ISSN 0030-5987. Orthopaedics, traumatology and prosthetics. 2021. № 4

ORIGINAL ARTICLES

УДК 617.547-089.8:616.8-003-06](045)

DOI: http://dx.doi.org/10.15674/0030-5987202145-12

Practical aspects of intraoperative neuromonitoring in patients with different spinal pathologies

O. O. Barkov, D. R. Duplii

Sytenko Institute of Spine and Joint Pathology National Academy of Medical Sciences of Ukraine, Kharkiv

Objective. To study the operating parameters and phenomena of intraoperative monitoring and to identify the specificity and sensitivity of its different modalities associated with postoperative neurological complications in patients with different spinal pathologies. Methods. The intraoperative neurophysiological monitoring (IOM) protocols of 88 patients who underwent spinal surgeries were analyzed: kyphoscoliotic spinal deformities — 58 (68 %), traumatic — 12 (13.3 %), degenerative diseases — 10 (11.7 %), neoplasms — 6 (6.7 %). In 33 (38.4 %) cases, a combination of modalities of motor evoked potentials (MEP) and transpedicular screws stimulation (TSS) was used, in 36 (41.9%) — only MEP, 17 (19.8 %) — TSS. In all cases, freerun and triggered EMG was used. Results. The most stable MEPs were recorded at mm. tibibalis anterior, mm. abductor hallucis longus. It has been proven that an unfavorable and reliable factor of the anxiety sign is a unilateral sustained decrease in the MEP amplitude by more than 80 %. According to the TSS results 424 (97.5 %) screws are installed correctly, 1 (0.2 %) false negative case of incorrect installation. False positive results for the TSS test ranged from 34.7 to 15.4 %, depending on the chosen critical threshold of the current applied to the pedicle screw. We consider the threshold of the TSS test at 13 mA satisfactory, and below it, unsatisfactory. A group of patients was identified who had 72 screws (16.6% of all analyzed) who, according to the results of the TSS test, received an unsatisfactory assessment, and X-ray did not reveal any deviations in the position of the screws.Conclusions. IOM modalities are highly sensitive and specific to damage to the structures of the spinal cord and spinal nerves, but dependence on a number of external factors reduces their information content, which leads to false positive and false negative results. It was established, that the dynamics of the MEP amplitudes of the target muscles differs in information content and efficiency during surgery due to individual morphological and motor characteristics. Key words. Intraoperative monitoring, motor evoked potentials, screw stimulation test, spinal pathology.

Мета. Дослідити робочі параметри та явища інтраопераційного моніторингу та виявити специфічність і чутливість різних його модальностей у зв'язку з післяопераційними неврологічними ускладненнями в пацієнтів із різною патологією хребта. Методи. Проаналізовано протоколи інтраопераційних нейрофізіологічних моніторингів (ІОМ) 88 хворих, яким проведено хірургічні втручання на хребті: кіфосколіотичні деформації хребта — 58 (68 %), травматичні — 12 (13,3 %), дегенеративні захворювання — 10 (11,7 %), новоутворення — 6 (6,7 %). У 33 (38,4 %) випадках використано поєднання модальностей моторних викликаних потенціалів (МВП) і стимуляцію транспедикулярних гвинтів (СТГ), у 36 (41,9 %) — лише МВП, 17 (19,8 %) — СТГ. У всіх випадках застосовано самопоточну і тригерну електроміографію. Результати. Найстабільніші МВП виявлено на mm. tibibalis anterior, mm. abductor hallucis longus. Підтверджено, що несприятливим і достовірним чинником ознаки тривоги є однобічне стійке зниження амплітуди МВП більш ніж на 80 %. За результатами СТГ 424 (97,5 %) гвинти встановлено коректно, 1 (0,2 %) — хибно негативний випадок некоректного проведення. Хибно позитивні результати за тестом СТГ склали від 34,7 до 15,4 % залежно від обраного критичного порога сили струму, який надходив на транспедикулярний гвинт. Уважаємо поріг тесту СТГ у 13 мА задовільним, а нижчий — незадовільним. Визначено групу пацієнтів, у яких встановлено 72 гвинти (16,6 % від усіх аналізованих), котрі за результатами тесту СТГ отримали незадовільну оцінку, а рентгенологічно не виявлено похибок у положенні гвинтів. Висновки. Модальності ІОМ високочутливі та специфічні до ушкоджень структур спинного мозку та спинномозкових нервів, але залежність від низки зовнішніх чинників знижує їхню інформативність, що призводить до отримання хибно позитивних і хибно негативних результатів. Визначено, що динаміка амплітуд МВП м'язів-мішеней відрізняється за інформативністю й ефективністю під час хірургічного втручання через індивідуальні морфологічні та моторні характеристики. Ключові слова. Інтраопераційний моніторинг, моторні викликані потенціали, тест стимуляції гвинтів, патологія хребта.

