

APPLICATION OF NON-INVASIVE ELECTRIC STIMULATION OF THE SPINAL CORD IN MOTOR REHABILITATION OF CHILDREN WITH CONSEQUENCES OF VERTEBRAL AND CEREBROSPINAL INJURY (PRELIMINARY REPORT)

© S.V. Vissarionov^{1, 2}, I.Yu. Solokhina¹, G.A. Ikoeva^{1, 2}, A.G. Baindurashvili^{1, 2}

¹The Turner Scientific Research Institute for Children's Orthopedics, Saint Petersburg, Russia;

²North-Western State Medical University n.a. I.I. Mechnikov, Saint Petersburg, Russia

Received: 02.10.2017

Accepted: 20.11.2017

Introduction. Vertebral and cerebrospinal injury and its consequences constitute an important problem in modern medicine. In recent years, studies have shown that percutaneous electric stimulation in patients with these injuries can influence the neuronal networks of different parts of the spinal cord to activate afferent and efferent reflex connections with complete or partial disorders of supraspinal influences of various geneses.

Aim. To investigate the effect of percutaneous electric stimulation of the spinal cord on the dynamics of recovery of neurological functions in children with vertebral and cerebrospinal injury.

Materials and methods. Seven patients aged 4 to 18 years with lesions of the spinal cord from C₅-C₆ to Th₁₂-L₁ and who mainly had a marked neurological deficit were examined from 1 month to 9 years after surgical treatment. All patients underwent neurophysiological studies, including electroneuromyography, electromyography, and somatosensory-evoked potentials. The patients and their parents kept a diary of urination.

Results. This clinical study showed that percutaneous electric stimulation of the spinal cord contributed to the rapid and complete restoration of the neurological functions in patients with vertebral and medullar conflict and depended directly on the early terms of surgical intervention.

Conclusion. The positive results obtained in the complex rehabilitation of children with vertebral and cerebrospinal injuries by using non-invasive percutaneous electric stimulation of the spinal cord support the use of this method in the early stages after surgical intervention.

Keywords: percutaneous electric spinal cord stimulation (PESCS); vertebral and cerebrospinal injury (VCSI); neurological disorders; rehabilitation; mechanotherapy.

ПРИМЕНЕНИЕ НЕИНВАЗИВНОЙ ЭЛЕКТРИЧЕСКОЙ СТИМУЛЯЦИИ СПИННОГО МОЗГА В ДВИГАТЕЛЬНОЙ РЕАБИЛИТАЦИИ ДЕТЕЙ С ПОСЛЕДСТВИЯМИ ПОЗВОНОЧНО-СПИННОМОЗГОВОЙ ТРАВМЫ (ПРЕДВАРИТЕЛЬНОЕ СООБЩЕНИЕ)

© С.В. Виссарионов^{1, 2}, И.Ю. Солохина¹, Г.А. Икоева^{1, 2}, А.Г. Баиндурашвили^{1, 2}

¹ФГБУ «НИДОИ им. Г.И. Турнера» Минздрава России, Санкт-Петербург;

²ФГБОУ ВО «СЗГМУ им. И.И. Мечникова» Минздрава России, Санкт-Петербург

Статья поступила в редакцию: 02.10.2017

Статья принята к печати: 20.11.2017

Введение. Позвоночно-спинномозговая травма и ее последствия представляют собой важную проблему современной медицины. В последние годы появились исследования, позволяющие использовать метод чрескожной электрической стимуляции у данной категории пациентов для воздействия на нейронные сети различных отделов спинного мозга с целью активации афферентных и эфферентных рефлекторных связей при полном или частичном нарушении супраспинальных влияний различного генеза.

Цель исследования — изучить влияние чрескожной электрической стимуляции спинного мозга на динамику восстановления неврологических функций у детей с позвоночно-спинномозговой травмой.

