*ORIGINAL ARTICLE*

# Sensitivity and Specificity of Intraoperative Neurophysiological Monitoring in Lumbar Spinal Surgery: A Meta-Analysis

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**ABSTRACT**

Our meta-analysis aimed to evaluate the specificity and sensitivity of various intraoperative neurophysiological monitoring (IONM) modalities during lumbar spinal surgeries, with a focus on their practical implications. Sensitivity and specificity are essential measures for assessing the effectiveness of IONM. Sensitivity refers to a test's ability to accurately detect patients with a neurological deficit, ensuring that no impairment is overlooked. Specificity represents the test's ability to correctly identify patients without a deficit, minimizing the occurrence of false positives and unnecessary concerns. The modalities examined included Somatosensory Evoked Potentials (SSEPs), Electromyography (EMG), and Motor-Evoked Potentials (MEPs).

Our findings suggest that utilizing a multimodal approach significantly enhances the accuracy of neurological monitoring, providing practical benefits for surgeons and patients alike. By employing two or more modalities simultaneously, comprehensive observation is achieved, where the strengths of one modality complement the limitations of another, ultimately improving the detection of potential complications. For instance, SSEPs monitor sensory pathways, while MEPs assess motor pathways, and together, they provide a more complete picture of spinal cord function. EMG further assists by detecting muscle responses, indicating nerve function. Thus, multimodal IONM is the most effective way to reduce the risk of neurological injury, improve surgical outcomes, and ensure optimal patient health during lumbar spine surgery.



## INTRODUCTION

The nervous system is responsible for most day-to-day functions, making neurological injury severe and debilitating. Among spinal disorders, lumbar disease and injury are the most common [1]. Lumbar degenerative disc disease occurs due to the breakdown of discs between the vertebrae, resulting in pain, nerve irritation, and inflammation [2]. A lumbar herniated disc is caused by the inner core pushing through a tear, leading to pain, numbness, and leg weakness [3]. Foraminal stenosis can occur when foramina narrow, pinching nerves and causing pain [4]. Lumbar spinal stenosis results from the narrowing of the spinal canal, compressing the spinal cord and nerves, leading to difficulty walking, numbness, and pain [4]. Spondylolisthesis occurs when one vertebra slips forward on the vertebra below it, causing numbness, weakness, and pain [5]. Additionally, trauma, vascular diseases, and fractures may necessitate lumbar treatment.

The treatment of lumbar disorders may involve medical or surgical options. Medical interventions can include pain relievers, muscle relaxants, cortisone injections, or narcotics[6]. However, in some cases, surgery may be necessary to address these issues and enhance the quality of life for patients. Due to the delicate nature of nervous tissue, surgeries have the potential to lead to significant postoperative deficits. Lumbar spinal surgery is a specific area where operations can result in postoperative sensory and motor deficits [6].

One effective method for addressing postoperative deficits is the use of Intraoperative Neurophysiological Monitoring (IONM), which has become increasingly popular in recent years. IONM allows for the real-time detection of potential complications or injuries to nervous tissue during surgery. Providing feedback from motor tracts, sensory pathways, and nerve roots enables immediate notification of any changes to the surgeons, helping to prevent potentially irreversible neurological damage. Commonly used IONM techniques in spinal surgery include somatosensory evoked potentials (SSEPs), electromyography (EMG), and motor-evoked potentials (MEPs) [7]. While these techniques are all forms of IONM, they have notable differences. SSEPs primarily focus on the somatosensory pathways, while EMGs and MEPs focus more on motor pathways. Additionally, SSEPs measure the response evoked from sensory stimuli within the somatosensory pathways, whereas EMGs and MEPs measure responses in the muscles by stimulating various parts of the motor cortex [8].

In cases involving individuals with lumbar stenosis, it is essential to utilize intraoperative neuromonitoring (IONM). By continuously monitoring nerve function throughout the surgery, IONM plays a crucial role in preventing neurological complications such as nerve injury or paralysis. Timely detection of changes in nerve function enables swift intervention to minimize potential damage. IONM also helps in evaluating the impact of surgical maneuvers on nerve function. For instance, during decompressive procedures like laminectomy or foraminotomy, monitoring can verify that the intended nerve roots are adequately decompressed without causing harm to adjacent structures [8].

