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Intraoperative Multimodal Monitoring in Pedicle Subtraction Osteotomies of the Lumbar Spine: A Narrative Literature Review

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Abstract

The use of intraoperative multimodal monitoring (IOM) in spinal deformity surgeries is well documented. In particular, pedicle subtraction osteotomy (PSO), a corrective procedure for sagittal deformity of the spine, often involves IOM usage. By providing immediate feedback to the operating surgeon, IOM has the potential to eliminate or at least minimize the risk of iatrogenic neurological injury. However, despite the widespread usage of IOM, there is currently no standardization of IOM usage in complex spine surgeries, including lumbar PSOs, and decisions concerning IOM utilization are often driven by surgeon experience and preference. This creates a state of clinical equipoise, which is further complicated by the varying degrees of benefit that IOM has on patient outcomes depending on the operation and spinal levels involved. For instance, while IOM use in thoracic PSOs has been shown to be effective, there is no established consensus on the net impact of IOM use in PSOs of the lumbar spine. While IOM has the potential to mitigate neurological damage, it also increases operation time and cost; thus, it should only be employed in operations where it will have a net positive impact on patient outcomes. The question thus becomes whether PSO of the lumbar spine is one such operation. To address this, we examine the most frequently employed IOM modalities and evaluate their current usage and efficacy in lumbar PSOs. Furthermore, we will also examine the utility of IOM for other surgeries of the lumbar

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spine, including corrective procedures for idiopathic scoliosis and degenerative scoliosis, and routine lumbar procedures, such as discectomies and decompression surgeries for foraminal and canal stenosis.

Keywords

Deformity correction; intraoperative monitoring; intraoperative multimodal monitoring; lumbar spine; pedicle subtraction osteotomy

INTRODUCTION

Iatrogenic spinal cord injury remains one of the most dreaded neurological complications of spine deformity surgery, with potential negative outcomes ranging from minor sensory disturbances to complete paralysis.^{1,2} The reported incidence rate of paralysis alone in deformity correcting spinal surgeries ranges from 0.25% to 3.2%.¹ As such, the prevention of iatrogenic injury during these operations should be a priority. To this end, intraoperative multimodal monitoring (IOM) is often utilized in an effort to minimize inadvertent neurological injury to the spinal cord, nerve roots, and other associated structures.^{3,4} Although IOM cannot directly prevent intraoperative neurological injury, it does provide real-time feedback on the integrity of neural pathways and may contribute to the prevention or mitigation of neurological damage.^{2,5} Thus, IOM has become a commonly used practice in complex spine cases and is almost always utilized in pedicle subtraction osteotomy (PSO), a procedure frequently performed for the correction of fixed sagittal plane deformity.⁶⁻⁸ However, despite the efficacy of IOM in certain contexts and its widespread usage in spine deformity cases, there is a lack of established guidelines for IOM usage in PSOs, and its efficacy seems to vary depending on the spinal levels involved.⁹⁻¹¹ For instance, while the utility of IOM in PSOs of the thoracic spine has been well-documented, there is little evidence on the benefits of IOM in lumbar PSOs, which are among the most frequently performed spine deformity surgeries.^{6,12,13} In this narrative review, the authors discuss the most commonly used IOM modalities in spine deformity surgeries and examine their efficacy in pedicle subtraction osteotomies of the lumbar spine.

EPIDEMIOLOGY AND ETIOLOGY

In a spine with normal sagittal alignment, a plumb line can be drawn from the center of the C7 vertebral body to the posterior superior corner of S1.^{7,14-16} However, in patients with sagittal imbalance, the center of the C7 vertebral body is shifted anteriorly, often leading to severe kyphosis.⁷ In general, sagittal imbalance can be classified as type 1 or type 2.⁷ The former describes a spine with regional imbalance, often manifested by a short hyperkyphotic segment, but with preserved overall balance such that the plumb line from C7 still falls over S1 as previously described.^{7,14} In these patients, compensation often takes the form of lordosis in the caudal vertebrae.^{7,14} In type 2, or global, sagittal imbalance, the plumb line from C7 falls over 5 cm anterior to the L5-S1 disc, resulting in a deformity that cannot be fully compensated.^{7,14} There are a multitude of etiologies for global sagittal imbalance, the

most common of which include degenerative lumbar kyphosis, ankylosing spondylitis, iatrogenic flat back syndrome, and post-laminectomy kyphosis.^{7,14}