Материалы и методы. Обследованы 7 пациентов в возрасте от 4 до 18 лет с уровнем поражения спинного мозга от C₅-C₆ до Th₁₂-L₁ в период от 1 мес. до 9 лет после хирургического лечения преимущественно с выраженным неврологическим дефицитом. Всем пациентам проводили нейрофизиологические исследования: электронейромиографию, электромиографию, соматосенсорные вызванные потенциалы. Пациенты и их родители заполняли дневник мочеиспускания.

Результаты. Клиническое исследование показало, что метод чрескожной электрической стимуляции спинного мозга способствует наиболее быстрому и полноценному восстановлению неврологических функций у пациентов с вертебро-медуллярным конфликтом и его эффективность напрямую зависит от сроков хирургического вмешательства (раннее хирургическое лечение коррелирует с лучшими результатами).

Заключение. Полученные положительные результаты в комплексной реабилитации детей с позвоночно-спинномозговой травмой с применением неинвазивной чрескожной электрической стимуляции спинного мозга позволяют рекомендовать к использованию данную методику и осуществлять ее в ранние сроки после хирургического вмешательства.

Ключевые слова: чрескожная электрическая стимуляция спинного мозга (ЧЭССМ); позвоночно-спинномозговая травма (ПСМТ); неврологические нарушения; реабилитация; механотерапия.

Introduction

The restorative treatment of patients with spinal cord injuries is a crucial problem of modern medicine. Its significance is motivated by a high incidence of spinal cord injuries, possible complications after surgery, and the inadequate efficacy of treatment outcomes [1–5]. One of the new and promising methods of rehabilitation of motor functions in these patients is the electrical stimulation of the spinal cord. In the locomotion of animals, an important role belongs to the generators of pacing movements, which are the intracentral neuronal mechanisms capable of generating cyclic activity even in the absence of supraspinal influences, peripheral feedbacks, and real limb movements [6]. Several years ago, a method of percutaneous electrical stimulation of the spinal cord (PESSC) was developed, which is capable of causing locomotor movements in paralyzed limbs in humans and experimental animals [7]. The peculiarity of the technique is the use of electrical pulses of complex shape instead of standard rectangular ones. The special shape of the pulses allows the use of high-intensity currents necessary for effective action on the spinal cord, and the effects are painless in humans. This method is noninvasive and therefore less painful and traumatic, which is particularly important in pediatric practice. In several clinics for the motor rehabilitation of patients with spinal cord injuries, PESSC was initiated in combination with mechanotherapy, including robotic therapy, which resulted in a higher efficacy of the technique in terms of increased muscle strength, improvement in tactile and pain sensitivity, the appearance of voluntary movements, and restoration of the body balance function [8, 9].

Aim. This study aimed to analyze the influence of PESSC on the dynamics of restoration of neurological functions in children with vertebral and spinal cord injury (VSCI).

Materials and methods

Percutaneous electrical stimulation was performed in seven patients aged 4–18 years with a spinal cord lesion from C₅–C₆ to Th₁₂–L₁ in the period from 1 month to 9 years after surgical treatment, mainly with marked neurologic impairment. Two of seven patients had trauma of the cervical spine, one patient had damage at the level of lumbar enlargement, and five patients had injury at the thoracic level. For VSCI lasting for several hours to 3 months, all patients underwent surgery for the decompression of the spinal cord and stabilization of the damaged vertebral and motor segments [2]. In case of damage to the cervical spine, the anterior approach was used, and for trauma of the thoracic and lumbar spine, a combined approach (dorsal and anterolateral) was used. All pediatric patients had severe neurological complications in the form of deep paresis and plegia of limbs, dysfunction of the pelvic organs, and violation of the various types of sensitivity. To assess the neurological changes, the ASIA scale [10] developed by the American Spinal Injury Association was used to maximize the standardization of clinical trial results. The scale enables the scoring of muscle strength and sensitivity (tactile and painful). All patients underwent neurophysiological studies such as electroneuromyography (ENMG), electromyography (EMG), and somatosensory evoked potentials (SSEP). The patients and their parents maintained a urination diary.

