DOI: https://doi.org/10.17816/PTORS322843

Review

Topical electrostimulation for correction of respiratory disorders in spinal cord injury: A review

Vakhtang G. Toriya, Sergei V. Vissarionov, Margarita V. Savina, Alexey G. Baindurashvili, Polina A. Pershina

H. Turner National Medical Research Center for Children's Orthopedics and Trauma Surgery, Saint Petersburg, Russia

ABSTRACT

BACKGROUND: A spinal cord injury can lead to paralysis of the respiratory muscles, resulting in a significant reduction in breathing ability. People with a spinal cord injury face an increased risk of developing various respiratory complications. To date, existing effective technologies positively affect the long-term recovery of respiratory function and create conditions for neuroplasticity in the injured spinal cord. The high relevance and lack of systematization of these techniques in the world literature served as the basis for describing a topical approach in electrostimulation for the correction of respiratory disorders in patients with traumatic spinal cord injuries.

AIM: To formulate an algorithm for topical electrostimulation of the spinal cord and respiratory muscles to correct respiratory dysfunction in patients with spinal cord injury based on the latest scientific literature.

MATERIALS AND METHODS: This article presents the results of the analysis of peer-reviewed articles that investigated the effects of various electrostimulation techniques on respiratory function in patients with spinal cord injury. Searches were performed on ScienceDirect, Google Scholar, and PubMed for the period from 2000 to 2022.

RESULTS: A spinal cord and muscle electrostimulation algorithm was formulated to personalize the treatment approach for patients with spinal cord injury depending on the level and period of traumatic spinal cord injury.

CONCLUSIONS: Electrostimulation techniques were found to be effective in the treatment of spinal cord injuries, particularly for the correction of respiratory disorders. The choice of the appropriate neurostimulation technique depends on the severity, injury level, and period of injury. Noninvasive techniques, such as FES and TSSM, can be used from the acute period to the chronic period, whereas invasive techniques, such as epidural stimulation and respiratory pacemaker placement, are appropriate in the chronic period. Despite the positive results of these techniques, further research is needed to develop effective treatment plans and improve their effectiveness and long-term outcomes.

Keywords: spinal cord injury; mechanical ventilation; respiratory muscle palsy; neuroprosthesis; neuroplasticity; neuromodulation; electrical stimulation; rhythm generator; rehabilitation.

To cite this article
Toriya VG, Vissarionov SV, Savina MV, Baindurashvili AG, Pershina PA. Topical electrostimulation for correction of respiratory disorders in spinal cord injury: A review. *Pediatric Traumatology, Orthopaedics and Reconstructive Surgery.* 2023;11(3):381–391. DOI: https://doi.org/10.17816/PTORS322843

Received: 13.04.2023 **Accepted:** 27.07.2023 **Published:** 29.09.2023

ECO•VECTOR

УДК 616.832-001-053-08-06:615.84
DOI: https://doi.org/10.17816/PTORS322843

Научный обзор

Топическая электростимуляция для коррекции дыхательных расстройств при травме спинного мозга (обзор литературы)

В.Г. Тория, С.В. Виссарионов, М.В. Савина, А.Г. Баиндурашвили, П.А. Першина

Национальный медицинский исследовательский центр детской травматологии и ортопедии имени Г.И. Турнера, Санкт-Петербург, Россия

АННОТАЦИЯ

Обоснование. Повреждение спинного мозга может привести к опасной форме паралича дыхательных мышц, что значительно снижает дыхательную способность. Люди с повреждением спинного мозга сталкиваются с повышенным риском развития различных респираторных осложнений. На сегодняшний день существуют эффективные технологии, обеспечивающие положительное воздействие на долгосрочное восстановление дыхательной функции и создающие условия для формирования нейропластичности в поврежденном спинном мозге. Высокая актуальность и отсутствие систематизации данных методик в мировой литературе послужили основой для описания топического подхода в электростимуляции для коррекции дыхательных расстройств у пациентов с травматическим повреждением спинного мозга.

Цель — сформировать алгоритм топической электростимуляции спинного мозга и дыхательных мышц для коррекции нарушений функции дыхания у пациентов с травмой спинного мозга, основываясь на последних научных литературных данных.

Материалы и методы. В статье представлены результаты поиска и анализа рецензируемых статей, в которых изучали влияние различных методик электростимуляции на дыхательную функцию у пациентов с травмой спинного мозга. Поиск выполнен в ресурсах ScienceDirect, Google Scholar, PubMed за период с 2000 по 2022 г.

Результаты. Сформирован алгоритм электростимуляции спинного мозга и мышц с целью персонализации подхода к лечению пациентов с позвоночно-спинномозговой травмой в зависимости от уровня и периода травматического повреждения спинного мозга.

Заключение. Методы электростимуляции показали свою эффективность в лечении травм спинного мозга, особенно с целью коррекции дыхательных расстройств. Выбор подходящего метода нейростимуляции зависит от тяжести, уровня повреждения и периода травмы. Неинвазивные методы, такие как функциональная электростимуляция и транскутанная стимуляция спинного мозга, могут быть применены и в остром, и в хроническом периоде, в то время как инвазивные методы, такие как эпидуральная стимуляция и постановка водителя дыхательного ритма, целесообразно использовать в хроническом периоде травмы. Несмотря на положительные результаты этих методов, необходимы дальнейшие исследования для разработки оптимальных планов лечения, повышения их эффективности и получения долгосрочных результатов.

Ключевые слова: травма спинного мозга; механическая вентиляция легких; паралич дыхательных мышц; нейропротезирование; нейропластичность; нейромодуляция; электростимуляция; генератор ритма; реабилитация.

Как цитировать
Тория В.Г., Виссарионов С.В., Савина М.В., Баиндурашвили А.Г., Першина П.А. Топическая электростимуляция для коррекции дыхательных расстройств при травме спинного мозга (обзор литературы) // Ортопедия, травматология и восстановительная хирургия детского возраста. 2023. Т. 11. № 3. С. 381–391. DOI: https://doi.org/10.17816/PTORS322843

Рукопись получена: 13.04.2023 **Рукопись одобрена:** 27.07.2023 **Опубликована:** 29.09.2023

BACKGROUND

Injury to the spinal cord, particularly to the cervical region, can cause paralysis of the respiratory muscles, which significantly reduces breathing capacity. Nearly 40% of patients with spinal cord injuries require mechanical ventilation to maintain respiratory function [1]. According to preliminary data, approximately 5% of patients who require mechanical ventilation in the acute period of traumatic injury will also require it in the future constantly [1].

People with spinal cord injuries have an increased risk for respiratory dysfunction and associated complications, including pneumonia, atelectasis, and potentially life-threatening respiratory failure [2, 3].

