensity adjusted to individual thresholds. Compound muscle action potentials were recorded from the target muscles.

SSEPs were recorded following stimulation of the posterior tibial or median nerves using constant-current square-wave pulses (pulse width 200–300 μ s; stimulation frequency 2–5 Hz), with cortical responses recorded from Cz–Fz scalp electrodes after signal averaging.

Continuous free-running EMG was used to detect spontaneous neurotonic discharges, repetitive bursts, or train activity suggestive of mechanical irritation or injury to neural structures. Triggered EMG was performed by direct electrical stimulation of nerve roots or pedicle screws using a monopolar stimulation probe to identify functional neural tissue and verify pedicle screw placement, with stimulation thresholds recorded for analysis.

D-wave monitoring was performed in selected intramedullary spinal cord tumour surgeries using epidural recording electrodes placed distal to the operative field to assess corticospinal tract conduction.

Bulbocavernosus reflex monitoring was performed in selected spinal dysraphism procedures by stimulating the dorsal penile or clitoral nerve and recording responses from the external anal sphincter to evaluate the integrity of the S2–S4 sacral reflex arc.

The choice of monitoring modalities was tailored to the surgical pathology. Patients with spinal dysraphism underwent TcMEP, SSEP, free-running EMG, triggered EMG, and BCR monitoring. Patients with spinal tumours underwent TcMEP, SSEP, and D-wave monitoring, whereas those undergoing surgery for spinal deformity or atlantoaxial instability were monitored using TcMEPs and SSEPs. Significant intraoperative neurophysiological changes were immediately communicated to the surgical and anaesthesia teams, and appropriate corrective measures were instituted according to the institutional IONM protocol.

Intraoperative Alert Criteria

Baseline neurophysiological recordings were obtained after induction of anaesthesia and before skin incision or surgical manipulation. Subsequent recordings were compared with these baseline values throughout the procedure.

A significant TcMEP alert was defined as a $\geq 50\%$ reduction in compound muscle action potential amplitude from baseline or complete loss of the motor response. A significant SSEP alert was defined as a $\geq 50\%$ reduction in amplitude and/or a $\geq 10\%$ increase in latency compared with baseline recordings. Guiz et al [23]

Continuous free-running EMG was monitored for sustained neurotonic discharges or train activity indicative of nerve root irritation, while triggered EMG responses were interpreted according to predetermined institutional stimulation thresholds for neural tissue identification and pedicle screw assessment. For cases in which D-wave monitoring was performed, a persistent reduction in D-wave amplitude of $\geq 50\%$ from baseline was considered clinically significant.

All intraoperative alerts were immediately communicated to the operating surgeon and neuroanaesthesiology team. Potential reversible causes—including hypotension, anaesthetic effects, hypothermia, technical or electrode-related issues, and surgical manoeuvres—were systematically evaluated and corrected before considering the alert indicative of neurological injury. Alert criteria and Response protocols were based on institutional practice and established recommendations from the American Clinical Neurophysiology Society (ACNS) and published guidelines on intraoperative neurophysiological monitoring.

Stimulation parameters in IONM:

TcMEPs	0–5 yrs	Scalp corkscrew electrodes over motor cortex	Lower limb muscles (abductor hallucis for S2), bilateral external anal sphincter, upper limb control muscles	Voltage: 300–450 V
TcMEPs	6–18 yrs	Scalp corkscrew electrodes over motor cortex	Lower limb muscles (abductor hallucis for S2), bilateral external anal sphincter, upper limb control muscles	Voltage: 150–300 V
SSEPs	0–5 yrs	Tibial nerve (ankle)	Scalp corkscrew electrodes over primary somatosensory cortex (Cz, Fz)	Current: 20–40 mA
SSEPs	6–18 yrs	Tibial nerve (ankle)	Scalp corkscrew electrodes over primary somatosensory cortex (Cz, Fz)	Current: 15–30 mA
Free-running EMG	0–18 yrs	—	Target muscles	No stimulation (passive recording)
Triggered EMG	0–5 yrs	Monopolar probe	Target muscles	Current: 1–7 mA; Pulse width: 75–200 µs
Triggered EMG	6–18 yrs	Monopolar probe	Target muscles	Current: 0.5–5 mA; Pulse width: 75–200 µs

Intraoperative Response Protocol

Following a significant reduction in TcMEP or SSEP amplitudes, a standardized multidisciplinary response protocol was immediately initiated to identify and correct reversible causes of neurophysiological deterioration. The operating neurosurgeon, neuroanaesthesiologist, and neurophysiology team jointly reviewed the neurophysiological recordings and implemented the following measures:

1. **Technical verification:** Electrode positions, stimulation parameters, recording channels, and equipment integrity were checked to exclude technical artefacts.
2. **Optimization of physiological and anaesthetic parameters:** Mean arterial pressure (MAP) was increased and maintained at ≥ 90 mmHg to improve spinal cord perfusion. Anaesthetic depth was optimized (Bispectral Index 40–60), volatile anaesthetic concentration was minimized (< 0.5 MAC, when used), normothermia (36–37°C) was maintained, and oxygenation, ventilation, haemoglobin concentration, electrolyte balance, and acid–base status were corrected as required.
3. **Surgical intervention:** The ongoing surgical manoeuvre was immediately suspended, and the operative field, including the exposed spinal cord, was irrigated with warm saline. Mechanical factors such as excessive traction, spinal cord compression, instrumentation, or deformity correction were reassessed and reversed or modified whenever feasible.

