DOI: https://doi.org/10.17816/vto630428

Neuro-microcirculatory interrelationships in patients with kyphoscoliosis associated with neurological deficits

Anton G. Nazarenko, Alexander I. Krupatkin, Alexander A. Kuleshov, Igor M. Militsa, Marchel S. Vetrile, Igor N. Lisyansky, Sergey N. Makarov

N.N. Priorov National Medical Research Center of Traumatology and Orthopedics, Moscow, Russia

ABSTRACT

BACKGROUND: The use of laser Doppler flowmetry with spectral wavelet analysis of blood flow fluctuations allows us to assess the functional state of thin unmyelinated nerve fibers and objectify the dynamics of recovery processes in patients with kyphoscoliotic spinal deformities associated with spinal cord compression.

AIM: To study the features of neuromicrocirculatory relationships in patients with kyphoscoliosis associated with neurological deficits before and after surgical treatment.

MATERIALS AND METHODS: 20 patients with spinal deformities associated with neurological deficits of varying severity were examined using the LDF method and operated on. Patients were examined before surgery, 1–2 weeks after surgery following regression of acute postoperative pain syndrome, 3–6 months, 6–12 months, and more than a year after surgery. The scope of the study included a general examination with a detailed assessment of the neurological status, radiation diagnostics (postural radiographs of the spine, computed tomography and magnetic resonance imaging of the spine with assessment of spinal canal stenosis). Patients with severe kyphoscoliotic deformities underwent CT myelography followed by the design of individual full-size 3D plastic models of the spine and myeloradicular structures. LDF with wavelet analysis was carried out at all periods of the survey. A perfusion study with determination of the average microcirculation was carried out at the level of the pad of the distal phalanx of the big toe using a two-channel LAKK-02 device with a semiconductor laser (sensing in the red Raman and infrared IR channels). The obtained LDF results were processed by spectral amplitude-frequency wavelet analysis to characterize microcirculation regulation factors in the ranges of sympathetic adrenergic regulation (0.02–0.046 Hz), sensory peptidergic influences (0.047–0.069 Hz), myogenic oscillations (0.07–0.145 Hz).

RESULTS: After surgery, the activity of trophotropic sensory peptidergic nerve fibers, the values of perfusion of the microcirculatory channel increased and was maintained starting from the early postoperative period. Ergotropic sympathetic adrenergic activity was significantly decreased in the period of 6-12 months after surgery. Maximum mobilization of trophotropic neurogenic mechanisms of sanogenesis was observed in the period of 6-12 months after surgery.

CONCLUSION: The obtained data indicate a significant participation of thin nerve fibers in the recovery processes after decompressive surgeries in the spinal canal zone and the creation of anatomical conditions for neurophysiological repair at the spinal cord level. The use of the LDF method with spectral wavelet analysis of blood flow fluctuations makes it possible to objectify the dynamics of thin unmyelinated nerve fibers and recovery processes in patients with kyphoscoliotic deformities of the spine associated with spinal cord compression.

Keywords: kyphosis; scoliosis; neurological deficit; laser doppler flowmetry; microcirculation; wavelet analysis.

To cite this article:
Nazarenko AG, Krupatkin AI, Kuleshov AA, Militsa IM, Vetrile MS, Lisyansky IN, Makarov SN. Neuro-microcirculatory interrelationships in patients with kyphoscoliosis associated with neurological deficits. *N.N. Priorov Journal of Traumatology and Orthopedics*. 2024;31(3):295–304. DOI: https://doi.org/10.17816/vto630428

Received: 17.04.2024 **Accepted:** 24.04.2024 **Published online:** 17.07.2024

DOI: https://doi.org/10.17816/vto630428

Функциональная оценка тонких немиелинизированных нервных волокон у пациентов с кифосколиозом, ассоциированным с компрессией спинного мозга

А.Г. Назаренко, А.И. Крупаткин, А.А. Кулешов, И.М. Милица, М.С. Ветрилэ, И.Н. Лисянский, С.Н. Макаров

Национальный медицинский исследовательский центр травматологии и ортопедии им. Н.Н. Приорова, Москва, Россия

АННОТАЦИЯ

Обоснование. Использование метода лазерной допплеровской флоуметрии со спектральным вейвлет-анализом колебаний кровотока позволяет оценить функциональное состояние тонких немиелинизированных нервных волокон и объективизировать динамику восстановительных процессов у пациентов с кифосколиотическими деформациями позвоночника, ассоциированными с компрессией спинного мозга.

Цель. Изучить особенности нейромикроциркуляторных взаимосвязей у пациентов с кифосколиозом, ассоциированным с неврологическим дефицитом, до и после оперативного лечения.

Материалы и методы. Обследованы с использованием метода ЛДФ и прооперированы 20 пациентов с деформациями позвоночника, ассоциированными с неврологическим дефицитом различной степени выраженности. Обследование пациентов проводилось до операции, через 1–2 недели после неё (после регресса острого послеоперационного болевого синдрома), через 3–6 месяцев, 6–12 месяцев и более года после операции. Объём исследования включал общий осмотр с подробной оценкой неврологического статуса, лучевую диагностику (постуральные рентгенограммы позвоночника, компьютерную и магнитно-резонансную томографию позвоночника с оценкой стеноза позвоночного канала). Пациентам с грубыми кифосколиотическими деформациями проводилась КТ-миелография с последующим проектированием индивидуальных полноразмерных 3D-моделей позвоночника и миелорадикулярных структур из пластика. На всех сроках обследования была проведена ЛДФ с вейвлет-анализом. Исследование перфузии с определением среднего показателя микроциркуляции проводилось на уровне подушечки дистальной фаланги большого пальца стопы с использованием двухканального аппарата ЛАКК-02 с полупроводниковым лазером (зондирование в красном и инфракрасном канале). Полученные результаты ЛДФ обрабатывались методом спектрального амплитудно-частотного вейвлет-анализа для характеристики факторов регуляции микроциркуляции в диапазонах симпатической адренергической регуляции (0,02–0,046 Гц), сенсорных пептидергических влияний (0,047–0,069 Гц), миогенных осцилляций (0,07–0,145 Гц).

