A MULTIMODAL APPROACH TO INTRAOPERATIVE NEUROMONITORING OF THE SPINAL CORD DURING SPINAL DEFORMITY CORRECTION

A.V. Buzunov, A.S. Vasyura, D.N. Dolotin, A.Yu. Sergunin, V.V. Novikov
Novosibirsk Research Institute of Traumatology and Orthopaedics n.a. Ya.L. Tsivyan, Novosibirsk, Russia

Objective. To analyze the results of a multimodal approach in intraoperative neurophysiological monitoring during surgical correction of spinal deformities.

Material and Methods. The paper describes a variant of intraoperative neurophysiological monitoring of the spinal cord and nerve root functions which was used in the correction of scoliotic deformity of the spine in 138 patients. Surgery was performed in 83 patients aged 10 to 17 years and in 55 patients older than 17 years. The average age of patients was 20.23 ± 8.3 years. There were 41 male and 97 female patients. The primary scoliotic curve was localized in the thoracic spine in 90 cases, in the thoracolumbar spine in 27 cases, and in the lumbar spine in 21 cases.

Results. In the early postoperative period, two patients developed neurological deficit, the electrophysiological predictors of which were recorded during intraoperative neurophysiological monitoring. In one case, the deficit gradually regressed completely due to the measures taken by the operating team during surgery; in the second case, a persistent neurological deficit in the form of lower paraplegia persisted, despite the measures taken during the surgical treatment. In other cases, intraoperative neurophysiological monitoring did not reveal any changes in the spinal cord and nerve roots, which in the early postoperative period would lead to the appearance or aggravation of motor deficit.

Conclusion. A multimodal approach to intraoperative neurophysiological monitoring provides an operating surgeon with an objective assessment of the state of the spinal cord and nerve roots at any stage of surgery, which allows timely identification and elimination of the causes of their damage, thereby reducing the likelihood of neurological deficit development or aggravation in the postoperative period.

Key Words: intraoperative neurophysiological monitoring, multimodal approach, somatosensory evoked potentials, motor evoked potentials, D-wave, spontaneous electromyography, TOF stimulation, temperature control, spine scoliotic deformity.

Please cite this paper as: *Buzunov AV, Vasyura AS, Dolotin DN, Sergunin AYu, Novikov VV. A multimodal approach to intraoperative neuromonitoring of the spinal cord during spinal deformity correction. Hir. Pozvonoc. 2021;18(1):31–38. In Russian.*

DOI: http://dx.doi.org/10.14531/ss2021.1.31-38.

Patients with spinal deformities in the form of vertebral malformations constitute a special group of individuals who require early disease diagnosis, constant follow-up by multidisciplinary specialists and, if necessary, timely high-tech surgical treatment aimed at deformity correction.

To date, there are no precise recommendations for the choice of a surgical technique for the treatment of congenital spinal deformities that would minimize possible complications and improve the patient's quality of life, since congenital kyphosis and scoliosis have different pathogenesis and require an individual approach.

To achieve a favorable outcome in the surgical treatment of this group of patients, the surgeon must have not only extensive clinical experience and modern surgical instruments but also a full range of radiology diagnosis methods and intraoperative monitoring of the functional state of the spinal cord. This approach to surgical treatment of patients is considered mandatory, since direct spinal cord injury and ischemic disorders during spinal deformity correction can lead to persistent neurological deficits and subsequent disability, thus reducing the patient's quality of life [1]. We believe that the risk of neurological complications depends on the spinal deformity type and severity. In case of combined approaches to surgery, intraoperative hypotension, profuse bleeding, and spinal cord revision also affect the risk of complications. According to foreign authors [2–4], the risk of neurological complications is approximately 1–2 %.

In the past, surgeons used the only highly reliable intraoperative method for detecting neurological deficits available at that time: the Stagnara wake-up test. The essence of the test is to awaken the patient during surgery and assess the voluntary movements of the lower limbs, i.e. the functions of the motor corticospinal tract. However, certain shortcomings were identified when performing the test. The anesthesiologist interrupted the effect of anesthesia and muscle relaxants, which did not always lead to awakening, and some pediatric patients were unable to follow the doctor's instructions due to difficulties with verbal expression [5]. Patient's neurological status was assessed real-time, i.e. during a specific time interval of awakening lasting for 15–20 min, then anesthetics had to be re-administered. Re-examination during surgery was problematic; because of that, the test was conducted at the end of the correction phase, which reduced its effectiveness.