CLINICAL PRESENTATION AND RADIOGRAPHIC EVALUATION

Sagittal imbalance has been shown to cause both significant pain and compromised quality of life in patients.^{14,15,17,18} Patients often present with severe kyphosis and a history of back pain. Often, due to the inability of the spine to compensate for global sagittal imbalance, affected patients will often demonstrate hip and knee flexion on presentation in an effort to maintain balance and horizontal gaze.^{7,14} As such, during a physical exam, these patients must be asked to stand with extended hips and knees to allow for optimal assessment of the spinal deformity.^{7,14} Neurological deficits such as weakness and a positive Lasegue sign can also be present and often serve as an indication for surgery.¹⁴

Radiological Evaluation

Specific parameters involved in radiological evaluation of patients with sagittal imbalance include the extent of local and global lordosis, C7 positioning with respect to the L5-L1 disc, pelvic parameters such as pelvic tilt, pelvic incidence, and sacral slope.^{7,14} Importantly, the physician must compare radiographs at multiple time points to determine progression of that patient's kyphosis.¹⁴ Spinal canal narrowing, which can lead to symptoms such as back pain, should also be assessed during radiological evaluation.^{8,15} Since PSOs are indicated for correction of global sagittal deformity, the amount of correction necessary should also be calculated via imaging. Specifically, a correction of greater than 25 degrees serves as an indication for PSO.^{7,14} Lastly, parameters that affect the integrity of bone, such as bone density and fractures, should also be assessed, as they can complicate the procedure and adversely affect patient outcomes.¹⁴

TREATMENT

Non-operative Treatment

Conservative management of sagittal imbalance often addresses the back pain associated with the deformity. Specifically, NSAIDs are utilized to alleviate pain and physical therapy is recommended to achieve core and pelvic stabilization.¹⁹ In addition, patients with neurologic symptoms may be treated with steroid injections, which has the potential to reduce radicular pain and neurogenic claudication. Despite these options, it is important to note that conservative treatment of sagittal imbalance is often unsuccessful, thereby necessitating surgical intervention. For instance, a study done by Farcy and Schwab on patients with sagittal imbalance showed that only 27% of patients achieved long-term success with conservative management.¹⁹

Surgical Indications and Treatment

For patients with fixed sagittal plane deformities, especially in the context of hypolordosis and spine stiffness, PSO of the lumbar spine is the surgery of choice for the correction of the deformity.^{7,8,14} Specific indications for PSO of the lumbar spine includes radiological evidence of kyphotic progression, sagittal deformity, hypolordosis of the lumbar spine,

stiffness of the spine, a necessary correction of 25 degrees or greater, and canal narrowing.¹⁴ A three-column posterior osteotomy, PSO has been shown to significantly improve the quality of life in patients with sagittal imbalance.^{14,15,19,20} Indeed, PSO can typically achieve 30–40 degrees of lordosis, whereas only 5–10 degrees of correction could be achieved with a posterior column osteotomy due to anatomical restrictions of the anterior column.^{14,15,17,21,22} Although PSOs can be performed in both the thoracic and lumbar spine, most procedures are performed at L3, since the vertebrae there are normally the apex of lumbar lordosis.^{7,14,23} Furthermore, while both thoracic kyphosis and lumbar lordosis influence the final sagittal alignment, the degree of lumbar lordosis has been shown to be the most significant parameter for the final alignment of the spine.^{7,14,24} As such, PSO of the lumbar spine is one of the most frequently performed procedures for the correction of severe sagittal imbalance in adults.^{7,14}

Risks of PSOs

While the potential benefits of PSOs to correct sagittal deformities are well documented, it is a technically challenging procedure that involves significant mobilization of the thecal sac and nerve roots, and is thus associated with a high complication rate, especially for iatrogenic spine injury.^{7,14,16,25} In particular, the literature indicates that the rate of major complications after a lumbar PSO ranges from 20% to 40%, and the rate of neurological injury is approximately 10%.¹² Post-operative sagittal decompensation represents another complication of PSOs; indeed, in one report, Kim *et al.* found the prevalence of post-operative sagittal decompensation to be a staggering 29%.⁷ Other major associated complications include neurological deficits, infection, and pulmonary emboli.^{7,14,15}

