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Methodological problems of intraoperative neuromonitoring during operative correction of spinal deformity (review of literature)

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Literature review in intraoperative neurophysiological monitoring during spinal deformity correction showed that the increase in the number of neuromonitoring modalities is viewed as a major trend with the technique. This makes the testing procedure more complicated and generates controversies in interpretations of the findings. Algorithmization of monitoring and formalization of the findings can be practical in addressing methodological problems.

Keywords: neurophysiological monitoring, evoked potentials, anesthesia, spine deformity

There is a variety of neurophysiological monitoring (IONM) techniques established to accurately assess the functional integrity of different parts of the central nervous system (CNS) including spinal cord and peripheral nerves, in particular, during operative intervention [1]. They are helpful in maximizing the safety of spinal procedures and limit the risk of iatrogenic neurologic injury [2]. IONM modalities should provide high sensitivity and specificity (1) and the possibility of multiple usage with minimal risk to the patient (2) [3]. Neuromonitors are subdivided into two groups. The first group includes methods of passive recording of such physiological parameters as spontaneous electrical activity of excitable tissues, body temperature at a target point [4], the second is aimed at getting electrical responses to a test stimulus with strict standardization of evoking conditions and signal recording. Electrical [5] or magnetic [6] impulses can be employed for this.

Several authors report effective usage of IONM in spinal deformity correction [7–15]. Neuromonitoring modalities have become available at regional hospitals of the Russian Federation [4, 16] and CIS countries [17].

However the evidence does not meet the level 1 standard and is based on level 2 and 3 [22] with all high values in IONM sensitivity, specificity and prediction [18, 19, 20, 21]. Therefore, extended applications of IONM modalities revealed some methodological problems that were originally neglected. IONM applications received optimistic reports [10, 21] followed by publications [22, 23] featuring a number of difficulties with IONM introduction into surgical practice (**Fig. 1**). There is a need to systematize the existing methodological problems with IONM and analyze Russian and foreign publications with the purpose of identifying ways of further improvement of intraoperative neurophysiological monitoring.

Among the problems identified in the review, reliable interpretation of the critical changes in test parameters remains difficult and controversial (**Fig. 1, A**). Critical values of test parameters suggested by most of the authors indicating to a greater risk of neural tissue injury were determined empirically. Controversies can be reviewed at summarizing accumulated data [22]. There are evident reasons for the existing controversies. Almost no controversies can be found in spontaneous electromyogram (EMG) activity or critical values in decreased amplitude of somatosensory evoked potentials (SSEP). Importance of changes in SSEP latency is still being discussed [4, 24] due to the fact that the parameter has a higher sensitivity to both injuries (mechanical trauma and ischemia) and background factors (temperature [23] and concentration of anesthetic components [4]).

Identifying critical response signs to operative intervention with motor evoked potentials (MEP) engendered a lot of controversy. Authors report critical decrease in amplitude by 50 % [17], 65 % [24], 80 % [25] from the baseline. Increase in latency is viewed as an ample warning sign by several authors [16], whereas others suggest recognizing it solely with decrease in amplitude [24]. There are also opinions to consider increase in test stimulus by more than 50 V, and increase in a number of impulses in a train [25]. Some authors offer to assess a warning extent based on dynamics in a response type. However, no correlations can be seen between changes in MEP configuration and functional condition of nerve structures when approaching a critical level [22].

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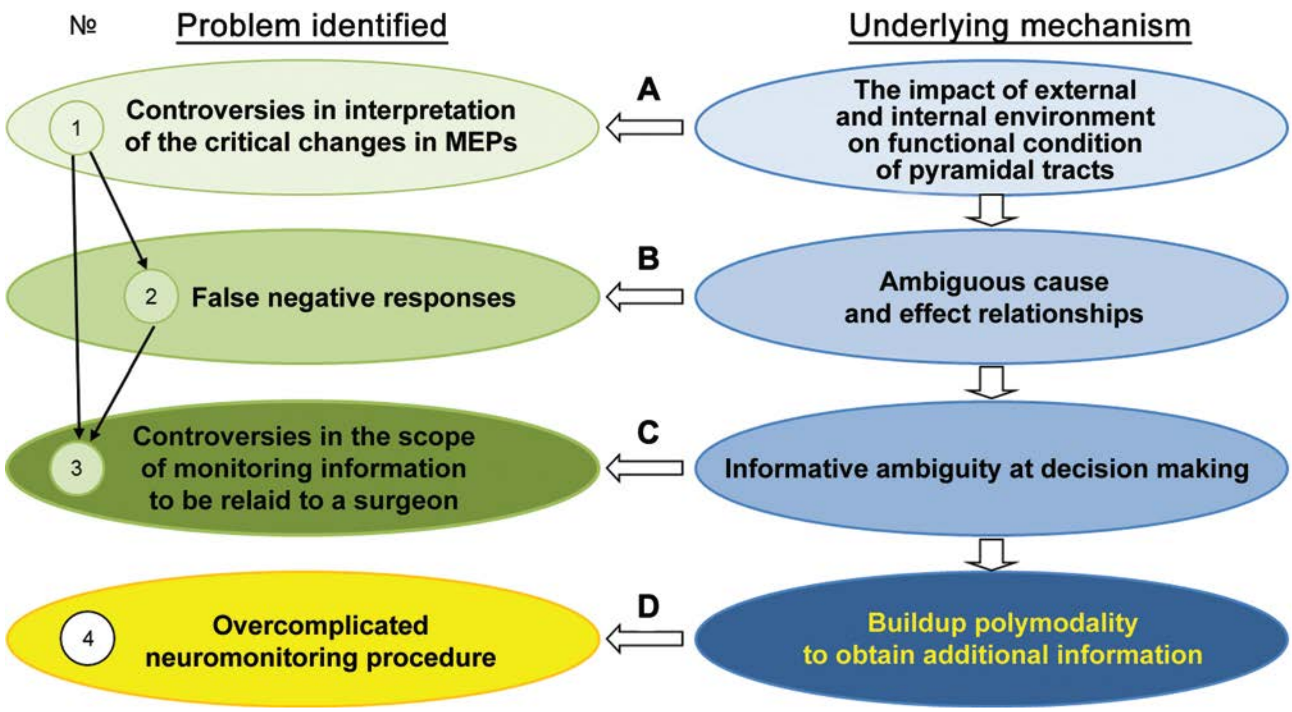

