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REALIZATION OF A LASER FIBER-OPTICAL DEVICE FOR ASSESSING TISSUE MICROCIRCULATION

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Анотація. Основною метою даної роботи було проведення досліджень, спрямованих на підвищення достовірності діагностики стану периферичного кровообігу шляхом вдосконалення методів реєстрації оптичного випромінювання та використання оптико-електронних засобів аналізу фотоплетизмографічної інформації. За результатами дослідження створено волоконно-оптичний пристрій для діагностики мікроциркуляції тканин із забезпеченням мініатюризації конструкції, зокрема чутливого елементу волоконно-оптичного сенсора, можливості проведення контролю, діагностики та скринінгу стану тканинної мікроциркуляції в різних оптичних режимах і умовах з високою надійністю.
Ключові слова: лазерне випромінювання, спектри пропускання, лазерний волоконно-оптичний пристрій, біологічні тканини, тканинна мікроциркуляція.
Abstract. The main goal of this study was to carry out research leading to an increase in the reliability of diagnosing the state of peripheral blood circulation by improving the methods of recording optical radiation and using optical-electronic means for the analysis of photoplethysmographic information. Based on the results of the study, we designed a fiber-optic device for diagnosing tissue microcirculation, ensuring miniaturization of the sensitive element of the fiber-optic sensor, and the possibility of monitoring, diagnosing, and screening the state of tissue microcirculation in various optical modes and conditions with high reliability.key words: laser radiation, transmission spectra, laser fiber-optic device, biological tissues, tissue microcirculation.

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INTRODUCTION

Monitoring the state of tissue microcirculation of blood is important for determining the state of tissues in medicine and scientific research. This method can be used for diagnostics and monitoring of health: Changes in tissue microcirculation can indicate various pathological changes. For example, deterioration of microcirculation can be associated with various diseases, such as diabetes, cardiovascular diseases, infections and other conditions. Monitoring microcirculation provides early detection of symptoms of these disorders. The device can be used to assess the effectiveness of treatment, because during the treatment process it is important to monitor how tissue microcirculation changes under the influence of medical drugs and procedures. This helps to determine how effective the treatment approach is and, if necessary, adjust the treatment to improve results. Monitoring microcirculation during treatment allows you to identify the risk of complications and possible side effects of therapy. Finally, the study of tissue microcirculation is important for biomedical scientific research in the field of physiology, pathology, pharmacy, in the development of new methods of diagnosis and treatment.

METHODOLOGY

To obtain the following results: an analysis of the methods of using optical fibers in fiber-optic sensors in biomedicine was carried out, to analyze the types of optical fibers and the prospects for their use in biomedical sensors, to systematize the obtained results; to obtain dependencies for analyzing the effects of radiation propagation through a bioobject based on the Monte Carlo method and to evaluate the nature of radiation propagation in bioobjects; developed a methodology for calculating the main parameters of radiation during propagation along a transmitting optical fiber, perform calculations of radiation attenuation, build models of changes in characteristics when the emitting and receiving optical fibers are displaced relative to the surface of the bioobject; a study of structural and technical options was carried out, schematic implementation and efficiency of optical-electronic means of diagnosing the state of peripheral blood circulation; to create an optical-electronic system for the study of peripheral blood circulation based on fiber-optic sensors; an algorithm and software were developed for registration, processing and storage of biomedical data in real time [1,2,3].

Violation of the microcirculation of the peripheral circulation becomes the cause of various kinds of disorders of the vital activity of the human body. For example, it leads to weak healing of postoperative wounds; criticalmicrocirculation disorders of the limbs can lead to amputation or complete loss. Therefore, non-invasive methods are introduced into medical practice for the timely and high-quality diagnosis of such disorders, allowing painless and non-destructive control of the affected areas. Among them, optical methods of registration, transformation, and control of biomedical information have received comprehensive development [4,5,6].

One of the promising methods of studying peripheral blood circulation is the photoplethysmographic (FPG) method, which allows the use of non-contact sensors, as a result of which there is no compression of blood vessels, which excludes a violation of blood circulation in the studied area. The method is based on photoelectric measurement of both transmitted and reflected light radiation in the red and infrared ranges. This method is used in most cases for vascular diseases to objectively assess the state and degree of regional blood flow disorders and vascular tone, to control the effectiveness of treatment used with subsequent laser and photonic methods of vascular function restoration, and for differential diagnosis of organic and functional vascular diseases. Particularly valuable information is provided by symmetrical studies of affected and unaffected vessels of the same patient and the dynamics of FPG under the influence of functional loads and when conducting pharmacological tests [7,8,9].