Key words. Intraoperative monitoring, motor evoked potentials, screw stimulation test, spinal pathology

Introduction

Intraoperative monitoring (IOM) during spinal surgery has become a routine practice worldwide [1]. Monitoring the response of the target muscles allows real-time detection of irritation of nerve structures in response to surgery and immediate action to eliminate neurological complications. This increases the surgeon's confidence in the safety of his actions during manipulations on the spine, for instance in correction of spinal deformities, following insertion of transpedicular screws, which significantly affects the quality of the intended outcome of surgical treatment. There is a big discrepancy between the criteria for assessing IOM, their specificity, which complicates the direct interpretation of intraoperative indicators [2–4]. This necessitates further studies of IOM parameters to determine their sensitivity and specificity.

The aim of the study: to assess the operating parameters and phenomena of intraoperative monitoring and to identify the specificity and sensitivity of its various modalities in connection with postoperative neurological complications in patients with various spinal abnormalities.

Material and methods

The study was performed according to the plan of research work of the State Institution «Professor M. I. Sytenko Institute of Abnormalities of the Spine and Joints of the National Academy of Medical Sciences of Ukraine»: «To study the main errors and complications of transpedicular fixation in spinal surgery and to develop measures for their prevention and treatment», state registration number 0118U006949. The study was discussed and approved at a meeting of the Committee on Bioethics at SI «M. I. Sytenko IASJ of the MAMS of Ukraine» (Minutes No. 180 of 14.05.2018).

The study involved an assessment of intraoperative neurophysiological monitoring protocols of 88 patients who underwent spinal surgery for the period from March 2014 to November 2021. All operations were performed in posterior approach. Table 1 shows the distribution of patients by nosology. Two protocols were excluded from the study for technical reasons (presence of external electrical leads).

IOM was performed using «NIM-Eclipse system», a neurophysiological unit for surgeons manufactured by «Medtronic». The procedure was carried out in compliance with the guidelines of the American Society of Neurophysiologists [5].

Modalities of transcranial electrical stimulation (TcES) with registration of motor evoked potentials (MEP), self-flow and trigger electromyography (EMG) (*free run EMG* in English literature), and modality of transpedicular screw stimulation (TSS) were used in combination during surgery. Electrodes were installed after initial anesthesia and intubation of the patient under endotracheal anesthesia. «Medtronic» disposable needle electrodes were used. Depending on the level of instrumentation, the muscles located in the corresponding myotomes were monitored: *mm. abdominis rectus* (Th_{II}–Th_{VIII}), *mm. abdominis obliqus* (Th_{X}–Th_{XII}), *mm. vastus lateralis* (L_{II}–L_{IV}), *mm. tibialis anterior* (L_{V}–S_{I}), *mm. abductor hallucis longus* (S_{I}–S_{II}) [6].

Stimulating spiral electrodes were located in the projection area of the motor cortex of the precentral gyrus of the brain at points C3, C4 according to the international classification for the application of electrodes during electroencephalography (EEG) [5]. MEP was induced by single stimuli lasting 0.2 ms and a voltage of 200 to 600 V. MEP was recorded simultaneously on eight channels, where the amplitude, latency and shape of each potential were evaluated. The first stimulation was performed before the intervention in the supine position, the second after turning to the abdominal position. The obtained amplitudes of the MEP (from peak to peak) were taken as individual reference values (baseline) for the patient. The recommended minimum effective amplitude of the MEP should exceed 50 μV [7].