IOM MODALITIES

Given the risks associated with pedicle subtraction osteotomy, every cautionary measure is taken to minimize the risk of iatrogenic spine injury. Since IOM has the potential to provide immediate feedback on cord integrity during the operation, it has become the standard of care in these procedures at many institutions across the United States.^{6,12} Although many IOM techniques are available, the three most common modalities utilized during spinal deformity cases are somatosensory evoked potentials (SEPs), motor evoked potentials (MEPs), and spontaneous, free-run electromyography (EMGs).^{1,2,26}

Somatosensory Evoked Potentials

Initially popularized by Nash et al in 1977 for detection of neurological injury during scoliosis surgery, somatosensory evoked potentials (SEPs) remain the most widely utilized IOM modality in spine surgery.^{2,5} In particular, short latency somatosensory evoked potentials (SSEPs) are recognized as the gold standard to which all other IOM modalities are compared.^{1,2} In this monitoring modality, stimulating electrodes are placed distally on the lower and upper extremities, and the resulting SSEPs are recorded via electrodes placed at the scalp, over the spinal cord, or on the posterior neck.^{1,2} Specifically, lower extremities are most commonly stimulated at the posterior tibial and peroneal nerves whereas the median and ulnar nerves are usually stimulated to test the upper extremities.^{1,2,27} Collectively, SSEPs represent the average responses to repetitive electrical stimulation of

peripheral nerves.^{2,27} Since signals travel through the dorsal column-medial lemniscus pathway, SSEPs provide a functional assessment of the integrity of afferent sensory transmission.² While the exact parameters of abnormal SSEP signals are not clearly delineated, amplitude decreases of 50% or more and increased latency of 10% or 2 milliseconds should be communicated to the surgeon and prompt subsequent troubleshooting to identify the source of the abnormal signal.^{2,6}

The efficacy of SSEP in mitigating the rate of neurological damage in complex spine surgery is well documented.^{2,28,29} Indeed, Nuwer et al found that SSEP led to the reduction of neurological deficits by approximately 60% in comparison to MacEwen et al's unmonitored study.^{28,30} The ability of SSEPs to evoke a large number of potentials and reliably monitor functional peripheral nerve integrity via noninvasive, surface-based electrodes are also critical strengths of this modality.²

However, despite its clinical utility, SSEP also has significant limitations. For one, SSEP exclusively monitors the integrity of the dorsal sensory pathways and does not convey information concerning the condition of anterior spinal pathways.^{1,2} Indeed, the increasing percentage of false negatives associated with SSEPs has been documented in a number of reports.^{1,2,27} Thus, motor injuries arising from direct damage to the corticospinal tract may very well go undetected if SSEPs are the only monitoring modality used.^{2,26} Another crucial limitation of SSEP monitoring is the delay in detection of neurological injury due to the temporal summation that underlie this modality.² Since SSEPs are essentially the computational averages of elicited responses, several minutes may pass between the infliction of a neurological insult and the corresponding response.^{2,27} Hilibrand et. al. demonstrated in a 2004 study that changes in SSEP signals lagged behind MEP responses by 16 minutes.²⁷ Thus, by the time that abnormal signals are present, irreversible neurological damage may have already occurred. Furthermore, SSEPs also have a documented low sensitivity for detection of nerve root injury; as such, damage caused by screw placements may pass undetected.² Given both the strengths and limitations of SSEPs, this modality is often utilized in combination with other IOM modalities, most prominently motor evoked potentials (MEP) and spontaneous EMG.^{2,26}

Transcranial Motor Evoked Potentials

Transcranial motor evoked potentials (tcMEP) were developed in response to the limitations of SSEP monitoring; specifically, tcMEPs provide direct monitoring of the corticospinal pathway.^{1,2,31} As such, tcMEPs provide an assessment of the integrity of the pyramidal tracts and motor pathways, rendering this modality a valuable complement to SSEPs. Employment of MEPs allow the detection of critical events that would go by undetected by SSEPs alone.^{1,2,31} One important example is anterior spinal artery occlusion, which severely compromises the integrity of the motor pathways but would leave the dorsal columns intact.^{1,2,26} In this modality, electrodes are placed on the scalp to stimulate the motor cortex via trains of high-voltage, short-duration signals and responses are recorded electromyographically as a muscle compound motor action potential (CAMP) or as a spinal cord signal via a caudal electrode (D wave).^{1,2,26}

