ORIGINAL ARTICLE

Evaluating the Effectiveness of Intraoperative Neuromonitoring Modalities in Spinal Dysraphism Surgeries: A Systematic Review

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Introduction: Spinal dysraphism encompasses a group of neural tube defects that can lead to significant neurological impairment, necessitating surgical intervention. Intraoperative neurophysiological monitoring (IONM) is integral to preserving neurological function during these high-risk surgeries. This systematic review evaluates the effectiveness of various IONM modalities, including somatosensory evoked potentials (SSEPs), motor evoked potentials (MEPs), electromyography (EMG), and bulbocavernosus reflex (BCR), in reducing postoperative deficits.

Methods: A systematic review of the PubMed database from 1998 to 2024 was conducted per PRISMA guidelines. The keywords used in the research included "spinal dysraphism," "IONM," "neuromonitoring," "spina bifida," "pediatric," "surgery," and "neurosurgery." Inclusion criteria specified that only English-language studies with at least 10 patients focused on IONM use in meningocele, myelomeningocele, and tethered spinal cord surgeries. Exclusion criteria ruled out reviews, case reports, conference abstracts, and animal studies. Neuromonitoring data were analyzed for efficacy in reducing postoperative neurological deficits compared to non-IONM surgeries.

Results: From 1,492 surgeries analyzed, 1,227 employed IONM, yielding a 7.25% postoperative neurological deficit rate compared to 15% in non-IONM procedures. Among the IONM group, multimodality monitoring consistently showed reduced risks of neurological complications. Variability in true positive and false negative rates among studies highlighted the need for standardized reporting and enhanced sensitivity across modalities.

Discussion: Multimodality IONM substantially reduces postoperative deficits, though its sensitivity and specificity require further refinement. Emerging techniques targeting sacral and autonomic pathways, such as pudendal nerve SSEPs and urinary bladder EMG and MEPs, offer promising advancements for comprehensive neural monitoring.

Conclusion: IONM significantly enhances surgical outcomes in spinal dysraphism by reducing postoperative neurological deficits. Standardized metrics, multimodal approaches, and innovation in monitoring techniques are essential to optimizing patient care. Future research should prioritize large-scale, controlled trials to validate these findings and enhance best practices.

INTRODUCTION

Spinal dysraphism is an overarching term that encompasses several types of neural tube defects. Neural tube defects are the second most common birth defect to occur in 1 to 2 in 1000 pregnancies worldwide [1]. These conditions can further be classified as open or closed spinal dysraphism based on appearance. A lesion is considered open if it is visible and closed if the lesion is not visible on the surface [2]. Open spinal dysraphism includes meningocele and myelomeningocele, which can be compatible with life - although patients may experience severe neurological deficits related to the level of the lesion. Closed spinal dysraphism includes spina bifida occulta, tethered cord syndrome, lipomyelomeningocele, split cord malformations, and others. These conditions are of lesser degree in severity but can also cause neurological impairment due to spinal cord tethering.

Symptoms may vary based on whether the lesion is classified as open or closed [3]. Conditions classified as 'open' may present as a defect of the posterior spine with extrusion of the meninges and CSF, with or without the involvement of neural elements. On the other hand, closed spinal dysraphism is not visually noticeable and is identified by a hairy patch of skin or dimple where the spinal defect is located. With respect to motor impairment, open spinal dysraphism is associated with an inability to ambulate, urinary incontinence, hydrocephalus, scoliosis, and gastrointestinal disorders. Closed spinal dysraphism is usually asymptomatic but is related to spinal cord tethering.

Common complications associated with spinal dysraphism include acute renal failure due to neurogenic bladder, scoliosis, chronic pain, and epilepsy. As with any medical condition, the prognosis varies on a case-by-case basis. Over the years, life expectancy has improved for these patients with the advent of modern healthcare. However, most of these patients remain dependent on their caregivers, even in adulthood. Spinal dysraphism has a global incidence of 1 to 3 cases per 1,000 live births; in the U.S., it is approximately 0.3 to 0.4 per 1,000 due to improved prenatal care [4]. Females are slightly more affected, primarily in the lumbar and sacral regions [5].

Treatment includes surgical interventions like myelomeningocele repair where symptoms worsen or severe symptoms are present at birth, while non-surgical management may involve monitoring and physical therapy for static deficits. Surgical risks include cerebrospinal fluid leaks, infection, and neurological and urological deficits, whereas non-surgical approaches can lead to symptom progression if not adequately monitored [6].

Intraoperative neurophysiological monitoring (IONM) has become an important part of surgeries, where it has an essential role in maintaining and preserving neurological function and reducing the associated surgical risks. IONM gives real-time feedback on the integrity of various neurological structures, such as the spinal cord and peripheral nerves, and warns the surgical team of potential neural damage before it

becomes irreversible. This neuromonitoring is significant in intricate surgical procedures with a high risk of neural injury.

Multimodality neurophysiological monitoring involves using multiple IONM techniques together and is beneficial. These techniques include Somatosensory Evoked Potentials (SSEPs) and Motor Evoked Potentials (MEPs), which both evaluate sensory and motor pathways. SSEPs provide information about the dorsal column pathways and sensory integrity, while MEPs give information on motor functions by assessing the corticospinal tract (CST) responses. These monitoring modalities allow neurophysiology teams to constantly monitor neural activity, improving the detection of neural injuries and reducing intraoperative risks overall [7].

The primary value of Intraoperative Neuromonitoring (IONM) lies in its ability to minimize the risk of postoperative neurological deficits. This monitoring enables surgeons to intervene when necessary, leading to improved surgical outcomes, particularly in procedures addressing spinal dysraphism, where the risk of neurological injury is significant. IONM has proven effective in safeguarding both sensory and motor functions, which enhances patient recovery and overall quality of life.

Effective intraoperative monitoring is essential during surgeries for spinal dysraphism due to the complexity and high risks involved in these procedures. Surgeries such as those performed for meningocele, myelomeningocele, and tethered cord can pose considerable risks to neurological structures. Consequently, IONM modalities play a critical role in providing safe and effective treatment, helping to preserve neural function and achieve successful surgical outcomes [8].

This systematic review and meta-analysis seek to assess the effectiveness of various IONM modalities in these surgeries affiliated with spinal dysraphism. By analyzing current evidence, we aim to clarify which multimodal monitoring techniques are most effective and offer a basis for IONM techniques in spinal dysraphism surgery based on evidence.

METHODS

Study Design

The study design involved a comprehensive systematic review of the PubMed database, encompassing an extensive range of publications from the years 1998 to 2024. This review was meticulously conducted using a targeted search strategy that employed seven carefully selected keywords: “spinal dysraphism,” “intraoperative neuromonitoring (IONM),” “neuromonitoring,” “spina bifida,” “pediatric,” “surgery,” and “neurosurgery.”

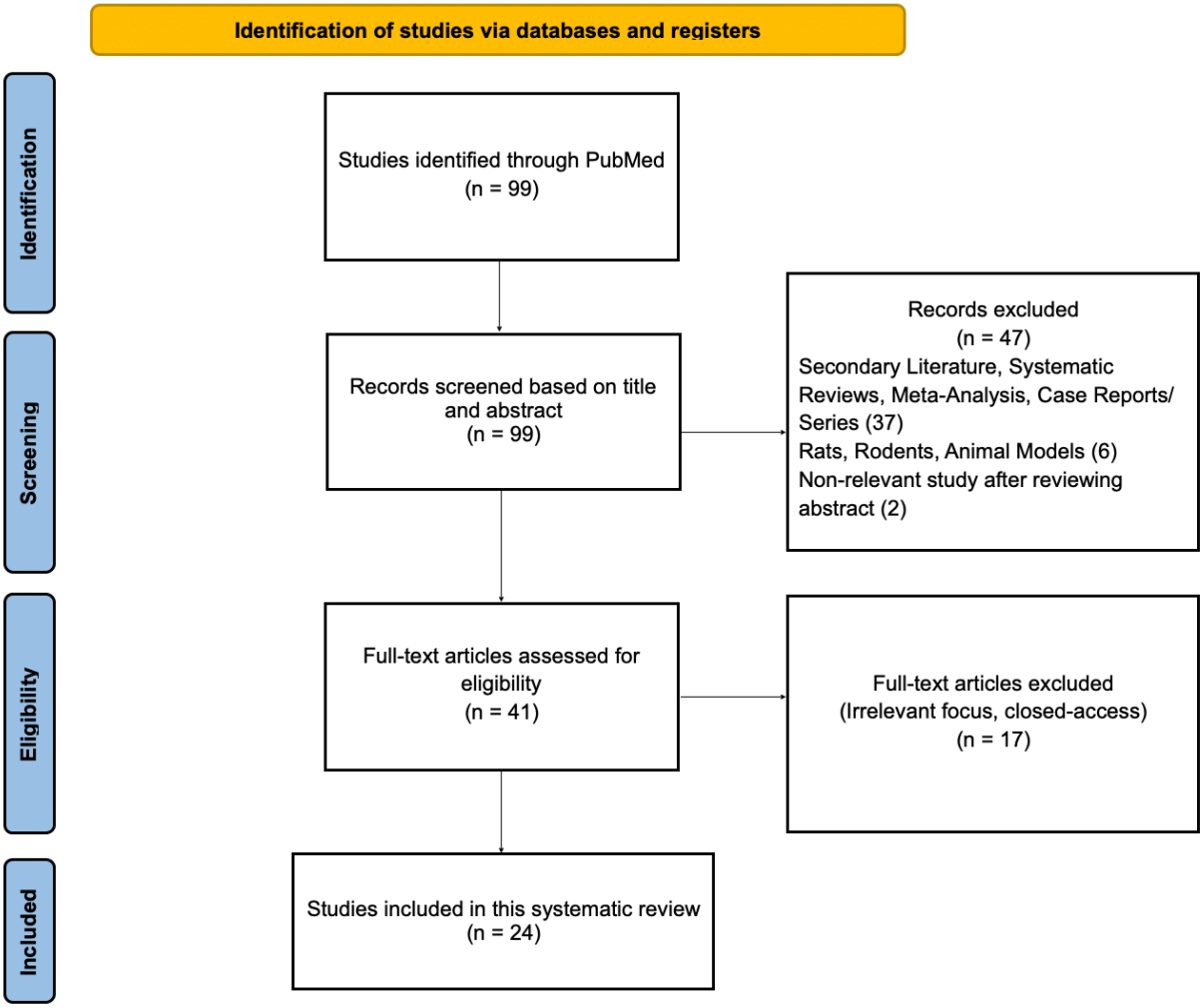

Figure 1. PRISMA Flow Diagram Identification of all studies and included articles in this systematic review.