TSS modality was based on the difference in electrical resistance of bone and nerve tissue. Using a probe, a constant current of 0 to 30 mA was applied to the screw head. If a screw is surrounded by high-resistance bone tissue, the current remains within the pin channel at currents up to 30 mA and does not trigger muscle activity. The test ends, the result is considered «excellent». In the case of penetration of the screw into the spinal canal (i. e. in its incorrect location), the current propagates in the direction of lower resistance through the screw and a break in the vertebral arch to the spinal canal, i.e. current leakage. This, in turn, leads to excitation of the nerve root, which manifests itself as a trigger EMG activity in the corresponding myotome at a lower stimulus intensity than in an intact cortical layer. The excita-

Table 1

Distribution of patients by nosology

Nosology	Number of patients (n = 86)
Kyphoscoliotic spinal deformities	58 (68,3 %)
Traumatic spinal injuries	12 (13,3 %)
Degenerative diseases of the spine	10 (11,7 %)
Neoplasms of the spine	6 (6,7 %)

tion threshold of the spinal nerve root is 5 mA [8]. Therefore, the occurrence of trigger EMG activity in a direct current of less than 6–10 mA may be a reason for re-insertion of the transpedicular screw. The absence of EMG activity in a current of 30 mA is an excellent sign of the correctness of the transpedicular screw insertion, 20–29 mA is good, and 10–19 mA is indeterminate, less than 10 μV is unsatisfactory [8]. If there is a current leakage in the event of a stimulus force of less than 10 mA, the TSS test automatically stops, the NIM-Eclipse system provides an alarm in the form of a red indicator on the monitor and surgical probe. If the leakage occurs at a stimulus force of 10–19 mA, the TSS test is stopped and a warning signal is given in the form of a yellow indicator. If the current leakage does not occur up to 30 mA, the TSS test ends, the signal «excellent» in the form of a green indicator is seen.

In 33 (38.4 %) cases the combination of MEP and TSS modalities was employed, in 36 (41.9 %) only MEP, 17 (19.8 %) TSS modality. In all cases, free run EMG was used.

Therefore, in order to avoid confusion of terms when evaluating the results of the neurophysiological test of correct transpedicular screw installation, the positive result of the TSS test will hereinafter be referred to as the presence of «alarm» or «warning»signals, and negative — their absence (i. e. the presence of an «excellent» signal).

The results of TSS modalities for detecting perforation of the medial pedicle of the vertebral arch with a screw were evaluated following determination of: 1) truly negative (absence of «alarm» and «warning» signals of the TSS test, intra- or postoperative radiological confirmation of the correct topographic position of the screw); 2) true positive (presence of «alarm» or «warning» signals of the TSS test, confirmation of incorrect location of the screw during intraoperative radiography; 3) false negative (absence of «alarm» and «warning» signals of the TSS test, but detection of incorrectly located screw on the intra — or postoperative radiography); 4) false positive (presence of «alarm» or «warning» signals of the TSS test against the background of the correct location of the screw on intraoperative radiography) (Fig. 1).

Results and discussion

The average duration of the operation was 7 hours and 6 minutes. During this time, from 4 to 35 TcES was performed, the average number was (14.3 ± 6.49). MEP is a complex action potential caused by stimulation of the motor cortex and recorded in peripheral target muscles. Proper selection of stimulation parameters, such as stimulus frequency, interstimulus interval, and stimulus intensity, is important for effective MEP in a patient under general anesthesia. For example, a group of scientists from France based on an evaluation of 77 operations on scoliosis showed that the optimal frequency for stimulation to obtain intraoperative motor potentials from the anterior tibialis muscle is from 5 to 7 ms (duration 5 ms), interstimulus interval from 2 to 4 ms, stimulus intensity from 300 to 700 V [9].

Typically, in our study, the working force of the stimulus was 200 V. Stimulus intensity was increased to obtain effective MEP in significant reductions in MEP amplitudes or loss of signals (alarm). At the end of the surgery, at the time of bandaging, the magnitude of the stimulus remained the same as in the beginning in 21 % of cases, in 12% the stimulus was increased to 225 V, in 14 % up to 250, in 2 % up to 500 V (Fig. 2).

As the operation progressed and the TcES stimulus voltage increased, the current acting on the patient also increased. In some cases, the current flowing through the patient increased from the first stimulation to the last up to 70 %.

