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FEATURES OF THE USE OF FIBER-OPTIC SENSORS FOR THE STUDY OF TISSUE MICROCIRCULATION

Анотація. Практична цінність hj,jnb полягає в представлених рекомендаціях щодо розробки системи дослідження мікроциркуляції тканин на основі одного випромінювального та групи приймальних світловодів, що дало змогу проаналізувати можливості використання світловодів різних параметрів і характеристик. Запропоновано схемні рішення побудови оптико-електронних систем діагностики тканинної мікроциркуляції на основі волоконно-оптичних сенсорів, що здійснюють реєстрацію та обробку фотоплетизмографічної інформації в режимі реального часу для здійснення апаратно-програмної реалізації системи дослідження периферичного кровообігу для оцінки біомедичних сигналів на основі отриманих фотоплетизмограм.
Ключові слова: фотоплетизмографічний сигнал, тканинна мікроциркуляція, волоконно-оптичні сенсори
Abstract. The practical value of the work consists in the presented recommendations for developing a system for the study of tissue microcirculation based on one emitting and a group of receiving optical fibers, which made it possible to analyze the use of optical fibers of various parameters and characteristics. Schematic solutions for the construction of optoelectronic systems for the diagnosis of tissue microcirculation based on fiber-optic sensors that perform registration and processing of photoplethysmographic information in real-time are proposed to carry out a hardware and software implementation of a system for the study of peripheral blood circulation for the evaluation of biomedical signals based on the received photoplethysmograms.
Key words: photoplethysmographic signal, tissue circulation, fiber optic sensors

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INTRODUCTION

The development of any branch of science, including biological and medical fields, includes, on the one hand, an analytical orientation of the functioning mechanisms of the object being studied and, on the other hand, a synthetic one, which seeks to generalize the obtained relationships. As the structural and functional basis of the human body's vital activity, microcirculatory and tissue systems are significant objects for study. Thanks to the development of non-invasive diagnostic methods, it became possible not only to study the mechanisms of functioning of microcirculation and the exchange of the internal environment but also to obtain new diagnostic information about the macroscopic parameters of the system's overall information-energy and nonlinear characteristics.

The primary goal of this study was to carry out research leading to an increase in the reliability of diagnosing the state of peripheral blood circulation. It was obtained by improving the methods of recording optical radiation and using the appropriate means of the analysis of photoplethysmographic information.

Achieving the goal of the research consisted of the following steps. The first was an analysis of the methods of using optical fibers in fiber-optic sensors in biomedicine. The next step was an analysis of optical fiber types and the possibilities for their use in biomedical sensors to systematize the results obtained. The following step was analyzing the effects of radiation propagation through a bio-object using the Monte Carlo method and propagation of radiation analysis in bio-objects. The next step was developing a methodology for calculating the main parameters of radiation during propagation along a transmitting optical fiber, calculations of radiation attenuation, and building models of changes in characteristics when the emitting and receiving optical fibers are displaced relative to the surface of the bio-object.

The following step was a study of structural and technical options, implementation, and efficiency of optoelectronic means of diagnosing the state of peripheral blood circulation. The final step was designing an optoelectronic system for the study of peripheral blood circulation, an algorithm for registration, processing, and storage of biomedical data and its implementation in real-time.

Today, many methods based on laser and optical-electronic devices are introduced into medical diagnostics. These include the photoplethysmographic method (FPM), which allows measuring blood filling and blood flow in powerful veins and arteries and in peripheral vessels and capillaries [1, 6, 7]. FPM, compared to other methods of diagnosing a biological object (BO) by optical indicators, for example, with the photoacoustic method, allows an increase in the reliability of registration of hemodynamic indicators of blood filling, as well as the fact that by introducing elements of optical fiber technology and sources of various wavelengths of probing radiation can be used to sufficiently accurately solve the problems of photodynamic studies, remote measurements of specific hemodynamic parameters [1,6].

There are two types of FPM - FPG in transmitted light and FPG in reflected light. Studies are often performed in transmitted light because, in this case, a direct assessment of the blood supply in the necessary area of the BO is carried out. However, it is often quite challenging to carry out such studies, for example, for optically opaque BOs or hard-to-reach areas of objects. Then, the FPG method in reflected light is used, which not only allows the assessment of the total blood flow in the studied area but also provides an integral assessment of the surface properties of the study.