Key findings from the literature were analyzed to assess the efficacy of various neuromonitoring modalities, including Somatosensory Evoked Potentials (SSEP), Motor Evoked Potentials (MEP), Electromyography (EMG), and Bulbocavernosus Reflex (BCR). All surgical procedures considered in this review were performed by highly skilled, fellowship-trained neurological and orthopedic spine surgeons. At the same time, the neurophysiological monitoring was conducted by board-certified neurophysiologists, ensuring a high standard of care and expertise.

The studies' inclusion criteria encompassed those that employed IONM during surgeries addressing conditions such as meningocele (in all its forms), myelomeningocele, and tethered cord syndrome. The review specifically targeted studies published in English, with a minimum sample size of ten patients and a focused examination of IONM applications. Meanwhile, exclusion criteria were strictly applied to eliminate

systematic reviews, meta-analyses, case reports, conference abstracts, and studies utilizing animal models, thereby refining the scope of the review.

This meta-analysis adhered to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, which are systematically depicted in a flowchart in Figure 1, reinforcing the structured approach taken in this scholarly endeavor.

Anesthesia Protocol

Total intravenous anesthesia (TIVA) with Propofol and Remifentanil was used in all procedures, a preferred approach for utilizing TCeMEP and SSEP modalities. Throughout surgery, a train of four (TOF) was recorded from the abductor hallucis muscle to measure the depth of muscle relaxation, with 4/4 twitches maintained during the procedures [9].

Intraoperative Neurophysiological Monitoring (IONM)

Somatosensory Evoked Potentials (SSEP)

Somatosensory Evoked Potentials (SSEPs) are performed by stimulating the lower and upper extremities. The stimulation electrodes were placed at the medial malleolus to stimulate the posterior tibial nerve and the fibular head to stimulate the fibular (peroneal) nerve. Pulse width is set to 300 microseconds with an intensity of 15-25 mA for the upper extremities and 40-100 mA for the lower extremities. The frequency is set to 3-5 Hz while avoiding multiples of 60 Hz to prevent electrical noise interference. For monitoring purposes, electrodes are also placed on the medial surface of the tibia to stimulate the saphenous nerve.

Recording electrodes are placed along the medial lemniscal pathway to record cortical, subcortical, and peripheral responses. The recording electrodes are placed at FPz, CPz, CP3, and CP4 for cortical responses by following the International 10-20 System. Subdermal needle electrodes are placed at Cv5 for subcortical responses. For peripheral responses, recording sites include ipsilateral Erb's point or the brachial plexus for the upper extremity SSEPs and ipsilateral popliteal fossa for the lower extremity SSEPs. The bandpass filters are set at 30-500 Hz and 30-1500 Hz for cortical and spinal/peripheral recordings, respectively. The sweep time for upper extremities is 50 ms, and for lower extremities, it is 100 ms. An amplitude reduction of more than 50% or a latency increase of more than 10% would raise an alert for nerve damage.

Stimulation Parameters for SSEPs					
Study	**Pulse Width (µs)**	**Stimulation Rate (Hz)**	**Sweep (Time)**	**Locut (Hz)**	**Hicut (Hz)**
Akhmediev et al., 2024	N/A	N/A	N/A	N/A	N/A
Aleem et al., 2015	N/A	N/A	N/A	N/A	N/A
Cha et al., 2018	N/A	N/A	N/A	N/A	N/A
Durdağ et al., 2015	N/A	N/A	N/A	N/A	N/A
Fang et al., 2015	N/A	N/A	N/A	N/A	N/A
Fekete et al., 2019	N/A	N/A	N/A	N/A	N/A
Finger et al., 2020	N/A	N/A	N/A	N/A	N/A
Gadhvi et al., 2023	N/A	N/A	N/A	N/A	N/A
Guo et al., 2024	N/A	N/A	N/A	N/A	N/A
Hoving et al., 2011	N/A	N/A	N/A	N/A	N/A
Jiang et al., 2020	N/A	N/A	N/A	N/A	N/A
Kobayashi et al., 2018	N/A	N/A	N/A	N/A	N/A
Leung et al., 2015	200-450	N/A	N/A	N/A	N/A
Maurya et al., 2016	N/A	N/A	N/A	N/A	N/A
McGrath et al., 2024	N/A	N/A	N/A	N/A	N/A
Mehrotra et al., 2024	N/A	N/A	N/A	N/A	N/A
Sapir et al., 2021	N/A	N/A	N/A	N/A	N/A
Selçuki et al., 1998	N/A	N/A	N/A	N/A	N/A
Squintani et al., 2024	0.5	4.7	N/A	30	300
Stavrinou et al., 2011	N/A	N/A	N/A	N/A	N/A
Udayakumaran et al., 2021	N/A	N/A	N/A	N/A	N/A
Valentini et al., 2013	N/A	N/A	N/A	N/A	N/A
Von Koch et el., 2002	N/A	N/A	N/A	N/A	N/A
Yi et al., 2019	N/A	N/A	N/A	N/A	N/A

Table 1A. Stimulation Parameters for Somatosensory Evoked Potentials (SSEPs). Overview for all included studies.

Recording Parameters for SSEP		
Study	**Locut (Hz)**	**Hicut (Hz)**
Akhmediev et al., 2024	Not mentioned	Not mentioned
Aleem et al., 2015	Not mentioned	Not mentioned
Cha et al., 2018	Not mentioned	Not mentioned
Durdağ et al., 2015	Not mentioned	Not mentioned
Fang et al., 2015	Not mentioned	Not mentioned
Fekete et al., 2019	Not mentioned	Not mentioned
Finger et al., 2020	Not mentioned	Not mentioned
Gadhvi et al., 2023	Not mentioned	Not mentioned
Guo et al., 2024	Not mentioned	Not mentioned
Hoving et al., 2011	Not mentioned	Not mentioned
Jiang et al., 2020	Not mentioned	Not mentioned
Kobayashi et al., 2018	Not mentioned	Not mentioned
Leung et al., 2015	Not mentioned	Not mentioned
Maurya et al., 2016	Not mentioned	Not mentioned
McGrath et al., 2024	Not mentioned	Not mentioned
Mehrotra et al., 2024	Not mentioned	Not mentioned
Sapir et al., 2021	Not mentioned	Not mentioned
Selçuki et al., 1998	Not mentioned	Not mentioned
Squintani et al., 2024	30	300
Stavrinou et al., 2011	Not mentioned	Not mentioned
Udayakumaran et al., 2021	Not mentioned	Not mentioned
Valentini et al., 2013	Not mentioned	Not mentioned
Von Koch et el., 2002	Not mentioned	Not mentioned
Yi et al., 2019	Not mentioned	Not mentioned

Table 1B. Recording Parameters for Somatosensory Evoked Potentials (SSEPs). Overview for all included studies.

Stimulation Parameters for MEPs					
Study	**Pulse Width (µs)**	**Stimulation Rate (Hz)**	**Sweep (Time)**	**Locut (Hz)**	**Hicut (Hz)**
Akhmediev et al., 2024	N/A	N/A	N/A	N/A	N/A
Aleem et al., 2015	N/A	N/A	N/A	N/A	N/A
Canaz et al., 2020	N/A	N/A	N/A	N/A	N/A
Durdağ et al., 2015	N/A	N/A	N/A	N/A	N/A
Fang et al., 2015	200-500	N/A	N/A	N/A	N/A
Fekete et al., 2019	N/A	N/A	N/A	N/A	N/A
Finger et al., 2020	N/A	N/A	N/A	N/A	N/A
Gadhvi et al., 2023	75	Train of 5 with Rate 333 p/s (Pulses Per Second)	100	30	1500
Guo et al., 2024	N/A	N/A	N/A	N/A	N/A
Hoving et al., 2011	100	N/A	N/A	N/A	N/A
Jiang et al., 2020	N/A	N/A	N/A	N/A	N/A
Kobayashi et al., 2018	500	5 Stimuli at 2-ms Intervals	N/A	50	1000
Leung et al., 2015	N/A	N/A	N/A	N/A	N/A
Maurya et al., 2016	N/A	N/A	N/A	N/A	N/A
McGrath et al., 2024	50	N/A	N/A	30	1000
Mehrotra et al., 2024	N/A	N/A	N/A	N/A	N/A
Sapir et al., 2021	N/A	N/A	N/A	N/A	N/A
Selçuki et al., 1998	N/A	N/A	N/A	N/A	N/A
Squintani et al., 2024	0.5	N/A	N/A	100	1000
Stavrinou et al., 2011	N/A	N/A	N/A	N/A	N/A
Udayakumaran et al., 2021	0.5	250	N/A	N/A	N/A
Valentini et al., 2013	0.05-0.1	3-5 Stimuli in a Train	N/A	30	3000
Von Koch et el., 2002	N/A	N/A	N/A	N/A	N/A
Yi et al., 2019	75	500	N/A	N/A	N/A

Table 2A. Stimulation Parameters for Motor Evoked Potentials (MEPs). Overview for all included studies.