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

Let us consider the principles of building mathematical models for calculating the interaction of optical radiation with heterogeneous biotissues. As noted earlier, environments in which there is both absorption and scattering of radiation are called inhomogeneous. One such example is human skin. At the same time, human skin is a living multi-layered environment that contains 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 is a huge number of mathematical and physical models, each of which solves one or another specific task. Let us consider the basic principles of building mathematical models that describe the interaction of optical radiation with multicomponent, multilayered heterogeneous media [10,11,12].

Practically all models are built according to the same scheme (Fig. 1).

First, the research object and its geometry are selected. Then the optical and physical parameters of all its components are determined. Next, the radiation distribution in the environment is calculated and for some models the temperature fields are calculated [13,14.15].

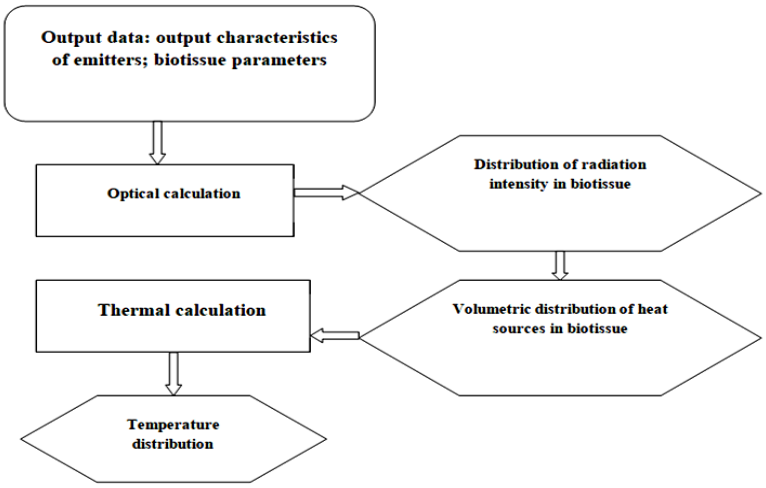

Figure 1 – Model construction scheme

The difference between the models becomes noticeable already at the stage of constructing the geometry. In most cases, the skin is a sequence of flat layers with different optical and thermophysical characteristics. The number of layers can vary from one to seven depending on the tasks.

Let's build a model that will make it possible to estimate the intensity of radiation when reflected from blood vessels.

Real biotissue is a heterogeneous environment in which there is both absorption and scattering of optical radiation, so it is practically impossible to investigate and describe the processes that take place in it. Let's consider one of the examples of biotissue, namely human skin.

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).

Measurement of transmission spectra of substances in different aggregate states is the basis of spectrophotometry, which is characterized by extreme simplicity, versatility, relatively high sensitivity and accuracy of analysis, which are quite sufficient for solving many tasks of fundamental and applied medicine. The measurement of the transmission spectra is based on the registration of the intensity of the incident I and the path z of the light I traveled in the absorbing medium depending on the wavelength λ:

$$I(\lambda, z) \equiv I_0(\lambda) \cdot \exp\left[-\mu_a(\lambda) z\right]$$

$$\mu_a(\lambda) = \sigma_a(\lambda) N$$

where $\mu_a(\lambda)$ - absorption coefficient; $\sigma_a(\lambda)$ - effective cross-section of absorbing particles, cm^2; N - their density, cm^{-3}.

It is assumed that the intensity of the incident light is very small. For small absorption coefficients, when $\exp\left[-\mu_a(\lambda) \cdot z\right] \approx 1 - \mu_a(\lambda) \cdot z$, it is easy to find that

$$\mu_a(\lambda) \approx \frac{I_0(\lambda) - I(\lambda, z)}{I_0(\lambda)} \cdot z \equiv \frac{\Delta I(\lambda, z)}{I_0(\lambda) \cdot z}$$

Broadband light sources are used in non-laser spectrophotometers, and wavelength adjustment is carried out using prisms or diffraction gratings. They have a resolution, Δλ, from several to hundredths of a nanometer. If the width of the absorption line is equal to δλ, and I0 (λ) varies slightly in the interval Δλ, then

$$\frac{\Delta I}{I_0} \approx \frac{\mu_a(\lambda)\delta\lambda}{\Delta\lambda}$$

where μa (λ) is the absorption coefficient averaged over the entire absorption line [7].