Evaluation of the TcES stimulus voltage and current showed that the electrical resistance of the patient's body did not change significantly or decreased until the end of the operation. The correlation between the duration of surgery and the increase

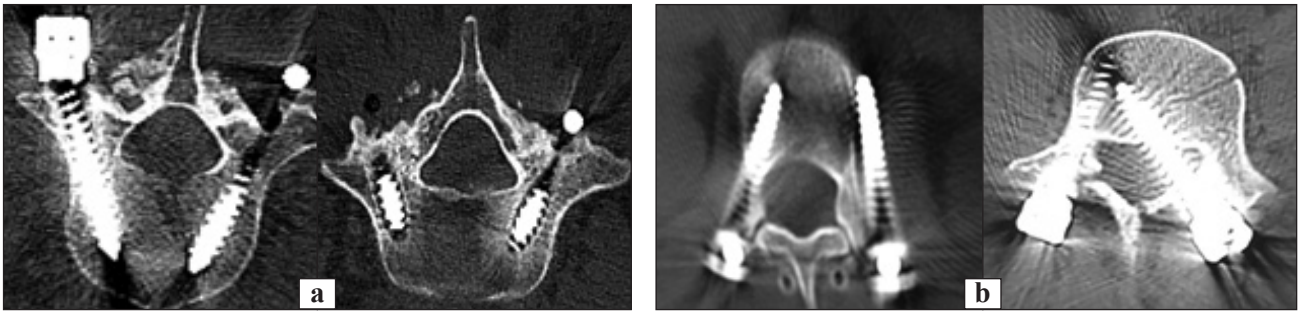

Fig. 1. X-ray control of the location of the screws in the vertebrae: correct (a) and incorrect (b)

in current was statistically insignificant (R < 0.5) (Fig. 3). These results indicate that the forced increase in TcES stimulus voltage and the increase in current flowing through the patient is probably due to decreased excitability of the motor area of the cerebral cortex and conduction of nerve structures due to anesthesia. At the end of the surgery, at the stage of wound suturing, in the case of IOM scenario without alarm signal, the amplitude of the MEP increases, and the strength of the stimulus can be reduced.

MEP amplitudes during surgery varied significantly. For example, there is a graph of the time course of MEP amplitude in a patient with traumatic spinal cord injury (Fig. 4). It shows MEP amplitudes on the lower extremities (*mm. tibialis anterior*) during surgery. The first points are MEP amplitudes obtained before the start of operations at 11:00, the values of which are taken as reference. Then there were amplitude fluctuations, growth tendency, one-time decrease and further increase.

MEP was registered on *mm. tibialis anterior*, *mm. abductor hallucis longus* in all 86 (100 %) patients, on *mm. abdominis rectus* in 59 (69 %), *mm. abdominis obliquus* in 64 (55%), *mm. vastus lateralis* in 59 (69 %). MEP amplitudes varied for technical, surgical and anesthetic reasons. The first MEPs were recorded before the intervention, the latter during suturing of the skin and bandaging. MEP amplitudes at the end of the operation were analyzed, when the effect of anesthesia was usually reduced (Table 2).

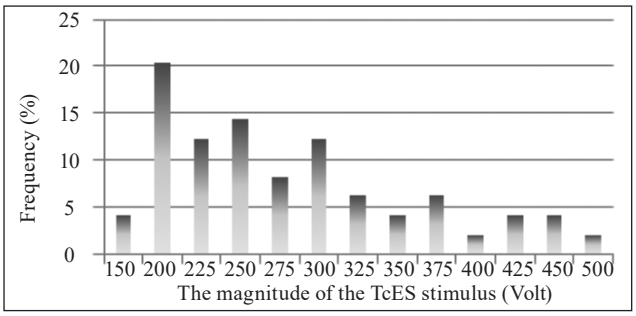

Fig. 2. Histogram of an increase in values of TcES stimuli at the end of surgery

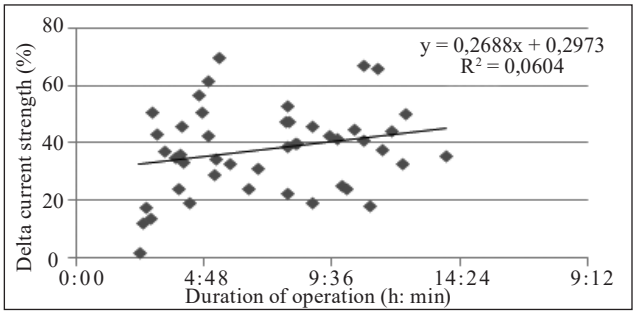

Fig. 3. Correlation between the increase in current flowing through the patient relative to the reference value and the duration of surgery

High MEP amplitudes were recorded on the anterior tibialis and abdominal muscles. MEPs on the quadriceps femoris were low, often less than 50 μV, which reduced their informative value. These findings can be explained by the fact that *mm. abductor hallucis longus* is a distal, compact muscle, has a wider representation in the motor cortex compared to, for example, *mm. vastus lateralis*. On *mm. abdominis rectus* MEPs were high, but there often were obstacles due to the patient's position. The most stable MEPs were observed on *mm. tibialis anterior* and *mm. abductor hallucis longus*, their amplitudes were less prone to mechanical interference and changes in blood pressure.