In the case of the application of FPG in reflected light, that is, when the photoplethysmographic measuring transducer (PFT) perceives the radiant flow reflected from the BO, it is shown that the FPM allows registering the amount of blood filling of the BO tissues by the pulsation of the surface of the BO closest to the FVP, i.e. the amount of change of the reflected from the BO tissue, that is being investigated, the light flux depending on the amplitude of tissue pulsation [8, 9, 10].

The use of optoelectronic and laser sensors in biology and medicine can be carried out in several directions, one of which can be considered development based on new optoelectronic and laser technologies for the detection, identification, and study of the structure of biological objects, as well as for studying the nature of processes, occurring in them [2, 11].

In this context, the study of human peripheral blood circulation is a fairly promising direction of diagnosis based on the state of the circulatory system for several reasons: diagnosis is a non-invasive method that uses the near-infrared spectrum of optical radiation; diagnostic results can be obtained from different parts of the human body, which allows for local diagnosis of the level of blood circulation; research results are recorded and processed in real-time, which ensures sufficient speed and informativeness of the method; the optical method is safe and therefore can be used together with other means of diagnosis.

PHYSICAL AND MATHEMATICAL MODELS FOR ANALYZING THE INTERACTION OF LASER RADIATION WITH BIOTISSUES

Violation of peripheral blood circulation is a common pathology which can indicate a particular disease. Depending on the stage, age, features, and terms of obliteration and reactivity, circulatory disorders of particular body parts are formed in each patient. Early diagnosis of such disorders is an essential task for modern medicine that requires developing new and improving existing diagnostic tools [1, 2].

Today, many diagnostics methods are based on laser and optoelectronic devices. Among them is the photoplethysmographic method, which measures blood flow through veins, arteries, and capillaries. Compared to other methods for diagnosing biological objects (BO), the photoacoustic method can improve the reliability of registration hemodynamic blood supply [1, 2].

The development of photoplethysmographic diagnostics devices based on detecting reflected or passed through the biological tissue optical radiation is significant. However, the intensity of the radiation recorded by the photodetector depends on the absorption capacity of matter. Primarily, it depends on the electronic structure of molecules and atoms, the radiation wavelength, absorbing sample thickness, temperature, and absorbing concentration centers.

The absorption maximum is in the blue region of the visible spectrum range, the green and yellow (500-600 nm) region has a less absorption and it’s absorbed by the red blood cells. Shorter wavelengths are absorbed by melanin. The absorption maximum is in the blue region of the visible spectrum range; the green and yellow (500-600 nm) wavelengths are weaker absorbed by the red blood cells. Shorter wavelengths are absorbed by melanin. In the ultraviolet and far-infrared spectral ranges, the light is absorbed by water. The red and near-infrared wavelengths have the least light losses due to absorption. Therefore, these optical ranges are used to develop optoelectronic sensors for diagnosing peripheral blood circulation (Fig. 1).

Blood has the highest absorption capacity of the surrounding tissues, so the intensity of light, recorded by the detector, is increased with blood volume reduction. The wavelength and the distance between the light source and photodetector determine the light penetration depth. Greenlight is suitable for measurements of surface blood flow in the skin. The light in the green-yellow region (5000-600nm) has the greatest modulation depth. The near-infrared region is suitable for blood flow measurements in the deeper tissues. A red band is used to determine blood oxygen saturation.