4. **Pharmacological intervention:** If neurophysiological signals failed to improve despite correction of reversible factors, an intravenous bolus of methylprednisolone (30 mg/kg) was administered over 15 minutes, according to the institutional protocol.
5. **Decision regarding continuation of surgery:** Surgery was resumed only after satisfactory recovery of TcMEP and/or SSEP signals. In cases where significant signal deterioration persisted despite all corrective measures, the planned surgical procedure was modified, staged, or terminated at the discretion of the operating surgeon to minimize the risk of permanent neurological injury.

Extent of Tumour Resection

For patients undergoing surgery for spinal tumours, the extent of tumour resection was classified according to the criteria described by **Lee et al.** [97] as follows:

- **Gross Total Resection (GTR):** Complete microsurgical removal of all visible tumour, with no residual tumour apparent intraoperatively.
- **Near Total Resection (NTR):** Removal of >90% of the tumour, with a small residual component (<10%) intentionally left because of adherence to eloquent neural structures or an unacceptable risk of neurological injury.
- **Subtotal Resection (STR):** Removal of approximately 50–90% of the tumour, with deliberate residual tumour left in situ when complete excision was considered unsafe.

Where available, the extent of resection was corroborated by early postoperative imaging and the operative records.

Outcome Measures

- The primary outcome was the occurrence of a new postoperative neurological deficit, defined as any new or worsening motor, sensory, or sphincter dysfunction compared with the preoperative neurological status, and its association with intraoperative neurophysiological changes.
- Secondary outcomes included the incidence of significant intraoperative neurophysiological monitoring (IONM) alerts; the rate of recovery following implementation of intraoperative Response protocol; extent of tumour resection, where applicable; postoperative neurological status at hospital discharge and at the 3-month follow-up; and the diagnostic performance of individual IONM modalities. Diagnostic performance was evaluated by calculating sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and overall diagnostic accuracy.

Follow-up

- Postoperative neurological assessments were performed immediately after surgery, at hospital discharge, and during a scheduled outpatient visit at 3 months. Neurological outcomes, including motor strength, sensory function, sphincter function, and overall functional status, were

documented using standardized neurological assessment forms. For patients with spinal cord tumours, the Modified McCormick Scale was reassessed at follow-up where applicable.

- All surviving patients completed the planned 3-month postoperative follow-up.

Missing Data- Patients with incomplete clinical, operative, or intraoperative neurophysiological monitoring data that precluded assessment of the primary outcome were excluded from the final analysis. For the retrospective cohort, missing variables were verified from the departmental Neuro-Patient Management System, operative records, anesthesia charts, inpatient case files, and hospital electronic medical records wherever possible before exclusion. No statistical imputation was performed for missing data.

During the study period, **two patients with intramedullary spinal cord tumours died in the early postoperative period** and were therefore unavailable for the planned 3-month neurological follow-up. These included a **2-year-old female with a C3–C5 intramedullary space-occupying lesion (IMSOL)** who died on **postoperative day (POD) 3**, and a **5-year-old male with a D12–L1 intramedullary IMSOL** who died on **POD 1**. Both patients remained ventilator-dependent postoperatively and could not be extubated because of severe neurological impairment and progressive clinical deterioration. These cases were included in the analysis of perioperative outcomes but were excluded from analyses requiring 3-month neurological follow-up.

Statistical Analysis

Statistical analysis was performed using IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA). Continuous variables were expressed as mean $\pm$ standard deviation (SD) or median (interquartile range) according to data distribution. Categorical variables were summarized as frequencies and percentages.

Associations between categorical variables were analyzed using the Chi-square test or Fisher's exact test, as appropriate. Continuous variables were compared using the Student's t-test or Mann–Whitney U test depending on data distribution.

The diagnostic performance of TcMEPs, SSEPs, free-running EMG, triggered EMG, D-wave monitoring, and bulbocavernosus reflex assessment was evaluated by calculating sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), diagnostic accuracy, and corresponding 95% confidence intervals. **Receiver operating characteristic (ROC) curve analysis** was performed to assess the discriminatory ability of each monitoring modality, and the **area under the ROC curve (AUC)** with **95% confidence intervals** was calculated. Odds ratios with 95% confidence intervals were calculated where appropriate. All statistical tests were two-sided, and a P value <0.05 was considered statistically significant.

RESULTS

Demographic and clinical characteristics:

A total of 64 paediatric patients who underwent spinal surgery with multimodal intraoperative neurophysiological monitoring (IONM) were included in the study. The mean age was 95 months, with a median age of 87 months. Patients aged 6–18 years comprised the majority of the cohort (39/64, 60.9%), whereas children aged 0–5 years accounted for 25/64 (39.1%). There was a slight male predominance, with 34 males (53.1%) and 30 females (46.9%) (Table 1). The most common indication for surgery was spinal dysraphism (44/64, 68.8%), followed by spinal tumours (14/64, 21.9%), atlantoaxial instability (5/64, 7.8%), and spinal deformity (1/64, 1.6%) (Table 2).