Fig. 1 Hierarchy of co-relation between major methodological problems of a large-scale IONM introduction into clinical practice (described in the text)

A variety of warning criteria with the MEP usage is associated with their high variability in the norm [26] that notably increases with anaesthesia [27]. This is the result of several factors the combination of which being unstable overtime and cannot be accurately established. Effects of the factors on human sensorimotor system are well understood and described. Effects of several factors (concentration of anaesthetic components, blood loss, body temperature) can be precisely estimated. Accuracy of other parameters can be provided in stringent laboratory conditions that are difficult to arrange at an operation theatre. Nevertheless, there is a clear understanding of the processes to occur at the time of a certain effect at the operation theatre. But there are no clear criteria to identify which of the possible factors act at electrophysiological warning signs.

These obstacles can partially be overcome by improving testing technology. For example, an effect from a test stimulus depends on resistance of biological tissues through which (as through discrete wire) it reaches excitable structures (neurons, nerve conductors, receptors). The resistance fluctuates depending on tissue blood filling and electrolytic saturation and is associated with the condition of autonomic nervous system. Consequently, changes in characteristics of the test signal contribute to MEP variability [22]. For this reason monitors are equipped with a current intensity indicator showing actual amount of the current passing through the tissues. Fluctuations in biological discrete wire can be a hidden factor being beyond control without such indication. All of the above hampers standardization of assessment criteria of significant changes in MEP. Though there are fewer controversies seen among neurophysiologists approaching to consensus can be provided rather by accumulated empirical IONM experience than by evolving an appropriate theory.

The group of factors influencing the patient's sensorimotor system can conventionally be divided into baseline and damaging. Baseline factors include blood pressure, hemoglobin level, etc. that function continuously. Intensity of the influence is within monitored range and the effect on excitable body structures can be assessed as neutral to moderate. The second group includes mechanical influence on sensorimotor structures and ischemia that are directly associated with surgical aggression and are the source of immediate threat generating from iatrogenic injury. However, certain scenarios can lead to intensity of baseline factors going beyond the acceptable limits. Moreover, baseline factors can become damaging or produce a secondary traumatic event that is revealed in changing characteristics of neurological responses [22, 23].

Electrophysiological response to damage and the response rate are largely dependent on a type of the injury. If it is a mechanical injury SSEP changes occur within two minutes, and if it is a vascular trauma SSEP changes are seen within 20 minutes [28], hence, there are continuing attempts of classifying damaging mechanisms [29].

The variety and ambiguity of the factors influencing the patient's intraoperative functional condition generate

(**Fig. 1, B**) the second problem in the usage of IONM technology, namely, false positives [7, 20], obtained in the absence of postoperative sensory and motor deficits with critical decrease in amplitude of corresponding responses all the way down to the complete suppression. A small number of such observations (about 10%) should also be interpreted. We suppose that false positives are not associated only with controversies regarding critical changes in monitored parameters. Although each possible factor being capable of causing critical changes in neurophysiological parameters is well known and thoroughly studied, the collective effect is very ambiguous in attempt to build up a system of cause-and-effect relations between alerts and the possible reasons. And a neurophysiologist together with an anesthesiologist addresses an inverse problem of looking for a cause (out of several probabilities) with a set of signs. However, inverse problems can be attributed to inadequate formulation [30].

The first and the second problems are closely associated with the third one (**Fig. 1, C**), a controversy regarding the scope of monitoring information to be relaid to a surgeon by a neurophysiologist. Does the surgeon need to know all the changes in the parameters being critical or not, or the surgeon needs to learn solely high alerts to experience minimum information pressure on his operation focus. In our opinion, a blend of skills and personal qualities in the team of a surgeon, neurophysiologist and anesthesiologist and a complexity of a surgical intervention must be considered with the issue.

The above issues can be solved with extensively developing IONM technology by increase in monitored parameters that provide additional intraoperative information about nerve tissue condition and contribute to reliability of neurophysiological findings for each critical episode.

Retrospective review of IONM history demonstrates strong evidence to the approach. Initial usage of SSEP as an IONM instrument [21] ensured the safety of sensory pathways and proper response to a situation leading to a devastating spinal cord injury [31]. There were reports indicating to absence of SSEP recordings followed by postoperative motor disorders [22, 32, 33, 34], as well as cases of considerable delay of SSEP response relative to MEP [35, 36].