Thus, MEP amplitudes of target muscles differ in informative value due to individual morphological and motor characteristics (Fig. 5).

That is why it is necessary to use as many muscles as possible for monitoring. For example, in the case of L_V–S_I segmentation, it is more expedient to monitor not only the anterior tibialis muscle, but the foot and thigh muscles as well. In patients with severe spinal deformities, the spinal cord is somewhat compressed, which under anesthesia may disrupt conduction in the corticospinal tract.

General physiological changes, such as a decrease in blood pressure and body temperature, are reflected by a simultaneous decrease in MEP on all channels and return to baseline values after appropriate measures. Various experts consider the reduction of amplitudes relative to the reference from 30 to 50–80 % as an alarm signal [10, 11].

In our study, a bilateral decrease in MEP amplitudes by more than 80 % was observed in 17 (19 %) cases. This decrease was reversible and after increasing the intensity of the stimulus, MEP amplitudes reached reference values. One patient (2 %) had a unilateral steady decrease in MEP amplitudes on

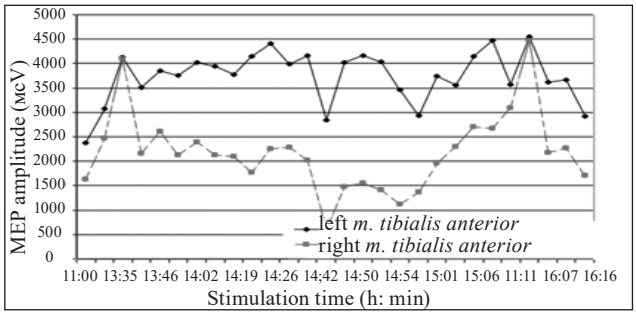

Fig. 4. Time course of MEP amplitudes during surgery

mm. tibialis anterior and *mm. abductor hallucis longus*. In the postoperative period she developed lower monoparesis.

In another case of unilateral decrease in MEP, which was observed 1.5 h after surgical manipulation (open repositioning of the L_V vertebra under conditions of grade IV spondylolisthesis), the amplitude fell on *mm. tibialis anterior* 20 times, and decreased by only 16 % on *mm. abductor hallucis longus*. In the early postoperative period, the patient was diagnosed with monoparesis with subsequent recovery on the 10th day. In other cases, no signs of neurological deficits have been identified.

We also stimulated 435 screws at Th_{IX}–S_I levels (Table 3). Intraoperative transfer of screws was performed in 11 cases in 9 patients. The criterion for the transfer of screws was the «alarm» signal and signs of its incorrect location according to the results of X-ray control. Revision surgical interventions due to incorrect installation of screws were not performed in the follow-up.

True negative results (absence of «alarm» signal and signs of incorrectly located screw) were obtained in 62 (72 %) patients who had 424 (97.5 %) screws installed. At the same time, 284 (86 %) screws were tested for a stimulus force of more than 20 mA, more than 13 mA in all of them. True positive results were obtained in 9 (1.05 %) patients with the installation of 11 (2.5 %) screws. TSS in all the patients was below 13 mA, and in 8 (72.7 %) screws below 10 mA. A false negative result was observed in one patient with one screw (0.2 %).

The presence of an «alarm» signal with correctly installed screws was observed in 13 (15.1 %) patients in case of installation of 151 screws on the test value up to 19 mA, among them in 7 people the TSS test was lower than 10 mA. A false positive result was obtained in 34.7 and 15.4 % of cases, respectively.

Therefore, only 84 screws below 13 mA (2 screws with 11 mA, 1 screw with 13 mA) received a truly positive result when performing 84 screws on the result of TSS from 10 to 19 mA. The TSS test from 13 to 19 mA showed the correct location of 81 screws. This indicates that the conclusion about the «positive» or «negative» result of the TSS test depends on the selected alarm threshold. In our study, the TSS score below 19 mA was classified as a warning signal, uncertainty, and below 10 mA as a defined alarm according to the recommendations of «Medtronic» [8]. Other authors suggest that the alarm threshold below 10–12 mA and even below 5 mA be assessed as unsatisfactory [12].