Another test disadvantage is that it does not allow for assessment of the spinothalamic tract state [3].

Intraoperative neurophysiological monitoring (IONM) is currently used worldwide to assess the spinal cord function at all stages of surgical treatment of scoliosis. In our clinic, we abandoned the methods of a separate study of either the sensory or motor system and decided to use a multimodal approach to IONM that includes a comprehensive study of the functioning of both the corticospinal and spinothalamic tracts [1, 3, 4]. We investigated the state of the autonomic function of the spinal cord by measuring the skin temperature of the lower limbs during surgical treatment while using the generally accepted methods [6].

We believe that this multimodal approach to IONM can increase the sensitivity and specificity of identifying the predictors of neurological deficit in injuries and ischemic disorders of the spinal cord and nerve roots during spinal deformity correction and provide its timely prevention.

Despite the worldwide use of IONM, there are limited data on effectiveness of the multimodal approach to IONM in the surgical correction of spinal deformities [7]; there are no data on the assessment of autonomic function of the spinal cord, except for publications by the researchers at our institute [6, 8].

The aim of the study is to analyze the results of a multimodal approach to intraoperative neurophysiological monitoring during surgical correction of spinal deformities.

Material and Methods

In a retrospective study, the treatment results of 138 patients with scoliosis of various etiologies operated on in 2019 using a multimodal approach to IONM were considered. The neurological status of patients was assessed pre- and postoperatively. There were 83 individuals aged 10–17 years and 55 patients aged > 17 years (after the end of active bone growth). The average age of the patients was 20.2 ± 8.3 years. There were 41 males and 97 females. There were 90 cases with the primary thoracic curve, 27 patients with the thoracolumbar curve, and 21 individuals with lumbar scoliosis. All patients underwent instrumented correction of spinal deformity followed by transpedicular fixation of thoracolumbar segments. Surgical correction of deformity using the VCR (Vertebral Column Resection) technique led to neurological deficit in the form of lower paraplegia in one case. No neurological deficits were recorded in the rest of the patients in the early postoperative period; the wake-up test was not performed.

After anesthetic induction and patient positioning, electrodes were inserted into the peripheral muscles for intraoperative neurophysiological monitoring. We used a 16-channel ISIS IOM system (Inomed, Germany) and a 24-channel IOM (Neurosoft, Russia); the latter was provided for testing at our clinic. Somatosensory evoked potentials (SSEPs), motor evoked potentials (MEPs), spontaneous (or free-running) electromyography (EMG), TOF stimulation, D-wave, and temperature were recorded.

Anesthesia. Operations were carried out under intravenous anesthesia with the hypnotic agent propofol and the analgesic agent fentanyl; mechanical ventilation was performed using an air-oxygen mixture combined with inhalation anesthetics, the dose of which depended on the maximum alveolar concentration. Depolarizing muscle relaxants were used only during intubation. General anesthesia and brain sedation were assessed in parallel based on the data obtained using the BIS monitor. The latter measures the bispectral index, which allows for reducing the risk of early recovery from anesthesia. This method of anesthesia is optimal for obtaining reliable data and excluding false negative results during IONM. The use of other anesthetics leads to the depressive effect in the form of decreased cortical excitability, delayed axonal conduction through the corticospinal tract, and reduced synaptic transmission in alpha motor neurons [9–11].

TOF stimulation. This method allows for an objective assessment of muscle relaxation degree at any stage of surgery. Either peroneal or median nerve is stimulated with four pulses of 2 Hz frequency, 200–500 μs duration, and 10–50 mA intensity (determined individually). Next, four sequential motor responses T1, T2, T3, and T4 were recorded from the target muscles. *M. abductor pollicis brevis* and *m. tibialis anterior* were used for obtaining an EMG from the upper and lower limbs, respectively. The device measured amplitude of the T4 motor response in relation to T1. The amplitude of all four responses was equal at 100 % TOF; T4, T3, and T2 motor responses were not recorded at 25, 20, and 10 % TOF, respectively. At 0 % TOF, the neuromuscular transmission was blocked completely, and no response was recorded.