Due to anatomical and physiological autonomy of sensory and motor pathways [22, 23] INOM cannot provide neurophysiological control for sensory-motor pathways and ventral roots with SSEP only [23]. Additional control of motor pathways of the spinal cord with spontaneous EMG and MEP is required due to higher sensitivity of motor pathways to ischemia as compared to that of sensory pathways [22], and autonomous blood supply of ascending sensory and pyramidal tracts [10, 13]. On the one hand, it provides a considerable reduction in postoperative motor deficits and cases of wake up tests [4], on the other hand, imposes strict criteria for anesthesia.

While comparing the dynamics in MEP changes throughout intervention less sensitivity of early SSEP components to anesthesia appears to be practical in assessing fluctuations of excitability of cortical and spinal neurons evoked by pharmacological stimulus [23, 37] that makes the recordings more reliable.

MEP used for IONM minimizes application of muscle relaxants that entails some technical difficulties. All cases of necessitous usage of muscle relaxants should be considered when interpreting neurophysiological recordings and included in IONM protocol. One can wait for excitability of muscle indicators to restore following myorelaxant application (if a surgeon does not produce a potentially risky maneuver for the spinal cord) or apply medications to restore synaptic transmission. However, the latter is associated with greater pharmacological loading on a patient.

Recorded activity from the spinal cord, D wave, can be used as an additional tool of neurophysiological monitoring of pathways if muscle relaxants to be applied intraoperatively [2]. It is not dependent on condition of neuro-muscular synapses. But electrodes are required close to surgical activity area and they can make surgeon's manipulations difficult in some cases. Furthermore, D wave does not allow for an accurate localization of an injury side.

According to many authors, a combination of SSEP and MEP provides a more effective monitoring than either technique does alone [12, 14, 38, 39]. The present IONM diagram (**Fig. 2**) has become the standard of spinal surgical intervention [2]. It allows for minimal usage of wake-up test, in particular [40].

Spontaneous EMG and SSEP monitoring are completely neutral to the patient's body. MEP monitoring can be associated with several contraindications [22] and possible complications [41]. Contraindications to MEP include epilepsy, a cerebral lesion, skull defects, elevated intracranial pressure, implanted intracranial devices (electrodes, vascular clips, shunts, etc.), cardiac pacemakers or other implanted biomedical devices [22].