Motor Evoked Potentials (MEP)

Motor Evoked Potentials (MEPs) are critical in intraoperative neurophysiological monitoring (IONM) for evaluating corticospinal tract functionality, especially in surgeries where neural integrity is at risk. Recordings are taken from the same muscles used in electromyography (EMG), with stimulation delivered via corkscrew electrodes positioned on the scalp at C1, C2, C3, and C4, directly over the primary motor

cortex as specified by the International 10-20 system. Alternatively, electrodes are placed on the scalp at M1, M2, M3, and M4 to stimulate muscle groups across the upper and lower extremities. Due to the high sensitivity of MEP responses to inhalational anesthetics, total intravenous anesthesia (TIVA) without muscle relaxants is recommended to preserve signal fidelity.

Recording Parameters for MEPs		
Study	**Locut (Hz)**	**Hicut (Hz)**
Akhmediev et al., 2024	Not mentioned	Not mentioned
Aleem et al., 2015	Not mentioned	Not mentioned
Cha et al., 2018	Not mentioned	Not mentioned
Durdağ et al., 2015	Not mentioned	Not mentioned
Fang et al., 2015	Not mentioned	Not mentioned
Fekete et al., 2019	Not mentioned	Not mentioned
Finger et al., 2020	Not mentioned	Not mentioned
Gadhvi et al., 2023	30	1500
Guo et al., 2024	Not mentioned	Not mentioned
Hoving et al., 2011	Not mentioned	Not mentioned
Jiang et al., 2020	Not mentioned	Not mentioned
Kobayashi et al., 2018	50	1000
Leung et al., 2015	Not mentioned	Not mentioned
Maurya et al., 2016	Not mentioned	Not mentioned
McGrath et al., 2024	30	1000
Mehrotra et al., 2024	Not mentioned	Not mentioned
Sapir et al., 2021	Not mentioned	Not mentioned
Selçuki et al., 1998	Not mentioned	Not mentioned
Squintani et al., 2024	100	1000
Stavrinou et al., 2011	Not mentioned	Not mentioned
Udayakumaran et al., 2021	Not mentioned	Not mentioned
Valentini et al., 2013	30	3000
Von Koch et el., 2002	Not mentioned	Not mentioned
Yi et al., 2019	Not mentioned	Not mentioned

Table 2B. Recording Parameters for Motor Evoked Potentials (MEPs). Overview for all included studies.

Stimulation parameters include a pulse width of 50 or 75 μs, with intensity increased until myogenic responses are elicited in target muscles, or a maximum of 600 V is reached. Frequencies typically range between 200 and 500 Hz, with a train count of 5-7 pulses for spinal procedures. Electrode placement varies according to the surgical site and the specific nerve roots at risk, using either surface or needle electrodes as appropriate. Bandpass filtering between 10 Hz and 5.0 kHz enhances signal clarity. Recordings are captured using a bipolar montage, with sweep settings typically configured at 10 ms/division and a sensitivity range of 200-500 μV/division. Recording electrode impedance should remain below 5 kOhms to ensure optimal signal quality.

In lumbar procedures, control muscles in the upper extremities, such as the abductor pollicis brevis and abductor digiti minimi, are commonly monitored. Lower extremity recording sites include the iliopsoas, adductor magnus, vastus lateralis, vastus medialis, tibialis anterior, peroneus longus, gastrocnemius, extensor hallucis brevis, and abductor hallucis. Additional electrodes may be placed at the anal sphincter and external urethral sphincter muscles to monitor pudendal nerve function. MEP alert criteria encompass a 70-80% decrease in amplitude, loss in waveform morphology, or a stimulation threshold increase exceeding 100 volts, each indicative of potential neural compromise requiring further assessment.

Electromyography (EMG)

Electromyography (EMG) is a crucial technique for monitoring motor nerve roots and the spinal cord during surgeries. There are two types of EMGs: spontaneous electromyography (S-EMG), which records the natural electrical activity of muscles and provides immediate feedback on nerve root integrity, and triggered electromyography (T-EMG), which involves stimulating nerves and recording muscle responses to identify nerves and assessing their function.

EMGs are used in procedures such as spinal stenosis decompression, tumor removal, and cranial nerve surgery. To perform EMGs, subdermal needles are placed in muscles, and electrodes are positioned 3 cm apart to capture electrical activity. Abnormal findings, like train activity and spikes, may indicate nerve irritation from various injuries.

In lateral spine procedures, the same muscles are used for monitoring EMG and Transcranial Electrical Motor Evoked Potentials (TCeMEP). Bandpass filters should be set between 10 Hz and 5 kHz for effective monitoring. S-EMG requires sweep settings of 100-300 ms/division and electrode impedance below 5 kOhms, while T-EMG uses monopolar or bipolar stimulation with sweep settings at 10 ms/division. Direct nerve stimulation should have a pulse width of 200 μs, a frequency of 2-4 Hz, and an intensity of 0.05-5 mA, while pedicle screw stimulation should range from 1.0 to 30 mA. The alert criteria for monitoring S-EMG include identifying abnormal train activity and prolonged neurotonic discharges, with a specific threshold of less than 8 mA for pedicle screw T-EMGs.

Stimulation Parameters for EMG					
Study	**Pulse Width (µs)**	**Stimulation Rate (Hz)**	**Sweep (ms)**	**Locut (Hz)**	**Hicut (Hz)**
Akhmediev et al., 2024	N/A	N/A	N/A	N/A	N/A
Aleem et al., 2015	N/A	N/A	N/A	N/A	N/A
Canaz et al., 2020	N/A	N/A	N/A	N/A	N/A
Durdağ et al., 2015	N/A	N/A	N/A	N/A	N/A
Fang et al., 2015	200	4.7	10ms/div	N/A	N/A
Fekete et al., 2019	200	3	N/A	N/A	N/A
Finger et al., 2020	N/A	N/A	N/A	N/A	N/A
Gadhvi et al., 2023	N/A	3	100	30	1500
Guo et al., 2024	N/A	N/A	N/A	N/A	N/A
Hoving et al., 2011	N/A	N/A	N/A	N/A	N/A
Jiang et al., 2020	200	5	N/A	20	5000
Kobayashi et al., 2018	N/A	N/A	N/A	N/A	N/A
Leung et al., 2015	N/A	N/A	N/A	N/A	N/A
Maurya et al., 2016	N/A	N/A	N/A	N/A	N/A
McGrath et al., 2024	50 or 100	1-3	N/A	30	1000
Mehrotra et al., 2024	N/A	N/A	N/A	N/A	N/A
Sapir et al., 2021	200	2	N/A	N/A	N/A
Selçuki et al., 1998	N/A	N/A	N/A	N/A	N/A
Squintani et al., 2024	N/A	N/A	N/A	N/A	N/A
Stavrinou et al., 2011	N/A	N/A	N/A	N/A	N/A
Udayakumaran et al., 2021	N/A	N/A	N/A	N/A	N/A
Valentini et al., 2013	0.05-0.1	4	N/A	30	3000
Von Koch et el., 2002	200	3.1	N/A	N/A	N/A
Yi et al., 2019	N/A	N/A	N/A	N/A	N/A

Table 3A. Stimulation Parameters for Electromyography (EMG). Overview for all included studies.

Recording Parameters for EMG		
Study	**Locut (Hz)**	**Hicut (Hz)**
Akhmediev et al., 2024	Not mentioned	Not mentioned
Aleem et al., 2015	Not mentioned	Not mentioned
Cha et al., 2018	Not mentioned	Not mentioned
Durdağ et al., 2015	Not mentioned	Not mentioned
Fang et al., 2015	30	10000
Fekete et al., 2019	Not mentioned	Not mentioned
Finger et al., 2020	Not mentioned	Not mentioned
Gadhvi et al., 2023	30	1500
Guo et al., 2024	Not mentioned	Not mentioned
Hoving et al., 2011	Not mentioned	Not mentioned
Jiang et al., 2020	20	5000
Kobayashi et al., 2018	Not mentioned	Not mentioned
Leung et al., 2015	Not mentioned	Not mentioned
Maurya et al., 2016	Not mentioned	Not mentioned
McGrath et al., 2024	30	1000
Mehrotra et al., 2024	Not mentioned	Not mentioned
Sapir et al., 2021	Not mentioned	Not mentioned
Selçuki et al., 1998	Not mentioned	Not mentioned
Squintani et al., 2024	Not mentioned	Not mentioned
Stavrinou et al., 2011	Not mentioned	Not mentioned
Udayakumaran et al., 2021	Not mentioned	Not mentioned
Valentini et al., 2013	30	3000
Von Koch et el., 2002	Not mentioned	Not mentioned
Yi et al., 2019	Not mentioned	Not mentioned

Table 3B. Recording Parameters for Electromyography (EMG). Overview for all included studies.