Spontaneous (free-running) EMG. Free-running EMG was recorded to assess the functional state of the spinal nerve roots and prevent injury during screw placement and the main stage of spinal deformity correction.

SSEPs. The cortical SSEP responses were recorded using corkscrew electrodes placed subcutaneously on the scalp at Cz–Fz points according to the international 10–20 system. Peroneal nerves were stimulated using needle electrodes placed on both sides. The stimulus duration was 200 μs; the stimulation frequency was 3.7–5.1 Hz. The intensity of the suprathreshold stimulation was selected individually (range, 15–25 mA). The high-frequency and low-frequency filter cutoffs were set at 30 Hz and 600 Hz, respectively; the EEG epoch was 100 μs, the number of averages was 200. No SSEPs were recorded from the upper limbs.

Transcranial electrical stimulation. Transcranial electrical stimulation of the precentral gyrus was performed using corkscrew electrodes placed subcutaneously at C3–C4 points according to the international 10–20 system. Responses were recorded from the target muscles of the lower limbs on both sides: *m. vastus lateralis, m. tibialis anterior*, and *m. abductor hallucis.* To exclude attenuation of motor responses during transcranial stimulation and their subsequent disappearance due to the action of muscle relaxants, *m. abductor pollicis brevis* on both sides were also used as target muscles of the upper limbs. The stimulation was carried out using a series of five pulses. The pulse current was selected individually (range, 70–220 mA) after obtaining motor responses from all peripheral target muscles. The pulse duration was 200 μs. The interstimulus interval was 4 μs. The high-frequency and low-frequency filter cutoffs were set at 30 and 2,000 Hz, respectively.

D-wave. According to the researchers [12, 13], D-wave is a reliable criterion for assessing the functional state of the corticospinal tract.

Transcranial stimulation of the precentral gyrus by a single rectangular pulse of 0.3–0.5 μs was used to record a D-wave. Responses were recorded from the epidural space using a three-terminal electrode, which is usually placed distally but not below the conus and epiconus, since they lack the motor corticospinal tract.

The advantage of using the D-wave is that it is independent on muscle relaxants and more resistant to general anesthesia than transcranial electrical stimulation. However, it should be kept in mind that the scoliotic curve deforms the spinal cord as well, which makes it difficult to place electrodes physically close to it and ensure their precise positioning along the midline [4, 14]. This results in a false absence of response. The recorded D-wave looks like a two-phase positive-negative complex.

The disappearance of MEPs from the target muscles is usually preceded by a change in the D-wave amplitude. However, the D-wave may remain stable, or the amplitude can slightly decrease, despite the complete disappearance of MEPs from the target muscles. The point of no return is the complete absence of MEPs upon > 50 % decrease in the D-wave amplitude. If this happens, surgical procedures should be suspended, and corrective measures should be taken to restore the MEP. If no MEP recovery is observed, the surgery should be stopped because of a very high risk of severe motor impairment. The disappearance of the D-wave is a predictor of development of persistent motor deficit after the patient wakes up [4, 14]. A decrease in the motor response amplitude from some key target muscles of the lower limbs followed by a complete disappearance of response from them either without a decrease in the D-wave amplitude or ⩽ 50 % decrease in the amplitude were also observed, which in the early postoperative period was manifested by a transient motor deficit.

Skin temperature measurement. Constant and continuous monitoring of surface skin temperature was performed every five minutes from the start of surgery until its end using digital thermography sensors (Dräger breathing apparatus); the sensors were placed on the posterior surface of the lower legs [6, 8, 15]. The control mechanism was based on the fact that an accidental (iatrogenic) injury to the thoracic spinal cord during corrective surgery leads to post-traumatic spinal sympathectomy. The latter may be not only due to damage to the sympathetic trunk at T1–L2 but also due to ischemia of the lateral (Clarke's) columns. Thus, a spinal cord injury with damage or compression of anterior structures, including the anterior spinal artery, results in impaired spinal cord microcirculation. The vascularization area between anterior and posterior spinal arteries, i.e. the area of the mid-central parts of the posterior horns and Clark's columns, is disturbed the most. The absence of functionally significant vascular anastomoses in this area leads to local ischemia, which is manifested by concomitant neurological symptoms, including spinal sympathectomy. This, in turn, decreases the tone of vasoconstrictors in skin vessels of the lower limbs and increases cutaneous blood flow and skin temperature in the lower limbs [6, 8].

