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Investigation of optical radiation penetration depth on theoretical models of inhomogeneous biological media

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This paper presents theoretical calculation of the penetration depth of optical radiation into different types of biological tissue. Theoretical models of the following tissues were formed: blood, dermis, arterial vessel wall, for which the penetration depth of radiation was theoretically calculated. Experimental study of the radiation penetration depth for human biological tissues with different modification of the position of the radiation source and receiver was carried out. The obtained theoretical and experimental results can be further used for the development of effective systems for monitoring of microcirculatory-tissue systems and confirm the prospects of noninvasive spectrophotometric diagnostics application in clinical practice.

Keywords: biological tissue, optical radiation, theoretical calculation, spectral characterization.

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Introduction

Human health and performance are largely determined by the metabolic processes in various organs and tissues, the products of which are distributed in the biological media of the body (in cells, blood, exhaled air, urine, etc.) and are indicative of the functional state of the physiological systems of the body. The functional state and functional reserve of a person are important indicators characterizing the body's protection from the occurrence of various diseases of the cardiovascular and respiratory systems. The main function of the cardiorespiratory system, all oxygen transport and utilization systems is to provide the body with a sufficient adequate amount of oxygen [1]. Deviation of the main indicators from a normal level is a sign of deterioration of the functional state of the body as a whole, which is why timely diagnosis of this system is so important [2]. This paper solves the problem of development of a non-invasive system for monitoring the functional state of a person, implemented through optical sensors at moments of physical exertion. A theoretical study of the interaction of optical radiation and biological tissue was conducted for a more conscious and detailed approach to solving this problem. Currently, contactless optical and acoustic technologies are used in Russia and the world [3]. Wearable health sensors are becoming particularly popular, ensuring monitoring of human physiological parameters owing to several biosensors on and inside the body [4]. The approach proposed by the authors, in contrast to existing solutions in this field, involves a qualitative analysis of the functional state of a person, i.e., based on the totality of data obtained by the developed system, the user receives a signal about a deviation of the parameters of the functional state of the body, which would mean the need to stop physical activity.

The spectrophotometric method for the analysis of biological tissues is a promising non-invasive assessment method based on the ability of various chemical compounds to interact with radiation by absorption.

The processes of interaction of radiation with the biological environment are shown in Fig. 1.

The ability of substances to absorb electromagnetic radiation is determined by such factors as the concentration of the substance, temperature (such a temperature difference as 30−90°C corresponds to a decrease of the absorption coefficient of water by $0.885\,\mathrm{cm}^{-1}$ [5]), radiation wavelength and thickness the absorbing layer. Molecules of water, fat, hemoglobin and other structural components are the main absorbing centers or chromophores in biological tissues.

Knowing the depth of radiation penetration into the biological tissue is important for medical procedures and research, as it allows determining the optimal dose (suffi-

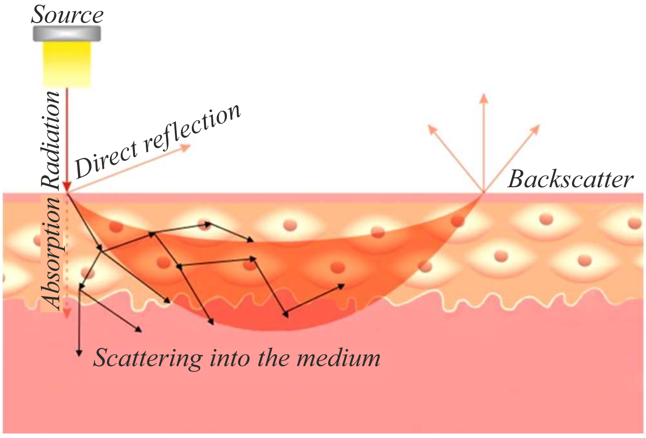

Figure 1. Interaction of optical radiation with biological tissue.