Результаты. После операции возрастала и поддерживалась активность трофотропных сенсорных пептидергических нервных волокон, величины перфузии микроциркуляторного русла, начиная с раннего послеоперационного периода. Эрготропная симпатическая адренергическая активность значимо снижалась в период 6–12 месяцев после операции. Максимальная мобилизация трофотропных нейрогенных механизмов саногенеза отмечалась в период 6–12 месяцев после операции.

Заключение. Полученные данные свидетельствуют о значимом участии тонких нервных волокон в восстановительных процессах после декомпрессивных операций в зоне позвоночного канала и создания анатомических условий для нейрофизиологической репарации на уровне спинного мозга. Использование метода ЛДФ со спектральным вейвлет-анализом колебаний кровотока позволяет объективизировать динамику состояния тонких немиелинизированных нервных волокон и восстановительных процессов у пациентов с кифосколиотическими деформациями позвоночника, ассоциированными с компрессией спинного мозга.

Ключевые слова: кифоз; сколиоз; неврологический дефицит; лазерная допплеровская флоуметрия; микроциркуляция; вейвлет-анализ.

Как цитировать:
Назаренко А.Г., Крупаткин А.И., Кулешов А.А., Милица И.М., Ветрилэ М.С., Лисянский И.Н., Макаров С.Н. Функциональная оценка тонких немиелинизированных нервных волокон у пациентов с кифосколиозом, ассоциированным с компрессией спинного мозга // Вестник травматологии и ортопедии им. Н.Н. Приорова. 2024. Т. 31, № 3. С. 295–304. DOI: https://doi.org/10.17816/vto630428

Рукопись получена: 17.04.2024 **Рукопись одобрена:** 24.04.2024 **Опубликована online:** 17.07.2024

BACKGROUND

Spinal deformities, such as kyphosis and scoliosis, may lead to spinal canal stenosis and subsequently to compression of the vascular-nerve structures, including the spinal cord. Imaging modalities for radiological–clinical and anatomical diagnostics [1] do not show the quantitative characteristics of the degree of damage and restoration of spinal cord function and the dynamics of the neurological status. Moreover, stenosis can cause changes in neurologic function parameters, such as the myelinated type A fibers and thin unmyelinated C-fibers. Myelinated structures contribute to specific functions within the body such as movements and deep sensitivity. Conversely, unmyelinated sympathetic and thin sensory fibers are involved in adaptation processes, tropism, patho- and sanogenesis, and pain systems. Sympathetic activity is associated with dystrophy, and sensory peptidergic nerve fibers play a crucial role in restorative processes, sanogenesis, and recovery [2]. In evaluating myelinated structures, including in spinal stenosis, electroneuromyography (ENMG) methods are used to determine the diagnostically significant indicators, namely, the amplitude of action potentials, motor and sensory response parameters, impulse conduction velocity and F-wave [3], and evoked potentials (somatosensory, cognitive, etc.) [4]. However, the state of thin unmyelinated and poorly myelinated fibers in spinal stenosis has not been studied; this may be due to the fact that these fibers have low conduction velocity and thus cannot be assessed using traditional ENMG. Thin fibers in the limbs are represented by sympathetic vegetative postganglionic C-fibers (vasomotor, to a lesser extent sweat-secreting, etc.) and sensory A-delta and C-fibers for pain and temperature sensitivity (sensory function, as well as trophic function, associated with neuropeptide secretion). Parasympathetic innervation is absent in the tissues of the limbs. In the field of vertebrology, some studies have investigated the function of thin nerve fibers. For example, using the thermography method, the role of the somatosympathetic reflex in the diagnosis of discopathy of the lumbar spine was determined [5].

Laser Doppler flowmetry (LDF) with spectral wavelet analysis of blood flow oscillations is a commonly used noninvasive method for assessing microcirculation [2, 6–9]. In the amplitude–frequency wavelet spectrum of the LDF records of microhemocirculatory signals, several characteristic frequency intervals ranging from 0.005 to 2 Hz were identified, each of which was associated with a specific physiological effect in skin microcirculation. This facilitates noninvasive assessment of the regulation of microcirculatory tissue systems. These include active tone-forming effects (endothelial, neurogenic, and myogenic) and passive effects caused by changes in pressure in microvessels (cardiac and respiratory) [2, 10]. Because the tone-forming ranges of 0.02–0.046 Hz and 0.047–0.069 Hz are associated, respectively, with sympathetic vasomotor adrenergic and sensory peptidergic influences on microvessels, respectively, the functional state of vasomotor sympathetic and sensory peptidergic innervation can be diagnosed noninvasively [2, 10]. This technique was first proposed in 2004 [10]. Regarding the range of microvessel perfusion oscillations, sympathetic adrenergic influences and accompanying angiospastic manifestations are considered ergotropic and sensory peptidergic, myogenic, and endothelial influences are trophotropic. The predominance of ergotropic factors is associated with degenerative–dystrophic processes, and the prevalence of trophotropic components of the regulation of microcirculatory tissue systems is linked to regeneration and restorative processes [2].