According to the results of the study, we propose to consider the threshold of the TSS test in 13 mA satisfactory, and below — unsatisfactory, because there were 3 screws incorrectly located on the TSS of 11–13 mA, and after transfer the TSS test was 25–30 mA. The sensitivity of the TSS test according to our results was 91.67 %; specificity under the conditions of the threshold of 19 mA was 73.74 %, 10 mA — 86.36 %. The obtained indicators correspond

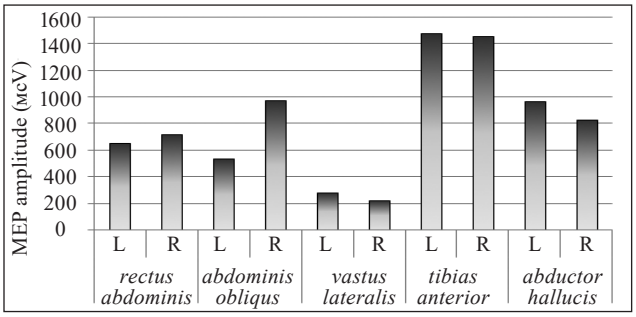

Fig. 5. Histogram of MEP amplitudes. The ordinate axis shows the muscle and the side

Table 2

Results of the evaluation of MEP amplitudes during surgery on the spine

Muscle	Side	Average MEP amplitude (μV)	Standard error	Max	Min	Interval	Quantity
abdominis rectus	left	655.98	±728,23	3017	18	2999	41
	right	721.02	±1205,67	7127	14	7127	41
abdominis obliquus	left	535.73	±86,31	1444	98	1346	22
	right	974.05	±237,13	3975	20	3955	22
vastus lateralis	left	282.73	±68,29	1370	29	1341	26
	right	220.92	±63,82	1647	15	1632	26
tibialis anterior	left	1479.98	±183,65	4993	106	4887	49
	right	1454.31	±179,35	4590	106	4484	49
abductor hallucis longus	left	969.10	±127,20	3645	19	3626	49
	right	829.51	±138,55	3692	20	3672	49

to the results of research by other scientists. In particular, according to the results of the TSS test for 3,112 screws at the L_I–S_I levels, true positive results in 7.8 % were obtained in the range from 2.6 to 19.8 mA. Sensitivity and specificity were estimated at 93.33 % and 92.88 % [13].

According to the criterion of the TSS test, patients were divided into 3 groups (Fig. 6). In the first group (21 patients) 137 screws were tested at a current of 30 μV, i.e. evaluated as an excellent result. In the second (8 people) 74 screws were tested, of which 26 (35.2 %) were rated «excellent», 24 (32.4 %) «good», 24 (32.4 %) «indeterminate». The third group consisted of 15 patients, in whom according to the results of the TSS test the quality of installation of 117 screws was classified as unsatisfactory in 72 (61.5 %) cases, indeterminate in 37 (31.6 %), good only in 8 (6.8 %).

Table 3

Results of the transpedicular screws stimulation test

Fixation level	Side	TSS test result (mA)				Total number of screws
		30	20–29	19–10	< 10	
Th_{IX}	left	—	—	—	1	1
	right	—	—	—	1	1
Th_X	left	2	—	2	2	6
	right	2	—	2	2	6
Th_{XI}	left	6	—	2	4	12
	right	6	—	2	5	13
Th_{XII}	left	7	1	6	3	17
	right	7	—	6	4	17
L_I	left	10	5	2	6	23
	right	10	5	3	5	23
L_{II}	left	13	3	2	3	21
	right	11	2	5	2	20
L_{III}	left	18	3	6	4	31
	right	18	4	4	5	31
L_{IV}	left	20	5	5	3	33
	right	21	6	3	4	34
L_V	left	23	5	5	4	37
	right	22	4	7	3	36
S_I	left	19	2	12	4	37
	right	20	4	10	2	36
Total number of screws		235	49	84	67	435

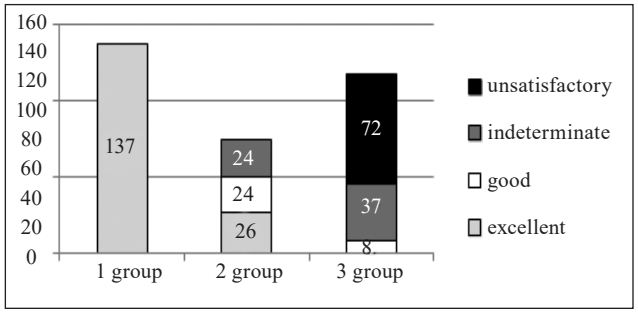

Fig. 6. Distribution of patients according to the results of the TSS test

Thus, there was a group of patients in whom the TSS test was unsatisfactory on all screws, but they were installed correctly and no neurological complications were observed. Convincing clinical features of patients of group 3 were not revealed. This issue requires a separate study.