In the context of intraoperative neurophysiological monitoring (IONM) in spinal surgery, a deficit typically refers to a decrease in the amplitude or an increase in the latency of the waveform. These changes in amplitude and latency can indicate dysfunction or injury to the spinal cord or nerves. Detecting deficits in IONM during surgery may prompt the surgical team to take corrective actions to prevent further damage or address the underlying issue. The presence of deficits in IONM is an important indicator for the surgical team to consider when making decisions about the procedure.

Sensitivity and specificity are crucial metrics for evaluating the effectiveness of intraoperative neurophysiological monitoring (IONM) in spinal surgery. Sensitivity measures the ability of a test to correctly identify patients with a deficit, ensuring that no neurological impairment goes undetected. In the context of SSEP, high sensitivity is vital as it indicates the test's ability to accurately detect deficits in sensory pathways, alerting surgeons of potential issues during surgery. Conversely, specificity measures the ability of a test to correctly identify patients without a deficit, reducing the likelihood of false alarms [7].

Even though significant advancements have been made in using IONM, there is still an ongoing debate about its efficacy and necessity. Hence, this systematic review aims to argue and investigate the efficacy of IONM in lumbar spinal surgery by providing a comprehensive summary of relevant literature.

## METHODS

A systematic examination was conducted to identify research studies focusing on the results of patients who underwent lumbar spine surgeries with intraoperative SSEP, EMG, and MEP monitoring alone or in a multimodality setting. The severity of deficits was assessed depending on the modality used.

### *Patient Selection*

Patients were selected based on age and response to previous treatments. The age criteria were 18 years and older. Children were not selected in this review. Response to previous treatment was used to determine the need for lumbar surgery. Patients who had not responded to medical interventions previously were selected. Additional patient selection included determining if the pain was due to a lumbar disorder or psychological.

### *Anesthesia*

After positioning the patient, intubation was carried out. Electrodes were placed depending on the type of IONM used. Total intravenous anesthesia was used, with no muscle relaxant. Propofol with fentanyl was the predominantly used anesthetic.

### Intraoperative Neurophysiological Monitoring (IONM)

### *Somatosensory Evoked Potentials (SSEP)*

Electrode placements for SSEP monitoring involve positioning to capture signals from specific nerve pathways. Cortical electrodes are placed on the scalp over the patient’s primary somatosensory cortex to capture cortical responses generated by the stimulation of peripheral nerves. Stimulating electrodes are placed on various peripheral nerves along the monitored pathway. It is common for stimulation electrodes