Stimulation Parameters for BCR					
Study	**Pulse Width (μs)**	**Stimulation Rate (Hz)**	**Sweep (Time)**	**Locut (Hz)**	**Hicut (Hz)**
Akhmediev et al., 2024	N/A	N/A	N/A	N/A	N/A
Aleem et al., 2015	N/A	N/A	N/A	N/A	N/A
Cha et al., 2018	N/A	N/A	N/A	N/A	N/A
Durdağ et al., 2015	N/A	N/A	N/A	N/A	N/A
Fang et al., 2015	N/A	N/A	N/A	N/A	N/A
Fekete et al., 2019	N/A	N/A	N/A	N/A	N/A
Finger et al., 2020	N/A	N/A	N/A	N/A	N/A
Gadhvi et al., 2023	N/A	N/A	N/A	N/A	N/A
Guo et al., 2024	N/A	N/A	N/A	N/A	N/A
Hoving et al., 2011	N/A	N/A	N/A	N/A	N/A
Jiang et al., 2020	N/A	N/A	N/A	N/A	N/A
Kobayashi et al., 2018	N/A	N/A	N/A	N/A	N/A
Leung et al., 2015	N/A	N/A	N/A	N/A	N/A
Maurya et al., 2016	N/A	N/A	N/A	N/A	N/A
McGrath et al., 2024	N/A	N/A	N/A	N/A	N/A
Mehrotra et al., 2024	N/A	N/A	N/A	N/A	N/A
Sapir et al., 2021	N/A	N/A	N/A	N/A	N/A
Selçuki et al., 1998	N/A	N/A	N/A	N/A	N/A
Squintani et al., 2024	N/A	N/A	N/A	N/A	N/A
Stavrinou et al., 2011	N/A	N/A	N/A	N/A	N/A
Udayakumaran et al., 2021	N/A	N/A	N/A	N/A	N/A
Valentini et al., 2013	N/A	N/A	N/A	N/A	N/A
Von Koch et el., 2002	N/A	N/A	N/A	N/A	N/A
Yi et al., 2019	N/A	N/A	N/A	N/A	N/A

Table 4A. Stimulation Parameters for Bulbocavernosus Reflex (BCR). Overview for all included studies.

Bulbocavernosus Reflex (BCR)

Stimulation of the dorsal penile or clitoral nerve to elicit the BCR using needle electrodes positioned at the dorsal base of the penile shaft or on the dorsal clitoral surface, just below the pubic bone. In male patients, electrodes are spaced 2–3 cm apart along the penile dorsum, with the cathode placed proximally. In female patients, the cathode was positioned on the clitoral dorsum, while the anode was positioned on the labia majora. A conductive paste was applied under the electrodes to ensure optimal contact, and they were secured with adhesive tape and a protective gauze layer. The stimulation parameters included a pulse width of 500 μs, an interstimulus interval of 3.1 ms, and an intensity of 30–40 mA. For most patients, a train of 4–5 pulses were applied to elicit a consistent reflex response, with pulse frequency adjusted to 1 Hz when necessary.

Recording Parameters for BCR		
Study	**Locut (Hz)**	**Hicut (Hz)**
Akhmediev et al., 2024	Not mentioned	Not mentioned
Aleem et al., 2015	Not mentioned	Not mentioned
Cha et al., 2018	0.3	1000
Durdağ et al., 2015	Not mentioned	Not mentioned
Fang et al., 2015	Not mentioned	Not mentioned
Fekete et al., 2019	Not mentioned	Not mentioned
Finger et al., 2020	Not mentioned	Not mentioned
Gadhvi et al., 2023	Not mentioned	Not mentioned
Guo et al., 2024	Not mentioned	Not mentioned
Hoving et al., 2011	Not mentioned	Not mentioned
Jiang et al., 2020	Not mentioned	Not mentioned
Kobayashi et al., 2018	Not mentioned	Not mentioned
Leung et al., 2015	Not mentioned	Not mentioned
Maurya et al., 2016	Not mentioned	Not mentioned
McGrath et al., 2024	Not mentioned	Not mentioned
Mehrotra et al., 2024	Not mentioned	Not mentioned
Sapir et al., 2021	Not mentioned	Not mentioned
Selçuki et al., 1998	Not mentioned	Not mentioned
Squintani et al., 2024	Not mentioned	Not mentioned
Stavrinou et al., 2011	Not mentioned	Not mentioned
Udayakumaran et al., 2021	Not mentioned	Not mentioned
Valentini et al., 2013	Not mentioned	Not mentioned
Von Koch et el., 2002	Not mentioned	Not mentioned
Yi et al., 2019	Not mentioned	Not mentioned

Table 4B. Recording Parameters for Bulbocavernosus Reflex (BCR). Overview for all included studies.

For BCR recording, needle electrodes were inserted into the anal sphincter muscle. Non-insulated, 19 mm stainless steel needles or Teflon-coated wire electrodes with bare tips are used, with two electrodes placed per hemi-sphincter at approximately 1 cm apart. The initial needle insertion depth reached 2.5 cm, corresponding to the depth of a standard disposable injection needle. Intramuscular positioning was confirmed by advancing the needles 2–5 mm beyond the point of initial resistance. Additionally, a low-intensity tetanic stimulus (10 mA, train of 4 stimuli with an ISI of 4 ms) was administered through the detecting electrodes to induce a muscle twitch response, further validating intramuscular placement. Electrodes were secured with adhesive tape to maintain stability during monitoring.

Participant Demographics Across Included Studies						
Study	**Sample Size (n)**	**Male (n)**	**Female (n)**	**Mean Age (Years)**	**Age Range**	**Country**
Akhmediev et al., 2024	56	17	39	5.7	10 Months - 15 Years	Uzbekistan
Aleem et al., 2015	82	31	51	12	1 - 20 Years	USA
Cha et al., 2018	106	49	57	3.3	Not Mentioned	Republic of Korea
Durdağ et al., 2015	40	14	26	6.25	9 Months - 18 Years	Turkey
Fang et al., 2015	37	17	20	41	2 - 68 Years	China
Fekete et al., 2019	91	46	45	8.44	0 - 59.43 Years	Hungary
Finger et al., 2020	32	12	20	25.7 (Median)	18 - 74 Years	Germany
Gadhvi et al., 2023	26	13	13	N/A	1 - 56 Years	India
Guo et al., 2024	454	215	239	1.75	0.3 - 178 Months	China
Hoving et al., 2011	65	24	41	22.0 ± 22.4	0.1 - 72.7 Years	Netherlands
Jiang et al., 2020	100	56	44	9.2 (IONM), 8.4 (non-IONM)	3 Months - 12 Years	China
Kobayashi et al., 2018	239	104	135	48.5	8 - 86 Years	Japan
Leung et al., 2015	14	N/A	N/A	Not Mentioned	Not Mentioned	Canada
Maurya et al., 2016	21	7	14	5.9 ± 7	1.5 - 30 Years	India
McGrath et al., 2024	20	8	12	10.39 (Median)	2 - 17 Years	United States
Mehrotra et al., 2024	22	7	15	15 ± 1.5	11 - 20 Years	India
Sapir et al., 2021	20	8	12	3.5 ± 4.4	0.5 - 18 Years	Israel
Selçuki et al., 1998	13	7	6	N/A	5 - 17 Years	Turkey
Squintani et al., 2024	48	N/A	N/A	21.6 ± 20.8	Not Mentioned	Italy
Stavrinou et al., 2011	20	9	11	5.4	3 Months - 17 Years	Germany
Udayakumaran et al., 2021	87	36	51	0.625 (7.5 Months)	0 - 12 Months	India
Valentini et al., 2013	149	83	66	7 (Children), 25 (Adults)	3 months - 16 Years (Children), 17 - 63 Years (Adults)	Italy
Von Koch et el., 2002	25	N/A	N/A	Not Mentioned	4 Months - 12 Years	United States
Yi et al., 2019	25	15	10	0.20 (72.8 Days)	39 - 87 Days	Republic of Korea
All Studies	**1792**	**778**	**927**	**13.04**		

Table 5. Participant Demographics. The systematic review includes a summary of sample size, sex distribution, age characteristics, and geographical distribution across studies. This includes data on various conditions, not limited to spinal dysraphism.

Train of Four (TOF)

The train of Four (TOF) monitoring was performed by stimulation of the posterior tibial nerve and recording from the abductor hallucis muscle in the foot. Intraoperative Train of Fours (TOF) parameters include 4 monophasic square pulses delivered at a 2.0 Hz stimulation rate, pulse width set to 0.2 ms, with sweep settings to 20 ms/division; sensitivity is adjusted according to signal strength and stimulation intensity. A neuromuscular blockade assessment is conducted following four delivered pulses: 0 twitches correspond to 100% blockade, one twitch corresponds to 95% blockade, two twitches correspond to 85% blockade, three twitches correspond to 65-75% blockade, and 4 twitches correspond to 5-75% blockade.

RESULTS

Rate of Deficit

The deficit rate is a critical measure in evaluating the effectiveness of IONM) during spinal dysraphism surgeries. In this meta-analysis, the rate of deficit refers to surgical cases where patients experienced postoperative deficits, including but not limited to urinary dysfunction and ambulatory deficits. By comparing the rate of deficits between non-IONM and IONM cases across various studies, the analysis aimed to determine the efficacy of intraoperative neurophysiological monitoring in minimizing postoperative complications and preserving neurological function during spinal cord surgeries.

In evaluating the effectiveness of intraoperative neuromonitoring (IONM) during spinal dysraphism surgeries, it was essential to distinguish between the number of patients and the number of procedures. Certain patients underwent multiple surgeries, making the total number of procedures a more accurate metric for assessing the impact of IONM. For this analysis, the cumulative number of procedures monitored with IONM across the included studies was analyzed to account for instances where a single patient underwent multiple surgeries. This approach ensured a more comprehensive evaluation of how IONM influenced postoperative outcomes, emphasizing its role in mitigating deficits across repeated interventions.