Notably, microcirculatory tissue systems are among the first to respond in the development of sanogenesis; therefore, the use of LDF indicators with wavelet analysis of blood flow oscillations before and after spinal surgeries is promising for the detection of the vector of functional dynamics [2, 9].

MATERIALS AND METHODS

Study design

A monocentric cohort retrospective comparative study was performed.

Eligibility criteria

At the N.N. Priorov National Medical Research Center of Traumatology and Orthopedics, 20 patients with spinal deformities associated with neurological deficits of varying severity were examined using the LDF method and operated on: 17 patients were below 18 years old (13.9±2.6 years) and three were adults. In the pediatric group, 10 cases of grade IV idiopathic kyphoscoliosis with Frankel neurological status C (seven patients) and D (three patients) and seven cases of thoracolumbar kyphosis that developed against hypoplasia of the Th12-L1 vertebral bodies were noted. This group of patients had spinal canal stenosis of 54.1±19.1%, assessed according to computed tomography (CT) myelography of the deformity apex in the sagittal plane. In adult patients, kyphotic deformity of the thoracic and thoracolumbar spine was registered. Examination showed a spinal canal stenosis of 53.3±16.4%. Frankel neurological status C (two patients) and D (one patient) were noted.

Study conditions

The patients were examined before the surgery, 1–2 weeks after surgery following regression of acute postoperative pain syndrome, and 3–6 months, 6–12 months, and more than a year after the surgery.

Method of medical intervention

Instrumental correction and fixation of the deformity without direct decompression of the spinal canal were performed in seven patients and two-stage surgical treatment involving dorsal stabilization of the spinal deformity and anterior decompression of the spinal canal in ten patients. Posterolateral decompression of the spinal canal was conducted in three patients.

Methods of recording outcomes

General examination including assessment of the neurological status and radiation diagnostics (i.e., postural radiographs of the spine and CT and magnetic resonance imaging of the spine with assessment of spinal stenosis) were carried out. Patients with severe kyphoscoliosis underwent CT myelography with subsequent design of individual full-size 3D models of the spine and myeloradicular structures made of plastic.

LDF with wavelet analysis was performed in all stages of the examination (Figs. 1–3). A perfusion study, with determination of the average microcirculation index (M, in perfusion units (p.u.)), was performed at the level of the pad of the distal phalanx of the big toe using a two-channel LAKK-02 device with a semiconductor laser (probing in the red and infrared channels) [2, 9]. The LDF results were processed using spectral amplitude–frequency wavelet analysis to characterize the factors of microcirculation regulation in the ranges of sympathetic adrenergic regulation (0.02–0.046 Hz), sensory peptidergic influences (0.047–0.069 Hz), and myogenic oscillations (0.07–0.145 Hz). The maximum average amplitude of oscillations in each range, normalized by the root-mean-square deviation (σ), was determined by the equation A/σ, where A is the amplitude value in p.u. according to the previously described technique [2, 9] (Figs. 1–3).

Statistical analysis

Statistical processing was performed using the Biostat 4.03 program. The Mann–Whitney test was used to compare two samples. Quantitative data were presented as mean ± standard deviation.

Ethical considerations

The study was conducted according to the standards of the local ethics committee (meeting no. 7, dated August 5, 2021) and the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. All patients (or their representatives) signed an informed consent to participate in the study.

RESULTS

After surgical treatment, the relative magnitude of spinal canal stenosis in patients in the postoperative period was 27.5±14.7% (before surgery: 54.1±19.1%). Eight patients with the Frankel C neurological status (in the form of lower mixed deep paraparesis) showed positive dynamics up to Frankel D. Seven of 12 patients with preoperative neurological status Frankel D did not show changes in neurological deficit, whereas five patients showed regression of neurological disorders up to Frankel E. The outcomes of surgical treatment of patients were assessed as good. In 13 patients (65%), regression of neurological deficit was detected during the follow-up period of 3–6 months after surgery. The delta of deformity correction in this group of patients was 29.3±12.1%.