Muscle MEPs (CAMPs)—In this type of monitoring, stimulating electrodes on the scalp stimulates the motor cortex, and responses are recorded at peripheral muscles.^{1,2,26,32} Unlike D-waves, muscle MEPS allow the assessment of the complete motor pathway, including the motor cortex, corticospinal tract, nerve roots, and peripheral nerves.^{1,2,33} Although there is a lack of standardization concerning CAMP warning criteria, the current literature supports an all-or-none approach, in which only a complete loss of CAMPs is considered a sign of motor damage.^{1,2,33} Recently, however, Langeloo et al reported that an 80% decrease in amplitude was indicative of neurological injury.⁹ An important advantage of MEPs is their high sensitivity, which is well documented in literature.^{1,2,9,26} Langeloo et al found a sensitivity of 100% when monitoring from six sites in a patient series with 145 subjects.⁹ This hallmark sensitivity has made muscle MEPs the gold standard for detection of post-operative motor defects.^{1,2,26,32} In addition, CAMP monitoring has been shown to lead to earlier detection of cord ischemia when compared with SSEPs and D-waves, and thus may contribute to possible injury reversal.^{1,2,32} However, there are also notable limitations to muscle MEPs; for one, since transcranial stimulation in this modality induces movement, this monitoring method precludes the use of neuromuscular blockade reagents.^{1,2} Furthermore, muscle MEPs are assessed periodically, usually by the surgeon's request or at set time intervals, as opposed to continuously and thus cannot provide continuous feedback to the operating team. As such, there may be delayed detection of a neurological injury.^{1,2,26} Thus, despite the obvious advantages of CAMPs and tcMEPs in general, ideal monitoring is achieved by utilizing tcMEPs concomitantly with other monitoring modalities such as SSEPs.^{2,27,32} The combination of both tcMEPs and SSEPs allows the operating team to assess both the patient's sensory and motor pathways throughout the procedure.^{2,26}

D-Waves—One important advantage of D-waves, in stark contrast to SSEPs, is their resistance to anesthetics such as neuromuscular blockade reagents.^{1,2,26} Although there is a lack of established monitoring parameters, a decrease of 20% in D-wave amplitude should be interpreted as a warning for possible impending injury, whereas a 50% decrease in amplitude is indicative of notable neurological damage.^{1,2,26} Despite their sensitivity, there are some critical imitations to D-waves, such as their insensitivity to nerve root function.^{1,2,26} Furthermore, since the recording electrode in this modality must be placed over the spinal cord, D-waves can only be used to detect signals above T10–11, thus rendering it obsolete for deformity procedures of the lumbar spine, such as lumbar PSOs.^{1,2,26}

Spontaneous EMG

Also known as free-running EMGs, spontaneous EMG is used widely to monitor nerve root function during spine surgery.^{1,2,26,34} Specifically, the nerve roots most at risk due to their anatomical position are determined prior to the surgery, and recordings are performed on the muscle groups innervated by those nerve roots.^{1,2,34} A healthy nerve root should not have any muscle activity and thus should show up as a “flat line” on the recordings.^{1,2} On the contrary, if the nerve root is irritated during surgery via mechanical or thermal insults, neurotonic discharges, characterized by spikes of activity, will result.^{1,2,34} The amplitude and frequency of these discharges are directly correlated with the degree of injury inflicted upon the nerve root.^{1,2,34} As such, free-running EMGs are the gold standard for monitoring nerve root integrity.^{1,2,34} Gunnarson et al found that EMGs had a sensitivity of 100% for

detection of nerve root injury in a study of 213 lumbosacral cases.³⁵ Another advantage of this imaging modality is its ability to provide continuous, real-time feedback since no stimulation is required.^{1,2,34,36} However, as with the modalities previously described, free-run EMGs also have several limitations. Like tcMEPs, this modality is very sensitive to anesthetic effects, thus precluding the use of neuromuscular blockade reagents.² Furthermore, EMG recordings are also sensitive to changes in temperature, and thus can cause false positives due to cold water irrigation or cauterization.^{1,2}

Triggered EMG

First described by Calancie et al in 1992, triggered EMGs evolved as a means to evaluate the accuracy of pedicle screw placement.^{1,2,31,34} Specifically, the rationale underlying this modality is the insulation properties of intact cortical bone, which should serve as a good electrical insulator for a pedicle screw.^{1,2,31} However, in the event of a medial pedicle breach, the screw would be relatively less insulated.^{1,2,31} Direct stimulation of the pedicle screw combined with electromyographical evaluation of the threshold voltage at which CAMPs are elicited thus allows the operating team to assess the likelihood of medial pedicle breach.² As such, triggered EMG is a population method of monitoring and preventing neurological injury in cases involving spinal instrumentation.² Despite its usefulness in detecting pedicle screw misplacement, triggered EMGs, like the other modalities, have no standardized guidelines for use, and while many studies have attempted to determine warning criteria for pedicle perforation, no established consensus exists.² One critical shortcoming of this modality is the high percentage of false positives, which could be caused by reduced pedicle integrity as a result of multiple passes within a single pedicle or by a wet field that results in current conduction to the adjacent nerve root.^{1,2} Despite the limitations of triggered EMG, it remains an instrumental tool in monitoring during complex spine cases.