Intraoperative Neurophysiological Monitoring Findings: Significant intraoperative neurophysiological changes were observed in 31 of 64 patients (48.4%), while 33 patients (51.6%) maintained stable neurophysiological signals throughout the procedure (Table 3). Following implementation of the institutional IONM Response protocol, neurophysiological signals recovered in 21 of the 31 patients with alerts (67.7%), whereas persistent IONM alerts remained until the completion of surgery in 10 patients (32.3%) (Table 4).

Comparison of patients with and without significant IONM alerts demonstrated that spinal tumours were significantly more likely to be associated with intraoperative neurophysiological deterioration than other pathologies (35.5% vs. 9.1%; $P = 0.009$). Conversely, spinal dysraphism was significantly more common among patients without IONM alerts than among those with alerts (78.8% vs. 58.1%; $P = 0.041$). No significant differences were observed between the two groups with respect to age or sex ($P > 0.05$) (Table 9).

Among the 10 patients with persistent IONM alerts despite corrective interventions, spinal tumour surgery accounted for the majority of cases (60.0%), followed by spinal dysraphism (30.0%) and spinal deformity (10.0%). No persistent alerts occurred in patients undergoing surgery for atlantoaxial instability (Table 5). The distribution of persistent IONM alerts differed significantly across diagnostic categories ($P = 0.002$), indicating that spinal tumour surgery was associated with a substantially higher risk of unresolved intraoperative neurophysiological deterioration compared with other spinal pathologies (Table 5).

Neurological Outcomes: Immediate postoperative neurological assessment revealed new neurological deficits in 3 of 64 patients (4.7%), while 59 patients (92.2%) had no new or worsening neurological deficits. Two patients (3.1%) died during the postoperative period due to the severity of their underlying disease (Table 6). At the 3-month follow-up, neurological recovery was observed in the majority of affected patients, with only one patient (1.6%) demonstrating a persistent neurological deficit. No additional deaths occurred during follow-up, and comparison of immediate postoperative and 3-month neurological status showed an overall improvement in neurological outcomes, although this difference was not statistically significant ($P = 0.317$) (Table 6).

Comparison of preoperative neurological status with findings at the 3-month follow-up demonstrated an overall improvement in neurological function (Table 8). Motor deficits showed the greatest recovery, decreasing from 76.6% preoperatively to 60.9% at follow-up ($P = 0.031$). Sensory deficits decreased from

59.4% to 50.0%, while bladder and bowel dysfunction declined from 56.3% to 50.0%; however, these changes were not statistically significant ($P > 0.05$) (Table 8).

Patients with Postoperative Neurological Deficits: Three patients (4.7%) developed new postoperative neurological deficits (Table 10). Two patients underwent surgery for spinal tumours and one for spinal dysraphism. All three demonstrated significant intraoperative TcMEP deterioration with persistent alerts despite implementation of the institutional IONM Response protocol. At the 3-month follow-up, two patients experienced complete neurological recovery, whereas one patient had a persistent residual neurological deficit. These findings suggest that persistent intraoperative neurophysiological deterioration, particularly persistent TcMEP alerts despite corrective interventions, is associated with an increased risk of postoperative neurological deficits.

Diagnostic Accuracy of Multimodal IONM: Diagnostic performance analysis demonstrated excellent accuracy of multimodal intraoperative neurophysiological monitoring (IONM) for predicting postoperative neurological deficits (Table 7). Somatosensory evoked potentials (SSEPs) achieved 100% sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV). Transcranial motor evoked potentials (TcMEPs) and electromyography (EMG) each demonstrated a sensitivity of 100%, with specificities of 93.3% and 94.4%, respectively. The corresponding 95% confidence intervals are presented in Table 7. Overall, multimodal IONM exhibited excellent diagnostic performance, with a particularly high negative predictive value, indicating reliable identification of patients at low risk for postoperative neurological deficits.

DISCUSSION

The present study evaluated the clinical utility of multimodal intraoperative neurophysiological monitoring (IONM) in 64 paediatric patients undergoing spinal surgery for spinal dysraphism, spinal tumours, atlantoaxial instability, and spinal deformity. Three principal findings emerged. First, significant intraoperative neurophysiological alerts occurred in nearly half of the patients (48.4%), underscoring the inherent risk of neurological compromise during paediatric spinal surgery. Second, implementation of a standardized IONM response protocol resulted in recovery of neurophysiological signals in 67.7% of patients with alerts, suggesting that many intraoperative changes represented reversible spinal cord dysfunction. Third, despite the high frequency of alerts, only three patients (4.7%) developed new postoperative neurological deficits, with persistent neurological impairment in only one patient (1.6%) at 3 months. These findings support multimodal IONM as an effective adjunct for real-time detection of neurological compromise and guidance of intraoperative decision-making.

Our findings are consistent with previous studies supporting multimodal IONM in paediatric spinal surgery. Charalampidis et al. [6] and Levin et al. [7] demonstrated that combining transcranial motor evoked potentials (TcMEPs), somatosensory evoked potentials (SSEPs), and electromyography (EMG) provides superior diagnostic reliability compared with individual modalities by simultaneously evaluating multiple neural pathways. Similarly, Iorio et al. [13], Tobert et al. [14], and Neira et al. [10] reported

excellent diagnostic accuracy and high negative predictive values, while Lewis et al. [16] and Vitale et al. [15] emphasized that favorable neurological outcomes depend not only on early detection of neurophysiological deterioration but also on prompt multidisciplinary corrective interventions. The recovery of neurophysiological signals in more than two-thirds of our patients following implementation of a structured rescue protocol closely parallels these observations.