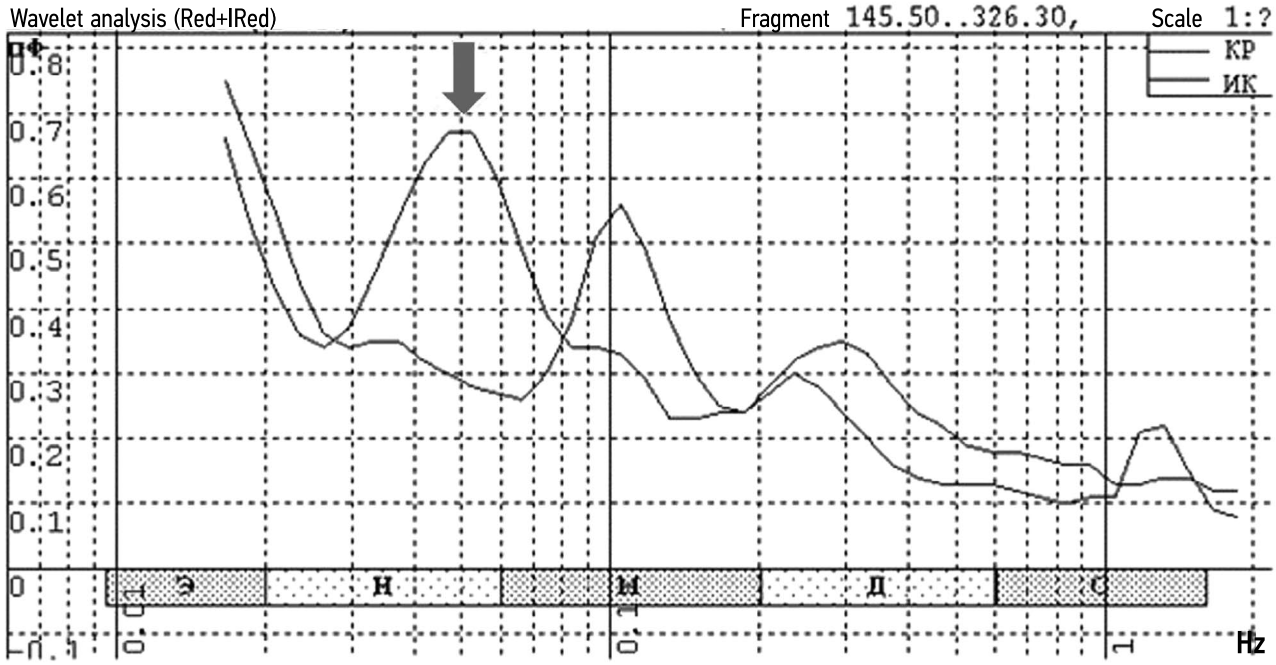

Fig. 1. An example of recording the wavelet spectrum of blood flow fluctuations according to laser Doppler flowmetry data before surgery.

Note. Horizontally — frequency ranges in Hz: e (endothelial), n (neurogenic), m (myogenic), rv (respiratory venular), c (cardiac). Vertically — the amplitude of fluctuations in blood flow in perfusion units. The red arrow is the activation of oscillations in the range of sympathetic adrenergic regulation of microvessels in the infrared channel. Sensory peptidergic activity has not been recorded.

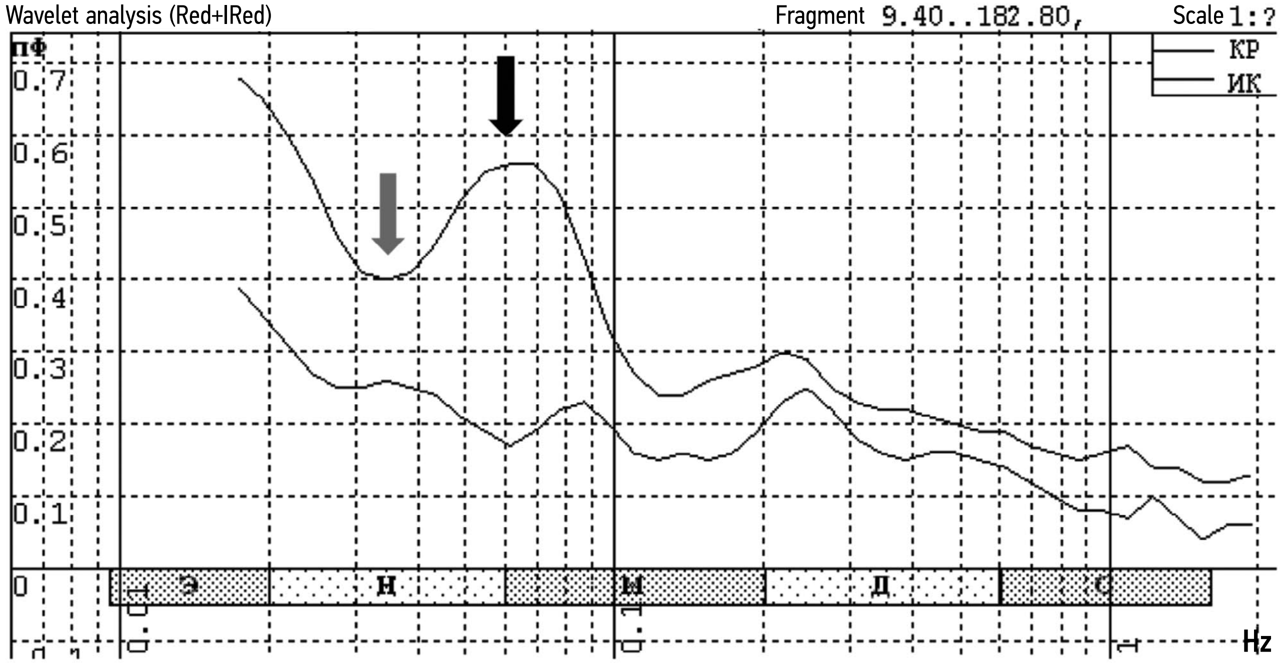

Fig. 2. An example of recording the wavelet spectrum of blood flow fluctuations according to laser Doppler flowmetry 8 months after surgery.

Note. Horizontally — frequency ranges in Hz: e (endothelial), n (neurogenic), m (myogenic), rv (respiratory venular), c (cardiac). Vertically — the amplitude of fluctuations in blood flow in perfusion units. The red arrow indicates the absence of sympathetic adrenergic activity in the infrared channel and its marked decrease in the red recording channel. The blue arrow indicates the pronounced activity of sensory peptidergic regulation in the infrared recording channel.