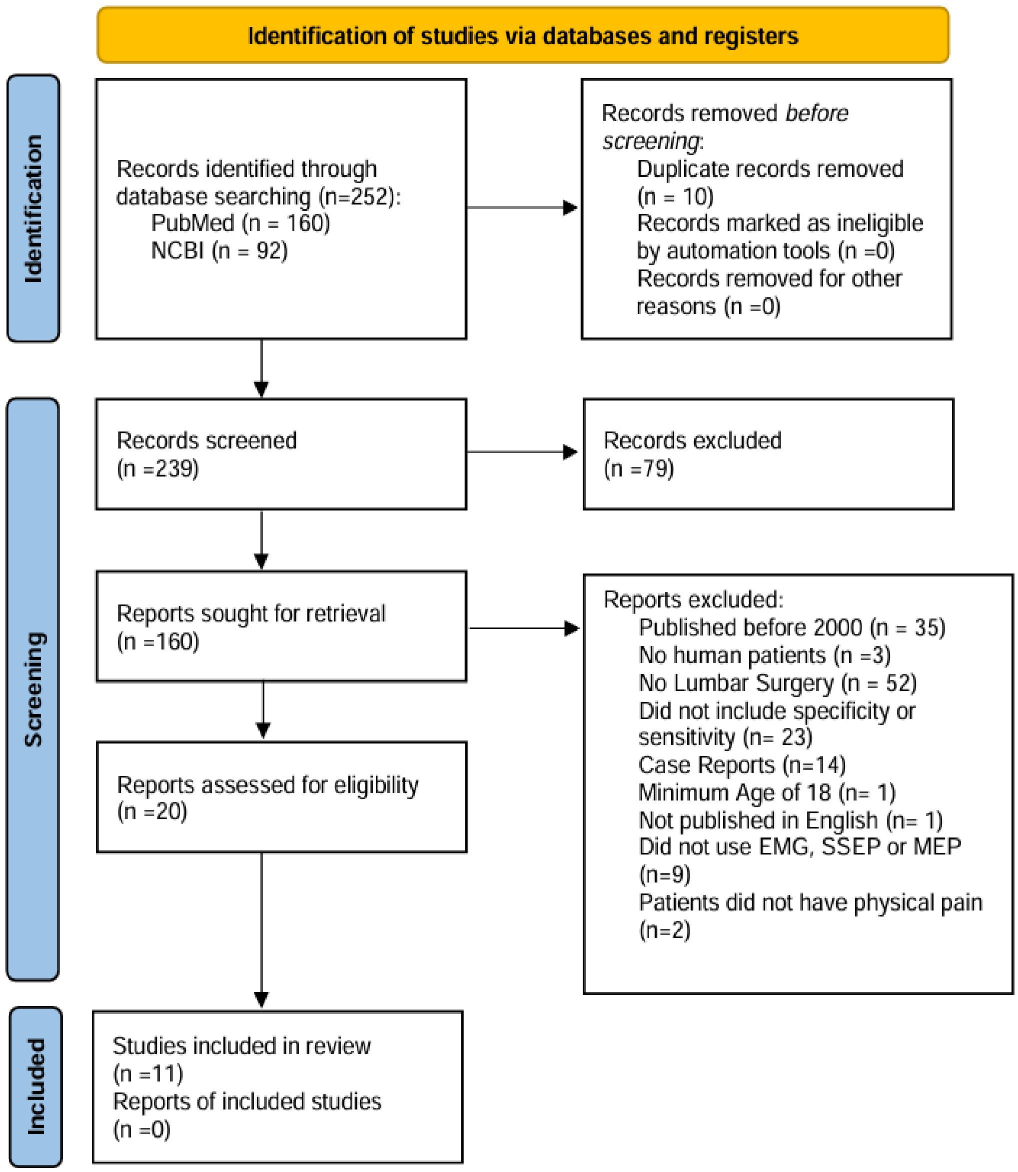


**Figure 1.** PRISMA Flow Diagram

to be placed on the posterior tibial nerve or the median nerve during lumbar surgeries. These nerves are stimulated to elicit responses that travel along the sensory pathways toward the spinal cord and brain. The recording electrodes were placed over the scalp according to the international 10-20 system along the sensory pathway to capture evoked potentials. In lumbar surgeries, placing recording electrodes on CP3, CP4, CPz, CV5, Erb's Point (EP), and Popliteal Fossa (PF) is common. These locations allow monitoring of the sensory signals as they travel from the stimulated peripheral nerves through the spinal cord and up to the brain [7].

### *Electromyography (EMG)*

The placement of subdermal EMG needle electrodes involves placement to detect signals from specific muscles and nerves relevant to the surgical procedure. For lumbar surgeries, muscles commonly monitored include the paraspinal muscles and the muscles innervated by nerves in the lumbosacral region. Commonly monitored muscles are the iliopsoas, adductors, quadriceps, tibialis anterior, gastrocnemius, abductor hallucis, anal sphincters, and urinary sphincter muscles. Subdermal needle electrodes are placed in the muscles to detect changes during a procedure. For lumbar surgeries, nerves such as the femoral, posterior tibial, fibular (peroneal), and pudendal nerves are utilized [8].

### *Motor Evoked Potentials (MEP)*

The placement of MEP electrodes involves positioning to stimulate specific areas of the brain and record muscle responses from relevant muscle groups. MEP monitoring involves the motor cortex's transcranial electrical stimulation (TES) or magnetic stimulation (TMS). For lumbar surgeries, stimulating electrodes are typically placed on the scalp over the motor cortex at C1/C2, C3/C4 according to the international 10-20 system. The alternate stimulation sites are M1/M2 and M3/M4. Recording electrodes are placed on the muscles corresponding to the motor pathways being monitored. For lumbar surgeries, muscles commonly monitored include the lower extremity muscles innervated by nerves in the lumbar spinal cord region. Ground electrodes are placed on the patient's body at a site that is not directly involved in the surgical procedure to provide a reference point for the electrical signals [9].