The excellent diagnostic performance of multimodal IONM reflects the complementary physiological information provided by each monitoring modality. TcMEPs are highly sensitive to corticospinal tract dysfunction, SSEPs assess dorsal column integrity and spinal cord perfusion, and EMG facilitates identification of nerve root irritation or injury. Simultaneous assessment of these pathways improves diagnostic accuracy and reduces the limitations of individual techniques, as advocated by Charalampidis et al. [6] and Neira et al. [10].

Disease-specific analysis further highlighted the value of pathology-tailored interpretation of IONM. Spinal dysraphism, the largest subgroup, demonstrated favorable neurological outcomes despite occasional alerts, with triggered EMG proving particularly useful during tethered cord release, consistent with McGrath et al. [17] and Guo et al. [21]. In contrast, spinal tumours accounted for most persistent IONM alerts and postoperative neurological deficits, supporting the findings of Sala et al. [12] that persistent TcMEP deterioration during intramedullary tumour surgery predicts postoperative motor deficits. Although only one patient underwent deformity correction, persistent TcMEP and SSEP deterioration was associated with postoperative motor weakness, consistent with Nagarajan et al. [18] and Pastorelli et al. [19]. No persistent alerts or neurological deficits occurred during atlantoaxial instability surgery, corroborating the excellent negative predictive value reported by Tobert et al. [14].

A notable strength of this study was the inclusion of a substantial proportion of children aged ≤ 5 years, in whom reliable IONM has traditionally been challenging because of immature corticospinal pathways and higher stimulation thresholds. Nevertheless, consistent TcMEP, SSEP, and EMG recordings were obtained across all age groups, supporting recent observations by Elmesallamy et al. [20] and Guo et al. [21] that advances in stimulation techniques, neuroanesthesia, and monitoring technology have expanded the feasibility of IONM even in very young children.

Although multimodal IONM demonstrated 100% sensitivity and negative predictive value, these estimates should be interpreted cautiously because only three patients developed postoperative neurological deficits. Persistent alerts without permanent deficits likely reflected reversible physiological disturbances or technical factors, while timely corrective interventions may have prevented irreversible injury. Consequently, some apparent false-positive alerts may represent successful rescue rather than inaccurate monitoring. No false-negative events occurred in the present study; however, such events have been reported because of technical failure, delayed neurological deterioration, or selective pathway injury not detected by monitored modalities [6,10]. The inclusion of diverse paediatric spinal pathologies, a standardized multimodal monitoring protocol, a structured response algorithm, and prospective neurological follow-up strengthen the clinical relevance of our findings. Nevertheless, larger prospective

multicentre studies are required to validate these results and further define pathology-specific applications of multimodal IONM in paediatric spinal surgery.

Indian Perspective

Although IONM has become standard practice in many developed countries, its availability remains limited in several resource-constrained healthcare settings. The present study demonstrates that successful implementation of standardized multimodal IONM is feasible in a high-volume tertiary pediatric neurosurgical center in India and may contribute to improved neurological safety during complex spinal procedures.

Clinical Implications

The findings of this study have important practical implications. Multimodal IONM should be considered for pediatric spinal procedures associated with significant risk of spinal cord or nerve root injury, particularly spinal dysraphism, intramedullary tumors, deformity correction, and craniovertebral junction surgery. Equally important is the availability of an experienced multidisciplinary team capable of promptly recognizing and responding to intraoperative neurophysiological changes.

Strengths

The strengths of this study include prospective data collection for a substantial proportion of patients, evaluation of multiple pediatric spinal pathologies, standardized IONM Response protocols to alerts, inclusion of children younger than five years, and comprehensive assessment using multiple neurophysiological modalities.

Limitations

This study has several limitations. First, it represents the experience of a single tertiary referral center, limiting generalizability. Second, the relatively small sample size, particularly within individual diagnostic subgroups, reduced statistical power for subgroup analyses. Third, the absence of a control group without IONM precluded direct assessment of the effect of monitoring on neurological outcomes. Fourth, the heterogeneous case mix introduced variability in operative complexity and baseline neurological status. Finally, the follow-up period of three months may not fully capture long-term neurological recovery. Future multicenter prospective studies with larger cohorts, longer follow-up, and standardized monitoring protocols are required to validate these findings. Multivariate analysis could not be possible due to inclusion of multiple diagnoses with wide variations on factors which cannot be compared.

CONCLUSION

Multimodal intraoperative neurophysiological monitoring demonstrated high diagnostic performance and was associated with favorable neurological outcomes in pediatric spinal surgery. Early identification

of intraoperative neurophysiological changes enabled timely rescue interventions and facilitated safe completion of surgery in most patients. Reliable monitoring was achieved across a broad spectrum of pediatric spinal pathologies, including children younger than five years, supporting the feasibility of multimodal IONM in this age group. Although these findings reinforce the value of multimodal IONM as an important adjunct during complex pediatric spinal procedures, they should be interpreted in the context of the study's single-center design and limited sample size. Larger multicenter prospective studies with longer follow-up are warranted to further validate these findings and establish standardized monitoring protocols.

Declarations

FUNDING: No funding was received for conducting the study.