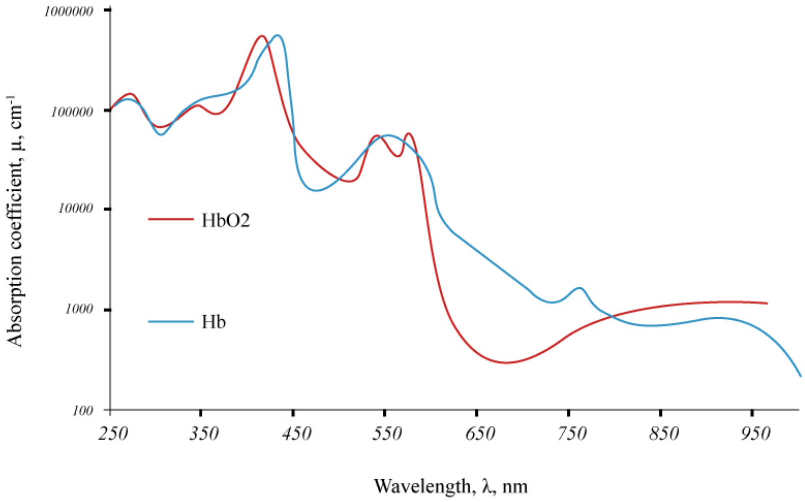

Figure 1 – Dependence the absorption coefficient on the wavelength

Human skin is a living multi-layered environment containing various inclusions, such as, for example, blood vessels in which blood moves. All this makes it difficult to understand the processes that occur when radiation affects the skin. To describe these processes, there are currently many different mathematical and physical models, each of which is designed to solve a specific problem, to describe a particular case. A simplified skin model is a three-layer system, and each layer has different biophysical properties, and therefore different optical parameters (Fig. 3.6).

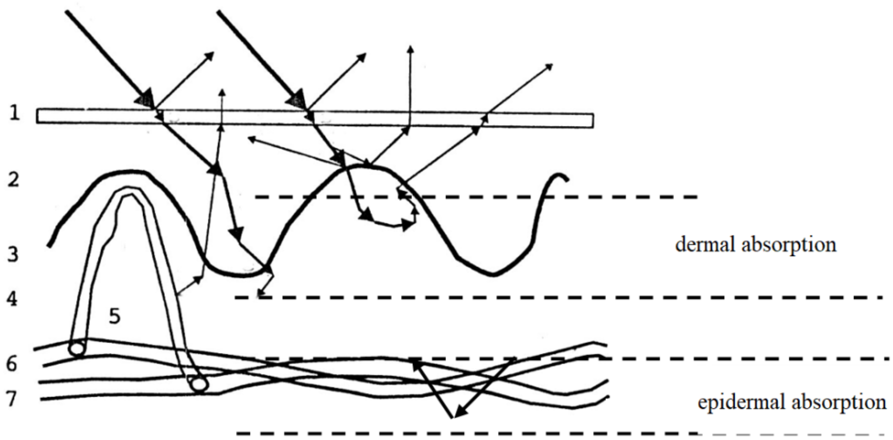

Figure 2 – Scheme of propagation of optical radiation in a biological object: 1 – stratum corneum; 2 – epidermis; 3 – zone between epidermis and dermis (basement membrane); 4 – dermis; 5 – arteriole; 6 – postcapillary venule

Radiation falling on the skin I_1, is partially reflected from its surface I'_1, passes through the epidermis, where it is absorbed by the melanin of the skin and is partially dispersed I_3, and part passes through the dermis and is reflected from the blood vessel I_3

$$\Delta I_{refl} = I_1 - (I'_1 + I_2 + I_3) \tag{1}$$

We denote $I_1 = f(I_0, R, \theta)$ as a function of the intensity of radiation that interacts with biotissue. $I_0 = f(\lambda)$, as well as its angle of incidence θ under the condition that Lambert's law $I_\theta = I_0 \cos(\theta)$ is fulfilled.

When reflected from the surface of the skin, the radiation changes intensity in a solid angle

$$dI_1^{'} = r_1 I_0 \cos\Theta d\Omega, \tag{2}$$

where $d\Omega = \sin\Theta d\Theta d\varphi$ elementary solid angle, r_1 – skin reflection coefficient.

PRACTICAL REALIZATION OPTICAL FIBER FOR INVESTIGATION OF TISSUE MICROCIRCULATION

The developed device operates on the wavelength 905nm for determining the basic parameters of the peripheral circulatory and 660nm for determining blood saturation. The advantage of the device is mobility and functionality [5, 6].

The practical realization of this sensor is that three models for implementing optical fibers have been implemented. The first model consists of one emitting optical fiber, which accepts the optical radiation from bio-object. The second model has been constructed on the base of the one emitting and accepting optical fibers. The last one consists of the one emitting and the group of accepting optical fibers (Fig. 3).