Respiratory distress is the main contributor to the development of secondary somatic and infectious diseases and death following traumatic injuries of the cervical spinal cord. This condition poses a serious problem for both patients and healthcare professionals because it is associated with significant risks to the overall health and well-being of the individual [4].

Patients who are dependent on mechanical ventilation are unable to live at home; therefore, long-term care facilities take on the responsibilities of care. Mindful care of a patient on ventilation involves 24-h supervision by qualified personnel. The caregiver must have experience in adjusting the ventilator settings to ensure optimal breathing function and adapt to changes in oxygen saturation. In addition, proper lung drainage is extremely important, including percussion of the chest for regular sanitation and induction of a cough reflex [5].

Mechanical ventilation not only interferes with the mobility and independence of a patient with impaired motor function of the limbs because of injury but also causes physical discomfort, speech, and smell impairment of varying degrees [6].

Given these facts, restoring independence from mechanical ventilation is important both from the point of view of medical and psychological state and socio-economic and domestic well-being. This minimizes the risk of respiratory complications, increases patient mobility, and frees them from constant dependence on medical care.

Nowadays, various technologies can positively affect the long-term restoration of respiratory function and create conditions for the development of neuroplasticity in the damaged spinal cord [7]. The high relevance and lack of systematization of these techniques in the world literature prompted the need for a topical approach to electrical stimulation for the treatment of respiratory disorders in patients with traumatic spinal cord injuries.

This study aimed to develop an algorithm for topical electrical stimulation of the respiratory muscles to treat respiratory dysfunction in patients with spinal cord injury based on the latest scientific literature data.

MATERIALS AND METHODS

This study presents the results of the search and analysis of peer-reviewed articles that evaluated the effect of various electrical stimulation techniques on respiratory function in patients with spinal cord injury.

The search was performed in ScienceDirect, Google Scholar, and PubMed databases for the period from 2000 to 2022. The following keywords were used: *respiratory center, breathing regulation, rhythmogenesis, ventilatory control, respiratory drive, inspiratory neurons, expiratory neurons, spinal cord injury, electrostimulation diaphragm pacing, transcutaneous spinal cord stimulation, epidural spinal cord stimulation, functional electrical stimulation, neuromodulation, neuroprosthesis, stimulation, electrical stimulation, muscle stimulation, respiration,* and *cough*.

The analysis included articles containing recent data on the effects of various electrical stimulation techniques on the respiratory function of patients with spinal cord injury. Duplicate articles (or articles where the study participants were not independent of previous publications) and editorial contributions were excluded. The initial search yielded 450 articles. After removing duplicates and reviewing titles and abstracts, the remaining 380 articles were screened against the predefined inclusion criteria. This left 78 articles for full-text evaluation. Articles that analyzed the effects of electrical stimulation techniques on the respiratory function of patients with spinal cord injury were included in the analysis.

The full-text review assessed the methodology, relevance, and information content of each article. After this review, the most relevant and high-quality articles (31 peer-reviewed articles) suitable for this study were selected.

RESULTS AND DISCUSSION

Anatomy and physiology

Respiratory muscles can be classified into two inspiratory and expiratory muscles. The inspiratory muscles (or inspiration muscles) expand the chest cavity and subsequently draw air into the lungs. For this purpose, they raise the ribs and sternum. The expiratory muscles help contract the thoracic cavity and are involved in exhaling air from the lungs and lowering the ribs and sternum. These muscles work concordantly to facilitate breathing and ensure proper oxygen and carbon dioxide metabolism in the body. Smooth and efficient breathing requires maintaining a balance between the inspiratory and expiratory muscles (Fig. 1).

The main inspiratory muscles are represented by the diaphragm and external intercostal muscles. The phrenic nerve is responsible for the motor innervation of the diaphragm, and the sensory innervation is provided by the phrenic nerve (tendon center of the diaphragm) and the sixth or seventh

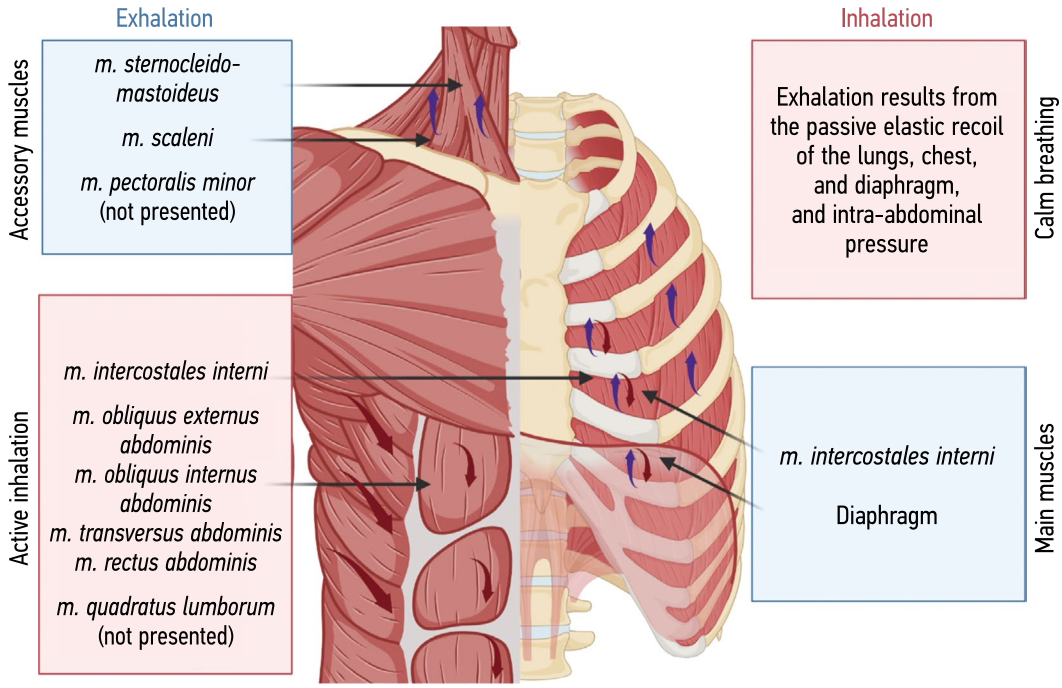

Fig. 1. Anatomy of the main and accessory respiratory muscles

pair of intercostal nerves (peripheral parts of the diaphragm). All intercostal muscles are innervated by their corresponding intercostal nerves.

The sternocleidomastoid muscles; anterior, middle, and posterior scalene muscles; pectoralis major and pectoralis minor; inferior fibers of the serratus anterior; and latissimus dorsi are accessory muscles of inspiration. The serratus posterior superior, as well as the cervical segment of the neck iliocostalis muscle, may be involved in inspiration.