Author Contribution

A.S. conceptualized and designed the study, performed data collection, analyzed and interpreted the data, and drafted the main manuscript text. S.J. supervised the project, contributed to the study design and clinical methodology, and critically revised the manuscript for important intellectual content. All authors reviewed and approved the final manuscript. b.k.o. supervised the project, contributed to the study design and clinical methodology, and critically revised the manuscript for important intellectual content. All authors reviewed and approved the final manuscript.

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Tables

Table 1. Baseline Demographic and Clinical Characteristics of the Study Population (n = 64)

Variable	Overall (n = 64)
Age (months), mean	95 ± 54.8
Age (months), median	87(36–194)
Age range	0–18 years
Age 0–5 years, n (%)	25 (39.1)
Age 6–18 years, n (%)	39 (60.9)
Male, n (%)	34 (53.1)
Female, n (%)	30 (46.9)

Table 2. Distribution of Diagnostic Groups (n = 64)

Diagnostic Group	n (%)
Spinal dysraphism	44 (68.8)
Spinal tumour	14 (21.9)
Atlantoaxial instability	5 (7.8)
Spinal deformity	1 (1.6)
Total	64 (100)

Table 3. Intraoperative Neurophysiological Monitoring Findings

Parameter	n (%)
Significant IONM alert	31 (48.4)
No significant IONM alert	33 (51.6)
Total	64 (100)

Table 4. Outcome of Significant IONM Alerts (n = 31)

Outcome	n (%)
Signals recovered after rescue protocol	21 (67.7)
Persistent alert at completion of surgery	10 (32.3)
Total	31 (100)

Table 5. Persistent Alerts According to Diagnostic Group

Diagnosis	Persistent Alerts	Total Cases	Percentage within Diagnosis
Spinal tumour	6	14	42.9
Spinal dysraphism	3	44	6.8
Spinal deformity	1	1	100
Atlantoaxial instability	0	5	0
P value*			0.002

Table 6. Neurological Outcomes

Outcome	Immediate Postoperative n (%)	Three-Month Follow-up n (%)	. P value*
New neurological deficit	3 (4.7)	1 (1.6)	0.317
No neurological deficit	59 (92.2)	61 (95.3)	
Death	2 (3.1)	2 (3.1)	

Table 7. Diagnostic Performance of IONM Modalities

Modality	Sensitivity % (95% CI)*	Specificity % (95% CI)*	PPV % (95% CI)*	NPV % (95% CI)*
TcMEP	100 (29.2–100)	93.3 (83.8–98.2)	50.0 (15.7–84.3)	100 (92.5–100)
EMG	100 (29.2–100)	94.4 (85.6–98.2)	50.0 (15.7–84.3)	100 (92.8–100)
SSEP	100 (29.2–100)	100 (93.4–100)	100 (29.2–100)	100 (93.4–100)

Table 8. Comparison of Clinical Symptoms Before Surgery and Three-Month Follow-up

Clinical Feature	Preoperative n (%)	Three Months n (%)	. P value*
Motor symptoms	49 (76.6)	39 (60.9)	0.031
Sensory symptoms	38 (59.4)	32 (50.0)	0.248
Bladder/Bowel involvement	36 (56.3)	32 (50.0)	0.453

Table 9. Comparison Between Patients With and Without Significant IONM Alerts

Variable	No IONM Alert (n = 33)	IONM Alert (n = 31)	. P value*
Mean age (months)	90	100	0.214
Male sex	17 (51.5)	17 (54.8)	0.796
Spinal dysraphism	26 (78.8)	18 (58.1)	0.041
Spinal tumour	3 (9.1)	11 (35.5)	0.009
New neurological deficit	0	3 (9.7)	0.071
Persistent alert	0	10 (32.3)	<0.001

Table 10. Characteristics of Patients With Postoperative Neurological Deficit

Patient	Diagnosis	TcMEP Alert	SSEP Alert	EMG Alert	Rescue Response	Three-Month Outcome
1	Spinal deformity	Yes	Yes	Yes	Persistent	Residual deficit
2	Spinal tumour	Yes	No	Yes	Persistent	Recovered
3	Spinal dysraphism	Yes	Yes	Yes	Persistent	Recovered