REALIZATION OF LASER FIBER-OPTIC DEVICE

The model is based on the task of creating a laser fiber-optic device for assessing tissue microcirculation, in which, by introducing new connections and combinations of blocks, it is possible to provide adaptive conditions for diagnosing the state of microcirculation, reduce the size of the sensitive element and reduce the number of structural elements in order to optimize the design. This leads to an expansion of the functional capabilities of the device, an increase in the sensitivity of the sensor and the manufacturability of its design.

The task is achieved by introducing a laser fiber-optic device for assessing tissue microcirculation, which consists of a photodetector sensitive in a wide spectral range, an amplifier, an analog-to-digital converter, a computer consisting of a power supply, a microcontroller, a graphic liquid crystal display and a slot for an SD memory card, into a laser fiber-optic sensor, which consists of three laser radiation sources of infrared, red and green radiation spectrum, a Y-shaped fiber-optic splitter with input and output fiber-optic channels, which are connected into one common optical channel, designed to direct the light flux to a biological object, with the control output of the microcontroller connected to the inputs for controlling the laser radiation sources.

Figure 2 shows a structural block diagram of the device.

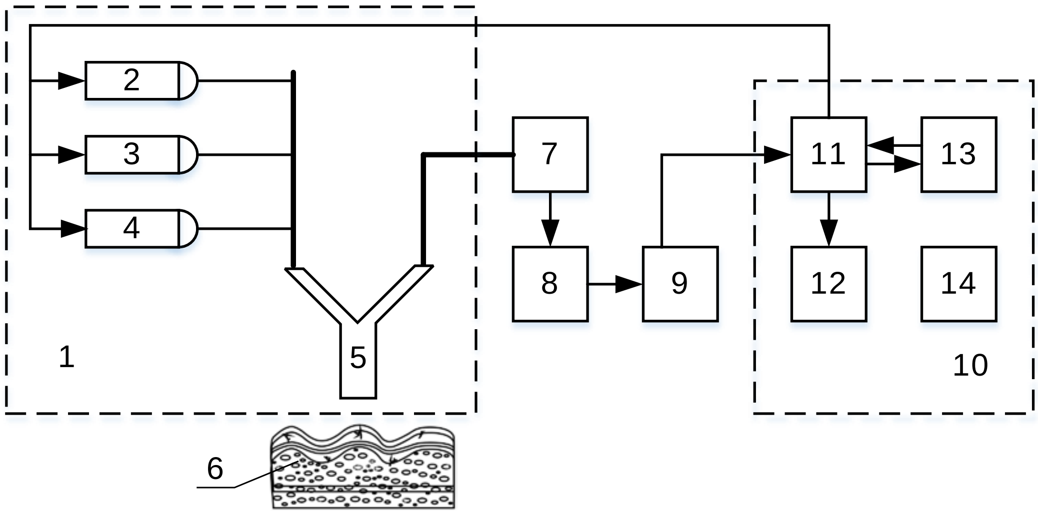

Figure 2 – Block diagram of the device of laser fiber-optic device

The device consists of a laser fiber-optic sensor 1, which consists of three laser sources of infrared 2, red 3 and green 4 radiation spectrum, a Y-shaped fiber-optic splitter 5 with input and output fiber-optic channels, which are connected into one common flexible optical channel, designed to direct the light flux to a biological object 6, a photodetector 7, sensitive in a wide spectral range, an amplifier 8, an analog-to-digital converter 9, a computer 10, which consists of a power supply 14, a microcontroller 11, a graphic liquid crystal display 12 and a slot for an SD memory card 13.