## RESULTS

The results of the studies highlight the varying sensitivity and specificity of different intraoperative neurophysiological monitoring (IONM) modalities in lumbar spinal surgery. Key findings include:

1. **MEP (Motor Evoked Potentials)** demonstrated consistently high sensitivity (100%) and specificity (97.9%) in detecting nerve root injury, making it one of the most reliable modalities.
2. **sEMG (Spontaneous EMG)** showed relatively low sensitivity (ranging from 13.6% to 18.8%) but higher specificity (up to 95.4%), indicating limited use in isolation for detecting nerve damage.
3. **SSEP (Somatosensory Evoked Potentials)** had mixed results, with sensitivity ranging from 9% to 50% and specificity from 94.7% to 99%, depending on the changes observed (reversible, irreversible, or total loss).

4. **Triggered EMG** showed a specificity of up to 100% at low thresholds but exhibited sensitivity ranging from 8.4% to 86%, depending on the threshold used.
5. **Multimodal Monitoring**, combining SSEP, MEP, and EMG, consistently showed superior sensitivity and specificity, with results as high as 100% sensitivity and 99% specificity in some studies. This approach was particularly effective for complex spinal surgeries, comprehensively evaluating sensory and motor pathways.

Multimodality monitoring consistently outperformed individual modalities, offering enhanced accuracy and reliability. However, limitations such as cost, a lack of standardization, and a shortage of qualified personnel were also identified. Despite these challenges, multimodal IONM remains the preferred method for ensuring patient safety and optimal outcomes in spinal surgeries.

| Articles | Focus | Sample Size | Modality | Sensitivity | Specificity |
|---|---|---|---|---|---|
| Wilent et al., 2020 | Lumbosacral Nerve Root Injury | 4,386 | MEPs | 100% | 97.90% |
| | | 4,385 | sEMG | 14.30% | 95.40% |
| | | 2,585 | SSEP | 28.60% | 99% |
| | | 2,585 | Multimodality | 100% | 92.20% |
| Chang et al. | SSEP Changes in Lumbar Surgery | 5,607 | SSEP | 44% | 97% |
| | Reversible SSEP changes | | SSEP | 28% | 97% |
| | Irreversible SSEP changes | | SSEP | 33% | 97% |
| | Total Loss of SSEP | | SSEP | 9% | 99% |
| Nguyen et al. | Lumbosacral Pedicle Screw Placement | 120 | SSEP | 50% | 94.70% |
| | | 120 | Raw EMG | 83.30% | 41.80% |
| | | 109 | Triggered EMG | 66.70% | 85.40% |
| Melachuri et al. | SSEP in Lumbar Interbody Fusions | | | | |
| | Significant Changes in SSEP | 1,057 | SSEP | 3% | 99% |
| | Loss of SSEP Response | | SSEP | 3% | 99% |
| Raynor et al. | EMG Threshold in Pedicle Screw Malposition | 4857 | | | |
| | 2.8 mA Triggered EMG | | EMG | 100% | 8.40% |
| | 4.0 mA Triggered EMG | | EMG | 99% | 36% |
| | 8.0 mA Triggered EMG | | EMG | 94% | 86% |
| Gunnarson et al. | Lumbar Spine Surgery | 213 | SSEP | 28.60% | 98.70% |
| | | 213 | EMG | 100% | 23.70% |
| Sutter et al. | All Spine, including Lumbar | 1017 | Mulitmodality (SSEP, MEP,EMG) | 89% | 99% |
| Quraishi et al. | All Spine, including Lumbar | 102 | Mulitmodality (SSEP, MEP,EMG) | 100% | 84.30% |
| Jain et al. | Lateral Lumbar Intrabody Fusion | 62 | SSEP | 52-100% | 90%-100% |
| Lieberman et al. | Dorsiflexion Injuries after Lumbosacral Surgery | 75 | 50% Threshold MEP | 96% | 97% |
| Wilent et al, 2022 | Lumbosacral Spine Fusion | | | | |
| | All Deficits | | sEMG | 13.60% | N/A |
| | | | SSEP | 25% | N/A |
| | | | MEP | 68.20% | N/A |
| | | | | | N/A |
| | Immediate Motor Deficits | | sEMG | 18.80% | N/A |
| | | | SSEP | 37.50% | N/A |
| | | | MEP | 93.80% | N/A |

