



# Spinal Mapping for Tumor Surgery: An Overview of Relevant Modalities, Clinical Impact, and Future Directions

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Intramedullary spinal cord tumor surgery demands precise intraoperative strategies to preserve neurological function while achieving maximal resection. Neurophysiological monitoring and direct spinal cord mapping have emerged as essential tools for guiding surgeons through these complex procedures by providing both functional and anatomical insight. This project examines the complementary contributions of somatosensory evoked potentials (SSEPs), motor evoked potentials (MEPs), D-waves, electromyography (EMG), train-of-four (TOF) monitoring, and direct cord mapping (DCM) during intramedullary tumor resection. Each modality offers distinct clinical value. SSEPs assess dorsal column sensory pathway integrity and help identify early ischemic or traction-related changes during surgical manipulation. MEPs and D-waves evaluate the functional status of the corticospinal tract and provide rapid detection of motor pathway compromise, with D-waves serving as a strong predictor of long-term postoperative motor outcomes. EMG detects nerve root irritation or mechanical stress, particularly relevant for cauda equina involvement, while TOF monitoring ensures adequate neuromuscular conditions for reliable motor and electromyography responses. DCM enhances anatomical accuracy by identifying the physiological midline and guiding safe myelotomy planning in cases where normal landmarks are distorted. Integration of these modalities creates a comprehensive monitoring framework that combines continuous functional assessment with precise anatomical localization. This multimodal approach allows early recognition of reversible changes, improves communication between surgical and neurophysiological teams, and supports timely intraoperative adjustments to protect critical pathways. The combined use of mapping and monitoring has been associated with improved sensory and motor outcomes by helping surgeons balance the goal of maximal tumor resection with the imperative of neurological preservation. This study highlights that incorporating multiple neurophysiological modalities offers the most robust safety and guidance system for intramedullary spinal cord tumor surgery. The complementary nature of these techniques underscores their importance in modern spinal oncology and supports continued advancement of multimodal intraoperative monitoring practices.

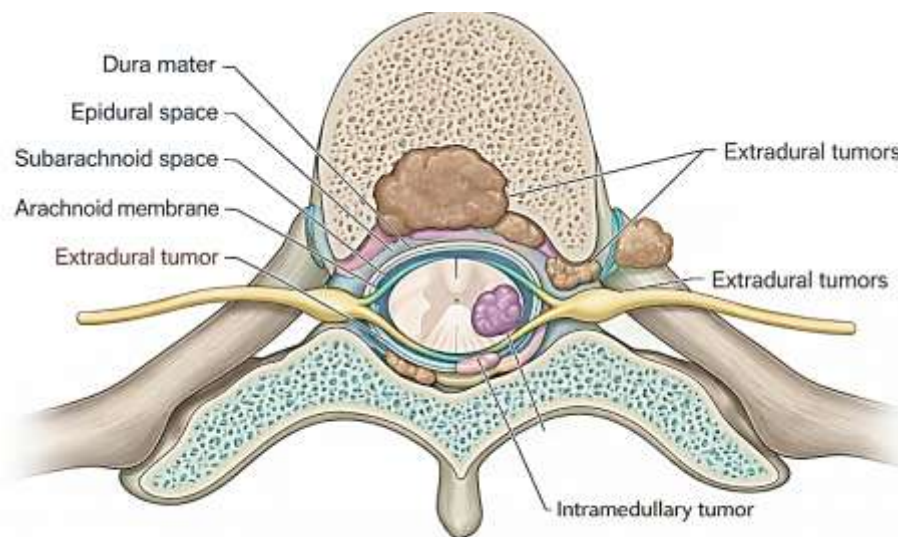
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## INTRODUCTION

### Pathology

Within the central nervous system (CNS), spinal lesions are uncommon, accounting for only 15% of CNS tumors. Such lesions are typically non-cancerous and may remain asymptomatic throughout the early stages. However, tumor growth may eventually lead to the compression of the spinal cord and spinal nerves, manifesting adverse symptoms (e.g., both diffuse and radicular pain) [5].

There are three primary categories of spinal tumors based on location (Figure 1). Extradural tumors are the most common, making up about 60% of all spinal tumors, and are most associated with metastatic behavior [16]. This form originates in the vertebral body or structures outside the dura [5]. Intradural extramedullary tumors are the second most common. Originating from the leptomeninges or nerve roots and located in the dura, but outside the spinal cord, examples include schwannomas, meningiomas, and neurofibromas [5]. Schwannomas are the most common extramedullary tumors, typically arising near nerve roots exiting the spinal cord and growing outward from the nerve [16]. Finally, intradural intramedullary (or just intramedullary) tumors are the rarest form, accounting for only 2-5% of all spinal tumors. Originating from the spinal parenchyma, and most commonly from glial tissue, these lesions erode nearby neural tissue, with ependymomas and astrocytomas being the most prevalent [5]. Ependymoma, as the name suggests, arises from the ependymal cells of the spinal cavity and is the most common intramedullary (glial) tumor [16].



**Figure 1.** Classification of Spinal Cord Tumors.

After pain, both widespread and localized, the second most common symptom of spinal lesions is paresthesia (abnormal sensations of the skin such as tingling, numbness, or a feeling of “pins and needles”).

Another chief complaint is motor impairment. Examples include ataxia, atrophy, uncontrollable twitches, and decreased deep tendon reflexes[5].