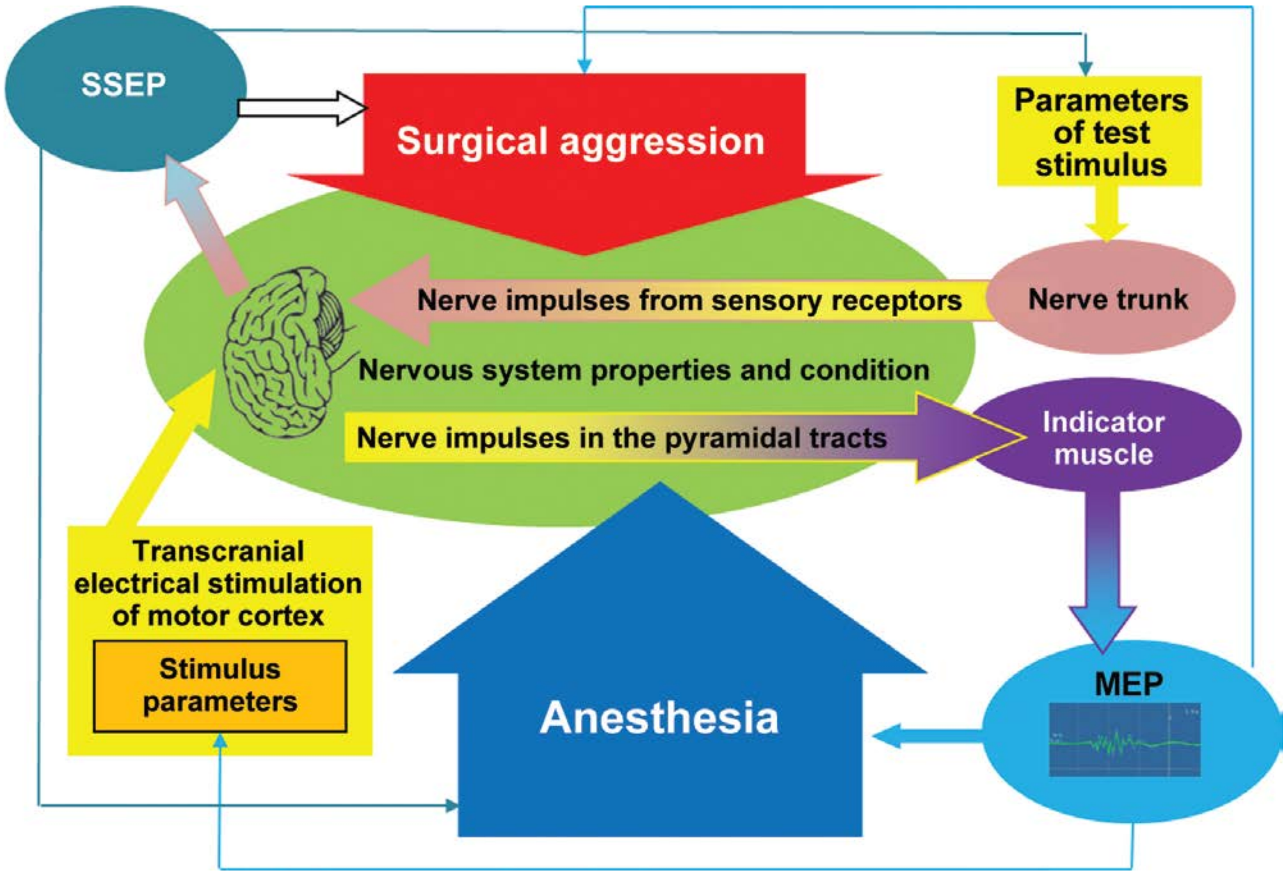

Fig. 2 A complex effect of surgical aggression and general anesthesia through intensive interoception (including nociceptive activity) in restructured microcirculation and fluctuations in excitability of CNS neural network results in changes in signal transmission from stimulus (sensory fraction of peripheral nerve for SSEP, cortical projection to the represented indicator muscle for MEP) to the take-over point of evoked response (sensory cortical representation of a limb, for SSEP; a set of indicator muscles, for MEP). Possible consequences from a mechanical injury/ischemia can influence the background effect

Tongue laceration is the most common complication of MEP modality and can be easily treated with a bite block created from rolled gauze pads. Cardiac arrhythmia is considered the next highest complication with MEP monitoring (a rare complication as compared to tongue laceration and is easily detected by anesthesiologist). Scalp electrode burns are very rare. There is a published report of a thermal injury to the motor cortex in response to transcranial stimulation [42]. It should be stressed that all possible complications are associated with high intensity stimulus to be repeated several times when CNS excitability is very low initially and/or there are expressed abnormalities localized at the projection area of motor cortex. The available reports published no cases of electrode related infection (although potentially it can happen), body movements related injuries through evoked stimulation, psychic problems, headaches or other changes in CNS associated with continuous electric impulses to the brain.

Testing general condition of pyramidal tracts require a minimal number of indicator muscles. However, placement of screws for construct fixation creates a potential threat to spinal nerve roots. This process can be controlled neurophysiologically with spontaneous EMG and MEP in transcranial stimulation of the motor cortex or with direct stimulation of paravertebral tissues while testing the contacts of transpedicular screws with spinal nerve roots. It would require more derivations in conformity with interested roots.

An additional temperature control was offered for target points of lower limbs since a combination of SSEP and MEP and greater derivations of activity does not exclude false positive responses [4].

The short retrospective review shows the major trend in intraoperative neurophysiological monitoring toward extensive development of derivations of activity and modalities of information channels. The volume of information has been growing respectively. There is reported evidence of the efficacy of such approach [43], in complicated high-risk operations, in particular [19].

The extension of control methods and monitored parameters leads to the fourth methodological problem with a complicated procedure of neuromonitoring, premonitoring preparation and more time to be spent with the technique (**Fig. 1, D**). There is also an increased need in expendable materials used for neurophysiological monitoring that results in higher costs of operative intervention.

With polymodality available for IONM, interpretations of changes become more complicated [23] due to multifactorial activity. The methodological aspect makes specialists focus on further development of theoretical rationale to interpret complex dynamics in a large number of parameters.

Side effects of extensive development of IONM technology were recognized by specialists and there were attempts to simplify the testing scheme. SSEP and MEP modalities were compared for the purpose [5, 9, 10, 45] to identify the cases when either technique can be used. Finally, a flexible scheme of a limited set of neurophysiological techniques can be established among a potentially large arsenal of control tools depending on a specific goal and conditions of an expected procedure. The approach requires further development of effective interpretation system for the findings. Tentative neurophysiological examination of the patient is important (**Fig. 3**) during preoperative period [2]. Electroencephalography and evoked potentials can be practical in evaluating CNS related contraindications and initial condition of sensory system that can be considerably changed in patients with severe spinal deformity. EMG provides important findings of motor system that serve the basis for choosing optimal muscles for MEP. Tentative neurophysiological information can be properly used during IONM.