After the neurological examination, two of the seven patients exhibited a baseline level of type A neurological disorders (syndrome of complete impulse disorder occurring due to the spinal cord being affected at the thoracic level), three patients had type B disorders, and two patients had neurologic impairment corresponding to type C on the ASIA scale. PESSC was performed with the stimulant BIOSTIM-5. The frequency of

stimulation was 5–30 Hz, and the pulse duration was 1 ms. The current intensity was selected during the procedure, depending on the patient's sensations or the emergence of motor activity in the lower limbs. The current strength varied from 20 to 140 mA, and the amplitude of the current was increased during each procedure. The duration of the procedure was 30–40 min, and it was conducted once per day (on every second day). The duration of the course was 10–30 sessions (1–3 courses). All patients undergoing the PESSC course additionally received motor rehabilitation using mechanized and robotic simulators. The robotic system Lokomat was used to restore the function of the lower extremities and the walking pattern, in addition to the exercise bike Tera, the robotic exercise simulator and the exerciser of the sole support load Korvit, the passive suspension system Ekzarta, and the verticalizer. The simulators Tera and Lokomat provided mechanical stimulation of the lower extremities through the regime of alternate flexion and extension of the hip, knee, and ankle joints. The patients were instructed to apply effort in the direction in which the simulator moved limbs. Previously, it was found that the vibration of the tendons of the hip muscles initiates involuntary pacing movements in subjects lying on their side with external support of the legs (in the swing frames) [9]. In our clinic, we used the kinesiotherapeutic device Ekzarta as an analog that enables to perform exercises in a suspended state synchronously with stimulation, to position the body, and to overcome the influence of gravity. In patients with damage to the cervical spine, two levels of the spinal cord were stimulated (cervical and lumbar enlargement). In all the observations, stimulation was initiated at the Th₁₁ level, and after 5–10 min, stimulation was performed at the C₅ level. Synchronous stimulation at the two levels caused movements in the extremities of all the patients. The current intensity at the level of the cervical enlargement was always low and did not exceed 40–50 mA. Studies have proven that stimulation of the cervical enlargement can be effective for the rehabilitation of hand movements in case of cervical injury. However, because of the uncertainty regarding the effect of electric stimulation of this part of the spinal cord on vital functions (anatomical proximity of the heart, innervation of inspiratory muscles, and proximity of the brainstem), electric stimulation is performed rarely and with due diligence at the level of the cervical spine.

Results and discussion

Neurological examination of five pediatric patients (from different groups on the ASIA scale) after five procedures revealed changes in the function of the pelvic organs in the form of an improved feeling of bladder filling and a minimum setting of the urination cycle manifested by an increase in the volume of excreted urine and frequency of urination. After a full course of stimulation, positive dynamics were noted to varying degrees but not in all patients. Subjectively, the patients noted a feeling of increased muscle strength and an increased tolerance of heavier loads (more complex tasks) during the impact of electrical stimulation when performing tasks on mechanical simulators and kinesiotherapy simulators. There was an increase in the number of exercises performed and in the tasks of the exercise therapy instructor and a reduction in the interval between tasks during the PESSC procedure. Clinically significant improvements in the function of the lower limbs were detected in three of seven patients, which were confirmed using instrumental research methods and based on neurological evaluation results. In these patients, positive dynamics were observed after 2–3 courses of PESSC; namely, in two patients, a transition of the level of neurological deficiency from type B to type D was noted, and in one patient, a transition from type C to type D was noted. One patient, initially having type C, remained in the same neurological status. In three patients with type A and B neurological disorders, no significant dynamics was observed in the motor sphere. This is explained by the severity and manifestation of the spinal cord injury as well as the duration of the damage. In this group of pediatric patients, the average values of motor functions corresponded to 50 points. However, in the sensitive area, a minimal increase in indicators was noted, and it amounted to an average of 10 on the ASIA scale. According to the EMG and ENMG data, no significant changes were recorded compared with the results obtained before the PESSC course. The analysis of SSEP in one of the patients with spinal cord injury at the thoracic level demonstrated positive dynamics in the form of the emergence of the cortical potential of P38-N46 upon the stimulation of *n. tibialis* on the right, which indicates an improvement in the conduction of somatosensory afferentation along