While extradural and intradural extramedullary tumors constitute most spinal lesions, the present discussion is limited to intramedullary spinal cord tumors (IMSCTs). This subset, though rare, presents unique diagnostic, surgical, and prognostic challenges that warrant focused examination.

### **Surgical Intervention**

To prevent the worsening of symptoms and in attempts to reverse present symptoms, surgical resection of intramedullary tumors is the primary treatment recommended upon diagnosis. Although surgical resection is the most effective treatment, postoperative neurological deterioration, as seen through dorsal column dysfunction, is not uncommon, ranging in rates between 43.6% to 55.1% [18]. These deficits can lead to significant postoperative morbidity worse than preoperative conditions. Throughout the procedure, various intraoperative neuromonitoring (IONM) procedures are utilized to both ensure preservation of neurological function as well as to facilitate the resection [5], functioning as a well-established practice to protect the spinal cord from intraoperative injury and prevent iatrogenic neurological deficits by helping to identify neural injury at an early reversible stage [8].

### **Intraoperative Neurophysiological Monitoring (IONM) Techniques**

During intramedullary tumor surgery, dorsal column mapping identifies the neurophysiological midline to preserve sensory pathways. SSEPs monitor afferent integrity, MEPs assess motor pathways, and EMG detects nerve root irritation [16]. Together, IONM reduces the risk of postoperative deficits and enhances surgical safety. Without IONM, the risk of neurological deficits, such as proprioceptive dysfunction, sensory ataxia, motor weakness, or neuropathic pain, is high due to the potential for misidentification or injury to neural structures during surgery.

## **METHODOLOGY**

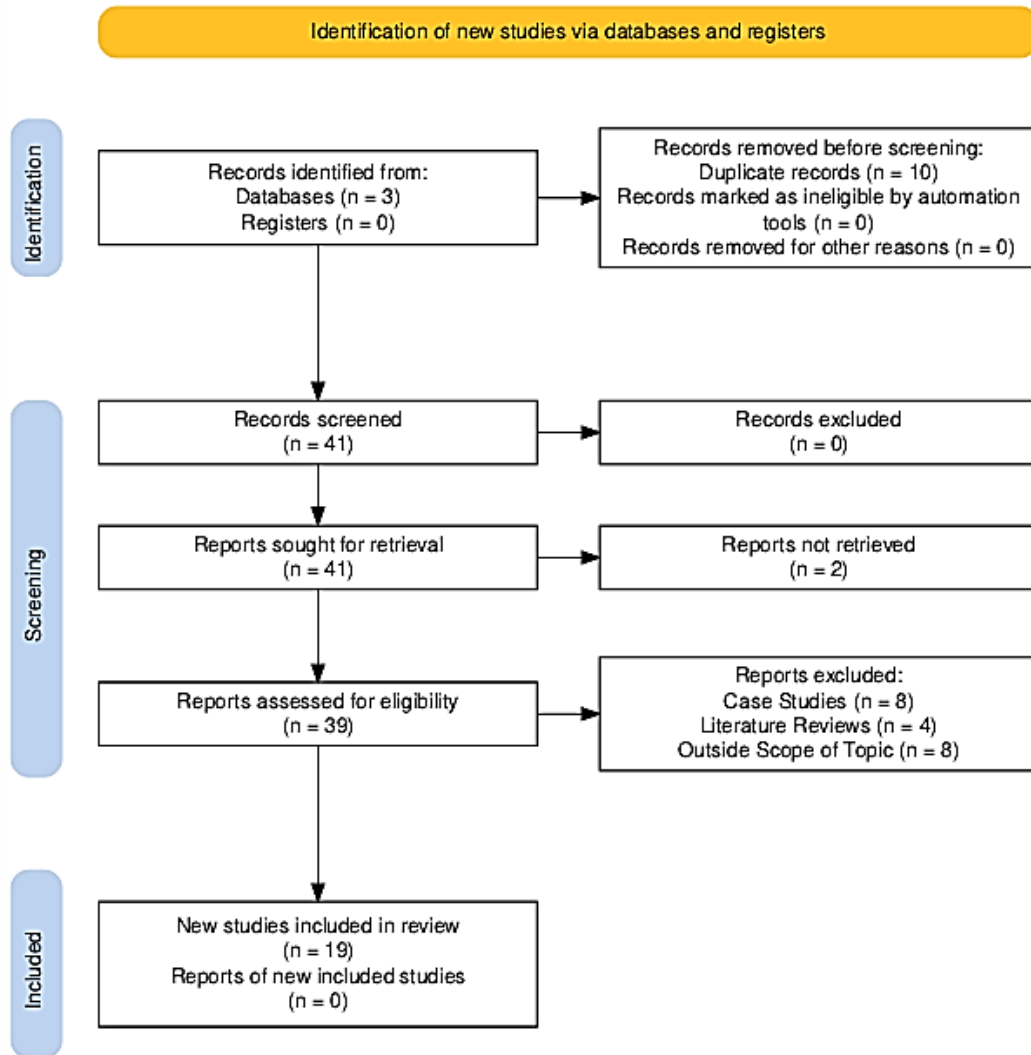
### **Analysis Program (Zotero)**

Zotero was used to store citation information, categorize papers as “included” or “excluded,” and add notes regarding exclusion reasons to maintain consistency. Each article was assessed using its abstract, title, and accessible full text (if available) to determine whether it met the inclusion criteria established by the group.