The device works as follows. After switching on the power supply 14, which supplies electricity to all the blocks of the device, the computer blocks 10 are reset, in particular the microcontroller 11 is reset to the zero state, the graphic liquid crystal display 12 is loaded and displays the readiness of the device for operation. According to the device operation program, which is set using the microcontroller 11, the laser radiation sources 2, 3, 4 are activated in turn, the duration and intensity of the glow of each of which can be adjusted. The laser radiation source of the infrared range 2 emits a light flux with a wavelength of 905 nm. The laser radiation source of the red range 3 emits a light flux with a wavelength of 660 nm. The laser radiation source of the green range 4 emits a light flux with a wavelength of 532 nm. The shorter the wavelength, the less depth the light flux penetrates into the biological tissue 6. By using a Y-shaped fiber optic splitter 5 with input and output fiber optic channels, which are connected into one common flexible optical channel, the solution to the problem of reducing the size of the sensitive element of the laser fiber optic sensor 1 is implemented, and also due to its flexibility and chemical and biological resistance, contact of the laser fiber optic sensor 1 with hard-to-reach biological tissues (for example, in a wound or under laparoscopic examination conditions) is ensured. The light flux is partially absorbed by the biological tissue 6, partially reflected and scattered. The reflected light, which enters the optical channel of the Y-shaped fiber optic splitter 5, is transmitted to the photodetector 7, sensitive in a wide spectral region. The pulse wave passing through peripheral vessels and capillaries causes periodic changes in the optical density of biological tissue 6, which is determined by registering changes in the intensity and spectral characteristics of the reflected light flux entering the photodetector 7. The photodetector 7 converts the optical signal into an electrical signal modulated by amplitude. This signal is amplified by an amplifier 8 and converted into digital form using an analog-to-digital converter 9, after which the digital signal is fed to the information input of the microcontroller 11, where it is processed, and the result is displayed on a graphic liquid crystal display 12 and recorded on an SD memory card through an SD memory card slot 13. The device is synchronized by control signals from the microcontroller 11, which activate the laser radiation source required at the current moment. The use of a red spectrum laser radiation source 3 allows you to determine the level of blood oxygen saturation (saturation) and recognize the periodicity of pulsations, which allows you to estimate the heart rate. The following data is displayed on the graphic liquid crystal display 12: a graphic representation of blood filling curves, the value of the estimated heart rate, the blood saturation index (SpO2), as well as the current time and battery charge level.

The principle of operation of the laser fiber-optic sensor 1 is based on the registration of changes in the optical signal and measurement of the parameters of the reflected light. A feature of the proposed laser fiber-optic sensor 1 is its high sensitivity to changes in such optical parameters of the studied area of biological tissue as the reflection coefficient and refractive index due to multiple internal reflections of light in the middle of the studied biological tissue 6. To solve the problems of studying tissue microcirculation, it is proposed to use a fiber-optic Y-shaped fiber-optic splitter 5 with input and output fiber-optic channels, which are connected into one common channel. The light flux from the laser radiation sources 2–4 through the input channel propagates into the common monofiber channel of the sensor to the area of biological tissue 6 and after reflections inside the tissue enters the same common channel, through which it propagates into the output channel and enters the receiving circuit from the photodetector 7, amplifier 8 and analog-to-digital converter 9, which converts the optical signal into a digital electrical signal. The microcontroller program 11 provides the amplitude-pulse mode of operation of the laser radiation sources 2–4, and also allows you to change the intensity of their radiation, which expands the functionality of the device [16-19].

The claimed device uses 50-micrometer quartz optical fibers, as laser radiation sources 2–4 semiconductor lasers (light-emitting diodes) with emission maxima at wavelengths of 905, 660 and 532 nm, respectively. The photodetector 7 is a silicon phototransistor, sensitive in a wide spectral range, which is well consistent with the spectral characteristics of incandescent lamps, infrared LEDs, semiconductor lasers and fiber optic cables, which allows spectral studies.

This design of the fiber-optic device provides miniaturization and reliability, which is especially relevant for medical screening and research of tissue microcirculation, especially in hard-to-reach areas of biological tissues and human organs.

To represent the model of radiation propagation from laser radiation sources, the Gaussian beam model is used

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

where *G(x,y)* is the distribution of the Gaussian beam in three-dimensional space according to x and y coordinates; σ is the scaling factor; μ_x та μ_y are shift coefficients along the abscissa and coordinate axes, respectively.