Each major monitoring modality contributes essential information concerning neurological integrity but also has significant limitations when utilized alone. Thus, multimodal intraoperative monitoring, which employs several of these techniques in conjunction, provides the most comprehensive and useful feedback on the patient's neurological integrity.

IOM USAGE IN LUMBAR PSO

Given the substantial risks associated with PSOs, every cautionary measure is taken to minimize the risk of iatrogenic spine injury during PSOs, and intraoperative multimodal monitoring has become the standard of care in PSOs in many institutions across the United States.^{6,12} At first glance, this is understandable; IOM's potential ability to provide real-time feedback to the surgeon regarding the integrity of the spine and associated neurological structures is valuable in reducing the risk associated with complex surgeries such as lumbar PSOs. Thus, it is unsurprising that IOM is considered the standard of care in clinical practice.⁶

However, despite the current recommendations, there is no definitive evidence linking the IOM usage in lumbar PSOs to reduced neurological complications.^{6,12} Indeed, the few studies that have been conducted in the IMO use in lumbar PSOs report high rates of false positives in these operations and no association with improved post-operative neurological

states.^{6,12} A study conducted by Trobisch et al in 2016, one of the few studies that directly studied patient outcomes after lumbar PSOs without IOM, found comparable complication rates in patients who underwent lumbar PSOs without IOM guidance as those who underwent the same procedure with neuromonitoring.¹² Indeed, the authors explicitly noted that the absence of IOM in lumbar PSOs does not seem to increase the risk of neurological injury.¹² Specifically, in their patient series, a total complication rate of 36% was reported among patients who did not utilize IOM during the procedure; as noted above, this is well within the range of complication rates for IOM-guided lumbar PSOs (20–40%).¹² The Scolio-Risk-1 study, a multi-center retrospective study comprised of 113 PSOs and 19 vertebral column resections, found a peri-operative complication rate of 47%.^{6,12} Similar results have also been reported in literature; in general, there is no clear evidence indicating any reduction in neurological complications from the IOM usage in lumbar PSOs.^{3,6,12,37} Similarly, Buchowski et al reported on a case series of 108 patients who underwent IOM-guided lumbar PSOs and had a neurological complication rate of 11%.¹⁶ While SSEPs, MEPs, and EMGs were utilized on all of these procedures, none of the modalities were able to predict the resulting post-operative deficits.¹⁶ In a similar vein, Bridwell et al reported that 15% of patients who underwent PSOs with SSEP and MEP guidance developed post-operative neurological deficits.¹⁵ Again, IOM did not predict these deficits.¹⁵ Similar complication rates in MEP-inclusive, IOM-guided PSOs have also been reported by several other studies.^{1,2,16,38}

IOM IN OTHER SURGERIES OF THE LUMBAR SPINE

In addition to examining the role of IOM usage in lumbar PSOs, it is also worthwhile to explore the efficacy of IOM usage in other surgeries of the lumbar spine, in particular correction surgeries for idiopathic scoliosis and degenerative scoliosis, and routine lumbar cases such as discectomies and instrumented lumbar fusions.

Deformity Corrections in Idiopathic Scoliosis and Degenerative Scoliosis

Several studies on the effect of IOM on outcomes of idiopathic scoliosis correction surgeries indicate that the IOM usage is associated with a decreased rate of post-operative neurological deficits.^{2,13,30} Furthermore, a review of literature also indicates that SSEP monitoring provides highly reliable information and is invaluable in the detection and prevention of iatrogenic injury.^{2,13} Indeed, SSEP monitoring in idiopathic scoliosis surgery exhibits both high sensitivity and specificity. A review of 477 patients who underwent correction surgery for idiopathic scoliosis found a sensitivity of 95.0% and a specificity of 99.8% for the procedure.¹³ In addition, there have been studies that concluded that the use of MEPs may also provide valuable information for idiopathic scoliosis surgeries and can possibly lead to the reduction of iatrogenic injuries, though future studies are necessary to establish a clearer association.³⁰ Thus, IOM usage is considered the standard of care in idiopathic scoliosis correction surgery.¹³ Given the ability of IOM to reduce neurological injuries during surgery, paired with its high sensitivity and specificity, we recommend that IOM should continue to be utilized in all idiopathic scoliosis correction surgeries.¹³