### **Key Words and Databases searched**

Literature search was conducted through PubMed, Google Scholar, and the Eugene McDermott Library’s online platform. The following search terms and keywords were used: spinal cord mapping, intraoperative

spinal mapping, spinal cord tumor surgery, spinal tumor resection, intraoperative neurophysiological monitoring, IONM, functional mapping, spinal cord monitoring, neurosurgical mapping, image guidance, navigation, spinal metastases, direct wave, neuromonitoring. These keywords were chosen to provide a broad range of literature for selection, offering a foundational background on imaging modalities and their clinical applications, while also eliciting specialized articles pertinent to the review’s focus on spinal tumors.



**Figure 1.** PRISMA Chart.

**Criteria**

Included were peer-reviewed, English-language studies published in or after 2000 that examined spinal mapping across all modalities. Both pediatric and adult populations were included, and all sources reported at least one relevant outcome (e.g., neurological outcomes, mapping accuracy, preservation of motor/sensory function, or correlation with postoperative deficits). Full-text availability and inclusion of any spinal tumor type were required. Excluded were non-English articles, paywalled or unavailable full

texts, literature reviews, case studies, studies outside the scope of spinal mapping, and work lacking adequate scientific rigor, as well as pre-2000 studies unless they provided essential foundational context.

**Somatosensory Evoked Potentials (SSEPs)**

SSEPs are used intraoperatively to monitor the integrity of the dorsal column–medial lemniscus pathway during spinal tumor resection and other neurosurgical procedures [16]. Electrical stimulation is applied to peripheral nerves, commonly the median or ulnar nerve in the upper extremity and the posterior tibial or peroneal nerve in the lower extremity, using repetitive low-frequency pulses. Typical parameters include a stimulus rate of 2-5 Hz, pulse duration of 200–300 microseconds, and intensity sufficient to elicit a visible twitch (Table 1). The evoked responses are recorded from scalp electrodes placed over the somatosensory cortex (such as CP3, CP4, CPz, and FPz) and subcortical sites along the pathway, including the cervical spine and peripheral response from the brachial plexus and popliteal fossa, depending on the nerve stimulated [16]. Baseline SSEPs are obtained after anesthesia induction, and subsequent recordings are continuously compared to detect increases in latency or decreases in amplitude, which may signal compromised sensory tract conduction because of ischemia, traction, or compression. Because SSEPs rely on synaptic transmission through sensory pathways, they are less affected by anesthetic agents than MEPs, making them valuable for continuous monitoring. A 70–80% decrease in amplitude, a significant change in waveform morphology, or a prolongation in latency greater than 10% from baseline are considered warning signs [15]. These changes indicate potential compromise to the dorsal column–medial lemniscus sensory pathway and should prompt immediate evaluation of surgical manipulation, anesthesia depth, temperature, or blood pressure.

Parameters	Upper SSEP	Lower SSEP
<b>Sensitivity</b>	1 – 5 $\mu$ V /div	1 – 5 $\mu$ V /div
<b>Low Frequency Filter</b>	30 Hz	30 Hz
<b>High Frequency Filter</b>	500 Hz	500 Hz
<b>Sweep</b>	50 ms	100 ms
<b>Stimulation Intensity</b>	15 – 35 mA	40 – 100 mA
<b>Stimulation Duration</b>	300 $\mu$ sec	300 $\mu$ sec
<b>Stim Rate</b>	2.66 - 4.79 / sec	2.66 - 4.79 / sec

**Table 1.** Somatosensory Evoked Potentials (SSEP) Parameters:  $\mu$ V /div = microvolts per division, Hz = Hertz, ms = milliseconds,  $\mu$ sec = microseconds, mA = milliamperes.

**Electromyography (EMG)**

EMG is a critical monitoring technique used to preserve motor nerve roots and ensure their function during spinal surgery. Spontaneous EMG (sEMG) records continuous, real-time electrical activity from muscles innervated by the spinal nerve roots. It does not require external stimulation, and it detects nerve irritation

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or injury as it occurs (Table 2). When a nerve root is mechanically stretched, compressed, or touched by surgical instruments, it may produce neurotonic discharges, bursts, or trains of EMG activity. A few isolated spikes may indicate mild irritation, while continuous or high-frequency discharges suggest possible nerve trauma. Because it provides immediate feedback, sEMG serves as an effective warning system for the surgical team, allowing them to adjust their manipulation before permanent damage occurs.

Triggered EMG (tEMG) involves the deliberate electrical stimulation of nerves to assess their functionality or to determine if a structure contains any functional nerve fibers. During surgery, the surgeon uses a probe to stimulate the tissues around the tumor. The stimulation produces a muscle response, indicating an intact motor root or a corticospinal connection. tEMG helps to distinguish tumor tissue from viable neural elements by guiding the surgeon to preserve functioning nerves while safely removing the lesion. tEMG is very important in tumor cases where anatomical distortion makes visual identification of nerve roots difficult.

Parameter	Value
Stimulation Current	0.1 - 10 mA
Pulse Width	100 - 300 $\mu$ s
Stimulation Frequency	1 - 4 Hz
Filter Setting	10 - 5000 Hz
Sweep Length	5 ms/div (50 ms)

**Table 2.** Electromyography (EMG) Stimulation Parameters: mA = milliamperes,  $\mu$ s = microseconds, Hz = hertz, ms = milliseconds.