In the first two cases of this construction, there are many advantages. Firstly, it permits us to use the sensor in samples of biological objects of small size, such as limbs of laboratory rats and mice or in remote places human mouth. Besides, it provides a high concentration of the optical signal that permits to research locally small areas of biological tissue.

In another case, we have more informative results because we use the group of optical fibers and obtain biomedical data from different parts of biological objects' surfaces. It is essential to study the spatial distribution of blood flow in tissue.

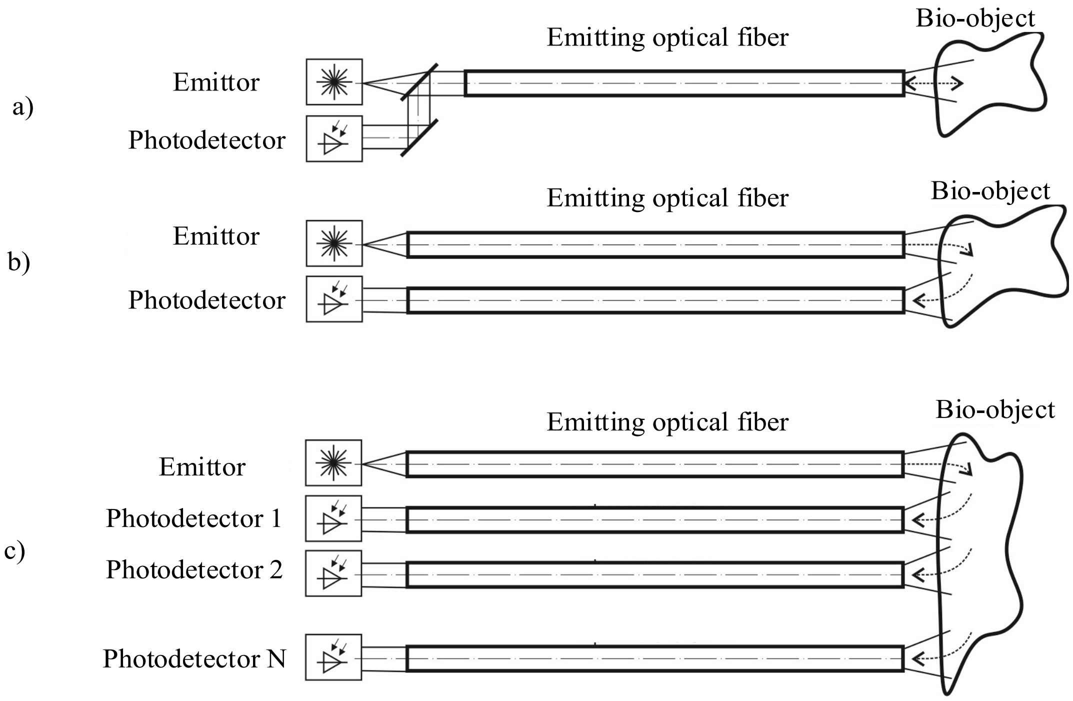

Figure 3 – Options for construction optical fiber

MODELLING

Dependence of efficacy of fiber-optic sensors on the reflected optical radiation from biological objects is represented on Fig. 4.