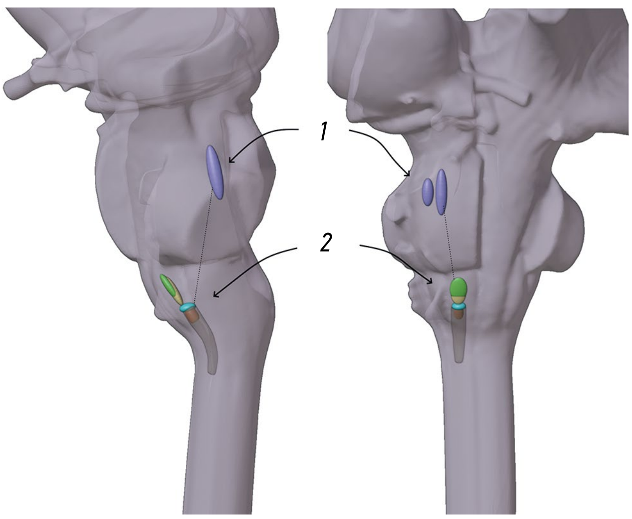

Fig. 2. Areas associated with breathing rhythm formation in the brainstem. *1,* pontine respiratory areas: Kolliker–Fuse nucleus and parabrachial complex; *2,* medullary respiratory centers, from top to bottom: parafacial respiratory group (green), retrotrapezoid nucleus (yellow), preBötzinger complex (turquoise), and Bötzinger complex (red). Superior cervical inspiratory neurons (black). Sagittal and frontal views

At rest, exhalation is a passive process that results from the elasticity of the chest and lung tissue and constant intra-abdominal pressure. The main expiratory muscles involved in active exhalation include the internal intercostal muscles, innermost intercostal muscles, subcostal muscles, and muscles of the anterior abdominal wall, namely, the rectus abdominis, external abdominal oblique, internal oblique muscle, and transverse abdominal muscle. The muscles of the anterior abdominal wall are innervated mainly by intercostal nerves Th_6–Th_{12}.

Accessory expiratory muscles include the serratus posterior inferior, quadratus lumborum, lowest fibers of the iliocostalis muscle, and longissimus muscle at the thoracolumbar transition [8].

In chronic spinal cord injury, accessory muscles are involved in breathing, namely, the upper part of the trapezius during inhalation and the pectoralis major and the latissimus dorsi during exhalation [9].

To formulate the view and paradigm of topical stimulation to treat respiratory disorders, modern ideas about the central mechanism of respiratory rhythm generation must be elucidated.

Recent evidence suggests the presence of two main respiratory rhythm generators, namely, the parafacial respiratory group and the preBötzinger complex (inspiratory pacemaker population). The inspiratory and expiratory activities in these medullary respiratory rhythm generators are modulated from various sites in the lower brainstem, including the pons and Bötzinger complex, and resulted in motoneuron activity through efferent networks in the brainstem and spinal cord (Fig. 2) [10, 11].

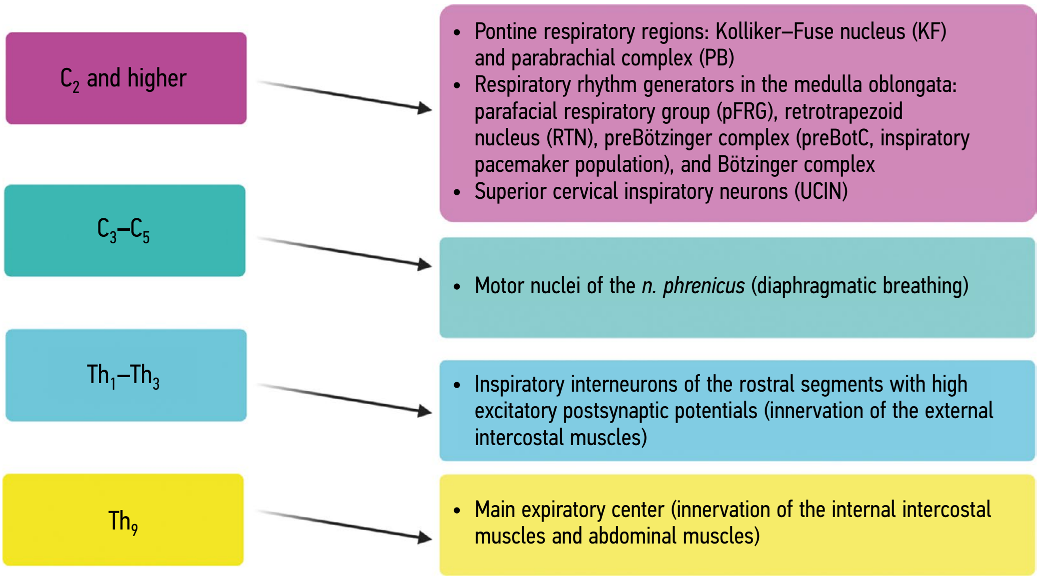

Fig. 3. Scheme of the rostrocaudal structure of respiratory rhythm generation including brainstem and spinal respiratory networks that organize the rostrocaudal gradient of inspiratory motor activities

Breathing involves a complex pattern of movements that requires the activation of numerous motor neurons along the spinal cord in the correct spatial and temporal sequence. Several studies have shown that the external intercostal muscles and their nerves are active during inspiration, and the inspiratory activity in the rostral intercostal spaces is stronger than that in the caudal ones [12]. Accordingly, the parasternal region of each internal intercostal muscle is activated during the inspiratory phase, with muscles in the rostral intercostal spaces showing greater activity than those in the caudal ones [13, 14]. The rostrocaudal structure of respiratory rhythm generation, which is conditionally divided into levels in accordance with the possibility of using stimulation techniques, is presented in Fig. 3.

In recent years, the use of electrical stimulation for the treatment of respiratory failure has received considerable attention. This approach improves respiratory function and reduces the need for mechanical ventilation in patients with spinal cord injury [7].

Segmental use of electrical stimulation

If the injury is located in the C_2 segment and above, the efferent rhythmogenic innervation of breathing is disrupted to the level of the motor neurons *n. phrenicus*, causing paresis of the diaphragm, intercostal muscles, and main expiratory muscles. The interneurons of the upper cervical inspiratory neurons can be a substrate for restoration. The upper cervical inspiratory neurons are not the region of the main generation of respiratory rhythms; however, they are involved in the formation of inspiratory respiratory patterns, and in the case of damage, they use auxiliary pathways to restore and reorganize the circuit and can even act as a reserve generator of respiratory rhythms. Thus, the respiratory neural circuits of the high cervical spinal cord represent a vital component of the respiratory network [15]. When affected at this level, patients experience disorders of inspiratory and expiratory functions.