### Motor Evoked Potentials (MEPs)

Transcranial motor evoked potentials (MEPs) are used intraoperatively to evaluate the functional integrity of the corticospinal tract during spinal tumor resection [4, 15, 18]. Stimulation is typically delivered through scalp electrodes placed over the motor cortex, using short trains of high-voltage electrical pulses [15, 18] (Table 3). Each pulse train usually consists of 5–7 pulses at 100–500 volts, with a pulse width of 50 or 75 microseconds and an interstimulus interval of 1–4 milliseconds [15]. The evoked responses are recorded from subdermal needle electrodes inserted into target limb muscles, most commonly in the upper and lower extremities [4, 7]. Baseline MEPs are obtained after anesthesia induction, and subsequent recordings are compared throughout surgery to detect any signal changes that may indicate injury or ischemia to motor pathways [4, 15]. Standard alert criteria include a 70% to 80% decrease in amplitude, a notable change in waveform morphology, or an increase in stimulation threshold of 100 volts or more [15, 18]. Since MEPs are highly sensitive to both anesthetic depth and temperature, total intravenous anesthesia (TIVA) is preferred to maintain cortical excitability [15, 18]. Their inclusion in spinal mapping allows real-time

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feedback on descending motor fiber integrity, guiding the surgeon in preserving motor function while achieving maximal tumor resection [4, 15].

Parameter	Value
<b>Pulse Train Length</b>	5-7 pulses
<b>Stimulation Intensity</b>	100 - 500 V
<b>Pulse Width</b>	50 - 75 $\mu$ s
<b>Interstimulus Interval (ISI)</b>	1 - 4 ms

**Table 3.** Motor Evoked Potentials (MEP) Stimulation Parameters: V = volts,  $\mu$ s = microseconds, ms = milliseconds.

### D-Waves (Epidural Recordings)

Direct waves (D-Waves) result from direct activation of layer V in the motor cortex, generating an electrical signal that travels down the corticospinal tract. The waves can be recorded epidurally or subdurally. Inhalational agents and muscle relaxants do not affect D-wave readings, allowing their use during surgery without pause. During spinal cord tumor resections and other high-risk spinal surgeries, D-waves are used to ensure that the corticospinal tract is not damaged. If the amplitude or morphology of the D-wave remains unchanged during surgery, it indicates that the descending motor pathways are preserved and the risk of permanent paralysis is low. However, a 50% or greater drop in amplitude or a total loss of the D-wave suggests potential injury or compromised conduction within the tract.

### Train of Four (TOF)

Train-of-four (TOF) monitoring is used intraoperatively to assess the degree of neuromuscular blockade and ensure that muscle responses remain adequate for reliable MEP and EMG interpretation [10, 15]. TOF stimulation involves delivering four supramaximal electrical pulses at 2 Hz to a peripheral nerve, most commonly the median or posterior tibial nerve, and observing or recording the corresponding muscle twitches [15]. The ratio of the fourth twitch to the first twitch (T4/T1) provides an estimate of blockade depth [15]. A TOF ratio greater than 0.9 indicates minimal blockade, which is essential for obtaining stable motor responses [10, 15]. During spinal tumor surgery, TOF monitoring assists the anesthesia team in titrating neuromuscular blocking agents to prevent excessive paralysis that suppresses MEP amplitudes or obscures EMG activity [15, 18]. Maintaining an appropriate TOF level supports accurate mapping of motor pathways and enhances the overall reliability of intraoperative monitoring [15, 18].

### Dorsal Column Mapping/Direct Spinal Cord Mapping

Direct spinal cord mapping (DSCM), also known in a narrower sense as dorsal column mapping (DCM), is a crucial IONM technique in the surgical resection of IMSCTs [18,16]. DSCM is primarily used to identify

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both the anatomical and physiological midline of the spinal cord, for example, the dorsal median sulcus or median raphe, to guide a safe myelotomy [18]. The necessity of this procedure arises from the likelihood of intramedullary lesions to distort the normal anatomical structures of the spinal cord due to compression, rotation, or edema, making solely visual identification of the physiological midline unreliable [17].

The dorsal columns consist of the medial lemniscus pathway, which integrates sensory information, including fine touch, vibration, two-point discrimination, and proprioception [17]. DCM helps prevent injury to these sensory tracts during the myelotomy [16]. There are two main approaches used for spinal sensory mapping (i.e., DCM): stimulation of the spinal cord and recording from cortical and peripheral nerves; and stimulation of peripheral nerves in the upper or lower limbs and recording from the spinal cord. Direct dorsal column stimulation (DCS) via phase reversal (also known as phase-reversal mapping) involves stimulating the dorsal surface of the spinal cord sequentially from lateral to medial using a handheld bipolar side-by-side electrical stimulation probe [12]. Stimulation parameters include a low intensity, typically 0.2-0.5 mA (up to 2 mA maximum), a 0.2  $\mu$ s pulse width, and a repetition rate of 2.7 Hz or 3.3 Hz [17]. The resultant SSEPs are recorded from the cortical scalp electrodes, commonly CP3-CP4, and CPz-FPz. The CP3-CP4 channel is analyzed for phase reversal. The neurophysiological midline is identified as the region where phase cancellation occurs (minimal or no evoked response in the CP3-CP4 channel) as the stimulation crosses the midline from one dorsal column to the other [16]. The second recording can be done from the popliteal fossa or medial malleolus of the ankle.