Unlike idiopathic scoliosis, degenerative scoliosis can develop during adulthood as a result of degeneration of spinal structures.^{13,39} Specifically, aging can lead to asymmetrical deterioration of the spinal disks and facet joints, which would cause tilting of the vertebrae.¹³ When multiple levels are involved, the patient develops curvature/scoliosis of the spine.¹³ It is worthwhile to note that this form of scoliosis primarily affects the lumbar spine.¹³ Corrective surgery for this condition involves decompression and fusion, and is usually associated with greater risks of iatrogenic complications than idiopathic scoliosis.^{2,13,30} As such, IOM is often used in an effort to reduce neurological complications during degenerative scoliosis correction surgery.

Routine Lumbar Cases

Since routine lumbar cases such as discectomies, lumbar decompression and instrumented fusion, and interbody fusions comprise the majority of surgeries of the lumbar spine, it is important to explore the usage of IOM in these cases.³⁶ A review of literature indicates that recommendations for IOM usage vary depending on the procedure performed, and that the usage of IOM in routine lumbar cases, such as simple decompression, is controversial.^{2,8,14} For decompressive lumbar surgery with instrumentation, free running EMGs can be utilized to monitor placement of pedicle screws.⁵ However, although EMG has a high sensitivity, it has a very low specificity.²⁸ Gunnarson et al found in a retrospective study of 213 patients that the sensitivity was 100% while the specificity was only 23%.³⁵ While EMGs are occasionally utilized in instrumented lumbar fusions, SSEPs and MEPs are not utilized for routine instrumented fusion cases.²⁸ Thus, the IOM usage during instrumented lumbar fusions is not as widespread as the IOM usage in thoracic PSOs or idiopathic scoliosis surgeries.⁵ Another routine lumbar case is minimally invasive surgery involving transforaminal interbody fusion (MIS-TLIF).²⁹ Studies have shown that IOM usage in these operations did not affect the incidence of pedicle screw malpositioning.⁵ Indeed, no significant statistical difference was found in patient outcomes or rates of neurological damage post-operation.⁵ Furthermore, IOM increases both the duration and cost of surgery. Ultimately, there is heterogeneity in the decision to use IOM (as well as the modality selected) for routine lumbar cases.^{5,8,14,20}

AUTHORS PREFERRED TREATMENT

Despite this clinical equipoise, it is worthwhile to note that IOM is progressively becoming the standard of care in spinal deformity surgery, and not without good reason. It's utility in detecting nerve and cord injury is well established in the thoracic spine, and while its sensitivity is not as robust in the lumbar spine, it nevertheless provides valuable real-time information regarding cord integrity to the operating surgeon and therefore allows him to modify his approach as necessary. Furthermore, while IOM usage in lumbar PSOs has not been shown to statistically decrease the complication rate, it is valuable if it prevents even one patient from undergoing iatrogenic injury. Thus, the authors contend that while imperfect, IOM is nonetheless a valuable tool in deformity surgeries of the spine, including lumbar PSOs. However, given the relative lack of studies in this arena, more research is necessary to achieve a systematic set of guidelines for monitoring and to establish the specific risks and benefits of IOM usage in PSOs of the lumbar spine.