Noninvasive methods for treating respiratory disorders are used in acute and chronic periods of spinal cord injury. In our clinical practice, we use functional electrical stimulation (FES) and transcutaneous spinal cord stimulation (TSCS) in the early period, from day 5 after surgery. The issue of the timing of using stimulation techniques is still being discussed. Most researchers describe the clinical effectiveness of noninvasive electrical stimulation in the chronic period, and little data are presented on its efficiency in the acute period [16].

To stimulate inspiratory function, transcutaneous spinal cord stimulation can be applied [17, 18]. Stimulation should be performed above and below the level of the damaged segment. The parameters of stimulation with electric current are selected individually in the presence of a resuscitator. This technique can be employed in pediatric patients at least 3 years old [19]. In our clinical practice, the minimum age of a patient who underwent transcutaneous stimulation was 6 years.

Abdominal FES is effective for stimulating expiratory function and inducing a cough reflex. The technique involves the stimulation of the external abdominal oblique and rectus abdominis muscles with electric current. Average stimulation values were a current strength of 90–100 mA, pulse duration of 200–300 μs, and stimulation frequency of 30–50 Hz [16]. According to the literature, the minimum age for using this technique in pediatric patients is 3 years [20].

The approach of using noninvasive TSCS and FES in the acute and chronic periods is similar to the approach for treating respiratory disorders at all levels of spinal cord injury.

In chronic spinal cord injury, when there is a need for long-term mechanical ventilation, placement of a respiratory pacemaker is indicated. Various manufacturers regulate the age of use independently, and no single standard has been established these days. For example, the phrenic nerve simulator made by Avery is approved by the Food and Drug Administration (USA) for implantation at any age [21].

Implantation requires an intact phrenic nerve, absence of pulmonary pathology, and preservation of consciousness. To confirm objectively phrenic nerve conduction, each nerve is stimulated with a source located over the sternal notch on the medial surface of the sternocleidomastoid, and the evoked activity of the diaphragm is assessed. The recording electrode is located at the level of the anterior costal edge of the ninth intercostal space (Fig. 4).

The device usually consists of an external transmitter and one or more implantable receivers that are connected to electrodes that stimulate the phrenic nerves. Implantation can be performed at the neck level or intrathoracically directly onto the phrenic nerves. Alternatively, a laparoscopic approach can be used on the abdominal surface of the diaphragm; to determine the optimal location of the electrodes, pinpoint electrical stimulation is performed, and the main motor point of the diaphragm is established [22, 23].

Injury at the C_3–C_5 level is morphologically characterized by damage to the motor nuclei of *n. phrenicus*, an impairment of the efferent respiratory rhythmogenic innervation to lower levels. A flaccid paresis of the diaphragm with atrophy of the phrenic nerves and paresis of the intercostal muscles and main expiratory muscles occur. The interneurons of the upper cervical inspiratory neurons can serve as a substrate for restoration. Damage at this level results in inspiratory and expiratory disorders.

In chronic spinal cord injury accompanied by diaphragmatic paralysis, continued mechanical ventilation is required,

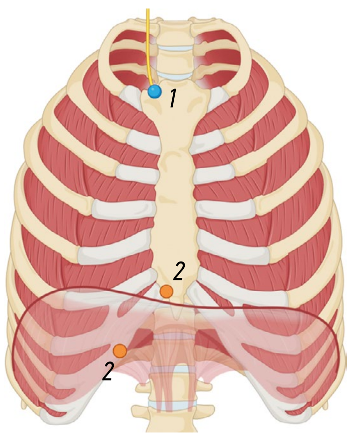

Fig. 4. Phrenic nerve conduction study and diagram of the position of the stimulating electrode (*1*) and recording electrodes (*2*)

placement of a diaphragmatic pacemaker is not always possible. If the motor nuclei of *n. phrenicus* are partially affected and conduction along the phrenic nerves is confirmed, then a respiratory pacemaker can be placed. However, in phrenic nerve atrophy, conduction disturbances confirmed by neurophysiological studies, and the pacemaker installation may not give the expected effect. In these cases, an epidural electrode can be implanted for neuromodulation and stimulation of neuroplasticity. This technique can be performed for pediatric patients at least 8 years old [24].

The inspiratory intercostal muscles are activated by the epidural implantation of an electrode on the ventral surface at the Th_2 level [25].

Clinical studies in patients with tetraplegia on mechanical ventilation showed that the activation of the intercostal muscles alone increased the volume of inspired air [26]. Stimulation is performed in a high-frequency mode of 300 Hz (high-frequency spinal cord stimulation), which can cause physiological activation of the inspiratory muscles [25].

Even in cases of clinically complete spinal cord injury, neuromodulation below the level of injury can restore autonomic and volitional sensorimotor functions [27–29].

Injury at the C_6–Th_1 level is characterized by the disruption of the efferent respiratory rhythmogenic innervation below the level of the *n. phrenicus*, maintaining control of diaphragmatic breathing and formation of paralysis of the intercostal and main expiratory muscles. This results in incomplete and complete disorders of inspiratory and expiratory functions, respectively [25].

In chronic spinal cord injury, an epidural electrode can be implanted at the Th_2 level for neuromodulation and stimulation of neuroplasticity to treat respiratory disorders.

Injury at the Th_1–Th_3 level. Many thoracic interneurons have respiratory activities [30]. Moreover, more inspiratory interneurons are found in the more rostral thoracic segments, whereas more inspiratory excitatory postsynaptic potentials in interneurons are located in more rostral segments, mainly in the Th_1–Th_3 levels [31].

Trauma at this level is morphologically characterized by damage to interneurons involved in the formation of the rostrocaudal gradient of inspiratory motor activity and located in more rostral segments of the spinal cord. This leads to paresis of the intercostal and expiratory muscles, and control of diaphragmatic breathing is preserved.

In chronic spinal cord injury, implantation of an epidural electrode at the Th_2 level for the treatment of respiratory disorders, as described for trauma of higher levels, may not yield the expected effect. For neuromodulation and stimulation of neuroplasticity at this level, epidural electrodes can be implanted at the level of adjacent segments, above and below the level of injury.

Injury at the Th_3–Th_9 level is characterized by damage to the preinterneurons and interneurons involved in

DOI: https://doi.org/10.17816/PTORS322843

the formation of the rostrocaudal gradient of inspiratory motor activity in the thoracic spinal cord. However, the main center for the development of the rostrocaudal gradient of inspiratory motor activity of Th_1–Th_3 remains intact. This leads to incomplete disruption of inspiratory function and incomplete and complete paresis of the intercostal and expiratory muscles, respectively.

The center of innervation of expiratory activity in Th_9 is intact, and the motor neurons of the main expiratory muscles are also intact.