A more encompassing mapping approach utilizes motor mapping in conjunction with sensory mapping. DSCM integrates previously mentioned modalities (SSEPs, EMGs, and MEPs) to plan the myelotomy site and direct spinal cord tract mapping during tumor resection to minimize neurological injury and maximize tumor removal [13]. The DSCM technique maps eloquent tissue adjacent to or associated with the tumor to protect motor control integrity. In this process, a handheld, bipolar stimulating probe stimulates the area of interest to test whether parts of the tumor have affected motor pathways. The stimulation parameters include a biphasic waveform, a 60.11 Hz repetition rate, a 10.9 millisecond pulse width, and a stimulation intensity of 0.1-1.0 mA. By distinguishing the fiber tracts associated with individual muscle groups, this approach provides detailed localization of the neural pathways governing fine yet essential motor functions [7].

High-resolution motor mapping further refines this approach by combining EMG and MEPs to enhance the precision and safety of IMSCT resection. Here, EMG activity serves as concurrent feedback for microstimulation, enabling functional localization of motor pathways within or adjacent to the tumor. Electrical stimulation of the spinal cord elicits compound muscle action potential (CMAP) recordings in target muscles, facilitating the identification of functional fiber components within specific muscle groups and defining safe resection margins. Concurrently, MEPs serve as a continuous monitoring modality to assess the overall integrity of the corticospinal tracts throughout the operation. Together, EMGs and MEPs provide a crucial assessment of the motor system, which is needed to protect it [7].

**RESULTS**

This review highlights the critical role of intraoperative neurophysiological monitoring (IONM) in improving surgical precision and neurological outcomes, particularly in intramedullary spinal cord tumor procedures. A systematic search of identified records across three databases, with 10 duplicate records removed prior to screening, resulted in a refined dataset for analysis. Across studies, multimodal approaches including SSEPs, MEPs, D-wave monitoring, EMG, and dorsal column mapping (DCM) consistently demonstrated superior accuracy in detecting neural compromise and guiding surgical decisions (Table 4). DCM and phase-reversal techniques effectively localize the physiological midline, while D-wave preservation remains the strongest predictor of long-term motor outcomes. Multimodal monitoring enhances sensitivity and specificity, allowing timely intraoperative interventions to prevent irreversible injury. However, limitations persist, including dependence on intact neural pathways, susceptibility to anesthetic and physiological variables, signal variability, and the inability of some mapping techniques to provide continuous functional monitoring. Overall, integrated IONM remains the gold standard for optimizing safety and outcomes.

Year	Author	Title	Techniques Used	Key Findings	Limitation
2023	Ueberschaer et al.	Dorsal column mapping in resection of intramedullary spinal cord tumors: a prospective comparison of two methods and neurological follow-up	Compared spinal SSEP-based DCM and direct spinal cord stimulation (SCS) for identifying the physiological midline during myelotomy. Used 8-channel DCM electrode vs. bipolar concentric probe; continuous SSEP/MEP monitoring; quantitative pre- and post-op ataxia & QoL scoring.	Both DCM and SCS effectively identified the midline, with 100% concordance when used together. SCS was faster, cheaper, and easier to apply, with 92% anatomical-physiological alignment and significant long-term sensory recovery.	SSEP-based DCM can fail when baseline SSEPs are poor (e.g., due to edema or severe pathology); it requires stable peripheral conduction and precise electrode placement; it is susceptible to movement artifacts and low signal-to-noise ratio. SCS requires cortical recording stability and may mislocalize the midline if phase reversal is weak or if scalp impedance is high. Both methods are less reliable when the dorsal surface is distorted or inaccessible.
2025	Jiang et al.	The application of the technique for dorsal median sulcus mapping in intramedullary space-occupying surgery: a single-center experience	Dorsal median sulcus (DMS) mapping via direct dorsal stimulation using concentric vs. double-fork bipolar probes to evoke SSEPs recorded cortically (C3'-C4')	Mapping reliably localized DMS in all cases. Concentric probes required lower current (0.2-0.3 mA) and yielded larger SEP amplitudes, improving precision and reducing dorsal column injury.	Accuracy depends on intact sensory pathways. Severely compressed cords can yield low-amplitude or absent SEPs. Requires a stable anesthetic depth (inhalation < 0.4 MAC) and minimal cord movement. SEPs are vulnerable to interference from electrocautery and temperature changes. The method only identifies the physiological midline and does not monitor function continuously during resection.