Figures

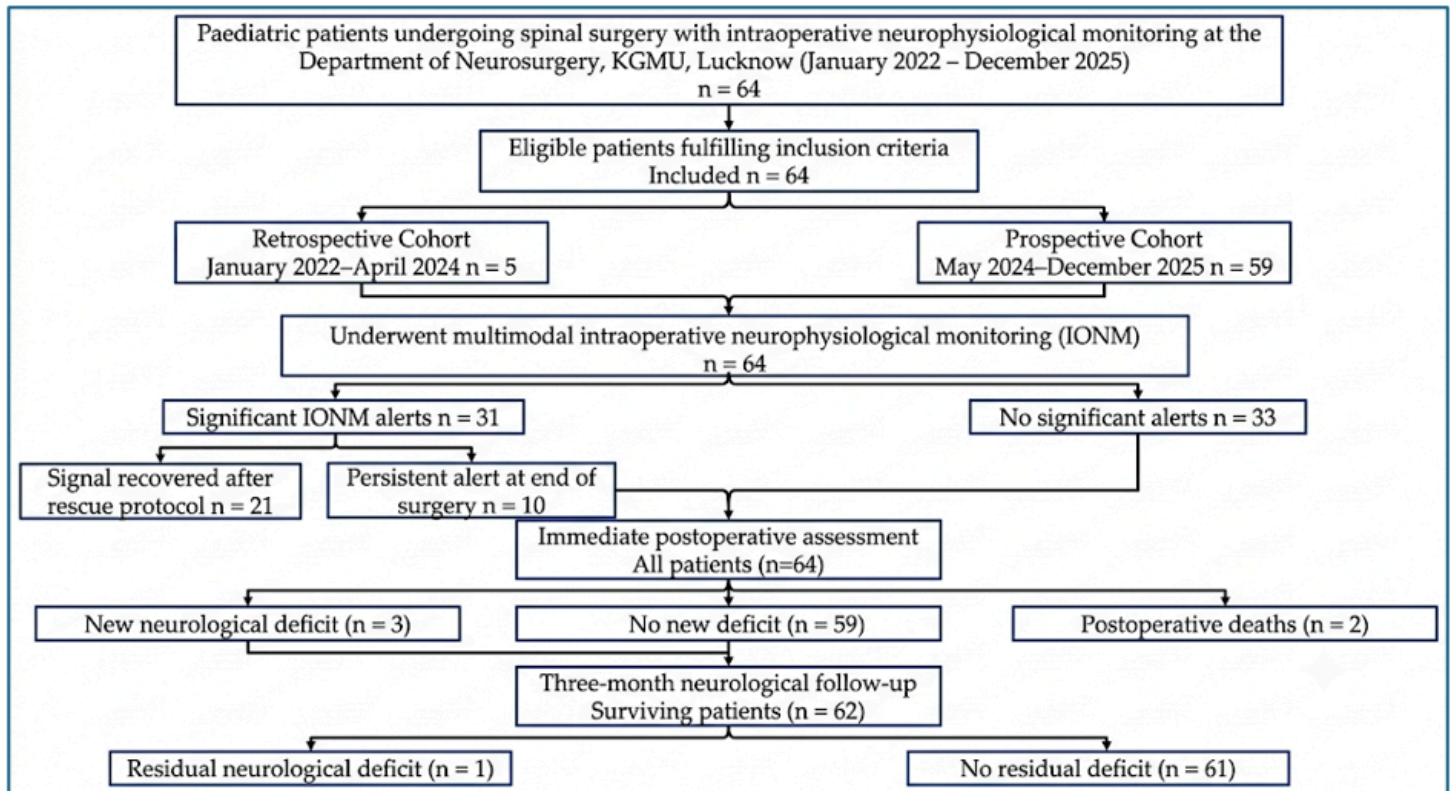


Figure 1

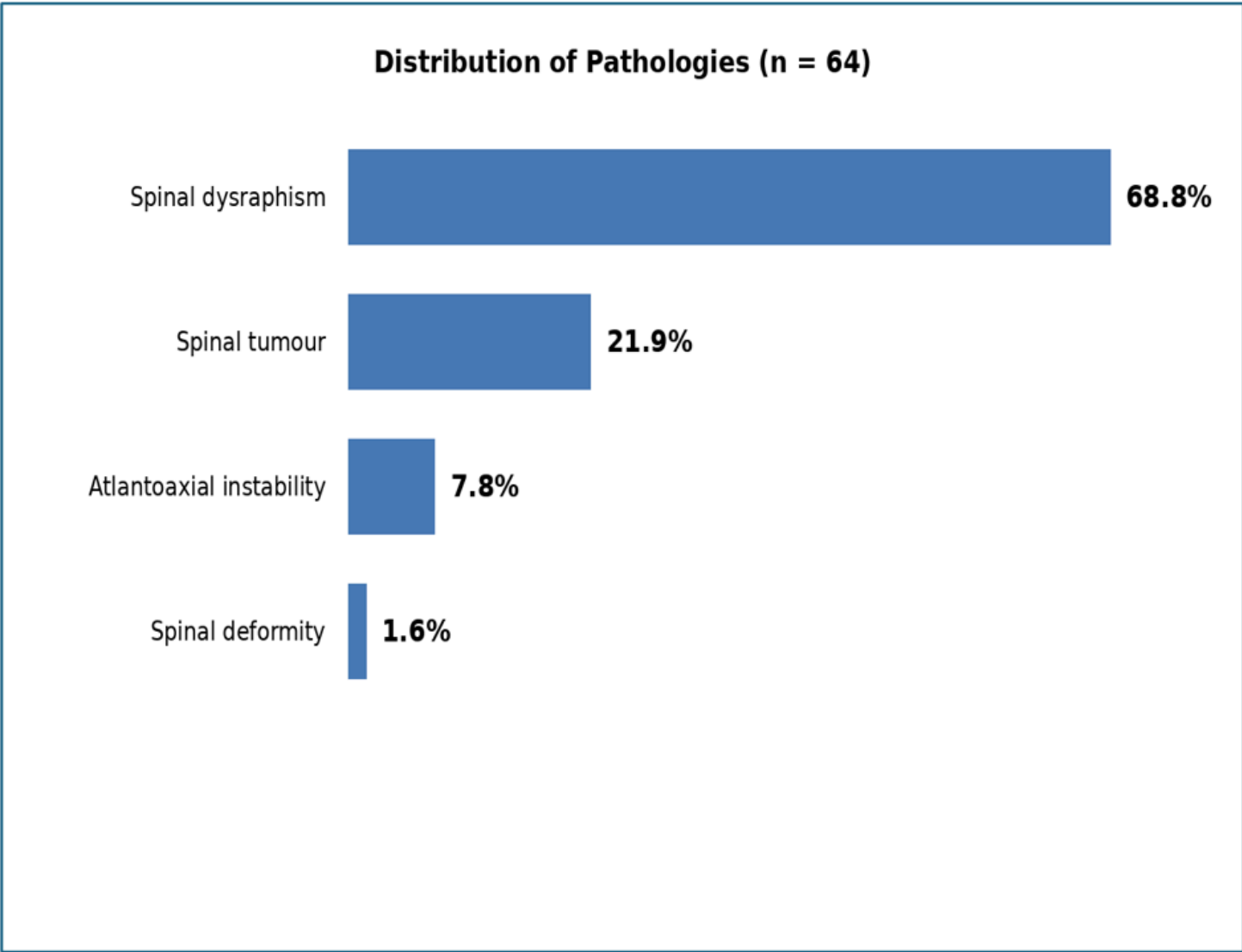


Figure 2

Outcome of Rescue Protocol (n = 31)