In chronic spinal cord injury, to improve expiratory and inspiratory respiratory functions, an epidural electrode can be implanted at the Th_9, Th_{11}, and L_1 levels, which can be used for neuromodulation and stimulation of neuroplasticity. However, to optimize the therapeutic effect, epidural electrodes can be implanted in adjacent segments above and below the lesion [32].

Injury at the Th_9 level. The main expiratory center in the spinal cord is located in the lower thoracic segments with the greatest activity at the Th_9 level. This center innervates the expiratory muscles, including the abdominal and internal intercostal muscles. The expiratory center is organized into segments, with different levels responsible for different aspects of expiratory control. Nerves at the Th_7–Th_8 levels are mainly responsible for the activation of the expiratory muscles located rostrally, and nerves at the Th_{10}–Th_{12} levels are mainly responsible for the activation of the expiratory muscles located more caudally [33]. Trauma at this level leads to damage to the motor neurons of the main expiratory muscles, formation of flaccid paresis, and absence of active exhalation and cough; as a result, passive expiration becomes the dominant mechanism. This leads to an imbalance in the activity of the respiratory muscles and reduced breathing efficiency. In these patients, atrophy of the expiratory muscles is possible; thus, electrical stimulation may be little effective or ineffective.

The development of an algorithm for personalized electrical stimulation of the spinal cord and muscles is a promising approach to the treatment of respiratory failure (Fig. 5).

The presented algorithm for the electrical stimulation of the spinal cord and muscles was developed to personalize the treatment approach to patients with spinal cord injuries, depending on their level and period. The algorithm is based on the analysis of literature data given in the article. It synthesizes and organizes knowledge to provide a personalized treatment approach to patients with spinal cord injuries.

In acute injury, noninvasive treatment methods are used, such as TSCS and FES of the muscles of the anterior abdominal wall. TSCS involves applying an electrical current through the skin to the spinal cord, which can improve respiratory function by modulating the excitability of respiratory neurons. In the FES of the muscles of the anterior abdominal wall, electrical stimulation activates the abdominal muscles, which can induce a cough reflex.

In chronic spinal cord injury, the algorithm includes a combination of noninvasive and invasive treatment methods. Invasive techniques, such as pacemaker placement and epidural spinal cord stimulation, are added to the treatment plan to further improve respiratory function.

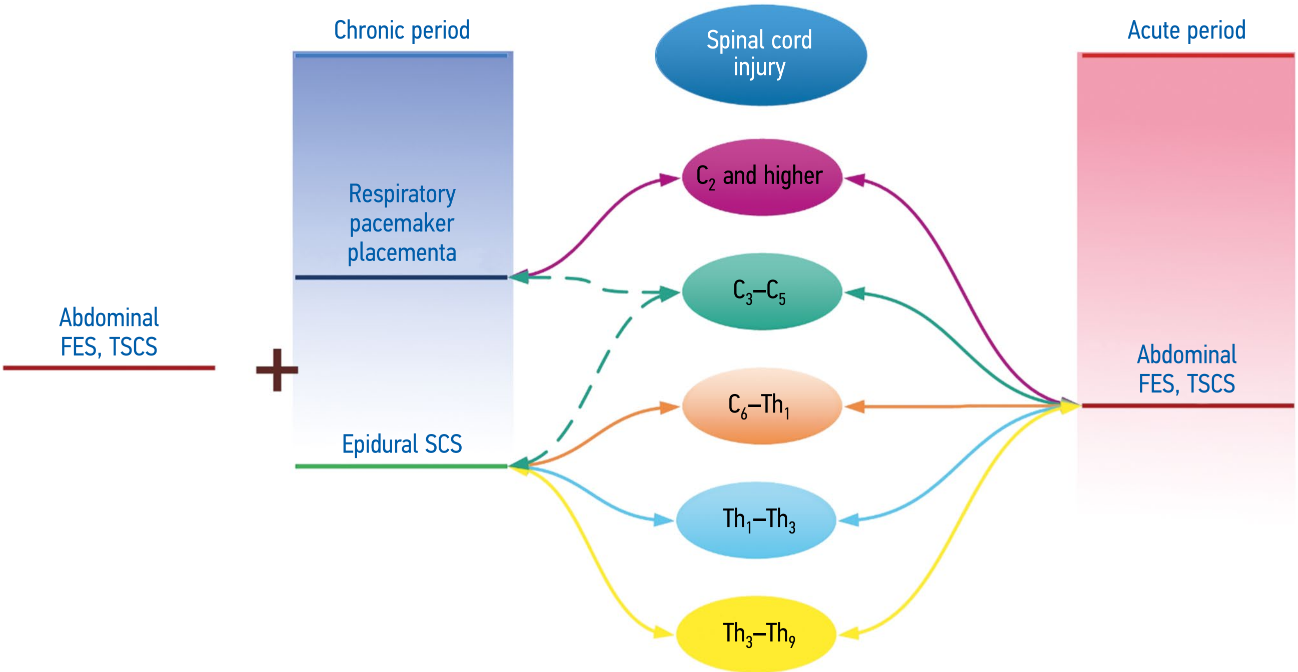

Fig. 5. Algorithm for the use of electrical stimulation techniques for the treatment and accelerated recovery of respiratory disorders in spinal cord injuries. FES, functional electrical stimulation; SCS, spinal cord stimulation; TSCS, transcutaneous spinal cord stimulation

Diaphragmatic pacemaker placement, a minimally invasive technique, involves placing electrodes on the phrenic nerve or motor point of the diaphragm to stimulate muscles, which can improve respiratory function [1]. Epidural spinal cord stimulation involves placing electrodes in the epidural space of the spinal cord to modulate the excitability of respiratory neurons [27].

CONCLUSION

Electrical stimulation methods have demonstrated efficiency in the treatment of spinal cord injuries, particularly for the treatment of respiratory disorders. A personalized approach represents a progressive step in the treatment of respiratory failure in patients with spinal cord injuries and has the potential to improve their outcomes.

The choice of the appropriate neurostimulation method depends on the severity, injury level, and period of injury. Noninvasive methods, such as FES and TSCS, can be used in both the acute and chronic periods, whereas invasive methods, such as epidural stimulation and pacemaker placement, are preferred in the chronic period. Despite the positive results of these methods, more studies are needed to develop optimal treatment plans, improve their efficiency, and achieve long-term outcomes.

ADDITIONAL INFORMATION

Funding. The study had no external funding.

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

Author contributions. *V.G. Toriya* wrote all sections of the article, collected and analyzed the data, analyzed the literature, and created the illustrations. *S.V. Vissarionov* performed staged and final editing of the article text. *M.V. Savina, A.G. Baidurashvili,* and *P.A. Pershina* performed the literature analysis, staged editing of the article text, and created the illustrations.

All authors made significant contributions to the study and preparation of the article, and they read and approved the final version before its publication.