**Figure 2.** Sensitivity and Specificity of Different Modalities During Lumbar Spinal Surgery.

## DISCUSSION

In the studies we reviewed, we focused on examining the sensitivity and specificity of different modalities. For instance, a study by Wilent et al. (2020) evaluated 4,385 patients for Lumbosacral nerve root injury using various modalities of IONM. The study found that MEP had a sensitivity of 100% and a specificity of 97.9%, while sEMG had a sensitivity of 14.3% and a specificity of 95.4%. SSEP showed a sensitivity of 28.6% and a specificity of 99%; multimodality exhibited a sensitivity of 100% and a specificity of 92.2%. Another study by Chang et al. (2021), which involved 5,607 patients undergoing lumbar surgery, recorded different sensitivity and specificity figures for SSEP based on reversible, irreversible, and total loss of SSEP activity. Total SSEP changes had a sensitivity of 44% and a specificity of 97%, reversible SSEP changes had a sensitivity of 28% and a specificity of 97%, irreversible SSEP changes had a sensitivity of 33% and a specificity of 97%, and total loss of SSEP had a sensitivity of 9% and a specificity of 99%. In a retrospective analysis of 120 patients by Nguyen et al. (2022), EMG and SSEP were used in lumbosacral pedicle screw placement. The study found that SSEP resulted in a sensitivity of 50% and a specificity of 94.7%, raw EMG had a sensitivity of 83.3% and a specificity of 41.8% and triggered EMG had a sensitivity of 66.7% and a specificity of 85.4%.

According to a study conducted by Melachuri et al. on 1057 patients undergoing lumbar fusions, the sensitivity to specificity ratio was 0.03/0.99 [13]. A study by Reynor et al. (2007) examining 4857 patients had a focus on lumbar pedicle screw malposition being detected via a triggered EMG [14]. The study found that in an analysis of 1078 procedures, as the EMG threshold decreases, the probability of detecting a breach pedicle screw increase [14]. They found that EMG has a specificity of 100% and a sensitivity of 8.4% at 2.8 mA. At 4.0 mA, the specificity is 99%, and the sensitivity is 36%. Lastly, at 8.8 mA, there are 94% and 86% specificity and sensitivity, respectively [14]. In a study, 213 monitored lumbar spine procedures had a 28.6% sensitivity and 98.7% specificity for SSEPs [15]. The same study showed 100% sensitivity and 23.7% specificity for EMG. A study examining lumbar and other spinal surgeries found that in 1,017 patients, a multimodality model of SSEP, MEP, and EMG has a sensitivity of 89% and a specificity of 99% [16]. Another study examining lumbar and other spinal surgeries found that in 102 patients, a multimodality model of SSEP, MEP, and EMG had a sensitivity of 100% and a specificity of 84.3% [17]. Saphenous SSEP in lateral lumbar interbody fusion was examined in 62 patients by Jain et al. (2021) [18]. The study found a 52-100% sensitivity and a 90-100% specificity. Another study analyzed MEP in distal lumbosacral deformity surgery [19]. Researchers utilized a 50% MEP threshold and found a sensitivity of 96% and a specificity of 97%. The last study reviewed and analyzed patients having lumbosacral spinal fusion surgery [20]. Researchers examined the sensitivity of sEMG, SSEP, and MEP in patients with major deficits and patients with immediate motor deficits. IONM, during major deficits, had a sEMG, SSEP, and MEP sensitivity of 13.6%, 25%, and 68.2%, respectively. Immediate motor deficits had a sEMG, SSEP, and MEP sensitivity of 18.8%, 37.5%, and 93.8%, respectively.