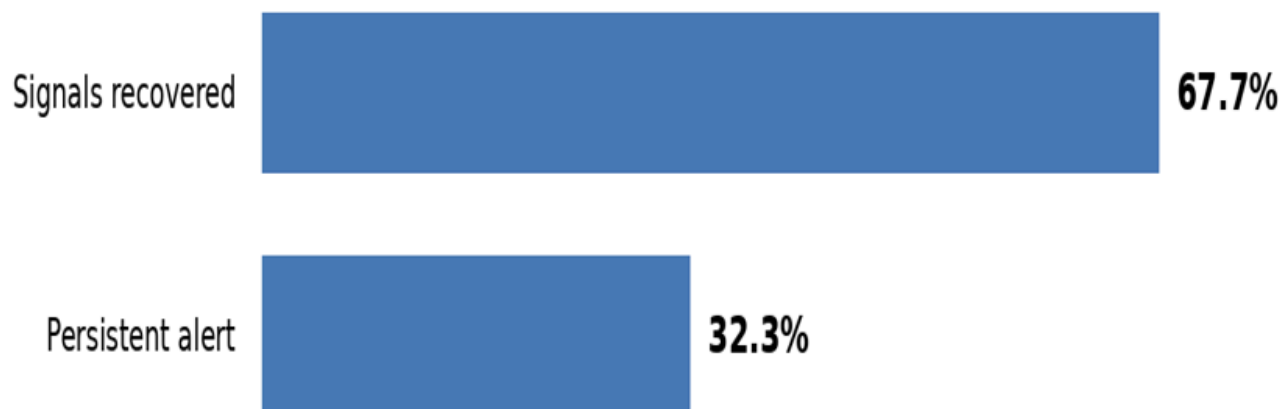


Figure 3

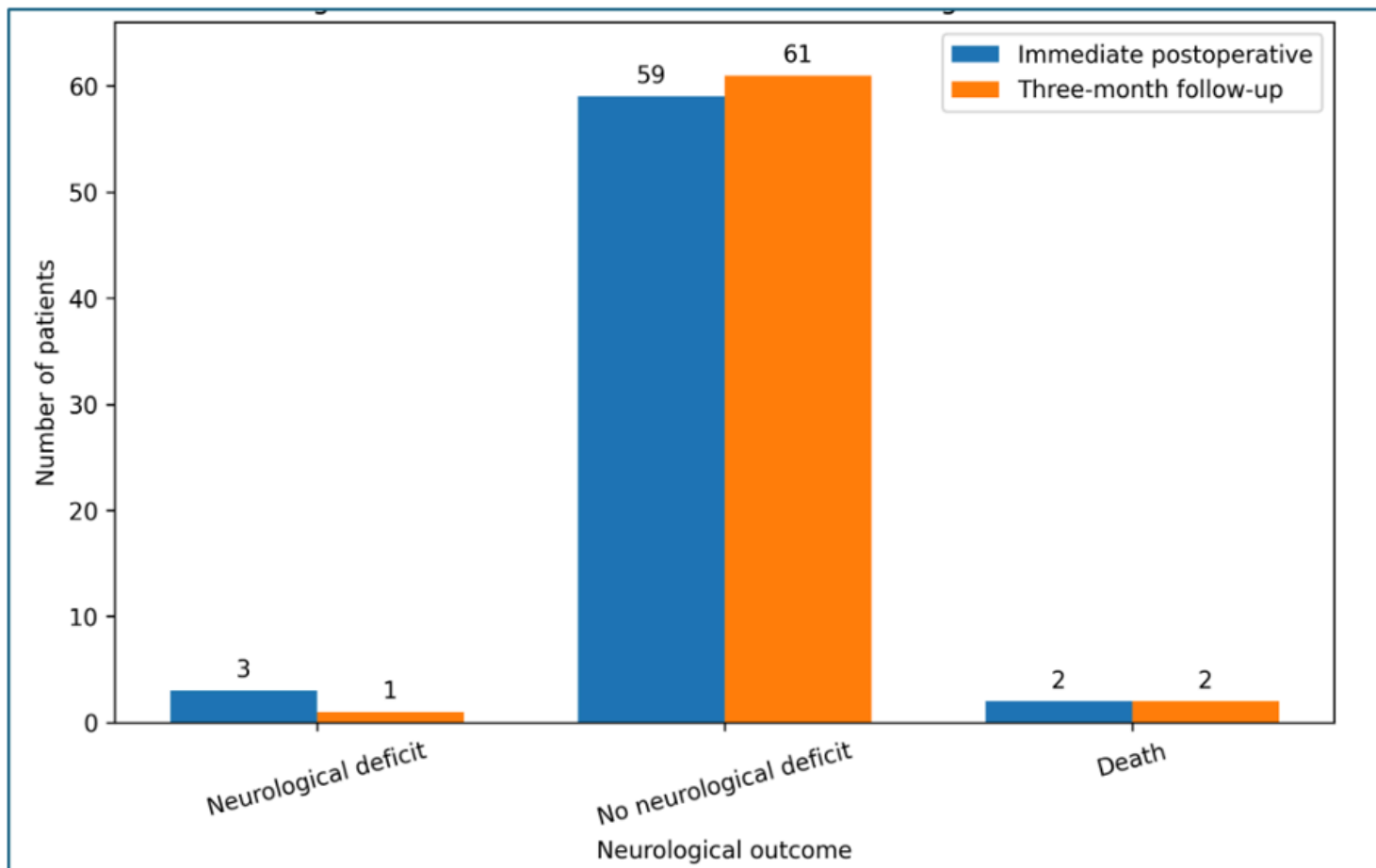


Figure 4