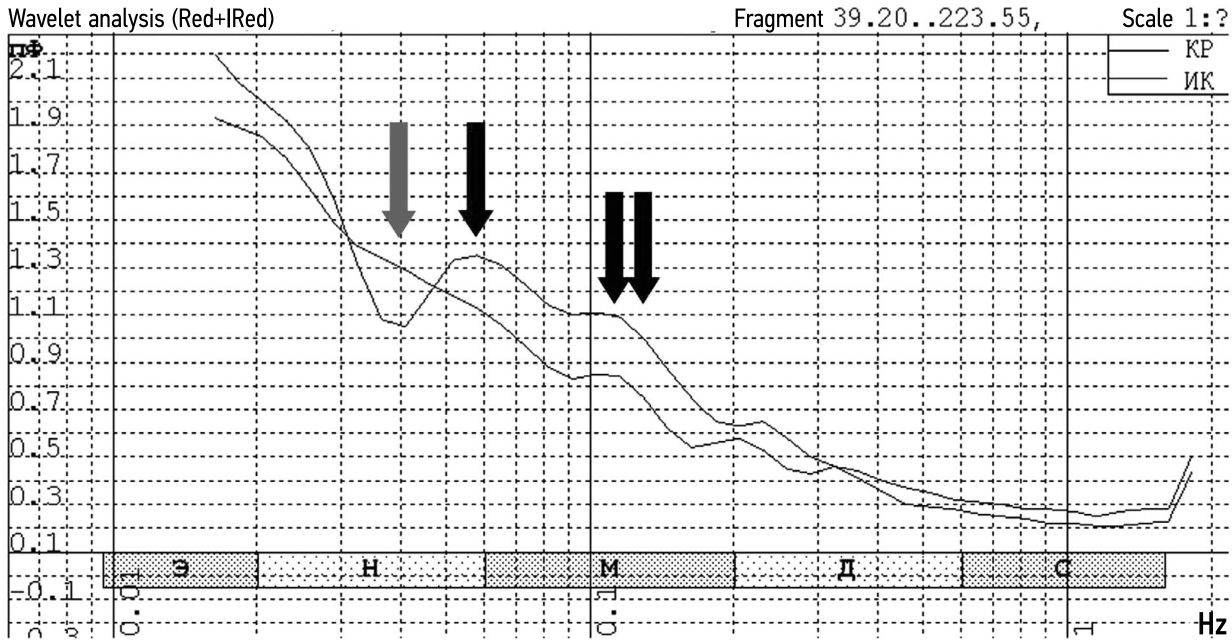

Fig. 3. An example of recording the wavelet spectrum of blood flow fluctuations according to laser Doppler flowmetry 1.5 years after surgery.

Note. Horizontally: frequency ranges in Hz — e (endothelial), n (neurogenic), m (myogenic), rv (respiratory venular), c (cardiac). Vertically — the amplitude of fluctuations in blood flow in perfusion units. The red arrow indicates the absence of sympathetic adrenergic activity in the red and infrared recording channels. The blue arrow is the activation of sensory peptidergic regulation in the infrared recording channel. The double blue arrow is the synchronization of the frequency of myogenic activity in the red and infrared channels.

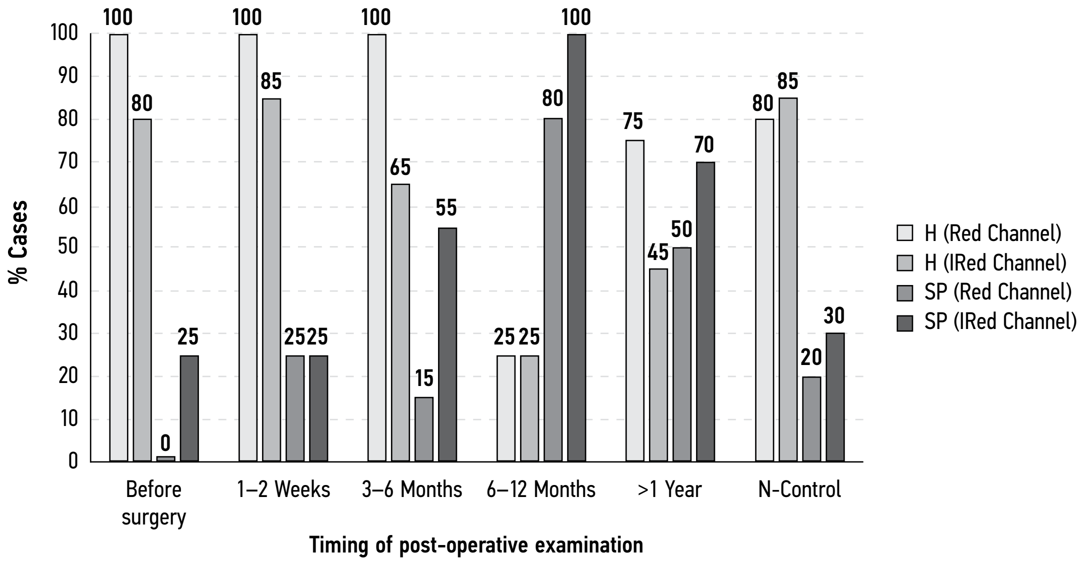

Fig. 4. Frequency of activity of sympathetic adrenergic and sensory peptidergic regulation of microvessels in the wavelet spectrum of blood flow fluctuations, %.

Note. H — sympathetic adrenergic regulation of microvessels, SP — sensory peptidergic regulation of microvessels, IRed — infrared.

Figure 4 and Table 1 present the results of the study using the LDF method.

Examples of recording the wavelet spectrum of blood flow oscillations are shown in Figures 1–3.