REFERENCES

1. DiMarco AF. Neural prostheses in the respiratory system. *J Rehabil Res Dev.* 2001;38(6):601–607.

2. Sezer N, Akkuş S, Uğurlu FG. Chronic complications of spinal cord injury. *World J Orthop.* 2015;6(1):24–33. DOI: 10.5312/wjo.v6.i1.24

3. Tester NJ, Fuller DD, Fromm JS, et al. Long-term facilitation of ventilation in humans with chronic spinal cord injury. *Am J Respir Crit Care Med.* 2014;189(1):57–65. DOI: 10.1164/rccm.201305-0848oc

4. Berlly M, Shem K. Respiratory management during the first five days after spinal cord injury. *J Spinal Cord Med.* 2007;30(4):309–318. DOI: 10.1080/10790268.2007.11753946

5. Jarosz R, Littlepage MM, Creasey G, et al. Functional electrical stimulation in spinal cord injury respiratory care. *Top Spinal Cord Inj Rehabil*. 2012;18(4):315–321. DOI: 10.1310/sci1804-315

6. Adler D, Gonzalez-Bermejo J, Duguet A, et al. Diaphragm pacing restores olfaction in tetraplegia. *Eur Respir J.* 2008;34(2):365–370. DOI: 10.1183/09031936.00177708

7. Hachmann JT, Grahn PJ, Calvert JS, et al. Electrical neuromodulation of the respiratory system after spinal cord injury. *Mayo Clin Proc.* 2017;92(9):1401–1414. DOI: 10.1016/j.mayocp.2017.04.011

8. Gray's anatomy 41st edition: the anatomical basis of clinical practice. Ed. by S. Standring. Elsevier Science; 2015.

9. Terson de Paleville D, Lorenz D. Compensatory muscle activation during forced respiratory tasks in individuals with chronic spinal cord injury. *Respir Physiol Neurobiol.* 2015;217:54–62. DOI: 10.1016/j.resp.2015.07.001

10. Smith JC, Abdala AP, Koizumi H, et al. Spatial and functional architecture of the mammalian brain stem respiratory network: a hierarchy of three oscillatory mechanisms. *J Neurophysiol*. 2007;98(6):3370–3387. DOI: 10.1152/jn.00985.2007

11. Paton JF, Abdala AP, Koizumi H, et al. Respiratory rhythm generation during gasping depends on persistent sodium current. *Nat Neurosci.* 2006;9(3):311–333. DOI: 10.1038/nn1650

12. De Troyer A, Kirkwood PA, Wilson TA. Respiratory action of the intercostal muscles. *Physiol Rev.* 2005;85(2):717–756. DOI: 10.1152/physrev.00007.2004

13. De Troyer A, Gorman RB, Gandevia SC. Distribution of inspiratory drive to the external intercostal muscles in humans. *J Physiol.* 2003;546:943–954. DOI: 10.1113/jphysiol.2002.028696

14. Gandevia SC, Hudson AL, Gorman RB, et al. Spatial distribution of inspiratory drive to the parasternal intercostal muscles in humans. *J Physiol.* 2006;573:263–275. DOI: 10.1113/jphysiol.2005.101915

15. Zaki Ghali MG, Britz G, Lee KZ. Pre-phrenic interneurons: Characterization and role in phrenic pattern formation and respiratory recovery following spinal cord injury. *Respir Physiol Neurobiol.* 2019;265:24–31. DOI: 10.1016/j.resp.2018.09.005

16. Caughey EJ, Borotkanics RJ, Gollee H, et al. Abdominal functional electrical stimulation to improve respiratory function after spinal cord injury: a systematic review and meta-analysis. *Spinal Cord.* 2016;54(9):628–639. DOI: 10.1038/sc.2016.31

17. Gad P, Kreydin E, Zhong H, et al. Enabling respiratory control after severe chronic tetraplegia: an exploratory case study. *J Neurophysiol*. 2020;124(3):774–780. DOI: 10.1152/jn.00320.2020

18. Minyaeva AV, Moiseev SA, Pukhov AM, et al. Response of external inspiration to the movements induced by transcutaneous spinal cord stimulation. *Hum Physiol*. 2017;43:524–531. DOI: 10.1134/s0362119717050115

19. Keller A, Singh G, Sommerfeld JH, et al. Noninvasive spinal stimulation safely enables upright posture in children with spinal cord injury. *Nat. Commun.* 2021;12(1). DOI: 10.1038/s41467-021-26026-z

20. Joffe JR. The effect of functional electrical stimulation on abdominal muscle strength and gross motor function in children with cerebral palsy a randomised control trial [dissertation]. Cape Town: University of Cape Town; 2014.

21. Averybiomedical.com [Internet] Avery Biomedical devices – leader in diaphragm pacemakers [cited 2022 Dec 20]. Available from: http://www.averybiomedical.com

22. Dalal K, DiMarco AF. Diaphragmatic pacing in spinal cord injury. *Phys Med Rehabil Clin N Am.* 2014;25(3):619–629. DOI: 10.1016/j.pmr.2014.04.004
23. Posluszny JA Jr, Onders R, Kerwin AJ, et al. Multicenter review of diaphragm pacing in spinal cord injury: successful not only in weaning from ventilators but also in bridging to independent respiration. *J Trauma Acute Care Surg.* 2014;76(2):303–309. DOI: 10.1097/ta.0000000000000112
24. Bakr SM, Knight J, Johnson SK, et al. Spinal cord stimulation improves functional outcomes in children with complex regional pain syndrome: case presentation and review of the literature. *Pain Pract.* 2020;20(6):647–655. DOI: 10.1111/papr.12882
25. DiMarco AF, Kowalski KE. Intercostal muscle pacing with high frequency spinal cord stimulation in dogs. *Respir Physiol Neurobiol.* 2010;171(3):218–24. DOI: 10.1016/j.resp.2010.03.017
26. Adachi T, Yokoyama M, Onuki T. Experimental evaluation of the optimal tidal volume for simultaneous pacing of the diaphragm and respiratory muscles. *J Artif Organs.* 2004;7(1):27–29. DOI: 10.1007/s10047-003-0246-4
27. Tator CH, Minassian K, Mushahwar VK. Spinal cord stimulation: therapeutic benefits and movement generation after spinal cord injury. *Handb Clin Neurol.* 2012;109:283–296. DOI: 10.1016/B978-0-444-52137-8.00018-8
28. Angeli CA, Edgerton VR, Gerasimenko YP, Harkema SJ. Altering spinal cord excitability enables voluntary movements after chronic complete paralysis in humans. *Brain.* 2014;137:1394–1409. DOI: 10.1093/brain/awu038
29. Harkema S, Gerasimenko Y, Hodes J, et al. Effect of epidural stimulation of the lumbosacral spinal cord on voluntary movement, standing, and assisted stepping after motor complete paraplegia: a case study. *Lancet.* 2011;377(9781):1938–1947. DOI: 10.1016/s0140-6736(11)60547-3
30. Saywell SA, Ford TW, Meehan CF, et al. Electrophysiological and morphological characterization of propriospinal interneurons in the thoracic spinal cord. *J Neurophysiol*. 2011;105(2):806–826. DOI: 10.1152/jn.00738.2010
31. Iizuka M, Onimaru H, Izumizaki M. Distribution of respiration-related neuronal activity in the thoracic spinal cord of the neonatal rat: an optical imaging study. *Neuroscience.* 2016;315:217–227. DOI: 10.1016/j.neuroscience.2015.12.015
32. DiMarco AF, Kowalski KE. Activation of inspiratory muscles via spinal cord stimulation. *Respir Physiol Neurobiol.* 2013;189(2):438–449. DOI: 10.1016/j.resp.2013.06.001
33. DiMarco AF, Kowalski KE. Activation of the expiratory muscles via lower thoracic high frequency spinal cord stimulation in awake animals. *Respir Physiol Neurobiol.* 2020;276. DOI: 10.1016/j.resp.2019.103360
34. Toriya VG, Vissarionov SV, Kubanov RR, et al. Personalized application of electrostimulation techniques for correction and accelerated recovery of respiratory disorders in spinal cord injury. Certificate of DB registration. RU 2023621031, 2023. (In Russ.)