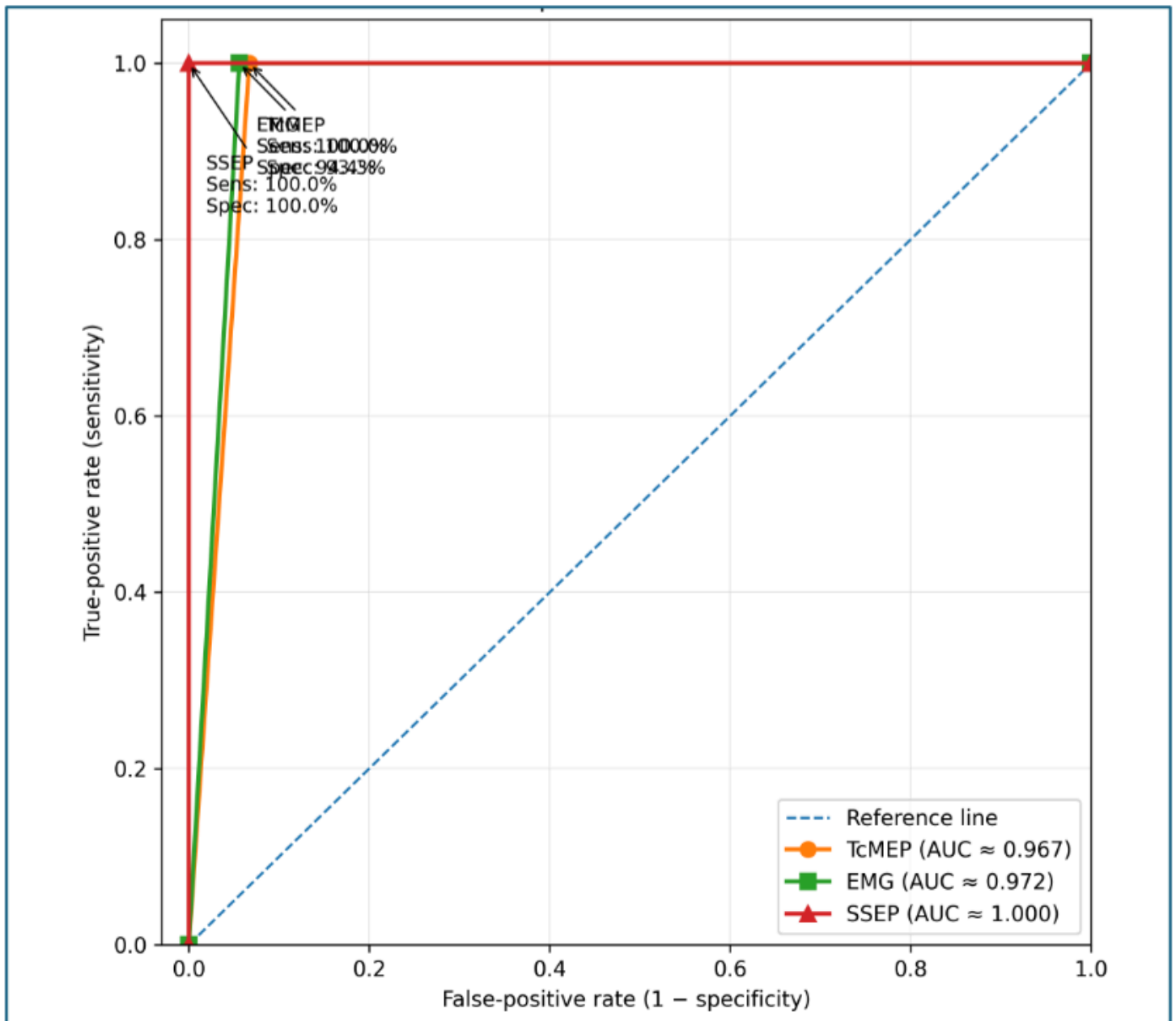


Figure 5

Supplementary Files

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