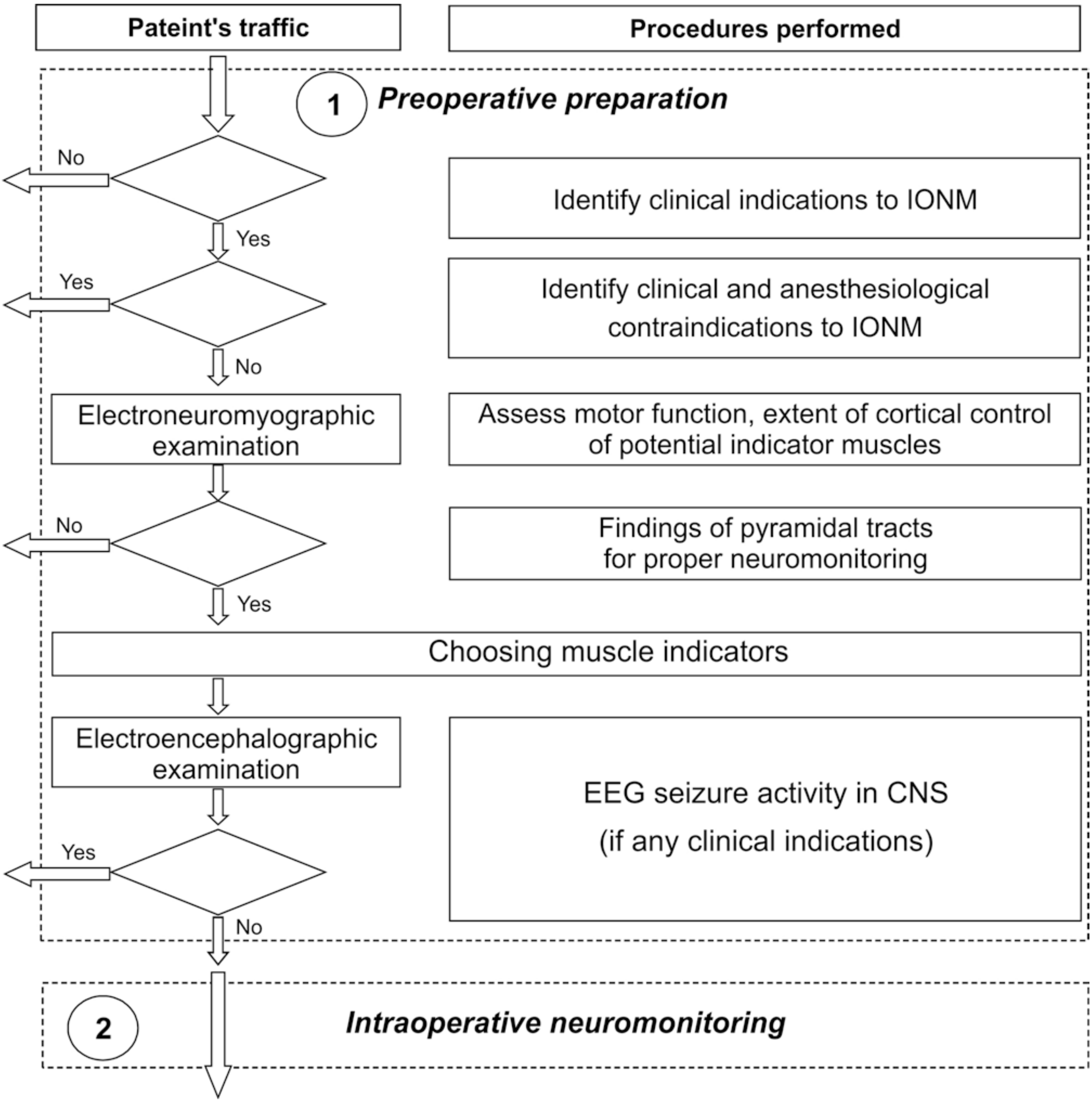

Fig. 3 Diagram of preoperative preparation of a patient for intraoperative neurophysiological monitoring established at the Russian Ilizarov Scientific Center for Restorative Traumatology and Orthopaedics

Summarizing the literature review and our own IONM experience of surgical correction of spinal deformity we conclude that the control method is successfully used in clinical practice and has high potentials for further improvement considering the four methodological problems we identified. First, the theory of the complex usage of IONM needs further improvement based on formalization obtained during intraoperative neurophysiological control. This would allow for more efficacious interpretation of the findings and less ambiguity when evaluating the reasons of a neurophysiological phenomenon observed in a particular condition (low response amplitude, changes in a number of phases and latency, etc.). Introduction of various rank tests and relevant scales can be the first step in the formalization to assess electrophysiological responses of the brain conduction systems and a risk of an iatrogenic injury.

Secondly, there is a need to optimize the complex polymodal IONM procedure using different modifications of EMG [46], SSEP and MEP [38]. An algorithm of preoperative IONM preparation (**Fig. 3**) and the monitoring process (**Fig. 4**) must be built. Formalization of the information can be successfully used to improve the algorithm suggested.