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2023	Liu et al.	The role of intraoperative neurophysiological monitoring in intramedullary spinal cord tumor surgery	<p>Multiple IONM techniques:</p> <p>SSEPs: Monitor DCML pathway</p> <p>MEPs: Monitor motor pathways using transcranial multipulse stimulation.</p> <p>D-Wave: Monitors fast-conducting corticospinal fibers using single-pulse stimulation recorded epidurally/subdurally.</p> <p>Dorsal Column Mapping (DCM): Locates the physiological midline based on SEP amplitude gradient after tibial nerve stimulation.</p> <p>EMG: Monitors nerve roots.</p> <p>Bulbocavernosus Reflex (BCR): Monitors urinary function integrity (S2-S4 reflex center).</p>	IONM is essential for IMSCT surgery to maximize resection while minimizing neurological complications. DCM can significantly decrease the rate of postoperative posterior column dysfunction by localizing the physiological midline. D-wave is highly specific; an amplitude drop below 50% often predicts permanent paraplegia. Multimodal IONM (e.g., combining SSEPs and MEPs) increases accuracy, sensitivity, and specificity. Timely surgical intervention (pausing resection, warm irrigation, increasing blood pressure) upon IONM alert can prevent irreversible neural damage	SSEP: slow averaging → delayed warning; insensitive to motor pathway injury; influenced by anesthesia. MEP/D-wave: highly sensitive to anesthetics and hypotension; limited use in caudal lesions. DCM: only provides static mapping, thus can't monitor ongoing function; requires good baseline SEPs. EMG: only detects root irritation, not tract integrity.
2010	Yanni et al.	Utility of neurophysiological monitoring using dorsal column mapping in intramedullary spinal cord surgery: Clinical article	Dorsal Column Mapping (DCM): Uses a custom-designed miniature multielectrode grid (8 parallel wires) placed on the dorsal surface. DCM Method: Maps the amplitude gradient of conducted spinal SSEPs elicited by bilateral tibial nerve stimulation to identify the midline. Monitoring: Routinely monitored MEPs, SSEPs, and D-wave.	DCM is useful for locating the functional midline for myelotomy. DCM helped reduce surgical morbidity related to dorsal column dysfunction. In 7 of 10 patients, identification of the anatomical midline was difficult or uncertain due to distorted anatomy. DCM allowed identification and confirmation of the midline in all patients. The technique is useful in patients with large tumors and syringomyelia.	Surface electrode mapping requires direct cord exposure and a dry, stable field; contact pressure can attenuate signals or cause cord indentation. Technique depends on strong peripheral SSEP responses and may fail in patients with conduction deficits. Signal averaging introduces a time delay, limiting real-time decision-making.
2009	Rick Abbott	The use of physiological mapping and monitoring during surgery for ependymomas	Mapping: Brainstem mapping (floor of IV ventricle stimulation); Dorsal Column Mapping (DCM) using an electrode array to locate the median raphe. Monitoring: SSEPs, MEPs (D-wave and muscle MEPs), spontaneous EMG, and Bulbocavernosus Reflex (BCR).	D-wave is extremely reliable: a drop of more than 50% indicates a significant long-term loss of motor function. Monitoring motor pathways (D-wave and muscle MEPs) improves functional outcome compared to surgery without monitoring. Preservation of BCR correlates with preservation of function in the conus and cauda equina. Propofol/narcotic anesthesia is preferred as inhalation agents strongly affect muscle MEPs. DCM can be used to establish the median raphe if anatomical markers are obscured.	Mapping degrades as surgery progresses. Monitoring of brainstem function is less reliable than spinal cord monitoring. Muscle MEPs fluctuate and are generally predictive only when completely lost. An inability to record D-wave or muscle MEPs preoperatively places the patient at extremely high risk for functional loss with aggressive surgery.
2021	Ali et al.	Emerging Super-specialty of Neurology: Intraoperative Neurophysiological Monitoring (IONM) and Experience in Various Neurosurgeries at a	somatosensory evoked potentials, transcranial electrical motor evoked potential, spontaneous and triggered electromyography, electroencephalography, electrocorticography, cortical	Multimodality intraoperative neurophysiologic monitoring is the gold standard of care for many surgical services and should be used to monitor in real time the functional integrity of neural structures at risk.	A small number of surgical samples were used due to the hospital just starting to adopt multimodal IONM

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		Tertiary Care Hospital in Doha, Qatar.	sensory mapping, and direct electrical cortical stimulation.		
2014	Cheng et al.	Intraoperative changes in transcranial motor evoked potentials and somatosensory evoked potentials predicting outcome in children with intramedullary spinal cord tumors	Dorsal column mapping, TCeMEP, SSEP	Intraoperative neurophysiological changes correlated with postoperative motor and sensory outcomes. All patients with decreased D-waveform complexity showed a temporary 1-point drop in motor scores, followed by good recovery. Somatosensory recordings helped define a possible traction threshold during tumor resection. Dorsal column stimulation proved effective for accurate pediatric spinal cord mapping.	Retrospective nature, small sample size. Did not directly monitor D-waves, and some patients received therapy, which could have changed motor examinations on follow-up visits.
2014	Nair et al.	Dorsal Column Mapping via Phase Reversal Method: The Refined Technique and Clinical Applications.	SSEP, Triggered SSEP	The study demonstrated that using direct dorsal column stimulation to elicit phase-reversal SSEPs allows surgeons to accurately localize the dorsal columns and the physiologic midline even in severely distorted anatomy, thereby guiding safe myelotomy and preventing postoperative deterioration of dorsal column-mediated sensory function in all 12 patients.	The authors could not compare their phase-reversal mapping technique with other established dorsal column mapping methods because surgeons considered the new method sufficient, thereby preventing direct validation or a head-to-head comparison.
2022	Sala et al.	Intraoperative neurophysiology in intramedullary spinal cord tumor surgery.	SSEP, MEP, D-Wave monitoring	The chapter concludes that while SEPs, mMEPs, and D-waves remain the essential and most reliable tools for continuously monitoring dorsal column and corticospinal tract function during intramedullary spinal cord tumor surgery, D-wave preservation is the strongest predictor of long-term motor outcome	The newly developed dorsal column and CST mapping techniques are promising but still require validation in larger patient cohorts.
2016	Alimohamadi et al.	Application of Awake Craniotomy and Intraoperative Brain Mapping for Surgical Resection of Insular Gliomas of the Dominant Hemisphere	Motor-evoked potentials (MEPs), electromyography (EMG), electrocorticography (ECoG), direct cortical electrical stimulation, and direct subcortical electrical stimulation.	Awake craniotomy with intraoperative cortical and subcortical brain mapping allowed high-extent resection of dominant-hemisphere insular gliomas (73–100%) with no new major postoperative neurological deficits, demonstrating that functional mapping significantly improves the safety of insular tumor surgery.	The main limitation of this study is its small, highly selected sample from a single experienced center, which, combined with the absence of a control group, limits the generalizability of its findings to broader surgical populations.
2021	Seo and Kang	Surgery of Spinal Cord Tumors Based on Anatomy	SSEPs, phase-reversal scalp SSEP	Phase-reversal scalp SEPs are the most practical dorsal column mapping technique, providing real-time identification of the neurophysiologic midline before myelotomy and potentially reducing dorsal column injury during intramedullary tumor surgery.	The phase-reversal dorsal column mapping technique still lacks robust clinical validation, and its ability to reliably prevent dorsal column injury remains uncertain without further systematic studies.
2020	Lee et al.	Intraoperative Monitoring for Cauda Equina Tumors: Surgical Outcomes and Neurophysiological Data Accrued Over 10 Years.	tEMG, SSEP, MEP	To maximize rootlet preservation, a combination of tEMG and IONM provided the greatest accuracy and specificity.	All surgeries were performed by a single surgeon throughout the entire study. Thresholds for IONM parameters may have been suboptimal. No histological