The significance criteria for the deviations from the normal amplitude and time parameters during SSEP recording were the following: a 50 % decrease in the peak amplitude relative to the baseline, ⩾ 80 % drop in the amplitude of the motor peaks up to their complete disappearance, a > 10–15 % increase in latency in both cases, a > 50 % drop in the D-wave amplitude relative to the initial values. For thermometry assessment, an increase in temperature by more than 1 °C was considered an alarm criterion [6].

Results and Discussion

Surgical correction of scoliotic deformities is a risk-associated treatment method, since it implies a high likelihood of iatrogenic spinal cord injury. Considering the nature of the surgical treatment for scoliosis correction, assessing the damage to the spinal cord in the surgical wound is impossible during surgery; it may remain unnoticed by the surgeon throughout the operation.

The risk of developing motor and sensory deficits is determined by the following factors: placement of transpedicular screws at the scoliotic apex, especially at its concave side, scoliosis severity, the nature of surgical correction, and a decrease in the perfusion pressure of the spinal cord as a result of hypotension and heavy blood loss [1, 2, 7, 13].

A complex of intraoperative neurophysiological techniques is currently used for evaluating the anatomical and functional state of the central and peripheral nervous systems in order to reduce the likelihood of intraoperative and early postoperative neurological complications.

To increase the IONM information capacity, we followed an extensive path: we increased the number of modules used for a more detailed assessment of the nervous tissue state during surgery, thereby increasing data reliability in critical situations, which also made it possible to use the wake-up test less often [15].

A single injection of the short-acting muscle relaxant Listenone during patient intubation and anesthesia induction was followed by TOF (train-of-four) stimulation with a 10-min interval to monitor the level of muscle relaxation in order to exclude the residual effects of anesthesia. This test was used to exclude false negative results associated with the muscle relaxant effect of the drug.

Next, the initial evoked potentials were recorded in the patient, and the baseline was determined based on the data obtained after skin incision and prior to administration of muscle relaxants [9, 10]. Next, the latency of the evoked responses, their amplitude, the shape of the baseline, and its reproducibility were assessed.

Spontaneous (free-running) EMG was recorded starting from the access to the posterior spinal structures until hemostasis was achieved, as well as during wound closure. It allowed for controlling the surgeon's actions in the surgical wound to assess mechanical irritation, which indicates the functioning of adjacent nerve structures, and, therefore, a possible iatrogenic mechanical and ischemic damage.

Bioelectric activity in the target muscles is recorded upon mechanical stimulation of the spinal root. A slight mechanical effect on the spinal root area or its displacement, provided that the risk of injury is minimized, allows for recording short (about 30-s) low-amplitude and low-frequency bursts of bioelectrical activity in the target muscles. Root compression or hyperextension resulting in its ischemia was recorded in spontaneous EMG by applying a continuous bioelectric stimulus, usually lasting more than 5 s (train type), to the target muscles. The surgeon is notified, after which the surgical intervention is corrected. Triggered EMG proved to be more informative: it allowed for visually better recording of an irritative effect on the spinal roots during surgical procedures that lacks stimulation artifacts, which was immediately notified to the surgeon.

Peripheral nerves of the lower limbs were stimulated to obtain cortical P39 SSEPs for further assessment of the nerve pulse through the spinothalamic tract from the periphery along the entire spinal cord to the cortex of the postcentral gyrus. SSEPs were assessed during the entire process of surgical treatment of scoliosis [16]. Isolated intraoperative damage to the posterior spinal cord regions can be detected only through the loss of SSEPs; however, SSEP registration alone is not effective enough to prevent the development of neurological deficits [4, 9, 10].

In most cases, the effect of muscle relaxants ended during the beginning of screw placement, which was confirmed by TOF stimulation.

Transcranial electrical stimulation of the precentral gyrus was performed alongside with SSEP. This resulted in a nerve pulse passing through the descending corticospinal tract to the peripheral target muscles, where the motor response was recorded. This study method allows for assessing the function of motor corticospinal tracts, alpha motor neurons of the anterior horns of the spinal cord, and segmental interneurons.

During installation and correction of both rods, MEP stimulation was usually maintained at a regular frequency of about one pulse per minute.