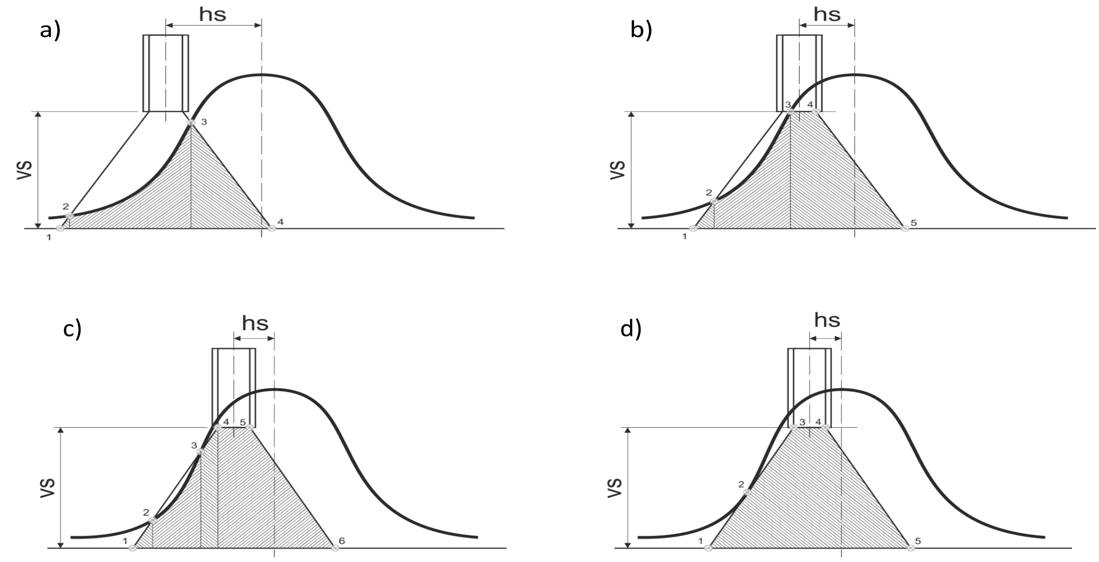

Figure 4 – Dependence of location of fiber-optic sensors on the reflected optical radiation from biological objects

A Gaussian beam model is used to represent the radiation propagation model from the emitting optical fiber (OF)

$$G(x,y) = \frac{1}{\sigma\sqrt{2\pi}} exp\left(-\frac{(x-\mu_x)^2+(y-\mu_y)^2}{2\sigma^2}\right)$$

where $G(x,y)$ – the Gaussian beam distribution in 3-dimensional space by coordinates x and y; σ– scaling factor; μ_x and μ_y – shift coefficients along the abscissa and ordinate axes, respectively.

In fig. 5 presents the functional dependences of the distribution of the Gaussian beam at the distance of the radiating OF type 1 and 2, respectively, from the surface of the biotissue. The abscissa axis represents the distribution of the Gaussian beam (μm), the ordinate axis represents the distance of the emitting OF from the surface of the biotissue (μm). The graphs represent sets of slices of the distribution of Gaussian beams at different values of distance.

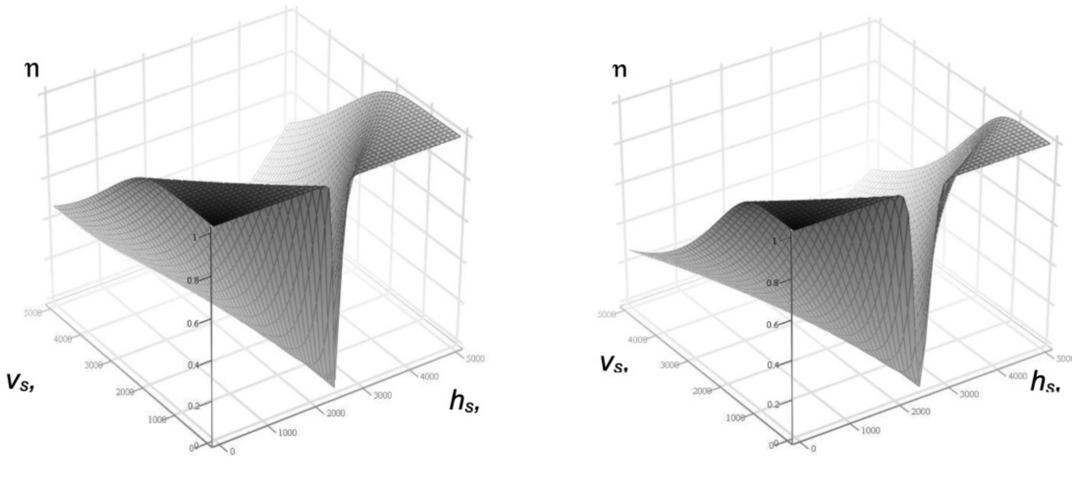

Figure 5 – Functional dependence of the distribution of the Gaussian beam at the distance of the radiating OB from the surface of the biotissue for fibers of type 1 (left) and 2 (right)

When calculating the efficiency of the location of the receiving OF, it is necessary to consider possible cases of the crossing of the Gaussian beam by the field of directed radiation. Based on the results of modeling the shapes of the figures when the optical fibers are displaced relative to the surface of the biological object (Fig. 6), it is possible to establish the permissible limits of the horizontal and vertical displacement of the emitting and receiving OFs.