СПИСОК ЛИТЕРАТУРЫ

1. Dimarco A.F. Neural prostheses in the respiratory system // J. Rehabil. Res. Dev. 2001. Vol. 38. No. 6. P. 601–607.
2. Sezer N., Akkuş S., Uğurlu F.G. Chronic complications of spinal cord injury // World J. Orthop. 2015. Vol. 6. No. 1. P. 24–33. DOI: 10.5312/wjo.v6.i1.24
3. Tester N.J., Fuller D.D., Fromm J.S., et al. Long-term facilitation of ventilation in humans with chronic spinal cord injury // Am. J. Respir. Crit. Care Med. 2014. Vol. 189. No. 1. P. 57–65. DOI: 10.1164/rccm.201305-0848oc
4. Berlly M., Shem K. Respiratory management during the first five days after spinal cord injury // J. Spinal Cord. Medicine. 2007. Vol. 30. No. 4. P. 309–318. DOI: 10.1080/10790268.2007.11753946
5. Jarosz R., Littlepage M.M., Creasey G., et al. Functional electrical stimulation in spinal cord injury respiratory care // Top. Spinal Cord Inj. Rehabil. 2012. Vol. 18. No. 4. P. 315–321. DOI: 10.1310/sci1804-315
6. Adler D., Gonzalez-Bermejo J., Duguet A., et al. Diaphragm pacing restores olfaction in tetraplegia // Eur. Respir. J. 2008. Vol. 34. No. 2. P. 365–370. DOI: 10.1183/09031936.00177708
7. Hachmann J.T., Grahn P.J., Calvert J.S., et al. Electrical neuromodulation of the respiratory system after spinal cord injury // Mayo Clin. Proceed. 2017. Vol. 92. No. 9. P. 1401–1414. DOI: 10.1016/j.mayocp.2017.04.011
8. Gray's anatomy 41st edition: the anatomical basis of clinical practice / ed. by S. Standring. Elsevier Science, 2015.
9. Terson de Paleville D., Lorenz D. Compensatory muscle activation during forced respiratory tasks in individuals with chronic spinal cord injury // Respir. Physiol. Neurobiol. 2015. Vol. 217. P. 54–62. DOI: 10.1016/j.resp.2015.07.001
10. Smith J.C., Abdala A.P., Koizumi H., et al. Spatial and functional architecture of the mammalian brain stem respiratory network: a hierarchy of three oscillatory mechanisms // J. Neurophysiol. 2007. Vol. 98. No. 6. P. 3370–3387. DOI: 10.1152/jn.00985.2007
11. Paton J.F.R., Abdala A.P., Koizumi H., et al. Respiratory rhythm generation during gasping depends on persistent sodium current // Nat. Neurosci. 2006. Vol. 9. No. 3. P. 311–313. DOI: 10.1038/nn1650
12. De Troyer A., Kirkwood P.A., Wilson T.A. Respiratory action of the intercostal muscles // Physiol. Rev. 2005. Vol. 85. No. 2. P. 717–756. DOI: 10.1152/physrev.00007.2004
13. De Troyer A., Gorman R.B., Gandevia S.C. Distribution of inspiratory drive to the external intercostal muscle in humans // J. Physiol. 2003. Vol. 546. No. 3. P. 943–954. DOI: 10.1113/jphysiol.2002.028696
14. Gandevia S.C., Hudson A.L., Gorman R.B., et al. Spatial distribution of inspiratory drive to the parasternal intercostal muscles in humans // J. Physiol. 2006. Vol. 573. No. 1. P. 263–275. DOI: 10.1113/jphysiol.2005.101915
15. Zaki Ghali M.G., Britz G., Lee K.Z. Pre-phrenic interneurons: Characterization and role in phrenic pattern formation and respiratory recovery following spinal cord injury // Respir. Physiol. Neurobiol. 2019. Vol. 265. P. 24–31. DOI: 10.1016/j.resp.2018.09.005
16. McCaughey E.J., Borotkanics R.J., Gollee H., et al. Abdominal functional electrical stimulation to improve respiratory function after spinal cord injury: a systematic review and meta-analysis // Spinal Cord. 2016. Vol. 54. No. 9. P. 628–639. DOI: 10.1038/sc.2016.31
17. Gad P., Kreydin E., Zhong H., et al. Enabling respiratory control after severe chronic tetraplegia: an exploratory case study // J. Neurophysiol. 2020. Vol. 124. No. 3. P. 774–780. DOI: 10.1152/jn.00320.2020