Photoplethysmographic signal recorded using an optical-electronic device for diagnosing the state of peripheral blood circulation is shown

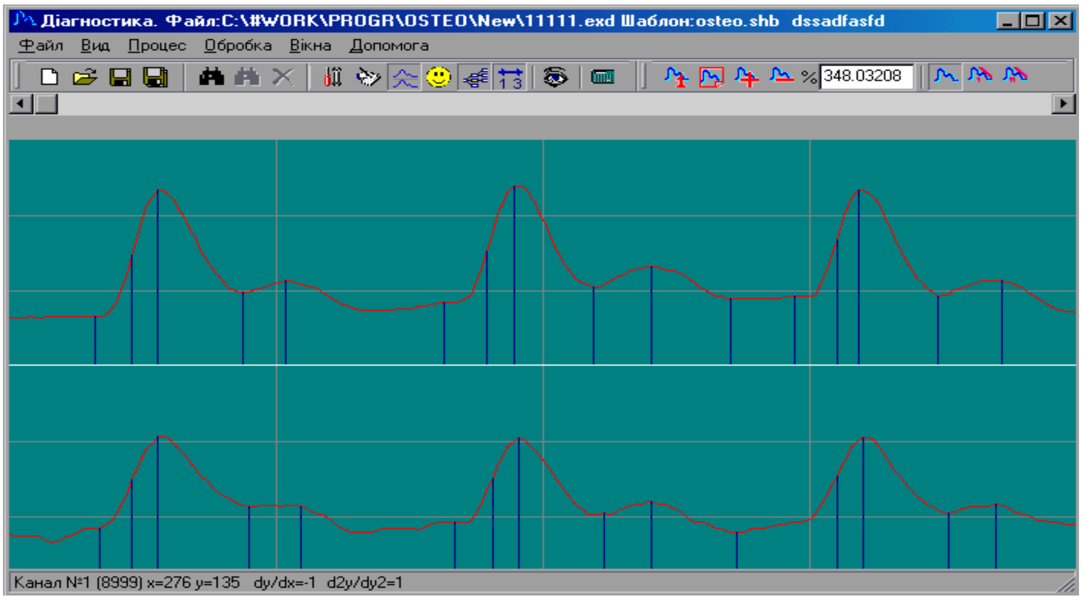

Figure 3- Photoplethysmographic signal recorded using an optical-electronic device for diagnosing the state of peripheral blood circulation

CONCLUSION

The proposed structure of the device allows for miniaturization of the design, monitoring, diagnostics and screening of the state of tissue microcirculation in various optical modes with high reliability, ensuring portability, mobility, access to hard-to-reach areas of biological tissue. Adaptive conditions for diagnosing the state of microcirculation are provided due to the amplitude-pulse mode of operation of radiation sources and the possibility of changing the intensity of the emitted light flux, which allows for the study of various types of biological tissues using a set of irradiation modes.

The results of the research solved the urgent task of increasing the informativeness, accuracy and reliability of the classification of the information system for the diagnosis of tissue microcirculation.

The work uses methods based on the basic principles of the theory of radiation transfer to describe the processes of interaction of optical radiation with biotissues, mathematical modeling - to study changes in the intensity of optical radiation, filtering methods - to eliminate background noise, methods of functional synthesis - to model optical-electronic schemes, mathematical statistics and computer information processing - to check the adequacy of the developed models.

To obtain the following results: an analysis of the methods of using optical fibers in fiber-optic sensors in biomedicine was carried out, to analyze the types of optical fibers and the prospects for their use in biomedical sensors, to systematize the obtained results; to obtain dependencies for analyzing the effects of radiation propagation through a bioobject based on the Monte Carlo method and to evaluate the nature of radiation propagation in bioobjects; developed a methodology for calculating the main parameters of radiation during propagation along a transmitting optical fiber, perform calculations of radiation attenuation, build models of changes in characteristics when the emitting and receiving optical fibers are displaced relative to the surface of the bioobject; a study of structural and technical options was carried out, schematic implementation and efficiency of optical-electronic means of diagnosing the state of peripheral blood circulation; to create an optical-electronic system for the study of peripheral blood circulation based on fiber-optic sensors; an algorithm and software were developed for registration, processing and storage of biomedical data in real time.

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РЕАЛІЗАЦІЯ ЛАЗЕРНОГО ВОЛОКОННО-ОПТИЧНОГО ПРИЛАДУ ДЛЯ ОЦІНЮВАННЯ ТКАНИННОЇ МІКРОЦИРКУЛЯЦІЇ

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