REFERENCES

1. Feng B et al. Impact of multimodal intraoperative monitoring during surgery for spine deformity and potential risk factors for neurological monitoring changes. *J. Spinal Disord. Tech* 25, E108–114 (2012). [PubMed: 22367467]
2. Lall RR et al. Intraoperative neurophysiological monitoring in spine surgery: indications, efficacy, and role of the preoperative checklist. *Neurosurg. Focus* 33, E10 (2012).
3. Raynor BL et al. Failure of Intraoperative Monitoring to Detect Postoperative Neurologic Deficits: A 25-year Experience in 12,375 Spinal Surgeries. *Spine* 41, 1387–1393 (2016). [PubMed: 26913466]
4. Qian B et al. Pedicle subtraction osteotomy through pseudarthrosis to correct thoracolumbar kyphotic deformity in advanced ankylosing spondylitis. *Eur. Spine J* 21, 711–718 (2012). [PubMed: 22065166]
5. Nuwer MR, Dawson EG, Carlson LG, Kanim LE & Sherman JE Somatosensory evoked potential spinal cord monitoring reduces neurologic deficits after scoliosis surgery: results of a large multicenter survey. *Electroencephalogr. Clin. Neurophysiol* 96, 6–11 (1995). [PubMed: 7530190]
6. Louie PK, Hassanzadeh H, Shimer AL & Shen FH Intraoperative neurophysiologic monitoring during spinal osteotomies. *Semin. Spine Surg* 27, 222–228 (2015).
7. Hyun S-J, Kim YJ & Rhim S-C Spinal pedicle subtraction osteotomy for fixed sagittal imbalance patients. *World J. Clin. Cases WJCC* 1, 242–248 (2013). [PubMed: 24340276]
8. Le Huec J-C & Aunoble S Pedicle subtraction osteotomy for sagittal imbalance. *Eur. Spine J* 21, 1896–1897 (2012). [PubMed: 22918511]
9. Langeloo DD, Lelivelt A, Louis Journée H, Slappendel R & de Kleuver M Transcranial electrical motor-evoked potential monitoring during surgery for spinal deformity: a study of 145 patients. *Spine* 28, 1043–1050 (2003). [PubMed: 12768147]
10. Laratta JL et al. Neuromonitoring in Spinal Deformity Surgery: A Multimodality Approach. *Glob. Spine J* 8, 68–77 (2018).
11. Lieberman JA, Lyon R, Feiner J, Hu SS & Berven SH The efficacy of motor evoked potentials in fixed sagittal imbalance deformity correction surgery. *Spine* 33, E414–424 (2008). [PubMed: 18520928]
12. Trobisch PD, Hwang SW & Drange S PSO without neuromonitoring: analysis of peri-op complication rate after lumbar pedicle subtraction osteotomy in adults. *Eur. Spine J. Off. Publ. Eur. Spine Soc. Eur. Spinal Deform. Soc. Eur. Sect. Cerv. Spine Res. Soc* 25, 2629–2632 (2016).
13. Sloan TB, Burger E, Kleck CJ & Oliva AM Neurophysiological Monitoring in Thoracic Spine Surgery in Monitoring the Nervous System for Anesthesiologists and Other Health Care Professionals 507–524 (Springer, Cham, 2017). doi:10.1007/978-3-319-46542-5_34
14. Berjano P & Aebi M Pedicle subtraction osteotomies (PSO) in the lumbar spine for sagittal deformities. *Eur. Spine J. Off. Publ. Eur. Spine Soc. Eur. Spinal Deform. Soc. Eur. Sect. Cerv. Spine Res. Soc* 24 Suppl 1, S49–57 (2015).
15. Bridwell KH et al. Complications and outcomes of pedicle subtraction osteotomies for fixed sagittal imbalance. *Spine* 28, 2093–2101 (2003). [PubMed: 14501920]
16. Buchowski JM et al. Neurologic complications of lumbar pedicle subtraction osteotomy: a 10-year assessment. *Spine* 32, 2245–2252 (2007). [PubMed: 17873818]
17. Cho K-J, Bridwell KH, Lenke LG, Berra A & Baldus C Comparison of Smith-Petersen versus pedicle subtraction osteotomy for the correction of fixed sagittal imbalance. *Spine* 30, 2030–2037; discussion 2038 (2005). [PubMed: 16166890]
18. Kim K-T, Suk K-S, Cho Y-J, Hong G-P & Park B-J Clinical outcome results of pedicle subtraction osteotomy in ankylosing spondylitis with kyphotic deformity. *Spine* 27, 612–618 (2002). [PubMed: 11884909]
19. Savage JW & Patel AA Fixed Sagittal Plane Imbalance. *Glob. Spine J* 4, 287–296 (2014).
20. Nash CL, Lorig RA, Schatzinger LA & Brown RH Spinal cord monitoring during operative treatment of the spine. *Clin. Orthop* 100–105 (1977).