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					distinctions were made during the outcomes analysis.
2015	Gandhi et al.	High-resolution direct microstimulation mapping of spinal cord motor pathways during resection of an intramedullary tumor.	SSEP, MEP, TceMEP	High-resolution mapping of the corticospinal tract accurately identified the displaced, functional fibers affected by the tumor. The use of mapping improved the safety of intramedullary tumor resection.	There was no control group, which made it difficult to determine whether mapping contributed to the resection's success. The sample was very small, which makes it less generalizable.
2009	Friedman & Grundy	Monitoring of sensory evoked potentials is highly reliable and helpful in the operating room	Friedman and Grundy used somatosensory evoked potentials elicited by median, tibial, and peroneal nerve stimulation, with recordings from cortical and subcortical scalp sites, including CP3, CP4, Cz, and Pz. They applied multi-channel phase analysis to evaluate changes across dorsal column pathways during spinal procedures.	Their study found that SSEPs are a highly reliable method for monitoring dorsal column sensory integrity in the operating room. Amplitude and latency changes consistently correlated with ischemia, traction, and malpositioning, allowing early detection of reversible surgical stress. The authors also reported that monitoring multiple limbs increased sensitivity for identifying hemodynamic instability and traction-related injury.	Despite their usefulness, SSEPs could not detect motor pathway injuries because they assess only dorsal column function. Their effectiveness was also reduced by anesthetic effects, temperature fluctuations, and preexisting neuropathy. Reliance on signal averaging led to delays that limited real-time responsiveness during rapidly evolving surgical events.
2015	Guo et al.	Monitoring spinal surgery for extramedullary tumors and fractures	Guo and colleagues employed a multimodal approach that included SSEPs for dorsal column assessment, MEPs for monitoring the corticospinal tract, and both free-running and triggered EMG to detect nerve root irritation. Waveform patterns were interpreted alongside surgical stages to improve risk detection.	They found that multimodal monitoring significantly enhanced intraoperative detection of neurologic stress in patients with extramedullary tumors and fractures. MEPs provided early warnings of CST dysfunction, while EMG bursts corresponded closely with mechanical root manipulation. The integration of sensory and motor modalities increased diagnostic sensitivity and improved the surgeon's ability to respond to impending deficits.	The authors noted that findings from extramedullary cases do not fully translate to intramedullary tumors because of differences in the patterns of anatomical distortion. Signal reliability varied with lesion displacement, and the study's small, heterogeneous cohort limited generalizability. These constraints reduced the ability to establish standardized alert criteria for broader application.
2014	Quiñones-Hinojosa et al.	Neuromonitoring during surgery for metastatic tumors to the spine: intraoperative interpretation and outcomes	This study utilized SSEPs to evaluate dorsal column pathways, transcranial MEPs to assess corticospinal integrity, and free-running EMG to identify root traction or compression. Monitoring strategies were adjusted to tumor location and patient baseline function.	The authors reported that combined sensory and motor monitoring improved the prediction of postoperative neurological deficits in metastatic tumor surgeries. MEPs demonstrated greater sensitivity than SSEPs for detecting acute motor pathway compromise, while EMG provided real-time indications of nerve root irritation. The multimodal approach helped guide safer decompression in patients with significant preoperative deficits.	A major limitation was the absence of D-wave monitoring, which reduced the ability to predict long-term motor recovery. Additionally, prior radiation therapy and tumor heterogeneity affected signal stability and interpretation. The retrospective nature of the study further limited standardization across cases.
2016	Verla et al.	Neuromonitoring for Intramedullary Spinal Cord Tumor Surgery	Verla et al. described a comprehensive IONM protocol that included upper- and lower-limb SSEPs, transcranial MEPs, D-wave recordings from epidural electrodes, free-running EMG, and TOF-controlled anesthesia to	They found that D-wave preservation strongly predicted long-term postoperative motor outcome, while MEPs served as highly sensitive indicators of immediate corticospinal tract compromise. SSEPs were essential for dorsal column protection during midline myelotomy, and the combined use of sensory, motor, and mapping modalities	Limitations included MEP vulnerability to inhalational anesthetics, technical challenges in acquiring D-wave signals for certain tumor locations, and the need for experienced neuromonitoring personnel to interpret complex intraoperative patterns. These factors impacted