Some authors suggest using not only the TSS modality, but also the modality of stimulating the walls of the channel to the screw. In particular, scientists from Italy showed on 161 correctly installed screws that the threshold of local stimulation of the pin channel walls was (7.5 ± 2.46) mA, against (21.8 ± 6.8) mA for screw stimulation. As a result of comparing these two thresholds on individual screws, it was determined that the TSS had an unpredictable leakage of current from 10 to 90 % of cases, which led to an increase in false-positive results. In addition, in the case of local channel stimulation, the authors did not observe cases of false-negative results in contrast to the TSS test. The stimulation threshold of the pin channel approached the threshold of direct excitation of the root (2.6 mA; $p < 0.05$). Thus, the authors emphasize that local stimulation of the current channel before the screw is much safer and prevents damage to the vertebral arch wall by traumatic, bulky and threaded screw [14].

Another study found that IOM can be a useful tool, but it is necessary to take into account the possibility of false-positive results that lead to prolonged surgery and blood loss, and false-negative results that cause complications [15]. Thus, the success of surgery depends on the experience and individual preferences of the surgeon. It is rational to share both IOM and visual navigation [16].

Conclusions

IOM modalities are highly sensitive and specific to damage to spinal cord structures and spinal nerves, but dependence on a number of external factors reduces their informative value, leading to false-positive and false-negative results.

The time course of MEP amplitudes of target muscles differ in informative value and efficiency during surgery due to individual morphological and motor characteristics. The most stable MEPs are recorded on *mm. tibialis anterior, mm. abductor hallucis longus*. It is confirmed that an unfavorable and reliable factor of the alarm sign is a unilateral steady decrease in MEP amplitude by more than

80 %. According to the results of TSS, 424 (97.5 %) screws were correctly installed, and one false-negative case (0.2 %) of incorrectly installed screw, which was confirmed by postoperative X-ray. False positive results of the TSS test ranged from 34.7 to 15.4 %, depending on the selected critical threshold of the current supplied to the transpedicular screw. According to the results of the study, we recommend that the threshold below 13 mA be considered critical, which necessarily requires checking the correctness of the screw under radiographic control.

At the same time, a group of patients was identified in whom 72 screws were installed (16.6 % of the total number analyzed), who received an unsatisfactory score according to the TSS test, and radiologically no errors in their topographic position were detected.

Conflict of interest. The authors declare no conflict of interest.