Based on the data presented, during the postoperative recovery, clear dynamics of the functional state of thin nerve fibers were noted (Fig. 4). Under physiological rest conditions in healthy individuals (control group), the sympathetic adrenergic regulation was predominant, whereas trophotropic sensory peptidergic activity was detected in the wavelet spectrum in no more than 30% of cases. In patients in the preoperative period, this distribution was preserved; however, in precapillary microvessels (red channel recordings), sensory peptidergic regulation was not detected in the wavelet spectrum. After the surgery, a progressive change in the vector of nervous control of microcirculatory tissue systems was noted, namely, a distinct increase in the contribution of trophotropic sensory peptidergic innervation against a decrease in the representation of the ergotropic sympathetic adrenergic channel of regulation. The highest trophotropic contribution was observed in the time interval of 6–12 months after the surgery, regarding it as the most active recovery period.

The quantitative indices of the state of microcirculation and its regulation are of interest (Table 1). The preoperative period was characterized by low values of perfusion (M, p.u.) of the microvascular bed in the red recording channel, reflecting predominantly nutritive blood flow, absence of trophotropic sensory peptidergic oscillations in the same recording channel, and relatively low values of the amplitudes

Table 1. Indicators of laser Doppler flowmetry before and after surgical treatment

Examination interval	An./σ R	An./σ IR	Asp./σ R	Asp./σ IR	Am./σ R	Am./σ IR	M, p.u. R	M, p.u. IR
Before surgery	0.45±0.12	0.53±0.11	–	0.38±0.08	0.38±0.04	0.24±0.03	1.1±0.07	11.7±1.1
1–2 weeks after surgery	0.4±0.2	0.64±0.04*	0.57±0.12*	0.53±0.05*	0.41±0.09	0.3±0.08	2.3±0.05*	10±1.5
3–6 months after surgery	0.6±0.1	0.65±0.06*	0.41±0.08*	0.54±0.04*	0.39±0.07	0.19±0.1	2.34±0.04*	13±1.4
6–12 months after surgery	0.37±0.07*	0.44±0.06*	0.47±0.11*	0.43±0.04*	0.43±0.03*	0.28±0.05	5.4±0.09*	13±2.3
More than 1 year after surgery	0.45±0.15	0.5±0.12	0.32±0.07*	0.54±0.12*	0.35±0.1	0.34±0.04*	7.2±1.1*	18.7±1.5*
Control (*n*=20)	0.4±0.09	0.48±0.1	0.27±0.1	0.29±0.1	0.45±0.07	0.4±0.03	5.1±0.09	11.8±1.3

Note. *, p <0.05 for data in dynamics after surgery compared with preoperative results; R, red channel; IR, infrared channel.

of myogenic blood flow oscillations associated with capillary perfusion. Positive changes of microvascular indices were determined after the surgery. The M value significantly increased, especially in the red recording channel. Moreover, the activity of sensory peptidergic nerve fibers increased and was maintained starting from the early postoperative period. Sympathetic adrenergic activity significantly decreased 6–12 months after the surgery.

DISCUSSION

In the present study, the laser Doppler flowmetry method was used to evaluate thin unmyelinated nerve fibers. LDF is widely used in modern fundamental and clinical medicine to evaluate microcirculatory tissue systems. In PubMed alone, approximately 12,000 publications on this topic in various fields of medicine were found. The advantages of the method are noninvasiveness, harmlessness of research, and the possibility of unlimited control over time, and for Russian devices of the LAKK series, it is also a computer quantitative analysis of records using spectral wavelet analysis of blood flow oscillations. This quantitative approach enables evaluation of the factors regulating microcirculation, including the functional state of thin unmyelinated nerve fibers involved in the innervation of microvessels (vasomotor sympathetic and sensory peptidergic). This is especially valuable for traumatology and orthopedics, as the results of LDF characterize not only the purely vascular component of tissue tropism implemented at the level of microcirculation but also the condition of the nervous component of tropism implemented through thin nerve fibers [2, 9]. Currently, this opportunity has become even more crucial owing to the fact that neurophysiological diagnostics in traumatology and orthopedics, including vertebrology, is based on an electrophysiological approach with an assessment of conductivity along myelinated nerve fibers. However, this approach is ineffective for diagnosing unmyelinated innervation.

The choice of the skin of the plantar surface of the big toe as the LDF registration zone was due to the high density of unmyelinated fibers, including perivascular, in the skin of the plantar and palmar surfaces in humans [9].

Results indicate that the contribution of trophotropic sensory peptidergic regulation begins to increase 3–6 months after surgery, reaches a maximum in 6–12 months, and decreases slightly, but remains a year or more after surgery. In this context, the participation of the ergotropic channel of regulation associated with sympathetic fibers is maintained at all stages; however, their contribution to the control of microcirculatory tissue systems decreased starting from month six after surgery, reaching a minimum in 6–12 months.

Among the quantitative parameters of microcirculation, the average perfusion value M demonstrated a clear progression in dynamics after the surgery. In quantitative terms, for cases of representation in the wavelet spectrum, the activity of the trophotropic sensory peptidergic channel of regulation (the values of the normalized amplitudes of blood flow oscillations of the corresponding genesis) increased significantly after surgery, and the activity of the ergotropic sympathetic channel (the values of the amplitudes of oscillations of the sympathetic adrenergic genesis) significantly decreased 6–12 months after surgery.

The obtained data indicate the significant participation of thin nerve fibers in the recovery processes after decompression surgeries in the spinal canal zone and in creating anatomical conditions for neurophysiological reparation in the spinal cord.