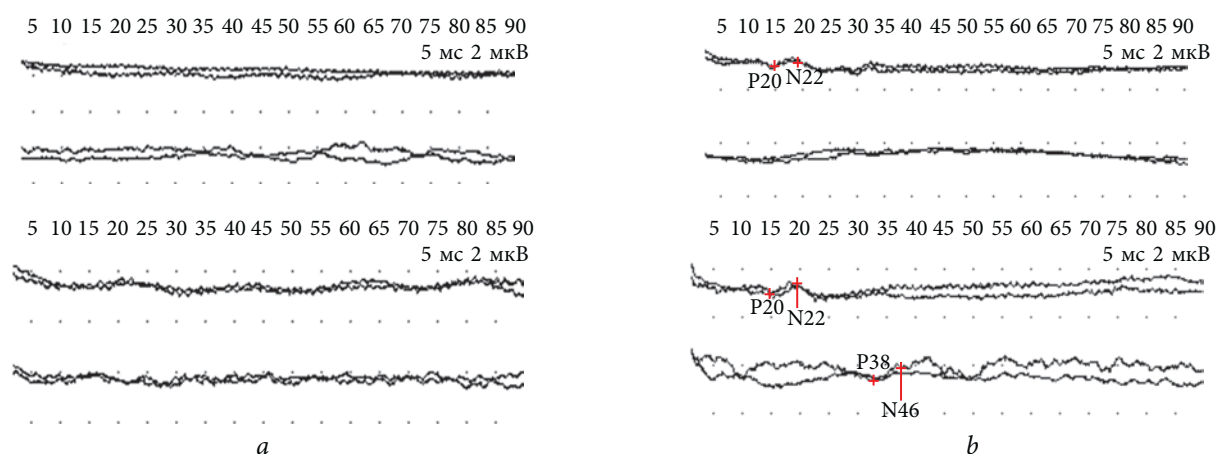


Fig. 1. Somatosensory evoked potentials upon the stimulation of *n. tibialis*: *a* — before the PESSC course; *b* — after the PESSC course (emergence of cortical potential of P38-N46 with the stimulation of *n. tibialis* on the right)

the conductors of the spinal cord above the lumbar enlargement (Fig. 1).

The majority of patients under SSEP had positive neurophysiological dynamics in the form of the emergence of neurophysiological signs of bringing to the effector muscles in the limbs, of acceleration of the time of motor conduction, and some increase in the functional activity of the neurons. Interestingly, the positive dynamics or its absence in SSEP did not always coincide with the clinical picture (neurologic examination using the ASIA scale). In one patient with an initial type B, after three stimulation courses, good recovery to type D was noted. The spine injury was obtained as a result of a fall from a height and was accompanied with damage to the spinal cord at the level of the lumbar enlargement. Initially in the neurological status, lower flaccid paraplegia with impaired pelvic function was noted. The patient was operated on the first day after the trauma due to a diagnosis of VSCI; dislocation fracture of L₃; lower flaccid paraplegia; and impaired function of the pelvic organs. After surgical treatment, the patient received three courses of PESSC and several courses of complex motor rehabilitation. Over 1 year, the increase in indices in the motor area amounted to 8 points compared with the primary neurological examination. At the repeat neurologic examination, the patient moved independently with the use of auxiliary means and could take several steps without exterior help.

Complete regression of neurological disorders was not observed in any patient.

In our study, we deliberately selected patients with severe neurologic disorders. From our point of view, the absence of a significant positive result in the restoration of neurological functions can

be explained by the severe deficit resulting from the affected level and the nature of the damage to the spinal cord caused by the trauma and by the irreversible changes in the spinal cord caused by secondary disorders affecting its structure that occurred due to the long duration from the moment of trauma to surgical intervention. This confirms the finding that the results were significantly better in patients operated on the first day after the trauma (four patients) compared with those who were operated after a week or more (three patients).