21. Erickson MM & Currier BL Surgical management of complex spinal deformity. *Orthop. Clin. North Am* 43, 109–122, ix (2012). [PubMed: 22082634]
22. Mummaneni PV, Dhall SS, Ondra SL, Mummaneni VP & Berven S Pedicle subtraction osteotomy. *Neurosurgery* 63, 171–176 (2008). [PubMed: 18812921]
23. Thomasen E Vertebral osteotomy for correction of kyphosis in ankylosing spondylitis. *Clin. Orthop* 142–152 (1985).
24. Sheha ED, Jo Kim H & Cunningham ME Vertebral column resection for complex spinal deformity. *Semin. Spine Surg* 29, 175–183 (2017).
25. Rose PS et al. Role of pelvic incidence, thoracic kyphosis, and patient factors on sagittal plane correction following pedicle subtraction osteotomy. *Spine* 34, 785–791 (2009). [PubMed: 19365245]
26. Kim S-S et al. Complications of Posterior Vertebral Resection for Spinal Deformity. *Asian Spine J* 6, 257–265 (2012). [PubMed: 23275809]
27. Hwang SW, Malhotra NR, Shaffrey CI & Samdani AF Intraoperative Neurophysiological Monitoring in Spine Deformity Surgery. *Spine Deform.* (2012). doi:10.1016/j.jspd.2012.05.006
28. Hilibrand AS, Schwartz DM, Sethuraman V, Vaccaro AR & Albert TJ Comparison of transcranial electric motor and somatosensory evoked potential monitoring during cervical spine surgery. *J. Bone Joint Surg. Am* 86-A, 1248–1253 (2004). [PubMed: 15173299]
29. Pajewski TN, Arlet V & Phillips LH Current approach on spinal cord monitoring: the point of view of the neurologist, the anesthesiologist and the spine surgeon. *Eur. Spine J* 16, 115–129 (2007). [PubMed: 16676151]
30. Thirumala PD et al. Somatosensory-evoked potential monitoring during instrumented scoliosis corrective procedures: validity revisited. *Spine J. Off. J. North Am. Spine Soc* 14, 1572–1580 (2014).
31. MacEwen GD, Bunnell WP & Sriram K Acute neurological complications in the treatment of scoliosis. A report of the Scoliosis Research Society. *J. Bone Joint Surg. Am* 57, 404–408 (1975). [PubMed: 1123394]
32. Calancie B, Harris W, Broton JG, Alexeeva N & Green BA ‘Threshold-level’ multipulse transcranial electrical stimulation of motor cortex for intraoperative monitoring of spinal motor tracts: description of method and comparison to somatosensory evoked potential monitoring. *J. Neurosurg* 88, 457–470 (1998). [PubMed: 9488299]
33. Minahan RE, Sepkuty JP, Lesser RP, Sponseller PD & Kostuik JP Anterior spinal cord injury with preserved neurogenic ‘motor’ evoked potentials. *Clin. Neurophysiol. Off. J. Int. Fed. Clin. Neurophysiol* 112, 1442–1450 (2001).
34. Devlin VJ & Schwartz DM Intraoperative neurophysiologic monitoring during spinal surgery. *J. Am. Acad. Orthop. Surg* 15, 549–560 (2007). [PubMed: 17761611]
35. Grigorian IC and EMG AA and Evoked Potentials in the Operating Room During Spinal Surgery. *EMG Methods Eval. Muscle Nerve Funct* (2012). doi:10.5772/25969
36. 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). [PubMed: 15014279]
37. Garces J, Berry JF, Valle-Giler EP & Sulaiman WAR Intraoperative neurophysiological monitoring for minimally invasive 1- and 2-level transforaminal lumbar interbody fusion: does it improve patient outcome? *Ochsner J.* 14, 57–61 (2014). [PubMed: 24688334]
38. Skinner SA, Transfeldt EE & Savik K Surface electrodes are not sufficient to detect neurotonic discharges: observations in a porcine model and clinical review of deltoid electromyographic monitoring using multiple electrodes. *J. Clin. Monit. Comput* 22, 131–139 (2008). [PubMed: 18335318]
39. Bhagat S et al. An evaluation of multimodal spinal cord monitoring in scoliosis surgery: a single centre experience of 354 operations. *Eur. Spine J. Off. Publ. Eur. Spine Soc. Eur. Spinal Deform. Soc. Eur. Sect. Cerv. Spine Res. Soc* 24, 1399–1407 (2015).
40. Stecker MM A review of intraoperative monitoring for spinal surgery. *Surg. Neurol. Int* 3, S174–S187 (2012). [PubMed: 22905324]