From the studies examined, we reinforce the benefits of IONM in lumbar surgery. Multimodality is often considered the best approach in lumbar spinal surgery because it provides comprehensive information about different aspects of the nervous system function. Each modality offers unique insights into sensory and motor pathways. This intel is crucial for detecting and preventing neurological deficits during surgery.

Each IONM modality focuses on different aspects of the nervous system. SSEP monitors the electrical activity of the sensory pathways in the nervous system. It involves stimulating peripheral nerves and recording the resulting electrical signals in the brain. SSEP is used to assess sensory pathways' integrity, helping identify potential spinal cord or nerve root injury during surgery. Changes in SSEP can indicate compromise of sensory pathways.

EMG, on the other hand, focuses on monitoring the electrical activity of muscles. It involves placing electrodes on specific muscles to monitor their activity in response to stimulation or movement. EMG is used to assess the integrity of nerve roots and detect potential nerve injury during surgery, helping to identify nerve irritation or damage caused by surgical maneuvers.

Last, MEP focuses on monitoring the electrical activity of motor pathways in the nervous system. It involves stimulating the brain's motor cortex and recording the resulting muscle responses. MEP is used to assess motor pathways' integrity, helping identify potential spinal cord or nerve root injury during surgery. Changes in MEP can indicate compromise of motor pathways, which could lead to postoperative motor deficits. By combining these modalities, surgeons gain a more comprehensive picture of the nervous system's status, allowing for a more thorough assessment of potential risks during surgery.

Multimodality monitoring is efficient. This means if one modality fails to detect a change, the other modality can serve as a backup. This efficiency enhances the reliability of the monitoring system, reducing the likelihood of missing important neurological changes. Since multimodal monitoring can also provide real-time feedback, surgeons can immediately adjust their surgical approach if any abnormalities are detected. This allows for a more proactive approach, which helps prevent unwanted neurological damage and improve patient outcomes.

The integration of various modalities can enhance both sensitivity and specificity in the detection of neurological deficits. Each modality has its own distinct strengths and limitations. SSEP allows for continuous monitoring and does not preclude the use of a neuromuscular blockade. However, it does not effectively measure individual nerve roots [21]. MEP allows for the detection of spinal cord ischemia but does preclude a neuromuscular blockade and is sensitive to inhalation anesthetics, demanding rigid protocols [21]. Spontaneous EMG is sensitive to nerve injury but precludes a neuromuscular blockade and is sensitive to temperature changes. Triggered EMG has a high sensitivity to pedicel wall breach [21]. Therefore, the combined use of different modalities effectively addresses the gaps that individual modalities cannot, thereby enhancing the overall accuracy of the monitoring system.

Overall, while using one modality of IONM in surgery is more effective than nothing, the best results are seen when using multi-modality. Individual IONM usage mostly gives either high specificity or sensitivity, but not both. However, multimodality gives high sensitivity and specificity ratings, making it the preferred methodology. While the benefits are innumerable, it is also important to look at possible limitations. One such limitation of the multimodality approach is cost [9]. Given that this is the cost for a singular modality, it leads to the conclusion that multimodality would be more expensive. Furthermore, there are limitations in the number of personnel qualified for IONM usage. As it is a growing field, there needs to be more accredited institutions willing to train people due to the severe lack of IONM personnel. This can also be linked to another limitation: the lack of standardization. Standardization refers to the IONM protocol and relevant modalities used for each type of surgery. For example, different authors use different numbers of channels and monitors for incomparable data. The setup and the information monitored vary widely between different groups in the field. The lack of standardization can cause variable results and even misleading results depending on who is interpreting the data. Despite these limitations, it is essential to consider the pain and cost of suffering with neurological deficits like paralysis, which could be prevented via IONM. Patient care is a priority, so investing in preventative technology should be a priority.