Conclusion

Thus, during the conducted research the following findings were established:

- the PESSC method promotes the most rapid and complete restoration of neurological functions (mainly functions of pelvic organs) in patients with vertebral and medullary conflicts;
- the implementation of PESSC in complex therapy with the “Exarta” system provides a pronounced positive effect, which facilitates a rapid regression of neurologic disorders in pediatric patients with this pathology;
- restoration of the functions of the spinal cord depends directly on earliness of surgical intervention; and
- restoration of the functions of even one segment of the spinal cord remarkably improves the social adaptation ability and quality of life of such patients.

The positive results obtained for the complex rehabilitation of pediatric patients with VSCI using noninvasive PESSC enable us to recommend this method for use in clinical practice and for implementation in the early stages after surgical intervention.

Funding and conflict of interest

The work was supported by the Turner Scientific and Research Institute for Children's Orthopedics of the Ministry of Health of Russia as a part of scientific research project. The authors declare no obvious and potential conflicts of interest related to the publication of this article.

References

1. Баиндурашвили А.Г., Виссарионов С.В., Александров Ю.С., Пшениснов К.В. Позвоночно-спинномозговая травма у детей. – СПб.: Онли-Пресс, 2016. – 87 с. [Baindurashvili AG, Vissarionov SV, Aleksandrov YuS, Pshenisnov KV. Pozvonochno-spinnomozgovaya travma u detei. Saint Petersburg: Onli-Press; 2016. 87p. (In Russ.)]
2. Виссарионов С.В., Белянчиков С.М. Оперативное лечение детей с осложненными переломами позвонков грудной и поясничной локализации // Травматология и ортопедия России. – 2010. – Т. 56. – № 2. – С. 48–50. [Vissarionov SV, Bel'anchikov SM. The surgical treatment of children with complicated fractures of thoracic and lumbar vertebrae. *Traumatology and Orthopedics of Russia*. 2010;56(2):48-50. (In Russ.)]. doi: 10.21823/2311-2905-2010-0-2-48-50.
3. Георгиева С.А., Бабиченко И.Е., Пучиньян Д.М. Гомеостаз, травматическая болезнь головного и спинного мозга. – Саратов: Изд-во Саратов. ун-та, 1993. – 223 с. [Georgieva SA, Babichenko IE, Puchin'yan DM. Gomeostaz, travmaticheskaya bolezнь golovnogo i spinnogo mozga. Saratov: Izd-vo Sarat. un-ta; 1993. 223 p. (In Russ.)]
4. Коновалов А.Н., Лихтерман Л.Б., Лившиц А.В., Ярцев В.В. Травма центральной нервной системы // Вопросы нейрохирургии. – 1986. – № 3. – С. 3–8. [Konovalov AN, Likhтерman LB, Livshits AV, Yartsev VV. Travma tsentral'noi nervnoi sistemy. *Voprosy neurokhirurgii*. 1986;(3):3-8. (In Russ.)]
5. Лившиц А.В. Хирургия спинного мозга. – М.: Медицина, 1990. – 350 с. [Livshits AV. Khirurgiya spinnogo mozga. Moscow: Meditsina; 1990. 350 p. (In Russ.)]
6. Jankowska E, et al. The effect of DOPA on the spinal cord. *Acta Physiologica Scandinavica*. 1967;70(3-4):389-402. doi: 10.1111/j.1748-1716.1967.tb03637.x.
7. Городничев Р.М., Пивоварова Е.А., Пухов А., и др. Чрескожная электрическая стимуляция спинного мозга: неинвазивный способ активации генераторов шагательных движений у человека // Физиология человека. – 2012. – Т. 38. – № 2. – С. 46–56. [Gorodnichev RM, Pivovarova EA, Puhov A, et al. Transcutaneous electrical stimulation of the spinal cord: A noninvasive tool for the activation of stepping pattern generators in humans. *Human Physiology*. 2012;38(2):46-56. (In Russ.)]
8. Мошонкина Т.Р., Мусиенко П.Е., Богачева И.Н., и др. Регуляция локомоторной активности при помощи эпидуральной и чрескожной стимуляции спинного мозга у животных и человека // Ульяновский медико-биологический журнал. – 2012. – № 3. – С. 129–137. [Moshonkina TR, Musienko PE, Bogacheva IN, et al. Regulation of locomotor activity by epidural and transcutaneous electrical spinal cord stimulation in the human and animals. *Ulyanovsk Medico-Biological Journal*. 2012;(3):129-137. (In Russ.)]
9. Gerasimenko Y, Lu D, Modaber M, Zdunowski S, et al. Noninvasive Reactivation of Motor Descending Control after Paralysis. *J Neurotrauma*. 2015Jun15. doi: 10.1089/neu. 2015.4008.
10. American Spinal Injury Association and International Medical Society of Paraplegia, eds. Reference manual of the international standards for neurological classification of spinal cord injury. Chicago, IL: American Spinal Injury Association; 2003.
11. Городничев Р.М., Мачуева Е.Н., Пивоварова Е.А., и др. Новый способ активации генераторов шагательных движений у человека // Физиология человека. – 2010. – № 6. – С. 95–103. [Gorodnichev RM, Machueva EN, Pivovarova EA. A new method for the activation of the locomotor circuitry in humans. *Human Physiology*. 2010;36(6):95-103. (In Russ.)]