A decrease in perfusion pressure of the spinal cord during surgical correction of spinal deformities leads to impaired blood supply to the anterior spinal cord and manifests itself as a bilateral loss of MEPs with SSEP preservation. In some cases, temporary false-positive events were observed during the surgical procedure, which were expressed in an isolated loss of MEPs with normal or decreased SSEPs; they were observed in approximately 10 % of the surgeries. According to our observations, these changes are more likely associated with low mean arterial pressure (< 60 mm Hg); MEPs occur and further reach the baseline upon an induced increase in the mean arterial pressure with a surgical pause of about 10–15 minutes. This allowed for continuing the surgery and correcting spinal deformity as originally planned.

Screw placement and the use of surgical instrumentation can cause damage to the posterior spinal cord structures leading to a significant reduction or loss of SSEPs without a decrease in MEPs. Lateral spinal cord injury caused by Kerrison rongeur leads to the Brown-Sequard syndrome, which is usually manifested by unilateral loss of MEPs and/or SSEPs [2]. Surgical correction of spinal deformities including shortening vertebrotomies poses a high risk of spinal cord injury and a bilateral decrease in SSEPs and MEPs with their subsequent absence, as evidenced by IONM [2]; this was observed in one case.

In borderline cases, as well as in severe scoliotic deformities, transcranial stimulation of the motor cortex by single electrical pulses with further registration of a D-wave by an epidural electrode at T10–T11 was used. In the absence of negative dynamics in the D-wave amplitude upon a decrease in SSEPs and the absence of MEPs on both sides, the so-called false-positive events were differentiated. This added some confidence in the absence of neurological deficit with further regression of changes in the recorded picture and an increase in both MEPs and SSEPs with a mean blood pressure elevation. A decrease in the amplitudes of the D-wave, SSEPs, and MEPs with their further disappearance was recorded in one case of surgical correction of scoliosis during vertebrotomy; the patient then developed lower paraplegia upon awakening, which was more likely due to the Adamkiewicz artery spasm.

The method developed in the clinic for measuring lower limb temperature is used on an ongoing basis [6]. Up to a 0.1 °C change in the skin temperature of the lower limbs were recorded during surgical treatment of spinal deformities using skin temperature monitoring. The alarm criterion was considered a ⩾ 1 °C temperature elevation.

When registering motor and sensory disorders of the spinal cord conduction, a surgical 10–15-min pause was usually made with the parallel application of glucocorticoids and diuretics; the mean arterial pressure was elevated, while the corrective effect of the transpedicular system was decreased. A ⩽ 50 % decrease in the D-wave amplitude relative to the baseline was observed in one case of surgery for severe scoliosis; a statistically significant decrease (by almost 80 %) in MEPs and the absence of SSEPs were noted with an increase in the temperature of the lower limbs by 0.5 and 0.4 °C compared to the preoperative value. All possible causes of these changes were considered, and all reasonable measures for their elimination were used. Scoliotic curve correction was carried out, although not to the planned extent. Lower limb paraparesis with further complete regression in the early postoperative period was observed in a patient upon awakening.

We believe that controlling the course of surgical treatment and understanding the aim of every surgical manipulation carried out at a specific period of time allows for timely cessation of procedures on the spinal cord, which in most cases would immediately lead to regression of negative changes in the spinal cord and restoration of evoked potentials thus preventing the development of persistent neurological deficit.

Considering the high percentage of positive outcomes after correction of severe (with a large scoliotic angle and the presence of hemivertebrae) scoliosis and no neurological deficit aggravation due to the IONM use, we can state that the obtained results may well indicate the correct choice of the modules used during IONM. However, the picture may be directly the opposite if IONM is not used, since it would be impossible to predict a change in the neurological status during scoliosis correction. We believe that the lack of development or aggravation of the existing neurological deficit is the main evidence of the correct choice of a neurophysiological method for intraoperative monitoring of the spinal cord and nerve root functions.

Conclusion

Our set of modules for IONM during surgery for spinal deformity correction allows one to quickly and reliably assess the physiological state of the spinal cord and obtain real-time data on the risk of iatrogenic neurotrauma. This makes it possible to take certain preventive measures when it is not too late.