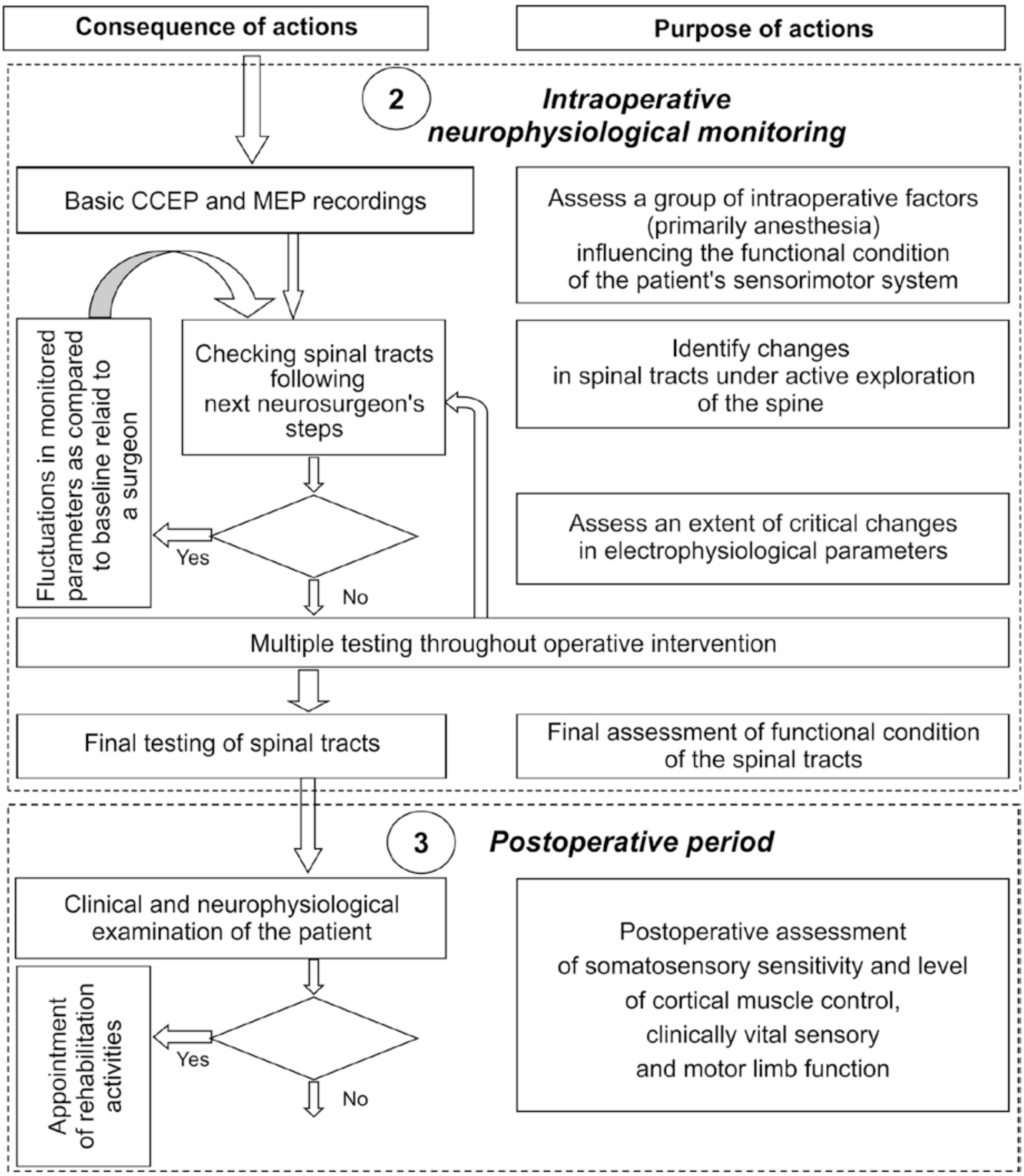

Fig. 4 Diagram of intraoperative neurophysiological monitoring established at the Russian Ilizarov Scientific Center for Restorative Traumatology and Orthopaedics

CONCLUSION

Intraoperative neurophysiological monitoring is a high technology method for control of the functional condition of somatosensory and pyramidal tracts during spinal deformity correction. It is effective in detecting and preventing most iatrogenic injuries to the nerve structures. IONM related technical, methodological problems cannot hamper its widespread application and can be successfully addressed in the near future. The solution contains potentials for further development of the method based on formalization of the information and optimization of IONM procedure.

REFERENCES

1. Peeling L., Hentschel S., Fox R., Hall H., Fourney D.R. Intraoperative spinal cord and nerve root monitoring: a survey of Canadian spine surgeons. *Can. J. Surg.*, 2010, vol. 53, no. 5, pp. 324-328.
2. Gibson P.R. Anaesthesia for correction of scoliosis in children. *Anaesth. Intensive Care*, 2004, vol.32, no. 4, pp. 548-559.
3. Padberg A.M., Bridwell K.H. Spinal cord monitoring: current state of the art. *Orthop. Clin. North. Am.*, 1999, vol. 30, no. 3, pp. 407-433.
4. Novikov V.V., Novikova M.V., Tsvetovskii S.B., Lebedeva M.N., Mikhailovskii M.V., Vasiura A.S., Dolotin D.N., Udalova I.G. Profilaktika nevrologicheskikh oslozhnenii pri khirurgicheskoi korrektsii grubykh deformatsii pozvonochnika [Prevention of neurological complications during surgical correction of the spine gross deformities]. *Khirurgiia pozvonochnika*, 2011, no.3, pp. 66-76. (In Russ.)
5. Calancie B., Harris W., Broton J.G., Alexeeva N., Green B.A. «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.*, 1998, vol. 88, no. 3, pp. 457-470.
6. Edmonds H.L.Jr., Paloheimo M.P., Backman M.H., Johnson J.R., Holt R.T., Shields C.B. Transcranial magnetic motor evoked potentials (tcMMEP) for functional monitoring of motor pathways during scoliosis surgery. *Spine*, 1989, vol. 14, no. 7, pp. 683-686.
7. Aleem A.W., Thuet E.D., Padberg A.M., Wallendorf M., Luhmann S.J. Spinal Cord Monitoring Data in Pediatric Spinal Deformity Patients With Spinal Cord Pathology. *Spine Deformity*, 2015, vol. 3, no. 1, pp. 88-94.
8. Deletis V., Sala F. Intraoperative neurophysiological monitoring of the spinal cord during spinal cord and spine surgery: a review focus on the corticospinal tracts. *Clin. Neurophysiol.*, 2008, vol. 119, no. 2, pp. 248-264.
9. Ferguson J., Hwang S.W., Tataryn Z., Samdani A.F. Neuromonitoring changes in pediatric spinal deformity surgery: a single-institution experience. *J. Neurosurg. Pediatr.*, 2014, vol. 13, no. 3, pp. 247-254.