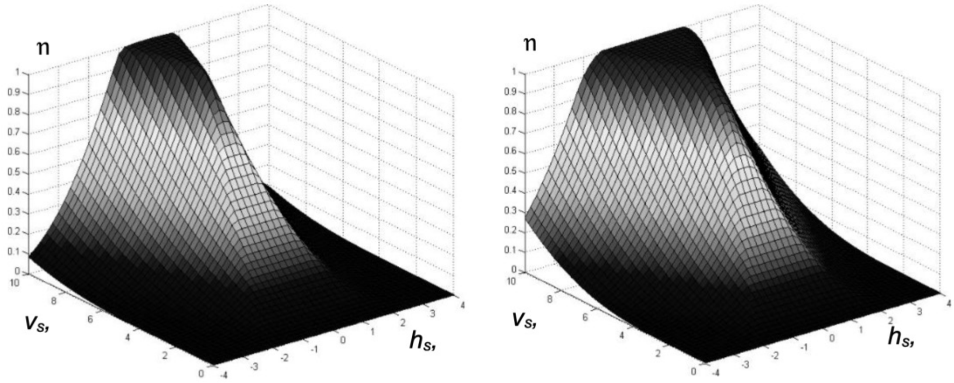

Figure 6 – The graph of the dependence of the amount of radiation that entered the receiving OB type 1 (left) and 2 (right) on the horizontal and vertical displacement of the fiber relative to the surface of the bioobject.

High-speed processing of significant arrays of information of various nature in areas such as processing, signal and image analysis, and pattern recognition requires highly parallel hardware as part of intelligent systems. It requires the definition of the nomenclature of the operational element basis for implementing basic procedures in intelligent systems for solving a wide range of applied problems.

The analysis of illustrative examples of the use of neurotechnologies in intelligent systems, particularly in trained robot control systems and biomedical signal classifiers, allows us to expand the known list of primary functional nodes. Therefore, the list includes a line of extrema, a maximum detector, and a discriminator.[92-94]

Two variants of building a row of cells of a uniform calculator structure have been developed, respectively, with parallel and sequential entries along the rows of the matrix of elements of discriminant functions, the maximum of which determines the class to which the input image belongs.

The hardware implementation of the defined primary nodes on a promising element base, for example, on an FPGA or using modern optoelectronic technologies, will significantly speed up the process of parallel information processing in intelligent systems, increasing their reliability and compactness during hardware implementation.

CONCLUSIONS

Optoelectronic systems for the study of tissue microcirculation, which take into account the dynamics of the optical propagation of probing radiation due to the identified features of the internal radiation distribution with controlled changes in the environment and sensor parameters, have received further development, which allowed to increase the reliability of biomedical information processing.

The practical value of the dissertation consists in the presented recommendations for developing a system for the study of tissue microcirculation based on one emitting and a group of receiving optical fibers, which made it possible to analyze the use of optical fibers of various parameters and characteristics.

Schematic solutions for the construction of optoelectronic systems for the diagnosis of tissue microcirculation based on fiber-optic sensors that perform registration and processing of photoplethysmographic information in real-time are proposed to carry out a hardware and software implementation of a system for the study of peripheral blood circulation for the evaluation of biomedical signals based on the received photoplethysmograms.

Recommendations for constructing fiber-optic sensors based on a group of optical fibers for the tissue microcirculation diagnostic system have been developed.

It has been proven that the photoplethysmographic method is the best for researching the state of peripheral blood circulation in human tissues, as it allows for non-contact research in both transmitted and reflected light. Also, it will enable microcirculation research in human tissues without disrupting blood circulation in the studied area, which is a significant advantage for medical practice.

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ОСОБЛИВОСТІ ВИКОРИСТАННЯ ВОЛОКОННО-ОПТИЧНИХ СЕНСОРІВ ДЛЯ ДОСЛІДЖЕННЯ ТКАНИННОЇ МІКРОЦИРКУЛЯЦІЇ

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