Information about the authors

Sergei V. Vissarionov — MD, PhD, professor, deputy director for research and academic affairs, head of the Department of Spinal Pathology and Neurosurgery. The Turner Scientific Research Institute for Children's Orthopedics; professor of the Chair of Pediatric Traumatology and Orthopedics. North-Western State Medical University n.a. I.I. Mechnikov, Saint Petersburg, Russia. E-mail: turner01@mail.ru.

Irina Yu. Solokhina — MD, neurologist, research associate of the Department of Spinal Pathology and Neurosurgery. The Turner Scientific Research Institute for Children's Orthopedics, Saint Petersburg, Russia.

Galina A. Ikoeva — MD, PhD, assistant professor of the Chair of Pediatric Neurology and Neurosurgery. North-Western State Medical University n.a. I.I. Mechnikov; chief of the Department of Motor Rehabilitation. The Turner Scientific Research Institute for Children's Orthopedics, Saint Petersburg, Russia. E-mail: ikoeva@inbox.ru.

Alexei G. Baindurashvili — MD, PhD, professor, member of RAS, honored doctor of the Russian Federation, director of The Turner Scientific Research Institute for Children's Orthopedics; head of the Chair of Pediatric Traumatology and Orthopedics of North-Western State Medical University n.a. I.I. Mechnikov, Saint Petersburg, Russia. E-mail: turner01@mail.ru.

Сергей Валентинович Виссарионов — д-р мед. наук, профессор, заместитель директора по научной и учебной работе, руководитель отделения патологии позвоночника и нейрохирургии ФГБУ «НИДОИ им. Г.И. Турнера» Минздрава России; профессор кафедры детской травматологии и ортопедии ФГБОУ ВО «СЗГМУ им. И.И. Мечникова» Минздрава России, Санкт-Петербург. E-mail: turner01@mail.ru.

Ирина Юрьевна Солохина — врач-невролог, научный сотрудник отделения патологии позвоночника и нейрохирургии ФГБУ «НИДОИ им. Г.И. Турнера» Минздрава России, Санкт-Петербург.

Галина Александровна Икоева — канд. мед. наук, доцент кафедры детской неврологии и нейрохирургии ФГБОУ ВО «СЗГМУ им. И.И. Мечникова» Минздрава России; заведующая отделением двигательной реабилитации ФГБУ «НИДОИ им. Г.И. Турнера» Минздрава России, Санкт-Петербург. E-mail: ikoeva@inbox.ru.

Алексей Георгиевич Баиндурашвили — д-р мед. наук, профессор, академик РАН, заслуженный врач РФ, директор ФГБУ «НИДОИ им. Г.И. Турнера» Минздрава России; заведующий кафедрой детской травматологии и ортопедии ФГБОУ ВО «СЗГМУ им. И.И. Мечникова» Минздрава России, Санкт-Петербург. E-mail: turner01@mail.ru.