Diagnostic Categories Across Included Studies						
Study	**Sample Size (n)**	**Tethered Cord Syndrome (n)**	**Spinal Bifida (n)**	**Myelomeningocele (n)**	**Other Categories**	**Comments**
Akhmediev et al., 2024	56	23	N/A	N/A	All patients underwent MRI and CT imaging to receive a diagnosis. The imaging findings included spinal cord distribution in hemicords (56), spinal canal divided into two (49), asymmetric hemicords (35), osteocartilaginous septum (49), fibrous septum (9)	Surgery was done by using a dorsal approach with IV anesthesia and IONM, specifically ECG monitoring.
Aleem et al., 2015	119	N/A	N/A	14	Arnold Chiari Malformation, Syringomyelia, Spinal Cord Tumor, etc.	Surgical procedures included posterior spinal fusion, growing rod procedure, revision of posterior spinal fusion, anterior spinal fusion, combined A/P spinal fusion, posterior spinal fusion with vertebral column resection, hardware removal, revision posterior spinal fusion with vertebral column resection, Shilla procedure, video-assisted thoracic stapling, vertical expandable prosthetic titanium rib
Cha et al., 2018	106	106	N/A	2	Congenital Dermal Sinus (6), Limited Dorsal Myeloschisis (19), Thick Filum Terminale (23), Lumbosacral Lipoma, (34) Lipomyelomeningocele (16), Retained Medullary cord (3), Currarino's Triad (2), Split Cord Malformation (1)	A retrospective study looked at the records of patients who underwent untethering surgery between January 2013 and November 2016.
Durdağ et al., 2015	40	40	Those with spina bifida were excluded from the study (0)	Those with myelomeningocele were excluded from this study (0)	N/A	This study examines the histopathology of the resected filum terminale and divides the findings into different categories that describe what was seen on the histopathology slide.
Fang et al., 2015	37	37	N/A	N/A	N/A	Retrospective Analysis
Fekete et al., 2019	91	91	N/A	N/A	N/A	The underlying diagnosis organizes surgical interventions. The following surgeries were performed: Resection of intraspinal lipoma (42), transection of a specific bundle (31), Scar tissue release (18), scar tissue release with lipoma resection (2), diastematomyelia (2), epidermoid tumor resection (1), dermoid tumor resection (1), meningocele reconstruction (2), dethering not possible (3)
Finger et al., 2020	32	32	Closed Defects (25)	Myelomeningocele or Open Defects (13)	Dorsal Lipoma, Transitional Lipoma, Terminal Lipoma, Lipomyelomeningocele, Split Cord Malformation Type 1 and Type 2	The microsurgical technique was used to untether neural structures from mesenchymal tissue. Patients were operated on via midline incision in the prone position.

Gadhvi et al., 2023	26	26	Spina Bifida Occulta with Low Lying Tethered Cord (1), Spina Bifida with Tethered Cord (1)	Lumbar Myelomeningocele with Tethered Cord (1)	The paper includes a distribution of individual cases based on diagnosis.	N/A
Guo et al., 2024	454	454	N/A	86	TCS Classifications: Filum Terminale (74), Sacrococcygeal Lipoma (195), Myelomeningocele (86), Mixed type (85), and Others (14)	N/A
Hoving et al., 2011	65	65	N/A	2	Morphology of Tethered Cord included High Risk Group (40), Tight Filum Terminale (10), Myelomeningocele (2), Dermoid Sinus (5), Tight Filum Terminale + Filum Lipoma (3), Other (5)	Goal of Surgery: To detether the cord by disconnecting aberrant tightening attachments and to relieve the cord from continuous stretching forces.
Jiang et al., 2020	100	100	93	N/A	Other Malformations Included Diastematomyelia and hydromyelia	The curved incision was made over the lumbosacral mass and skin depression. The meningeal sac was isolated after exposing the spinous processes and lamina. A longitudinal dural incision was made using a microscope, and the dura mater was dissected. Cavitron ultrasonic surgical aspirator (CUSA) was then used to remove the lipoma.
Kobayashi et al., 2018	239	5	N/A	N/A	Spinal Tumor, Scoliosis, Lumbar Degenerative Disease, Ossification of the Posterior Longitudinal Ligament, Lumbar Intradural Extramedullary, Cervical Spondylitic Myelopathy, Cervical Involvement in Rheumatoid Arthritis, Spinal Infection, Spinal Cord Hernia, Tethered Cord Syndrome, Others	This study focused on the relationship between postoperative bowel bladder disorder and the efficacy of needle electrodes for the external anal sphincter in intraoperative spinal cord monitoring with transcranial muscle action potentials.
Leung et al., 2015	14	14	N/A	N/A	All Patients Had a Fatty Filum Terminale	N/A
Maurya et al., 2016	21	21	Open Spinal Dysraphism (4)	Lipomyelomeningocele (2)	Dermal Sinus (6), Fatty Filum (6), Open Spinal Dysraphism (4), Lipomyelomeningocele (2), Dermoid (3), Sacral Cyst (1), Split Cord Malformation (2)	This study assesses changes in CSF levels of markers of neuronal injury and alterations in the spinal cord's electrophysiologic functioning.
McGrath et al., 2024	20	20	N/A	19	Myelomeningocele (19), Lipomyelomeningocele (1)	N/A
Mehrotra et al., 2024	22	0	1	0	Spondylolisthesis in various areas of the lumbosacral spine	N/A
Sapir et al., 2021	20	0	Spina Bifida Occulta Lipomyelomeningocele (20)	N/A	N/A	Surgery was performed in the prone position. The extradural element of LMMC was separated to expose the spinal canal and dura. A microscope was used to pen the dura proximally to the penetrated intradural part of LMMC. The location of the motor nerve roots was identified using IONM, and the border between the lipoma and nerve roots was delineated.
Selçuki et al., 1998	13	13	0	0	N/A	A flavotomy approach without a laminectomy was used to release the filum terminale.

Squintani et al., 2024	50	50	N/A	6	Myelomeningocele, Diastematomyelia, Filum Lipoma, Conus Lipoma, and Other Spinal Dysraphism	The surgical approach is not mentioned.
Stavrinou et al., 2011	20	20	N/A	8	Fatty Filum, Myelomeningocele, Intradural Lipoma, Dermal Sinus, Lipomyelocele	Retrospective analysis: Detethering was considered complete when total liberation of the conus medullaris or the former neural placode was achieved, and rostral migration was visualized via ultrasound.
Udayakumaran et al., 2021	87	87	Neonates operated for open spina bifida were not included in the study (0)	16	Lipomyelomeningocele, Myelomeningocele, Lipomatous Filum, Dermal Sinus, Lipoma, Dermoid, Diastematomyelia, Sacral Agenesis	The surgical approach is not mentioned.
Valentini et al., 2013	149	149	N/A	N/A	Lipomas of the Conus, Lipomas of the Filum, Limited Dorsal Myeloschisis, Retained Medullary Cord, Terminal Myelocystocele, Redos, Reoperations for Retethering, Split Cord Malformations, Syringomyelia, Anorectal Malformations, Chiari Malformation Type 1, Teratoma, Dermoid	The surgical approach includes a more radical lipoma resection to create a dural mega sac. The patient's dura was left open and suspended laterally to the ligaments, and a wide bovine pericardium dural graft was attached by a 5-0 proline continuous suture.
Von Koch et el., 2002	25	25	N/A	N/A	No Other Categories	The surgical approach consisted of loupe magnification. Routine hemilaminectomy at one level was performed either at lumbar 4/5 or lumbar 5/sacral 1 to expose the dura overlying the film. The conus was not exposed. After opening the dura, the film was identified. After a neuro-physiological evaluation, the film was transected. The dura, fascia, and skin were closed routinely.
Yi et al., 2019	25	19	N/A	N/A	Tethered Cord Syndrome, Lumbosacral Lipoma, Lipomeningomyelocele, Limited Dorsal Myeloschisis, Currarino's Triad, Congenital Dermal Sinus, Thick Filum Terminale, Brain Tumors (Supratentorial, Infratentorial), and Chondrodysplasia Punctata.	The surgical approach is not mentioned.
All Studies	**1831**	**1397**	**145**	**169**		

Table 6. Diagnostic Categories Across Study Populations. Distribution of neurological conditions and diagnosis among included studies.

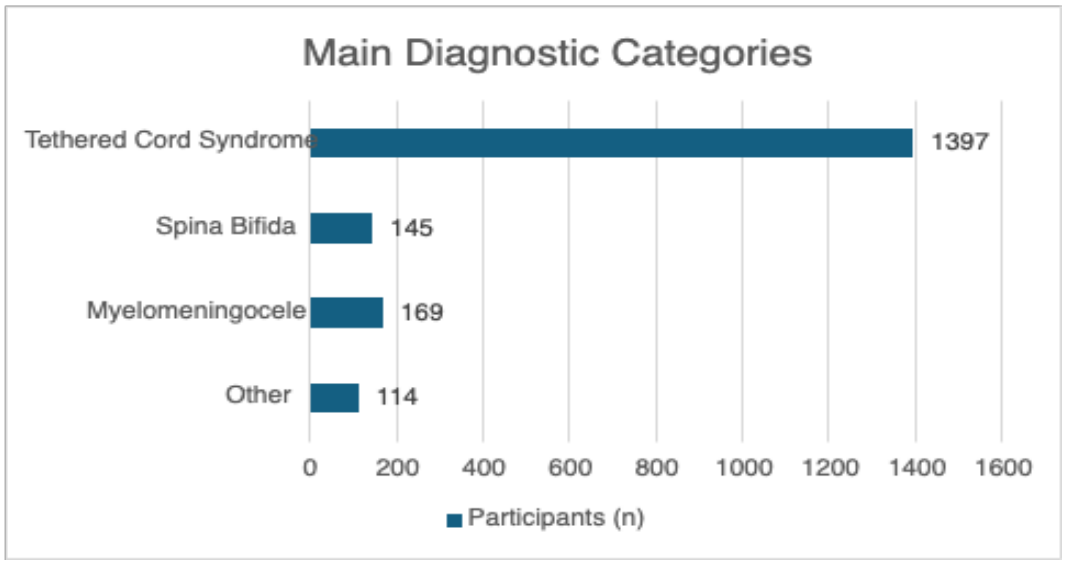

Figure 2. Summary of Diagnostic Subcategories in Spinal Dysraphism. Distribution across included studies.