CONCLUSION

Using the LDF with spectral wavelet analysis of blood flow oscillations enables evaluation of the dynamics of the state of thin unmyelinated nerve fibers and recovery processes in patients with kyphoscoliotic spinal deformities associated with spinal cord compression. After surgery, the activity of trophotropic sensory peptidergic nerve fibers and microcirculatory bed perfusion increased and were maintained since the early postoperative period. Ergotropic sympathetic adrenergic activity significantly decreased 6–12 months after surgery. Maximum mobilization of trophotropic neurogenic mechanisms of sanogenesis was noted 6–12 months after the intervention.

ADDITIONAL INFO

Autor contribution. All authors confirm that their authorship meets the international ICMJE criteria (all authors have made a significant contribution to the development of the concept, research and preparation of the article, read and approved the final version before publication). The greatest contribution is distributed as follows: A.I. Krupatkin and I.M. Militsa — data collection and analysis, writing the text of the article, analysis of literary sources; A.G. Nazarenko and A.A. Kuleshov — writing and editing the text of the article; M.S. Vetrile, I.N. Lisyansky, S.N. Makarov — editing the text of the article.

Funding source. The authors state that there is no external funding when conducting the research and preparing the publication.

Competing interests. The authors declare that they have no competing interests.

Consent for publication. The patient gave his written consent for publication of his medical data.

ДОПОЛНИТЕЛЬНО

Вклад авторов. Все авторы подтверждают соответствие своего авторства международным критериям ICMJE (все авторы внесли существенный вклад в разработку концепции, проведение исследования и подготовку статьи, прочли и одобрили финальную версию перед публикацией). Наибольший вклад распределён следующим образом: А.И. Крупаткин и И.М. Милица — сбор

и анализ данных, написание текста статьи, анализ литературных источников; А.Г. Назаренко и А.А. Кулешов — написание и редактирование текста статьи; М.С. Ветрилэ, И.Н. Лисянский, С.Н. Макаров — редактирование текста статьи.

Источник финансирования. Авторы заявляют об отсутствии внешнего финансирования при проведении исследования и подготовке публикации.

Конфликт интересов. Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с проведённым исследованием и публикацией настоящей статьи.

Информированное согласие. Авторы получили письменное согласие пациента на публикацию его медицинских данных.

REFERENCES

1. Alsaleh K, Alduhaish A. A limited unilateral transpedicular approach for anterior decompression of the thoracolumbar spinal cord in elderly and high-risk patients. *J Craniovertebr Junction Spine.* 2019;10(2):88–93. doi: 10.4103/jcvjs.JCVJS_20_19

2. Krupatkin AI, Sidorov VV. Laser Doppler flowmetry. In: Beresten NF, Sandrikova VA, Fedorova SI, editors. *Functional diagnostics: National guidelines.* Moscow: GEOTAR-Media; 2019. P. 488–499.

3. Ippolitova EG, Damdinov BB, Koshkareva ZV, Verkhozina TK. Electroneuromyographic parameters in patients with spinal canal stenosis at the cervical level. *Acta Biomedica Scientifica.* 2020;5(5):68–72. doi: 10.29413/ABS.2020-5.5.9

4. Adambaev ZI. Prognostic significance of electroneuromyography and evoked potentials in spinal canal stenosis. *Medical news.* 2019;(6):69–71. EDN: GPZGZQ

5. Mironov SP, Vetrile ST, Krupatkin AI, Shvets VV. Features of regional vegetative regulation and radicular microhemocirculation in patients with osteochondrosis of the spine before and after lumbar discectomy. *N.N. Priorov Journal of Traumatology and Orthopedics*. 2008;(2):15–19. EDN: JTGFYB

6. Srinivasan G, Sujatha N. Fractal Dimension Characterization of in-vivo Laser Doppler Flowmetry signals. *Physics Procedia.* 2011;19:49–54. doi: 10.1016/j.phpro.2011.06.124

7. Gallagher MJ, Hogg FRA, Zoumprouli A, et al. Spinal Cord Blood Flow in Patients with Acute Spinal Cord Injuries. *J Neurotrauma.* 2019;36(6):919–929. doi: 10.1089/neu.2018.5961

8. Reynès C, Vinet A, Maltinti O, Knapp Y. Minimizing the duration of laser Doppler flowmetry recordings while maintaining wavelet analysis quality: A methodological study. *Microvasc Res.* 2020;131:104034. doi: 10.1016/j.mvr.2020.104034

9. Krupatkin AI, Sidorov VV. *Functional diagnostics of the state of microcirculatory and tissue systems. Fluctuations, information, nonlinearity. A guide for doctors.* Moscow: LIBROCOM Book House; 2013. 496 p.

10. Krupatkin AI. Functional assessment of perivascular innervation of the skin of the extremities using laser Doppler flowmetry. *Human Physiology.* 2004;30(1):99–104. EDN: OXNWFR

СПИСОК ЛИТЕРАТУРЫ

1. Alsaleh K., Alduhaish A. A limited unilateral transpedicular approach for anterior decompression of the thoracolumbar spinal cord in elderly and high-risk patients // J Craniovertebr Junction Spine. 2019. Vol. 10, № 2. P. 88–93. doi: 10.4103/jcvjs.JCVJS_20_19

2. Крупаткин А.И., Сидоров В.В. Лазерная допплеровская флоуметрия. В кн.: Функциональная диагностика: национальное руководство / под ред. Н.Ф. Берестень, В.А. Сандрикова, С.И. Фёдоровой. Москва: ГЭОТАР-Медиа, 2019. С. 488–499.