## Spinal Mapping

			optimize motor pathway monitoring.	significantly reduced postoperative morbidity.	consistency across different surgical settings.
2009	Quiñones-Hinojosa et al.	Spinal Cord Mapping as an Adjunct for Resection of Intramedullary Tumors: Surgical Technique	In this study, the authors used bipolar stimulation for direct dorsal column mapping, applying phase-reversal techniques recorded from CP3-CP4 scalp channels to identify the physiological midline. Mapping was paired with SSEP and MEP monitoring for combined anatomical and functional assessment.	The authors demonstrated that direct mapping substantially improves myelotomy accuracy by identifying the functional midline in anatomically distorted spinal cords. Phase-reversal mapping was shown to enhance spatial precision and reduce dorsal column injury, providing information that continuous monitoring alone cannot supply. When combined with IONM, mapping supported safer dissection and deeper tumor resection.	Mapping required a dry surgical field, stable exposure, and minimal bleeding, all of which can be difficult to maintain in tumor cases. Physiological midline shifts caused by mass effect, edema, or rotation made interpretation more complex. Additionally, mapping does not provide continuous functional assessment, underscoring the need for simultaneous neuromonitoring.

**Table 4.** Literature Results: DCM = Dorsal Column Mapping, SCS = Spinal Cord Stimulation, BCR = Bulbocavernosus Reflex.

## DISCUSSION

### Integrating Modalities

A multimodal intraoperative neuromonitoring (IONM) strategy provides the most effective protection of sensory and motor pathways during intramedullary spinal cord tumor surgery. Each modality offers complementary strengths, creating a comprehensive framework for real-time surgical guidance. Somatosensory evoked potentials (SSEPs) continuously assess dorsal column integrity and provide early warning of ischemia or traction, while motor evoked potentials (MEPs) detect corticospinal tract compromise with high sensitivity. D-waves are the most reliable predictor of long-term motor outcomes, remaining stable even when MEPs decline. Electromyography (EMG) identifies nerve root irritation and helps differentiate functional tissue in distorted anatomy, while train-of-four monitoring ensures optimal neuromuscular conditions. Direct spinal cord mapping adds spatial precision by localizing the physiological midline. Together, these modalities improve intraoperative decision-making, reduce neurological deficits, and significantly enhance long-term functional outcomes compared to single-modality monitoring [7,15,18].

### Clinical Impact

Surgical success in intramedullary spinal cord tumor (IMSCT) resection depends on preoperative neurological status, tumor aggressiveness, and the extent of safe resection. Patients with minimal deficits (McCormick grade I-II) have better outcomes and are more likely to demonstrate reliable mMEPs and D-waves, which correlate with improved prognosis. Early diagnosis and timely intervention further enhance

recovery [15]. Achieving maximal safe resection requires balancing oncologic goals with preservation of neurological function, especially as tumors often distort normal spinal cord anatomy [19]. Dorsal column mapping (DCM) plays a critical role by identifying the physiological midline and guiding precise myelotomy, thereby reducing postoperative sensory deficits such as ataxia and proprioceptive loss. While DCM provides spatial localization, continuous intraoperative neuromonitoring (IONM) tracks functional integrity. Among monitoring modalities, D-wave stability is the strongest predictor of long-term motor outcomes, with significant amplitude loss indicating a high risk of permanent deficits.

### **Challenges and Limitations**

Variability in stimulation parameters, electrode placement, equipment, and interpretation across institutions limits generalizability. Small sample sizes and differing personnel further affect consistency. In multimodal IONM, isolating the specific impact of dorsal column mapping is difficult, as improved outcomes likely result from integrated monitoring rather than any single modality alone.

### **Future Directions**

Future advancements in managing intramedullary tumors require improved spinal cord mapping technologies, particularly dorsal column mapping (DCM), which remains in early development [16]. Standardization of techniques, stimulation parameters, and intervention thresholds through multicenter trials is essential. Further research should clarify IONM's true impact, determine its necessity in all tumor types, and better understand tumor natural history to guide the timing of intervention [11]. Ultimately, innovations aim to transform IONM from a diagnostic tool into a proactive, therapeutic strategy that prevents neurological deficits.

## **CONCLUSION**

The integration of SSEPs, MEPs, D-waves, EMG, train-of-four monitoring, and direct spinal cord mapping enables surgeons to make safer, data-driven decisions throughout intramedullary spinal cord tumor resection. By combining functional monitoring with precise spatial localization, these modalities overcome individual limitations and enhance pathway identification. Evidence supports improved neurological outcomes and reduced postoperative deficits with this multimodal approach. Despite variability in methodology and sample sizes, literature strongly supports its utility. Future efforts should focus on standardization, technological advancement, and refinement of intraoperative monitoring and mapping strategies.

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