## CONCLUSION

In conclusion, the reviewed studies emphasize the significant advantages of multimodal intraoperative neurophysiological monitoring (IONM) in lumbar spinal surgery. While individual modalities like SSEP, EMG, and MEP provide valuable insights into specific aspects of the nervous system, their combined use enhances sensitivity and specificity, ensuring more comprehensive and reliable detection of neurological deficits. Multimodal monitoring allows for real-time feedback, enabling immediate surgical adjustments and minimizes the likelihood of postoperative complications. However, despite its clear benefits, limitations such as increased costs, a shortage of trained personnel, and a lack of standardization across the field remain. Nonetheless, the potential to prevent severe neurological deficits makes multimodal IONM a crucial tool in modern spinal surgery. Investing in this technology aligns with prioritizing patient care and long-term health outcomes**.**

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## REFERENCES


1. De Luca K, Tavares P, Yang H, Hurwitz EL, Green BN, Dale H, Haldeman S. Spinal Pain, Chronic Health Conditions and Health Behaviors: Data from the 2016-2018 National Health Interview Survey. Int J Environ Res Public Health. 2023 Apr 3;20(7):5369. doi: 10.3390/ijerph20075369. PMID: 37047983; PMCID: PMC10094294.
2. Kirnaz S, Capadona C, Wong T, Goldberg JL, Medary B, Sommer F, McGrath LB Jr, Härtl R. Fundamentals of Intervertebral Disc Degeneration. World Neurosurg. 2022 Jan;157:264-273. doi: 10.1016/j.wneu.2021.09.066. PMID: 34929784.
3. Al Qaraghli MI, De Jesus O. Lumbar Disc Herniation. [Updated 2023 Aug 23]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2024 Jan-. Available from: https://www.ncbi.nlm.nih.gov/books/NBK560878/
4. Özer AF, Akyoldaş G, Çevik OM, Aydın AL, Hekimoğlu M, Sasani M, Öktenoğlu T, Çerezci Ö, Süzer T. Lumbar Foraminal Stenosis Classification That Guides Surgical Treatment. Int J Spine Surg. 2022 Jun 16;16(4):666–73. doi: 10.14444/8311. Epub ahead of print. PMID: 35710724; PMCID: PMC9421203.
5. Li N, Scofield J, Mangham P, Cooper J, Sherman W, Kaye A. Spondylolisthesis. Orthop Rev (Pavia). 2022 Jul 27;14(4):36917. doi: 10.52965/001c.36917. PMID: 35910544; PMCID: PMC9329062.
6. Seki S, Akeda K, Kaito T, Ohba T. What Types of Strategies Are Effective in Lumbar Spine Surgery? Considering the Etiology, Imaging Findings, and Risk of Complications. J Clin Med. 2023 Jul 1;12(13):4443. doi: 10.3390/jcm12134443. PMID: 37445478; PMCID: PMC10342249.
7. Jahangiri, F. R. (2012). Surgical neurophysiology: A reference guide to intraoperative neurophysiological monitoring. Createspace.
8. Agarwal N, Shabani S, Huang J, Ben-Natan AR, Mummaneni PV. Intraoperative Monitoring for Spinal Surgery. Neurol Clin. 2022 May;40(2):269-281. doi: 10.1016/j.ncl.2021.11.006. Epub 2022 Mar 31. PMID: 35465874.
9. Sala, F., Dvorak, J., & Faccioli, F. (2007). Cost effectiveness of multimodal intraoperative monitoring during spine surgery. European spine journal: official publication of the European Spine Society, the European Spinal Deformity Society, and the European Section of the Cervical Spine Research Society, 16 Suppl 2(Suppl 2), S229–S231. https://doi.org/10.1007/s00586-007-0420-0
10. Wilent, W. B., Tesdahl, E. A., Harrop, J. S., Welch, W. C., Cannestra, A. F., Poelstra, K. A., Epplin-Zapf, T., Stivali, T., Cohen, J., & Sestokas, A. K. (2020). Utility of motor evoked potentials to diagnose and reduce lower extremity motor nerve root injuries during 4,386 extradural posterior lumbosacral spine procedures. *The spine journal: official journal of the North American Spine Society*, *20*(2), 191–198. https://doi.org/10.1016/j.spinee.2019.08.013