10. Hsu B., Cree A.K., Lagopoulos J., Cummine J.L. Transcranial motor-evoked potentials combined with response recording through compound muscle action potential as the sole modality of spinal cord monitoring in spinal deformity surgery. *Spine*, 2008, vol. 33, no. 10, pp. 1100-1106.
11. Hwang S.W., Malhotra N.R., Shaffrey C.I., Samdani A.F. Intraoperative neurophysiological monitoring in spine deformity surgery. *Spine Deformity* [Preview September], 2012, pp. 64-70.
12. MacDonald D.B., Al Zayed Z., Khoudeir I., Stigsby B. Monitoring scoliosis surgery with combined multiple pulse transcranial electric motor and cortical somatosensory-evoked potentials from the lower and upper extremities. *Spine*, 2003, vol. 28, no. 2, pp. 194-203.
13. Minahan R.E., Sepkuty J.P., Lesser R.P., Sponseller P.D., Kostuik J.P. Anterior spinal cord injury with preserved neurogenic 'motor' evoked potentials. *Clin. Neurophysiol.*, 2001, vol. 112, no. 8, pp. 1442-1450.
14. Pelosi L., Lamb J., Grevitt M., Mehdian S.M., Webb J.K., Blumhardt L.D. Combined monitoring of motor and somatosensory evoked potentials in orthopaedic spinal surgery. *Clin. Neurophysiol.*, 2002, vol. 113, no. 7, pp. 1082-1091.
15. Stecker M.M. A review of intraoperative monitoring for spinal surgery. *Surg. Neurol. Int.*, 2012, vol. 3, no. Suppl. 3, pp. S174-S87.
16. Belova A.N., Baldova S.N., Kaz'min A.V. Ispol'zovanie intraoperatsionnogo neirofiziologicheskogo monitoringa pri operatsiiakh na pozvonochnike i spinnom mozge [Use of intraoperative neurophysiological monitoring when performing surgeries of the spine and spinal cord]. V*opr. travmatologii i ortopedii*, 2014, no. 2 (9), pp. 21-25. (In Russ.)
17. Karibai S.D., Nurpeisov A.Z., Akhmetzhanov A.V., Tankacheev R.Sh., Galiev I.Zh., Dikhtiar' Iu.A., Akhmetov K.K., Mustafaev B.S., Semenova A.E. Opyt primeneniia intraoperatsionnogo neiromonitoringa pri provedenii khirurgicheskikh vmeshatel'stv na pozvonochnike [Experience of using intraoperative neuromonitoring in the process of surgical interventions of the spine]. *Neirokhirurgiia i nevrologiia Kazakhstana*, 2014, no. 1, pp. 25-28. (In Russ.)
18. Bednarík J., Kadanka Z., Vohánka S., Stejskal L., Vlach O., Schröder R. The value of somatosensory- and motor-evoked potentials in predicting and monitoring the effect of therapy in spondylotic cervical myelopathy. Prospective randomized study. *Spine*, 1999, vol. 24, no. 15, pp. 1593-1598.
19. Kai Y., Owen J.H., Lenke L.G., Bridwell K.H., Oakley D.M., Sugioka Y. Predictive value of intraoperative neurophysiological monitoring during cervical spine surgery: a prospective analysis of 1055 consecutive patients. *J. Neurosurg. Spine*, 2008, vol. 8, no. 3, pp. 215-221.