We believe that a decrease in MEPs and their subsequent attenuation, as well as a reduction in the D-wave amplitude followed by its disappearance and a ⩾ 1 °C increase in the skin temperature on one or both lower limbs in the absence of positive dynamics but with a further regression of these changes when cancelling the correction during IONM, despite all the measures, is an indicator that the surgery should be stopped and performed later (staged operation).

Conducting IONM according to our method is safe, reproducible and, in our opinion, more reliable and informative in assessing motor and sensory conduction of the spinal cord, which allows for preventing the development of persistent neurological deficit or its aggravation, patient disability and, as a result, ensures no reduction in the patient's quality of life.

The study was not supported by a specific funding.
The authors declare that there is no conflict of interests.

References

1. **Vitale MG, Skaggs DL, Pace GI, Wright ML, Matsumoto H, Anderson RC, Brockmeyer DL, Dormans JP, Emans JB, Erickson MA, Flynn JM, Glotzbecker MP, Ibrahim KN, Lewis SJ, Luhmann SJ, Mendiratta A, Richard BS 3rd, Sanders JO, Shah SA, Smith JT, Song KM, Sponseller PD, Sucato DJ, Roye DP, Lenke LG.** Best practices in intraoperative neuromonitoring in spine deformity surgery: development of an intraoperative checklist to optimize response. Spine Deform. 2014;2:333–339. DOI: 10.1016/j.jspd.2014.05.003.
2. **Lewis SJ, Wong IHY, Strantzas S, Holmes LM, Vreugdenhil I, Bensky H, Nielsen CJ, Zeller R, Lebel DE, de Kleuver M, Germscheid N, Alanay A, Berven S, Cheung KMC, Ito M, Polly DW, Shaffrey CI, Qiu Y, Lenke LG.** Responding to intraoperative neuromonitoring changes during pediatric coronal spinal deformity surgery. Global Spine J. 2019;9(1 Suppl):15S–21S. DOI: 10.1177/2192568219836993.
3. **Pastorelli F, Di Silvestre M, Plasmati R, Michelucci R, Greggi T, Morigi A, Bacchin MR, Bonarelli S, Cioni A, Vommaro F, Fini N, Lolli F, Parisini P.** The prevention of neural complications in the surgical treatment of scoliosis: the role of the neurophysiological intraoperative monitoring. Eur Spine J. 2011;20(Suppl 1):S105–S114. DOI: 10.1007/s00586-011-1756-z.
4. **Stecker MM.** A review of intraoperative monitoring for spinal surgery. Surg Neurol Int. 2012;3(Suppl 3):S174–S187. DOI: 10.4103/2152-7806.98579.
5. **Khit MA, Kolesov SV, Kolbovskiy DA, Morozova NS.** The role of the neurophysiological intraoperative monitoring to prevention of postoperative neurological complication in the surgical treatment of scoliosis. Nervno-mysecnye bolezni. 2014;(2):36–41. In Russian. DOI: 10.17650/2222-8721-2014-0-2-36-41.
6. **Novikov VV, Vasjura AS, Lebedeva MN, Mikhaylovskiy MV.** Method of intraoperative diagnostics of neurological complications in operations on spine. Patent RU 2423935. Appl. 19.08.2009; publ. 20.07.2011, Bull. 20. In Russian.
7. **Thuet ED, Winscher JC, Padberg AM, Bridwell KH, Lenke LG, Dobbs MB, Schootman M, Luhmann S J.** Validity and reliability of intraoperative monitoring in pediatric spinal deformity surgery: a 23-year experience of 3436 surgical cases. Spine. 2010;35:1880–1886. DOI: 10.1097/brs.0b013e3181e53434.
8. **Vasyura AS, Mikhaylovskiy MV, Novikov VV, Chesheva EV.** Intraoperative diagnosis of neurological complications in surgery of severe scoliosis: report of clinical cases. Hir. Pozvonoc. 2018;15(2):7–11. In Russian. DOI: 10.14531/ss2018.2.7-11.
9. **Bjerke BT, Zuchelli DM, Nemani VM, Emerson RG, Kim HJ, Boachie-Adjei O.** Prognosis of significant intraoperative neurophysiologic monitoring events in severe spinal deformity surgery. Spine Deform. 2017;5:117–123. DOI: 10.1016/j.jspd.2016.11.002.
10. **Gupta M, Taylor SE, O'Brien RA, Taylor WR, Hein L.** Intraoperative Neurophysiology Monitoring. In: Phillips F, Lieberman I, Polly Jr. D, Wang M. (eds). Minimally Invasive Spine Surgery. Springer, Cham, 2019:69–81. DOI: 10.1007/978-3-030-19007-1_7.
11. **Koruk S, Mizrak A, Kaya Ugur B, Ilhan O, Baspinar O, Oner U.** Propofol/dexmedetomidine and propofol/ketamine combinations for anesthesia in pediatric patients undergoing transcatheter atrial septal defect closure: a prospective randomized study. Clin Ther. 2010;32:701–709. DOI: 10.1016/j.clinthera.2010.04.010.
12. **Kothbauer KF, Deletis V.** Intraoperative neurophysiology of the conus medullaris and cauda equina. Childs Nerv Syst. 2010;26:247–253. DOI: 10.1007/s00381-009-1020-6.
13. **Yoshida G, Ando M, Imagama S.** Alert timing and corresponding intervention with intraoperative spinal cord monitoring for high-risk spinal surgery. Spine. 2019;44:E470–E479. DOI: 10.1097/BRS.0000000000002900.
14. **Ulkatan S, Neuwirth M, Bitan F, Minardi C, Kokoszka A, Deletis V.** Monitoring of scoliosis surgery with epidurally recorded motor evoked potentials (D wave) revealed false results. Clin Neurophysiol. 2006;117:2093–2101. DOI: 10.1016/j.clinph.2006.05.021.
15. **Novikov VV, Novikova MV, Tsvetovsky SB, Lebedeva MN, Mikhailovsky MV, Vasyura AS, Dolotin DN, Udalova IG.** Prevention of neurological complications in correction surgery for severe spinal deformities. Hir. Pozvonoc. 2011;(3):66–76. In Russian. DOI: 10.14531/ss2011.3.66-76.
16. **Sacko O, Lauwers-Cances V, Brauge D, Sesay M, Brenner A, Roux FE.** Awake craniotomy vs surgery under general anesthesia for resection of supratentorial lesions. Neurosurgery. 2011;68:1192–1199. DOI: 10.1227/NEU.0b013e31820c02a3.