18. Minyaeva A.V., Moiseev S.A., Pukhov A.M, et al. Response of external inspiration to the movements induced by transcutaneous spinal cord stimulation // Hum. Physiol. 2017. Vol. 43. No. 5. P. 524–531. DOI: 10.1134/s0362119717050115
19. Keller A., Singh G., Sommerfeld J.H., et al. Noninvasive spinal stimulation safely enables upright posture in children with spinal cord injury // Nat. Commun. 2021. Vol. 12. No. 1. DOI: 10.1038/s41467-021-26026-z
20. Joffe J.R. The effect of functional electrical stimulation on abdominal muscle strength and gross motor function in children with cerebral palsy a randomised control trial: dissertation. Cape Town: University of Cape Town; 2014.
21. Averybiomedical.com [Internet] Avery Biomedical devices – leader in diaphragm pacemakers [дата обращения 20.12.2022]. Доступ по ссылке: http://www.averybiomedical.com
22. Dalal K., DiMarco A.F. Diaphragmatic pacing in spinal cord injury // Physical. Med. Rehabil. Clin. N. Am. 2014. Vol. 25. No. 3. P. 619–629. DOI: 10.1016/j.pmr.2014.04.004
23. Posluszny J.A. Jr., Onders R., Kerwin A.J., et al. Multicenter review of diaphragm pacing in spinal cord injury: successful not only in weaning from ventilators but also in bridging to independent respiration // J. Trauma Acute Care Surg. 2014. Vol. 76. No. 2. P. 303–309. DOI: 10.1097/ta.0000000000000112
24. Bakr S.M., Knight J., Johnson S.K., et al. Spinal cord stimulation improves functional outcomes in children with complex regional pain syndrome: case presentation and review of the literature // Pain Practice. 2020. Vol. 20. No. 6. P. 647–655. DOI: 10.1111/papr.12882
25. DiMarco A.F., Kowalski K.E. Intercostal muscle pacing with high frequency spinal cord stimulation in dogs // Respir. Physiol. Neurobiol. 2010. Vol. 171. No. 3. P. 218–224. DOI: 10.1016/j.resp.2010.03.017
26. Adachi T., Yokoyama M., Onuki T. Experimental evaluation of the optimal tidal volume for simultaneous pacing of the diaphragm and respiratory muscles // J. Artif. Organs. 2004. Vol. 7. No. 1. P. 27–29. DOI: 10.1007/s10047-003-0246-4
27. Tator C.H., Minassian K., Mushahwar V.K. Spinal cord stimulation: therapeutic benefits and movement generation after spinal cord injury // Handbook Clin. Neurol. 2012. Vol. 109. P. 283–296. DOI: 10.1016/B978-0-444-52137-8.00018-8
28. Angeli C.A., Edgerton V.R., Gerasimenko Y.P., et al. Altering spinal cord excitability enables voluntary movements after chronic complete paralysis in humans // Brain. 2014. Vol. 137. No. 5. DOI: 10.1093/brain/awu038
29. Harkema S., Gerasimenko Y., Hodes J., et al. Effect of epidural stimulation of the lumbosacral spinal cord on voluntary movement, standing, and assisted stepping after motor complete paraplegia: a case study // Lancet. 2011. Vol. 377. No. 9781. P. 1938–1947. DOI: 10.1016/s0140-6736(11)60547-3
30. Saywell S.A., Ford T.W., Meehan C.F., et al. Electrophysiological and morphological characterization of propriospinal interneurons in the thoracic spinal cord // J. Neurophysiol. 2011. Vol. 105. No. 2. P. 806–826. DOI: 10.1152/jn.00738.2010
31. Iizuka M., Onimaru H., Izumizaki M. Distribution of respiration-related neuronal activity in the thoracic spinal cord of the neonatal rat: an optical imaging study // Neuroscience. 2016. Vol. 315. P. 217–227. DOI: 10.1016/j.neuroscience.2015.12.015
32. DiMarco A.F., Kowalski K.E. Activation of inspiratory muscles via spinal cord stimulation // Respir. Physiol. Neurobiol. 2013. Vol. 189. No. 2. P. 438–449. DOI: 10.1016/j.resp.2013.06.001
33. DiMarco A.F., Kowalski K.E. Activation of the expiratory muscles via lower thoracic high frequency spinal cord stimulation in awake animals // Respir. Physiol. Neurobiol. 2020. Vol. 276. DOI: 10.1016/j.resp.2019.103360
34. Тория В.Г., Виссарионов С.В., Кубанов Р.Р., и др. Персонифицированное применение методик электростимуляции для коррекции и ускоренного восстановления дыхательных расстройств при травме спинного мозга: Свидетельство о регистрации базы данных № 2023621031 RU, 2023.

AUTHOR INFORMATION

*** Vakhtang G. Toriya**, MD, Neurosurgeon;
address: 64-68 Parkovaya str., Pushkin,
Saint Petersburg, 196603, Russia;
ORCID: 0000-0002-2056-9726;
eLibrary SPIN: 1797-5031;
e-mail: vakdiss@yandex.ru

Sergei V. Vissarionov, MD, PhD, Dr. Sci. (Med.),
Professor, Corresponding Member of RAS;
ORCID: 0000-0003-4235-5048;
ResearcherID: P-8596-2015;
Scopus Author ID: 6504128319;
eLibrary SPIN: 7125-4930;
e-mail: vissarionovs@gmail.com

Margarita V. Savina, MD, PhD, Cand. Sci. (Med.);
ORCID: 0000-0001-8225-3885;
Scopus Author ID: 57193277614;
eLibrary SPIN: 5710-4790;
e-mail: drevma@yandex.ru

ОБ АВТОРАХ

*** Вахтанг Гамлетович Тория**, врач-нейрохирург;
адрес: Россия, 196603, Санкт-Петербург,
Пушкин, ул. Парковая, д. 64–68;
ORCID: 0000-0002-2056-9726;
eLibrary SPIN: 1797-5031;
e-mail: vakdiss@yandex.ru

Сергей Валентинович Виссарионов, д-р мед. наук,
профессор, чл.-корр. РАН;
ORCID: 0000-0003-4235-5048;
ResearcherID: P-8596-2015;
Scopus Author ID: 6504128319;
eLibrary SPIN: 7125-4930;
e-mail: vissarionovs@gmail.com

Маргарита Владимировна Савина, канд. мед. наук;
ORCID: 0000-0001-8225-3885;
Scopus Author ID: 57193277614;
eLibrary SPIN: 5710-4790;
e-mail: drevma@yandex.ru

* Corresponding author / Автор, ответственный за переписку

Alexey G. Baindurashvili, MD, PhD, Dr. Sci. (Med.), Professor, Member of RAS, Honored Doctor of the Russian Federation;
ORCID: 0000-0001-8123-6944;
Scopus Author ID: 6603212551;
eLibrary SPIN: 2153-9050;
e-mail: turner011@mail.ru

Polina A. Pershina, MD, resident;
ORCID: 0000-0001-5665-3009;
eLibrary SPIN: 2484-9463;
e-mail: polinaiva2772@gmail.com

Алексей Георгиевич Баиндурашвили, д-р мед. наук, профессор, академик РАН, заслуженный врач РФ;
ORCID: 0000-0001-8123-6944;
Scopus Author ID: 6603212551;
eLibrary SPIN: 2153-9050;
e-mail: turner011@mail.ru

Полина Андреевна Першина, ординатор;
ORCID: 0000-0001-5665-3009;
eLibrary SPIN: 2484-9463;
e-mail: polinaiva2772@gmail.com