Postoperative Neurological Deficits in Spinal Dysraphism Cases
IONM vs Non-IONM Procedures

Study	IONM Procedures (n)	Postoperative Deficits (n) in IONM Group	Non-IONM Procedures (n)	Postoperative Deficits (n) in Non-IONM Group	Comments
Akhmediev et al., 2024*	23	6	N/A	N/A	Out of the 56 total cases, 23 were related to spinal dysraphism. The article reported postoperative sphincter dysfunction in 6 of the 56 cases, but it did not specify whether these (6) cases were related to spinal dysraphism. Although no cases of neurological deterioration were noted, we included sphincter dysfunction in our analysis, as we consider bladder and bowel dysfunction to be a neurological deficit.
Aleem et al., 2015	119	5	N/A	N/A	Five adverse outcomes (4.2%) in the IONM group: 4 True Positives (TP), 1 False Negative (FN)
Cha et al., 2018	106	14	N/A	N/A	(14) cases in the IONM group developed postoperative deterioration of voiding function
Durdağ et al., 2015	40	0	N/A	N/A	No neurological deficits: CSF fistula reported as a surgical complication
Fang et al., 2015	37	0	N/A	N/A	No postoperative neurological deterioration was noted.
Fekete et al., 2019	70	2	32	3	Initially, eight cases with postoperative neurological deficits were identified, with three cases fully recovered, resulting in a total of (5) cases with persisting postoperative neurological deficits: (2) in the IONM group and (3) in the non-IONM group.
Finger et al., 2020	25	1	13	2	Odom's criteria utilized poor outcomes (3) cases counted with neurological deterioration: (1) in the IONM group, (2) in the non-IONM group.
Gadhvi et al., 2023	26	0	N/A	N/A	N/A

Guo et al., 2024	250	14	115	9	Of the 454 cases, 365 were included in the final analysis after matching propensity scores to balance baseline characteristics between the IONM group (250) and the non-IONM group (115). Post-operative neurological deficits were observed in (14) cases in the IONM group and (9) cases in the non-IONM group.
Hoving et al., 2011	65	2	N/A	N/A	(1) cases in the IONM group with combined neurological and urological deterioration; (1) in the IONM group with pain deterioration
Jiang et al., 2020	49	9	51	19	Post-operative neurological deficits were noted with (9) cases in the IONM group and (19) cases in the non-IONM group.
Kobayashi et al., 2018	5	1	N/A	N/A	Of 239 total procedures with IONM, the analysis included five procedures involving spinal dysraphism, using either a needle or plug-surface electrodes. (1) case with plug-surface electrode developed postoperative bowel/bladder disorder aggravation.
Leung et al., 2015	14	0	N/A	N/A	No postoperative neurological deterioration was noted.
Maurya et al., 2016	21	11	N/A	N/A	(11) cases in the IONM group with postoperative neurological deficits. The remainder of cases are asymptomatic.
McGrath et al., 2024	20	0	N/A	N/A	N/A
Mehrotra et al., 2024	22	0	N/A	N/A	No postoperative neurological deterioration was noted.
Sapir et al., 2021	20	3	N/A	N/A	(3) cases developed postoperative neurological deficits in the IONM group: (2) with urinary retention, (1) with combined urinary retention and bowel dysfunction
Selçuki et al., 1998	13	0	N/A	N/A	No postoperative neurological deterioration was noted. (4) poor outcome cases were not counted as deficits since neurological symptoms were pre-existing, with no improvement from baseline
Squintani et al., 2024	50	9	N/A	N/A	(9) cases developed postoperative neurological deficits in the IONM group: (3) with Motor weakness/spasticity, (1) with Sensory Disturbances, (5) with Bladder/Anal Dysfunction
Stavrinou et al., 2011	20	0	N/A	N/A	No postoperative neurological deterioration was noted.
Udayakumaran et al., 2021	87	9	N/A	N/A	(9) cases developed in the IONM group with postoperative bowel and bladder dysfunction at 1-year follow-up. No motor deterioration was noted.
Valentini et al., 2013	95	1	54	8	Post-operative neurological deficits were noted in (1) the case of the IONM group and (8) the case of the non-IONM group.
Von Koch et el., 2002	25	0	N/A	N/A	No postoperative neurological deterioration was noted; urinary tract infections were reported as surgical complications.
Yi et al., 2019	25	2	N/A	N/A	(2) cases in the IONM group developed postoperative neurological deficits: (1) with left ankle weakness, (1) with left ankle weakness and neurogenic bowel dysfunction
All Studies	**1227**	**89**	**265**	**41**	

Table 7. Postoperative Neurological Deficits in Spinal Dysraphism Cases. Comprehensive analysis of neurological deficits across intraoperative neurophysiological monitoring (IONM) and non-IONM procedures.

The accuracy of intraoperative neuromonitoring (IONM) in predicting postoperative deficits was influenced by its ability to detect true positive and false negative events. Among the studies in our paper, only one article by Aleem addressed these technical aspects. Aleem defined a true positive as an event where evoked potential data met warning criteria, correlating with a neurological deficit or returning to acceptable limits following surgical intervention. A false negative occurred when the monitoring data remained stable at baseline throughout the procedure, yet the patient experienced a postoperative neurological deficit. In Aleem's study, 119 procedures were monitored, resulting in 5 adverse outcomes—a deficit rate of 4.2%. Of these, 4 were true positive cases where IONM accurately detected potential deficits, while 1 was a false negative, highlighting the limitations of IONM in ensuring 100% sensitivity [10].

More studies focusing on the technical aspects, including true positives and false negatives, are needed to accurately assess the effectiveness of IONM alerts in preventing postoperative deficits. Such data would provide a clearer understanding of IONM's predictive reliability and potential areas for improvement.

A total of 1492 procedures involved with spinal dysraphism were analyzed across the included studies, with 1227 of these conducted using intraoperative neuromonitoring (IONM). Among the IONM-monitored procedures, 89 cases resulted in postoperative neurological deterioration or deficits, yielding a deficit rate of 7.25% (89/1227). However, it is essential to note that the deficit rate for IONM procedures may be slightly skewed higher due to the limitation of Akhmediev's study [31]. Due to the focus of our paper, we only included 23/56 cases relating to spinal dysraphism. Still, Akhmediev's study was that the article reported postoperative dysfunction in 6/56 instances but did not specify whether these (6) cases were related to spinal dysraphism. In contrast to these postoperative IONM findings, surgeries performed without IONM —reported in only five articles—included 265 procedures, with 41 resulting in postoperative neurological deficits, giving a higher deficit rate of 15% (41/265).

These findings indicate that procedures without IONM had a nearly 2 times greater likelihood of postoperative deterioration compared to those monitored with IONM. However, the limited number of studies reporting on control groups without IONM represents a significant limitation, underscoring the need for further research to validate these findings and assess the full impact of IONM on reducing postoperative deficits.

Intraoperative Neuromonitoring (IONM) Alerts

In our systematic review, only five out of the 24 studies reported the number of intraoperative alerts and explicitly detailed the outcomes for each patient associated with these alerts, specifically regarding neurological stability or deterioration [9, 11-14]. Unfortunately, most of the studies did not emphasize the role of IONM in predicting adverse outcomes or guiding neurosurgical interventions during procedures.

Intraoperative Neuromonitoring (IONM) Alerts							
Study	**Modalities Used**	**Alert Thresholds**	**Procedures With IONM (n)**	**Number of IONM Alerts (n) Noted**	**Sensitivity (%) of IONM Signal**	**Specificity (%) of IONM Signal**	**Comments**
Akhmediev et al., 2024	Electromyography	Not Mentioned	23	Not Mentioned	Not Mentioned	Not Mentioned	N/A
Aleem et al., 2015	Somatosensory Evoked Potential, Descending Neurogenic Evoked Potential, Motor Evoked Potential	Not Mentioned	119	5	80%	92%	N/A
Cha et al., 2018	Bulbocavernosus reflex (BCR), Electromyography, Motor and Sensory Evoked Potentials	**BCR**: Oscillation Amplitude < 10% Intraoperative Baseline BCR/undiscernable with baseline. **EMG**: Evidence of lumbosacral radiculopathy such as denervation potential, long duration or increased amplitude of motor unit action potential, and delayed recruitment pattern.	106	15	35.70%	88.50%	BCR: 60 patients. EMG: Not mentioned
Durdağ et al., 2015	Not Mentioned	Not Mentioned	40	Not Mentioned	Not Mentioned	Not Mentioned	N/A
Fang et al., 2015	Electromyography, Transcranial Motor Evoked Potential (TCeMEP) and Peripheral Myogenic Motor Compound Potential	Change in TCeMEP amplitude	37	0	Not Mentioned	Not Mentioned	Electromyography: 37 TCeMEP: 32
Fekete et al., 2019	Motor Evoked Potential, Electromyography and Bulbocavernosus reflex	Not Mentioned	70	Not Mentioned	Not Mentioned	Not Mentioned	70 surgeries overall. Bulbocavernosus reflex specifically in 8 surgeries
Finger et al., 2020	Motor Evoked Potential, Electromyography and Bulbocavernosus reflex	Not Mentioned	25	Not Mentioned	Not Mentioned	Not Mentioned	N/A
Gadhvi et al., 2023	Transcranial Motor Evoked Potential (TCeMEP), Free-running Electromyography (fEMG), Triggered electromyography (tEMG)	Disappearance of signals or reduction in amplitude > 50%	26	0	100%	Not Mentioned	TCeMEP: 20 patients, tEMG: 26 patients, fEMG: Not mentioned
Guo et al., 2024	Transcranial Motor Evoked Potential (TCeMEP), Somatosensory Evoked Potential (SSEP), Free-running Electromyography (fEMG), Triggered electromyography (tEMG)	Not Mentioned	250	Not Mentioned	Not Mentioned	Not Mentioned	N/A