3. Ипполитова Е.Г., Дамдинов Б.Б., Кошкарёва З.В., Верхозина Т.К. Электронейромиографические показатели у больных со стенозирующим процессом позвоночного канала на шейном уровне // Acta Biomedica Scientifica. 2020. Т. 5, № 5. С. 68–72. doi: 10.29413/ABS.2020-5.5.9

4. Адамбаев З.И. Прогностическая значимость показателей электронейромиографии и вызванных потенциалов при стенозе позвоночного канала // Медицинские новости. 2019. № 6 (297). С. 69–71. EDN: GPZGZQ

5. Миронов С.П., Ветрилэ С.Т., Крупаткин А.И., Швец В.В. Особенности регионарной вегетативной регуляции и корешковой микрогемоциркуляции у больных остеохондрозом позвоночника до и после поясничной дискэктомии // Вестник травматологии и ортопедии им. Н.Н. Приорова. 2008. № 2. С. 15–19. EDN: JTGFYB

6. Srinivasan G., Sujatha N. Fractal Dimension Characterization of in-vivo Laser Doppler Flowmetry signals // Physics Procedia. 2011. Vol. 19. P. 49–54. doi: 10.1016/j.phpro.2011.06.124

7. Gallagher M.J., Hogg F.R.A., Zoumprouli A., et al. Spinal Cord Blood Flow in Patients with Acute Spinal Cord Injuries // J Neurotrauma. 2019. Vol. 36, № 6. P. 919–929. doi: 10.1089/neu.2018.5961

8. Reynès C., Vinet A., Maltinti O., Knapp Y. Minimizing the duration of laser Doppler flowmetry recordings while maintaining wavelet analysis quality: A methodological study // Microvasc Res. 2020. Vol. 131. P. 104034. doi: 10.1016/j.mvr.2020.104034

9. Крупаткин А.И., Сидоров В.В. Функциональная диагностика состояния микроциркуляторно-тканевых систем. Колебания, информация, нелинейность. Руководство для врачей. Москва: Книжный дом ЛИБРОКОМ, 2013. 496 с.

10. Крупаткин А.И. Функциональная оценка периваскулярной иннервации кожи конечностей с помощью лазерной допплеровской флоуметрии // Физиология человека. 2004. Т. 30, № 1. С. 99–104. EDN: OXNWFR

AUTHORS' INFO

Anton G. Nazarenko, MD, Dr. Sci. (Medicine), professor of RAS;
ORCID: 0000-0003-1314-2887;
eLibrary SPIN: 1402-5186;
e-mail: nazarenkoag@cito-priorov.ru

Alexander I. Krupatkin, MD, Dr. Sci. (Medicine), professor;
ORCID: 0000-0001-5582-5200;
eLibrary SPIN: 3671-5540;
e-mail: krup.61@mail.ru

Alexander A. Kuleshov, MD, Dr. Sci. (Medicine);
ORCID: 0000-0002-9526-8274;
eLibrary SPIN: 7052-0220;
e-mail: cito-spine@mail.ru

*** Igor M. Militsa;**
address: 10 Priorova str., 127299 Moscow, Russia;
ORCID: 0009-0005-9832-316X;
eLibrary SPIN: 4015-8113;
e-mail: igor.milica@mail.ru

Marchel S. Vetrile, MD, Cand. Sci. (Medicine);
ORCID: 0000-0001-6689-5220;
eLibrary SPIN: 9690-5117;
e-mail: vetrilams@cito-priorov.ru

Igor N. Lisyansky, MD, Cand. Sci. (Medicine);
ORCID: 0000-0002-2479-4381;
eLibrary SPIN: 9845-1251;
e-mail: lisigornik@list.ru

Sergey N. Makarov, MD, Cand. Sci. (Medicine);
ORCID: 0000-0003-0406-1997;
eLibrary SPIN: 2767-2429;
e-mail: moscow.makarov@gmail.com

ОБ АВТОРАХ

Назаренко Антон Герасимович, д-р мед. наук, профессор РАН;
ORCID: 0000-0003-1314-2887;
eLibrary SPIN: 1402-5186;
e-mail: nazarenkoag@cito-priorov.ru

Крупаткин Александр Ильич, д-р мед. наук, профессор;
ORCID: 0000-0001-5582-5200;
eLibrary SPIN: 3671-5540;
e-mail: krup.61@mail.ru

Кулешов Александр Алексеевич, д-р мед. наук;
ORCID: 0000-0002-9526-8274;
eLibrary SPIN: 7052-0220;
e-mail: cito-spine@mail.ru

*** Милица Игорь Михайлович;**
адрес: Россия, 127299, Москва, ул. Приорова, 10;
ORCID: 0009-0005-9832-316X;
eLibrary SPIN: 4015-8113;
e-mail: igor.milica@mail.ru

Ветрилэ Марчел Степанович, канд. мед. наук;
ORCID: 0000-0001-6689-5220;
eLibrary SPIN: 9690-5117;
e-mail: vetrilams@cito-priorov.ru

Лисянский Игорь Николаевич, канд. мед. наук;
ORCID: 0000-0002-2479-4381;
eLibrary SPIN: 9845-1251;
e-mail: lisigornik@list.ru

Макаров Сергей Николаевич, канд. мед. наук;
ORCID: 0000-0003-0406-1997;
eLibrary SPIN: 2767-2429;
e-mail: moscow.makarov@gmail.com

* Corresponding author / Автор, ответственный за переписку