11. Chang, Robert BSa; Reddy, Rajiv P. BSb; Coutinho, Dominic V. BSa; Chang, Yue-Fang PhDa; Anetakis, Katherine M. MDa; Crammond, Donald J. PhDa; Balzer, Jeffrey R. PhDa,c; Thirumala, Parthasarathy D. MD, MSa,d. Diagnostic Accuracy of SSEP Changes During Lumbar Spine Surgery for Predicting Postoperative Neurological Deficit: A Systematic Review and Meta-Analysis. SPINE 46(24):p E1343-E1352, December 15, 2021. | DOI: 10.1097/BRS.0000000000004099
12. Nguyen AM, Ngo PA, Dang PL. Assessment of Intraoperative Neurophysiological Monitoring Techniques in Lumbosacral Pedicle Screw Placement Surgery, Interdisciplinary Neurosurgery, Volume 29, 2022, 101555, ISSN 2214-7519, https://doi.org/10.1016/j.inat.2022.101555.
13. Melachuri, S. R., Kaur, J., Melachuri, M. K., Ninaci, D., Crammond, D. J., Balzer, J. R., & Thirumala, P. D. (2019). The diagnostic accuracy of somatosensory evoked potentials in evaluating neurological deficits during 1057 lumbar interbody fusions. *Journal of clinical neuroscience : official journal of the Neurosurgical Society of Australasia*, *61*, 78–83. https://doi.org/10.1016/j.jocn.2018.10.140
14. Raynor, Barry L. BA; Lenke, Lawrence G. MD; Bridwell, Keith H. MD; Taylor, Brett A. MD; Padberg, Anne M. MS. Correlation Between Low Triggered Electromyographic Thresholds and Lumbar Pedicle Screw Malposition: Analysis of 4857 Screws. Spine 32(24):p 2673-2678, November 15, 2007. DOI: 10.1097/BRS.0b013e31815a524f
15. Gunnarsson T, Krassioukov AV, Sarjeant R, Fehlings MG: Real-time continuous intraoperative electromyographic and somatosensory evoked potential recordings in spinal surgery: correlation of clinical and electrophysiologic findings in a prospective, consecutive series of 213 cases. Spine 29:677–684, 2004
16. Sutter, M., Eggspuehler, A., Grob, D. et al. The diagnostic value of multimodal intraoperative monitoring (MIOM) during spine surgery: a prospective study of 1,017 patients. Eur Spine J 16 (Suppl 2), 162–170 (2007). https://doi.org/10.1007/s00586-007-0418-7
17. Quraishi, N. A., Lewis, S. J., Kelleher, M. O., Sarjeant, R., Rampersaud, Y. R., & Fehlings, M. G. (2009). Intraoperative multimodality monitoring in adult spinal deformity: analysis of a prospective series of one hundred two cases with independent evaluation. *Spine*, *34*(14), 1504–1512. https://doi.org/10.1097/BRS.0b013e3181a87b66
18. Jain N, Alluri R, Phan K, et al. Saphenous Nerve Somatosensory-Evoked Potentials Monitoring During Lateral Interbody Fusion. Global Spine Journal. 2021;11(5):722-726. doi:10.1177/2192568220922979
19. Jeremy A. Lieberman, Russ Lyon, Paul Jasiukaitis, Sigurd H. Berven, Shane Burch, John Feiner, The Reliability of Motor Evoked Potentials to Predict Dorsiflexion Injuries During Lumbosacral Deformity Surgery: Importance of Multiple Myotomal Monitoring, The Spine Journal, Volume 19, Issue 3,2019, Pages 377-385, ISSN 1529-9430, https://doi.org/10.1016/j.spinee.2018.07.006.
20. Wilent, W.B., Trott, J., Epplin-Zapf, T., Sestokas, A.K. (2022). IONM During Lumbosacral Spinal Fusion Procedures. In: Seubert, C.N., Balzer, J.R. (eds) Koht, Sloan, Toleikis's Monitoring the Nervous System for Anesthesiologists and Other Health Care Professionals. Springer, Cham. https://doi.org/10.1007/978-3-031-09719-5_33
21. Charalampidis, A., Jiang, F., Wilson, J. R. F., Badhiwala, J. H., Brodke, D. S., & Fehlings, M. G. (2020). The Use of Intraoperative Neurophysiological Monitoring in Spine Surgery. *Global spine journal*, *10*(1 Suppl), 104S–114S. https://doi.org/10.1177/2192568219859314