Hoving et al., 2011	Evoked Muscular Motor Potential and Transcranial Electrical Stimulation	Presence of an MEP amplitude well above 100 µV	65	Not Mentioned	Not Mentioned	Not Mentioned	N/A
Jiang et al., 2020	Electromyography, Motor Evoked Potential, Somatosensory Evoked Potential	Not Mentioned	49	Not Mentioned	Not Mentioned	Not Mentioned	N/A
Kobayashi et al., 2018	Transcranial Muscle Action Potential	Amplitude reduction of 70%	5	Not Mentioned	Needle electrodes: 88% Plug surface electrodes: 89%	Needle electrodes: 85% Plug surface electrodes: 80%	N/A
Leung et al., 2015	Somatosensory Evoked Potential and Motor Evoked Potential	Not Mentioned	14	Not Mentioned	Not Mentioned	Not Mentioned	N/A
Maurya et al., 2016	SSEP	Not Mentioned	21	Not Mentioned	Not Mentioned	Not Mentioned	N/A
McGrath et al., 2024	TCeMEP and tEMG	Not Mentioned	20	Not Mentioned	Not Mentioned	Not Mentioned	N/A
Mehrotra et al., 2024	EMG	Not Mentioned	22	Not Mentioned	Not Mentioned	Not Mentioned	N/A
Sapir et al., 2021	TCeMEP, SSEP and EMG	Not Mentioned	20	3	Not Mentioned	Not Mentioned	EMG for 12 cases
Selçuki et al., 1998	SSEP	Delay in N22 wave latency, low amplitude, and blockade of conduction were considered to be pathological results.	13	Not Mentioned	Not Mentioned	Not Mentioned	N/A
Squintani et al., 2024	TCeMEP, Tibial Nerve Somatosensory Evoked Potential, BCR, EMG,	Marked drop in TCeMEP amplitude for TNSEP: Reduction in > 50% amplitude, for BCR: A drop of > 80% amplitude	20	4	TCeMEP: 100% TNSEP: 100% BCR: 20%	TCeMEP: 100% TNSEP: 97% BCR: 89%	TCeMEP: 43, TNSEP: 43, BCR: 46, EMG: 50
Stavrinou et al., 2011	SSEP, MEP	5 cases - latency delays	50	Not Mentioned	Not Mentioned	Not Mentioned	N/A
Udayakumaran et al., 2021	Transcranial motor evoked potentials (TCeMEP),	A drop of ≥50% in motor evoked potential (MEP) amplitude or a 10% increase in latency	87	Not Mentioned	100%	100%	N/A
Valentini et al., 2013	EMG, Transcortical Motor Evoked Potentials (tMEP), Compound Muscle Action Potential	Not Mentioned	95	Not Mentioned	Not Mentioned	Not Mentioned	N/A
Von Koch et el., 2002	EMG, Compound Muscle Action Potential	Absence of a low threshold (!1 V) CMAP response.	25	Not Mentioned	70%	Not Mentioned	N/A
Yi et al., 2019	MEP, SSEP and BCR	MEP: A sustained reduction in amplitude of more than 50% compared with the baseline amplitude.	25	4	Not Mentioned	Not Mentioned	N/A
All Studies			**1227**	**31**			

Table 8. Intraoperative Neuromonitoring (IONM) Alerts. Comprehensive analysis of neuromonitoring techniques, alert thresholds, and signal characteristics across procedures involving spinal dysraphism, detailing the modalities, sensitivity, and specificity of IONM methodologies.

Table 9: Intraoperative Neuromonitoring (IONM) Modalities Used Across Studies					
Study	**Sample Size (n)**	**EMG (n)**	**SEP (n)**	**MEP (n)**	**BCR (n)**
Akhmediev et al., 2024	56	56	N/A	56	N/A
Aleem et al., 2015	82	82	82	82	N/A
Cha et al., 2018	106	106	106	106	91
Durdağ et al., 2015	40	N/A	N/A	40	N/A
Fang et al., 2015	37	37	37	37	37
Fekete et al., 2019	91	91	91	91	8
Finger et al., 2020	32	21	N/A	21	21
Gadhvi et al., 2023	26	26	N/A	26	N/A
Guo et al., 2024	454	336	336	336	N/A
Hoving et al., 2011	65	N/A	N/A	65	65
Jiang et al., 2020	49	49	49	49	N/A
Kobayashi et al., 2018	239	N/A	N/A	239	N/A
Leung et al., 2015	14	N/A	14	14	N/A
Maurya et al., 2016	21	N/A	21	N/A	N/A
McGrath et al., 2024	20	20	N/A	20	N/A
Mehrotra et al., 2024	22	22	N/A	N/A	N/A
Sapir et al., 2021	20	20	20	20	N/A
Selçuki et al., 1998	13	13	13	N/A	N/A
Squintani et al., 2024	48	N/A	48	48	N/A
Stavrinou et al., 2011	20	20	20	20	N/A
Udayakumaran et al., 2021	87	N/A	N/A	87	N/A
Valentini et al., 2013	149	149	N/A	149	N/A
Von Koch et el., 2002	25	25	N/A	N/A	N/A
Yi et al., 2019	25	N/A	25	25	N/A
All Studies	**1741**	**1073**	**862**	**1531**	**222**

Table 9. Intraoperative Neuromonitoring (IONM) Modalities Used Across Studies. Comprehensive overview of neurophysiological monitoring modalities in procedures involved with spinal dysraphism cases.

As previously noted, only approximately 20% of the studies in our review explicitly provided the IONM alert data to assess the significance of IONM in predicting neurological outcomes. Among these studies, three reported a sample size of 50 or fewer patients [11-13], which further limits the generalizability of the findings. Additionally, there was considerable variability in accurate positive rates across the studies, raising questions about the overall effectiveness and appropriate application of IONM. It is also plausible

that different IONM modalities exhibit varying sensitivities in detecting neurophysiological signals; thus, the frequency and number of alerts may differ based on the specific modality employed, as the included studies utilized at least four distinct IONM techniques.

Many authors of studies including collectively emphasize the need for further research to enhance the understanding and application of IONM. Durdağ et al. [15] call for larger cohorts to assess the significance of intraoperative electrophysiological data about the histopathological profile of the Filum Terminale, a topic they specifically focused on. Similarly, Guo et al. [16] stress the importance of evaluating the predictive value of IONM data in determining surgical outcomes. Additionally, Jiang et al. [17] suggest that logistic or multivariate analyses are crucial for establishing associations, advocating for randomized controlled trials to address potential loss to follow-up. It was also proposed by Leung et al. [18] that future studies should focus on younger patient populations to enhance the relevance of findings.

The relationship between the number of IONM modalities used, and the rates of postoperative neurological deficits in our reviewed studies are complex and not definitively established. Studies utilizing a single modality, such as MEP, report varied deficit rates. For example, the study by Durdağ et al. [14] that used MEP only shows a 0% rate of deficit, while Kobayashi's [19] study, which also used MEP only, shows a significantly higher rate of 17.1%. This inconsistency suggests that relying solely on one modality may not provide comprehensive monitoring. The combination of EMG, SEP, and MEP yields varying results. In studies by Aleem et al. and Jiang et al. ([9], [16]), both employing this combination but differing in sample size, the rates are 4.2% and 18.4%, respectively. This discrepancy highlights the influence of other factors, such as patient demographics or surgical complexity. While one might expect that employing a more considerable number of modalities would reduce the risk of developing such deficits, the findings indicate that this is not consistently the case. Based on the data from the studies reviewed, we cannot establish a definitive relationship between the number of IONM modalities used and the rates of postoperative deficits observed ($p = 0.45$). There was also no significant relationship between sample size and the rates of deficit observed across studies ($p = 0.15$).

DISCUSSION

Multimodal IONM allows for a holistic monitoring approach to further reduce the risks associated with permanent motor and/or sensory neurologic injury. There are various types of IONM modalities, such as somatosensory evoked potentials (SSEPs), motor evoked potentials (MEPs), electromyography (EMG), and bulbocavernosus reflex (BCR) monitoring [20]. Firstly, SSEPs allow for the monitoring of the dorsal column-medial lemniscus pathways. SSEPs can also provide insight into motor function, as ischemic and/or mechanical injury will affect both pathways. MEPs evaluate motor function based on the response from a targeted muscle to intermittent stimulation. EMG is employed to detect any injury in nerve roots, and

BCR is specific for preserving the function of the lower sacral nerve roots [21]. Considering these points, multiple IONM modalities can complement each other simultaneously and decrease the likelihood of developing postoperative deficits.