Address correspondence to:
Buzunov Aleksey Vladimirovich
Novisibirsk Research Institute of Traumatology and Orthopaedics
n.a. Ya.L. Tsivyan,
17 Frunze str., Novosibirsk, 630091, Russia,
alekseibuzunov@mail.ru

Received 16.09.2021
Review completed 24.02.2021
Passed for printing 26.02.2021

Aleksey Vladimirovich Buzunov, MD, PhD, neurosurgeon, neurophysiologist, Novisibirsk Research Institute of Traumatology and Orthopaedics n.a. Ya.L. Tsivyan, 17 Frunze str., Novosibirsk, 630091, Russia, ORCID: 0000-0003-4438-8863, alekseibuzunov@mail.ru;
Aleksandr Sergeyevich Vasyura, MD, PhD, trauma orthopaedist, Department of Pediatric Orthopedics, Novosibirsk Research Institute of Traumatology and Orthopaedics n.a. Ya.L. Tsivyan, 17 Frunze str., Novosibirsk, 630091, Russia, ORCID: 0000-0002-2473-3140, niito@niito.ru;
Denis Nikolayevich Dolotin, trauma orthopaedist, Department of Pediatric Orthopedics, Novisibirsk Research Institute of Traumatology and Orthopaedics n.a. Ya.L. Tsivyan, 17 Frunze str., Novosibirsk, 630091, Russia, ORCID: 0000-0003-0430-6595, d.dolotin@mail.ru;
Aleksandr Yuryevich Sergunin, trauma orthopaedist, Department of Pediatric Orthopedics, Novisibirsk Research Institute of Traumatology and Orthopaedics n.a. Ya.L. Tsivyan, 17 Frunze str., Novosibirsk, 630091, Russia, ORCID: 0000-0001-6555-2007, Saport2010@ngs.ru;
Vyacheslav Viktorovich Novikov, DMSc, Head of the Research Department of Pediatric and Adolescent Vertebrology, Novisibirsk Research Institute of Traumatology and Orthopaedics n.a. Ya.L. Tsivyan, 17 Frunze str., Novosibirsk, 630091, Russia, ORCID: 0000-0002-9130-1081, niito@niito.ru.