References

1. Does intraoperative CT navigation increase the accuracy of pedicle screw placement in pediatric spinal deformity surgery? A systematic review and meta-analysis / M. D. Kadiyala, W. N. Sankar, T. D. Flynn [et.al] // Spine Deformity. — 2021. — DOI: 10.1007/s43390-021-00385-5.
2. Biscevic M. Intraoperative Neuromonitoring in Spine Deformity Surgery: Modalities, Advantages, Limitations, Medico legal Issues — Surgeons' Views / M. Biscevic, A. Sehic, F. Krupic // Review EFORT Open Review. — 2020. — Vol. 5 (1). — P. 9–16. — DOI: 10.1302/2058-5241.5.180032.
3. Triggered electromyography is a useful intraoperative adjunct to predict postoperative neurological deficit following lumbar pedicle screw instrumentation / R. Reddy. R. Chang, D. Coutinho [et al] // Global Spine Journal. — 2021. — DOI: 10.1177/21925682211018472.
4. Deletis V. Basic methodological principles of multimodal intraoperative monitoring during spine surgeries / V. Deletis // European Spine Journal. — 2007. — Vol. 16 (Suppl 2). — P. S147–S152. — DOI: 10.1007/s00586-007-0429-4.
5. American Society of Neurophysiological Monitoring. Intraoperative motor evoked potential monitoring — a position statement by the American Society of Neurophysiological Monitoring / D. B. Macdonald, S. Skinner, J. Shils [et al.] // Clinical Neurophysiology. — 2013. — Vol. 124 (12). — P. 2291–2316. — DOI: 10.1016/j.clinph.2013.07.025.
6. Heuristic map of myotomal innervation in humans using direct intraoperative nerve root stimulation / C. M. Schirmer, J. L. Shils, J. E. Arle [et al.] // Journal of Neurosurgery. Spine. — 2011. — Vol. 15 (1). — P. 64–70. — DOI: 10.3171/2011.2.SPINE1068.
7. Intraoperative neuromonitoring practice patterns in spinal deformity surgery: a global survey of the Scoliosis Research Society / P. Y. Dikmen, M. F. Halsey, A. Yucekul [et al.] // Spine deformity. — 2021. — Vol. 9 (2). — P. 315–325. — DOI: 10.1007/s43390-020-00246-7.
8. NIM-ECLIPSE SD System User's Manual, Version 3.5.350.
9. Optimal parameters of transcranial electrical stimulation for intraoperative monitoring of motor evoked potentials of the tibialis anterior muscle during pediatric scoliosis surgery / E. Azabon, V. Manel, N. Andre-Obadia [et al.] // Neurophysiologie Clinique. — 2013. — Vol. 43 (4). — P. 243–250. — DOI: 10.1016/j.neucli.2013.08.001.
10. Transcranial motor evoked potential monitoring for the detection of nerve root injury during adult spinal deformity surgery / H. Ushirozako, G. Yoshida, S. Kobayashi [et al.] // Asian Spine Journal. — 2018. — Vol. 12 (4). — P. 639–647. — DOI: 10.31616/asj.2018.12.4.639.
11. Transcranial electrical motor-evoked potential monitoring during surgery for spinal deformity: a study of 145 patients / D. D. Langeloo, A. Lelivelt, H. Louis Journée [et al.] // Spine. — 2003. — Vol. 28 (10). — P. 1043–1050. — DOI: 10.1097/01.BRS.0000061995.75709.78.
12. Mikula A. L. The use of intraoperative triggered electromyography to detect misplacedpedicle screws: a systematic review and meta-analysis / A. L. Mikula, S. K. Williams, P. A. Anderson // Journal of Neurosurgery. Spine. — 2016. — Vol. 24 (4). — P. 624–638. — DOI: 10.3171/2015.6.SPINE141323.
13. Intraoperative electromyographic monitoring to optimize safe lumbar pedicle screw placement — a retrospective analysis / A. K. Kaliya-Perumal, J. R. Charng, C. C. Nju [et al.] // BMC Musculoskeletal Disorders. — 2017. — Vol. 18 (1). — DOI: 10.1186/s12891-017-1594-1.
14. Troni W. Focal hole versus screw stimulation to prevent false negative results in detecting Pedicle breaches during spinal instrumentation / W. Troni, C. A. Benech, R. Perez // Clinical Neurophysiology. — 2018. — Vol. 130 (4). — P. 573–581. — DOI: 10.1016/j.clinph.2018.11.029.
15. Effectiveness of EMG use in pedicle screw placement for thoracic spinal deformities / A. Oner, C. G. Ely, J. T. Hermsmeyer, D. C. Norvell // Evidence-based spine-care journal. — 2012. — Vol. 3 (1). — P. 35–43. — DOI: 10.1055/s-0031-1298599.
16. Combining pedicle screw stimulation with spinal navigation, a protocol to maximize the safety of neural elements and minimize radiation exposure in thoracolumbar spine instrumentation / S. Z. Kassis, L. K. Abukwedar, A. K. Msaddi [et al.] // European spine journal. — 2016. — Vol. 25 (6). — P. 1724–1728. — DOI: 10.1007/s00586-015-3973-3.

The article has been sent to the editors 24.11.2021

PRACTICAL ASPECTS OF INTRAOPERATIVE NEUROMONITORING IN PATIENTS WITH DIFFERENT SPINAL PATHOLOGIES

O. O. Barkov, D. R. Duplii

Sytenko Institute of Spine and Joint Pathology National Academy of Medical Sciences of Ukraine, Kharkiv

✉ Oleksandr Barkov, MD, PhD in Traumatology and Orthopaedics: a.barkov.79@gmail.com

✉ Diana Duplii, PhD in Biol. Sci.: duplijd@gmail.com