Comparing the Rate of Postoperative Neurological Deficits: IONM vs non-IONM

As previously mentioned, non-IONM patients who had undergone spinal surgeries had approximately two times the risk of developing postoperative neurological deficits when compared to their IONM counterparts. Across the non-IONM procedures in our included studies, the rate of deficit ranged from the highest 37.3% or 19/51 [16], to the lowest 7.83% or 9/115 [15], with an intermediate rate of 14.8% or 8/54 [30]. In comparison, the IONM procedures in our included studies reported the rate of deficit ranging from the highest 52.4% or 11/21 [24] to the lowest 0% in several studies [9], with a median deficit rate of 3.08% or 2/65 [32] and 4% or 1/25 [21]. Notably, despite one study showing an IONM group with the highest deficit rate of 52.4% compared to the highest deficit rate of 37.3% reported in the non-IONM group of another study, most procedures paired with IONM have demonstrated the preservation of normal neurological function with eight studies reporting zero postoperative complications. These findings suggest that the implementation of IONM in surgeries involving spinal dysraphism can reduce the risk of a wide range of postoperative complications, such as motor impairments, sensory deficits, mobility issues, and neurogenic bladder dysfunction, depending on the level of injury on different segments of the spinal cord and areas of nerve damage.

Despite the promising findings, it is important to emphasize that we were only able to include five (5) studies for our control group (non-IONM) rate of deficit data. This limitation stems from the utilization of just one keyword list, where we screened all 99 articles found in PubMed including both non-IONM and IONM data. A specific keyword list designated for the non-IONM data alone would have enabled us to create more robust conclusions by determining the efficacy of IONM in minimizing the rate of deficit in spinal dysraphism surgeries through an improved comparative analysis with the expanded non-IONM data. In addition, our keyword list did not include [MESH] which would have allowed PubMed to search using its official standardized medical vocabulary system that would automatically include related terms and synonyms rather than searching for the specific terms from the keyword list. In addition, restricting our studies to PubMed alone may have contributed to our limited data. Expanding on other platforms such as Science Direct or Google Scholar would have improved the scope of our study.

The Clinical Significance of IONM Alerts and Parameters

The utility of intraoperative neuromonitoring is significantly influenced by its accuracy in predicting and preventing postoperative morbidities. While studies focus on the ability of IONM to reduce the risks of surgery, there is a general lack of information on false positives and negatives, without which the reliability of a false positive may lead to inappropriate surgical corrections, increasing the length of surgery time, while a false negative may lead to neural insults not being corrected. Complete documentation of such events is needed to develop IONM protocols and improve predictive power. Future studies should utilize

standardized definitions for true positive, false positive, true negative, and false negative events, thereby affording a much clearer view of the ability of IONM in its diagnostic capacity.

Furthermore, the sensitivity and specificities of IONM modalities are most reported inconsistently, which complicates the determination of their real efficacy. Standardized metrics will enable clinicians to evaluate the reliability of different techniques of IONM in detecting neural injuries. Sensitivity measures the ability to detect true neurological compromise, while specificity reflects the capacity to avoid false alarms. Standardization of studies would allow more valid comparison of the different modalities involved, such as SSEPs, MEPs, and EMG, to customize surgical monitoring.

The lack of consensus regarding IONM alert thresholds and corresponding surgical responses creates variability in outcomes and interpretations. Standardization of alert criteria, such as specific amplitude reductions, latency increases, or waveform abnormalities, could help ensure uniformity in practice. In the same regard, documenting surgical responses to alerts in a detailed and systematic manner would be very valuable for gaining insight into the effectiveness of interventions. This may also provide guidance for best practices and contribute to improved surgical outcomes and complication rates.

In addition, future studies emphasizing the clinical outcome of surgeries involved with IONM should also include more technical information not just limiting to the IONM alerts but also the stimulation and recording parameters as well. This detailed information would provide a more comprehensive overview of how the IONM setup also contributes to the clinical outcome in patients overall. By documenting this crucial information in future studies, clinicians would be able to replicate IONM protocols which would maintain the consistency for system set up and improve the overall clinical outcome in patients.

While multimodal IONM is in wide use, the exact correlation between specific changes in monitoring parameters and their predictive value regarding postoperative deficits remains unknown. A detailed analysis of the relationship between changes in SSEPs, MEPs, EMG, or BCR and different neurological outcomes would significantly enhance the clinical utility of IONM. Patterns specific to motor or sensory deficits may help clinicians distinguish between reversible and irreversible injury. Future studies should focus on determining the relationship between IONM information and patient outcomes in the long term, to inform surgical decision-making and refine predictive algorithms.

Advancements in IONM for Spinal Dysraphism: Exploring New Modalities

Intraoperative neuromonitoring (IONM) has been well proven to reduce the risk of neurological injury in the surgery for spinal dysraphism. However, most of the existing monitoring modalities have certain limitations, including somatosensory evoked potentials, motor evoked potentials, and electromyography [19, 25, 26]. These modalities are usually associated with a lack of sensitivity in defining subtle neural function changes, specifically within certain pathways such as autonomic or mixed motor-sensory nerves. SSEPs primarily monitor the integrity of the dorsal columns, whereas MEPs monitor the function of the corticospinal tracts, with less comprehensive monitoring of other vital neural structures. This gap in

monitoring capability limits the detection of injury to the neural circuits responsible for autonomic functions, which are frequently implicated in common postoperative complications.

The high incidence of postoperative urinary and bowel dysfunction among patients with spinal dysraphism underscores the need for more focused approaches to monitoring. These complications may be associated with injury in the sacral nerve roots or autonomic pathways, which are not well monitored with current IONM modalities [19]. Bulbocavernosus reflex (BCR) monitoring provides some information about lower sacral nerve root function but is not commonly used or standardized in practice. Moreover, current methodologies often miss subclinical injuries that may progress to major postoperative disabilities, further compounding the critical need for advanced detection systems.

To improve surgical outcomes and decrease the risk of neurologic and functional deficits, supplementation with other monitoring modalities that target underrepresented neural structures should be incorporated. Advanced methodologies include autonomic nervous system monitoring or functional imaging, which may more completely assess neural integrity intraoperatively. The ability to incorporate such strategies into a treatment plan would enable the surgical team to address a broader range of neural risks. The integration of technologies, such as direct nerve stimulation or high-resolution nerve conduction studies, may potentially increase the ability to both predict and reduce complications related to neurogenic bladder or bowel dysfunction.

The addition of electromyography to the urinary bladder is a promising supplementation of intraoperative monitoring toolkits. Standard EMG in intraoperative settings is common for the monitoring of peripheral nerves and motor roots. The direct testing of its neural control in extension to the bladder is really appealing, particularly in spinal dysraphism surgery when there is frequently an involvement risk for sacral nerves in charge of bladder function. The urinary bladder electromyogram allows for the monitoring in real time of neural interruption or irritation that may ensue subsequent to postoperative neurogenic bladder dysfunction [27]. This modality, if incorporated into surgical protocols, may allow for the early identification of injuries to the innervation of the bladder and hence enable immediate corrective interventions. Motor evoked potentials (MEPs), conventionally applied for monitoring the corticospinal tract, may be modified for the assessment of urinary tract function. The external urinary sphincter MEPs (EUS-MEP) provide direct measurements of the integrity of the motor pathways by stimulating the cortical areas associated with the sacral motor outputs and recording the responses from muscles in charge of the bladder and the urinary sphincter [28]. The inclusion of external urinary sphincter MEPs overcomes the limitation of the inability of conventional MEPs to monitor autonomic and sacral nerve motor pathways.

Somatosensory evoked potentials recorded from the pudendal nerve (Pudendal SSEP) provides a specific modality for monitoring the integrity of the sacral nerves. The pudendal nerve participates in both sensory and motor functions of the pelvic floor including continence of urine and stool. Current SSEP protocols predominantly reflect dorsal column pathways and are nonspecific to the sacral nerves [29]. The inclusion of the pudendal nerve SSEPs allows surgical teams to better monitor sacral nerve function with much

greater precision and potentially offers early detection of injuries that might otherwise lead to urinary or bowel dysfunction. Advanced techniques like these directly address critical gaps in current IONM practices. However, the value of existing SSEP and MEP modalities gives certain valuable information regarding the pathways concerning sensory and motor functions, leaving a great deficiency in autonomic and sacral-specific neural structures that involve either urinary or bowel functions. Thus, adding urinary sphincter (bladder) EMG, urinary sphincter MEP, and pudendal nerve SSEPs could offer completeness to the mentioned above.

LIMITATIONS

Our limitation to the study related to the literature search. The keywords were tailored towards papers that mentioned intraoperative neuromonitoring (IONM). However, since our comparative analysis required more control group data, tailoring a separate keyword list for the control group (non-IONM) would have helped us get more robust data. Thus, our keyword list which searched for articles mentioning IONM led to our limited number of studies on control group data. By omitting any IONM terms for our separate keyword list for the control group as well as expanding to additional library databases such as Science Direct would have allowed us to provide more comprehensive data. Despite these constraints, this review highlights the clinical utility of IONM as well addressing gaps in literature such as the need for larger, more inclusive datasets as well as the importance in addressing more technical aspects of IONM with standardized reporting. Future studies should consider tailoring to a dual-keyword approach for comparative analysis when evaluating the efficacy of intraoperative neuromonitoring in clinical outcome.

CONCLUSION

Multimodal intraoperative neuromonitoring during spinal dysraphism surgeries offers many significant advantages, including comprehensive assessments involving the multiple perspectives of the different modalities, reducing the likelihood of postoperative complications, and enhancing the improved outcomes of patients. The current studies are dedicated to achieving these improved outcomes, which is a hopeful and optimistic prospect for the future of spinal dysraphism surgeries. We recommend the increased use of multimodal intraoperative neuromonitoring techniques, including SSEPs, MEPs, EMG, and BCR as a standard approach in all spinal dysraphism surgeries, based on the evidence presented in this meta-analysis demonstrating their effectiveness in improving surgical safety and outcomes. To fully assess IONM's effectiveness, future research should focus on large, multimodal trials that utilize IONM techniques and standardized reporting metrics to evaluate sensitivity, specificity, and the correlation between IONM signals and surgical outcomes.

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