20. Kim D.H., Zaremski J., Kwon B., Jenis L., Woodard E., Bode R., Banco R.J. Risk factors for false positive transcranial motor evoked potential monitoring alerts during surgical treatment of cervical myelopathy. *Spine*, 2007, vol. 32, no. 26, pp. 3041-3046.
21. Nuwer M.R., Dawson E.G., Carlson L.G., Kanim L.E., Sherman J.E. Somatosensory evoked potential spinal cord monitoring reduces neurologic deficits after scoliosis surgery: results of a large multicenter survey. *Electroencephalogr. Clin. Neurophysiol.*, 1995, vol. 96, no. 1, pp. 6-11.
22. Jameson L.C. Transcranial Motor Evoked Potentials. In: Koht A., Sloan T.B., Toleikis J.R., eds. Monitoring the Nervous System for Anesthesiologists and Other Health Care Professionals. Chapter 2. 2012, vol. XXXVI, pp. 27-45.
23. Gonzalez A.A., Jeyanandarajan D., Hansen C., Zada G., Hsieh P.C. Intraoperative neurophysiological monitoring during spine surgery: a review. *Neurosurg. Focus*, 2009, vol. 27, no. 4, pp. E6.
24. Khit' M.A., Kolesov S.V., Kolbovskii D.A., Morozova N.S. Rol' intraoperatsionnogo neirofiziologicheskogo monitoringa v predotvrashchenii razvitiia posleoperatsionnykh nevrologicheskikh oslozhnenii v khirurgii skolioticheskoi deformatsii pozvonochnika [Role of intraoperative neurophysiological monitoring in preventing postoperative neurological complications in the surgery of the spine scoliotic deformity]. *Nervno-myshechnye bolezni*, 2014, no. 2, pp. 36-41. (In Russ.)
25. Langeloo D.D., 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*, 2003, vol. 28, no. 10, pp. 1043-1050.
26. Wassermann E.M. Variation in the response to transcranial magnetic brain stimulation in the general population. *Clin. Neurophysiol.*, 2002, vol. 113, no. 7, pp. 1165-1171.
27. Sloan T.B. Evoked potentials. Anesthesia and motor evoked potentials monitoring. In: Deletis V., Shils J.L., eds. Neurophysiology in Neurosurgery. California: Academic Press, 2002, pp. 25-51.
28. Kai Y., Owen J.H., Lenke L.G., Bridwell K.H., Oakley D.M., Sugioka Y. Use of sciatic neurogenic motor evoked potentials versus spinal potentials to predict early-onset neurologic deficits when intervention is still possible during overdistraction. *Spine*, 1993, vol. 18, no. 9, pp. 1134-1139.
29. Delecrin J., Bernard J.M., Pereon Y. et al. Various mechanisms of spinal cord injury during scoliosis surgery. In: Neurological Complications of Spinal Surgery: Proc. of the 11th Intern. GICD Congress. Arcachon, France, 1994, pp. 13-14.
30. Gnezditskii V.V. *Obratnaia zadacha EEG i klinicheskaia elektroentsefalografiia* [EEG inverse problem and clinical electroencephalography]. Taganrog, 2000, 680 p. (In Russ.)
31. Nuwer M.R. Spinal cord monitoring with somatosensory techniques. *J. Clin. Neurophysiol.*, 1998, vol. 15, no. 3, pp. 183-193.
32. Ben-David B., Haller G., Taylor P. Anterior spinal fusion complicated by paraplegia. A case report of a false-negative somatosensory-evoked potential. *Spine*, 1987, vol. 12, no. 6, pp. 536-539.
33. Dawson E.G., Sherman J.E., Kanim L.E., Nuwer M.R. Spinal cord monitoring: Results of the Scoliosis Research Society and the European Spinal Deformity Society survey. *Spine*, 1991, vol. 16, no. 8 Suppl., pp. S361-S364.
34. Padberg A.M., Russo M.H., Lenke L.G., Bridwell K.H., Komanetsky R.M. Validity and reliability of spinal cord monitoring in neuromuscular spinal deformity surgery. *J. Spinal Disord.*, 1996, vol. 9, no. 2, pp. 150-158.
35. Schwartz D.M., Auerbach J.D., Dormans J.P., Flynn J., Drummond D.S., Bowe J.A., Laufer S., Shah S.A., Bowen J.R., Pizzutillo P.D., Jones K.J., Drummond D.S. Neurophysiological detection of impending spinal cord injury during scoliosis surgery. *J. Bone Joint Surg. Am.*, 2007, vol. 89, no. 11, P. 2440-2449.
36. Wang A.C., Than K.D., Etame A.B., La Marca F., Park P. Impact of anesthesia on transcranial electric motor evoked potential monitoring during spine surgery: a review of the literature. *Neurosurg. Focus*, 2009, vol. 27, no. 4, pp. E7.
37. Furmaga H., Park H.J., Cooperrider J., Baker K.B., Johnson M., Gale J.T., Machado A.G. Effects of ketamine and propofol on motor evoked potentials elicited by intracranial microstimulation during deep brain stimulation. *Front. Syst. Neurosci.*, 2014, vol. 8, pp. 89.
38. Burke D., Hicks R., Stephen J., Woodforth I., Crawford M. Assessment of corticospinal and somatosensory conduction simultaneously during scoliosis surgery. *Electroencephalogr. Clin. Neurophysiol.*, 1992, vol. 85, no. 6, pp. 388-396.
39. Nuwer M.R., Emerson R.G., Galloway G., Legatt A.D., Lopez J., Minahan R., Yamada T., Goodin D.S., Armon C., Chaudhry V., Gronseth G.S., Harden C.L.; American Association of Neuromuscular and Electrodiagnostic Medicine. Evidence-based guideline update: intraoperative spinal monitoring with somatosensory and transcranial electrical motor evoked potentials. *J. Clin. Neurophysiol.*, 2012, vol. 29, no. 1, pp. 101-108.
40. Padberg A.M., Wilson-Holden T.J., Lenke L.G., Bridwell K.H. Somatosensory- and motor-evoked potential monitoring without a wake-up test during idiopathic scoliosis surgery. An accepted standard of care. *Spine*, 1998, vol. 23, no. 12, pp. 1392-1400.
41. Legatt A.D. Current practice of motor evoked potential monitoring: results of a survey. *J. Clin. Neurophysiol.*, 2002, vol. 19, no. 5, pp. 454-460.
42. Macdonald D.B. Intraoperative motor evoked potential monitoring: overview and update. *J. Clin. Monit. Comput.*, 2006, vol. 20, no. 5, pp. 347-377.
43. Sutter M.A., Eggspuehler A., Grob D., Porchet F., Jeszenszky D., Dvorak J. Multimodal intraoperative monitoring (MIOM) during 409 lumbosacral surgical procedures in 409 patients. *Eur. Spine J.*, 2007, vol. 16, no. Suppl. 2, pp. S221-S228.
44. Bose B., Sestokas A.K., Schwartz D.M. Neurophysiological monitoring of spinal cord function during instrumented anterior cervical fusion. *Spine J.*, 2004, vol. 4, no. 2, pp. 202-207.
45. Hilibrand A.S., Schwartz D.M., Sethuraman V., Vaccaro A.R., Albert T.J. Comparison of transcranial electric motor and somatosensory evoked potential monitoring during cervical spine surgery. *J. Bone Joint Surg. Am.*, 2004, vol. 86-A, no. 6, pp. 1248-1253.

46. Oner A., Ely C.G., Hermsmeyer J.T., Norvell D.C. Effectiveness of EMG use in pedicle screw placement for thoracic spinal deformities. *Evid. Based Spine Care J.*, 2012, vol. 3, no. 1, pp. 35-43.
47. Jones S.J., Buonamassa S., Crockard H.A. Two cases of quadriparesis following anterior cervical discectomy, with normal peri-operative somatosensory evoked potentials. *J. Neurol. Neurosurg. Psychiatry*, 2003, vol. 74, no. 2, pp. 273-276.

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