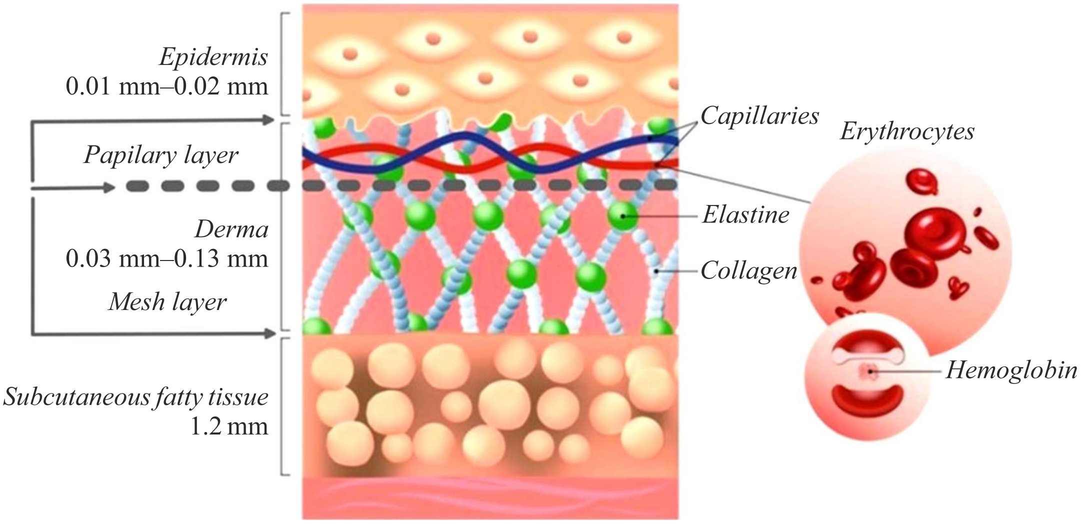

Figure 2. Structure of the human skin.

cient to obtain the necessary information, but not harmful to the patient's health) and the type of radiation.

1. Theoretical study of the process of penetration of the study into biological tissue

The study was concerned with the processes of interaction of optical radiation with biological tissue, specifically the process of radiation penetration to different depths depending on the type of tissue. Biological tissue is a system that includes cells and intercellular matter, which are united by a common origin and functions performed [6]. Epithelial (dermis) and connective (blood, blood arterial vessels) tissues were examined in this study.

The dermis is the middle layer of the skin, which includes two inner layers: reticular layer (the lower and thick component of the dermis, which forms a plastic boundary with subcutaneous fat) and papillary layer (the upper part of the dermis, which forms a clear wavy boundary with the epidermis). Connective tissue proteins such as collagen and elastin are the main structural components of the dermis, namely collagen and elastin, are the main structural components of the dermis and provide it with strength and elasticity [7] (Fig. 2).

Blood is a liquid connective tissue consisting of plasma (intercellular substance) constituting 55% and blood cells constituting 45%. Blood proteins, metabolic products and nutrients are organic components of plasma. Plasma inorganic substances include various ions that maintain osmotic pressure and blood pH. Cells and post-cellular elements are the shaped elements of blood that perform various functions, the most important of which is the transfer of oxygen to internal tissues and organs by erythrocytes containing hemoglobin [8].

The structure of the arterial vessel wall is shown in Fig. 3.

The width of the layers shown in the figure: intima — 10^{-5}–10^{-4} cm, media — $3\cdot10^{-3}$–$2\cdot10^{-2}$ cm, adventitia —$3\cdot10^{-3}$–$3\cdot10^{-2}$ cm.

Since the objective of the study is to optimize the design of optical detectors in such a way that the penetration depth of radiation is physiologically optimal, theoretical calculations of the penetration depth of radiation into the tissue were performed using the Booger-Lambert-Beer law, responsible for the qualitative part of spectrophotometric analysis, which states that the intensity of radiation passing through the medium decreases exponentially with distance [9.10]:

$$I(z) = I_0 \exp(-\mu_a z), \tag{1}$$

where I_0 —initial intensity of incident radiation; $I(z)$ — intensity of radiation at depth z; μ_a —absorption coefficient; z — radiation penetration depth, [cm]; d — width of the absorbing layer.

The depth of penetration (h) is the depth (z) at which the intensity $I(z)$ in e times less than the intensity I_0. Hence

$$\frac{I_0}{e} = I_0 \exp(-\mu_a h). \tag{2}$$

By reducing I_0 and equating the resulting expression to one, we obtain

$$e^{1-\mu_a h} = 1. \tag{3}$$

We shall find the expression for the depth of penetration h given that the expression $1-\mu_a h$ equals zero (from equation (3)):

$$h = \frac{1}{\mu_a}. \tag{4}$$

The absorption coefficient of oxygenated blood μ_{blood} was calculated with different values of blood oxygen

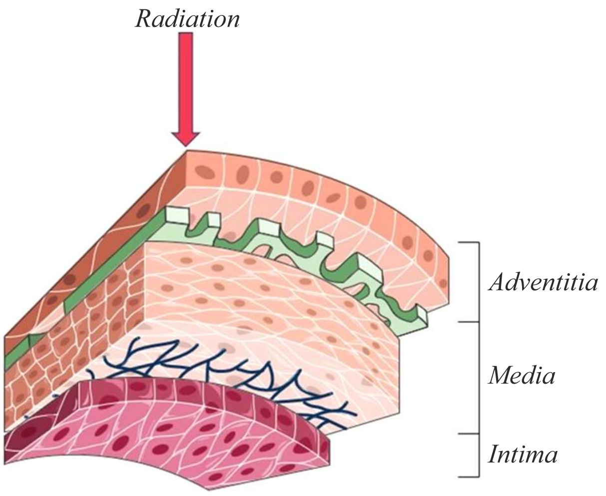

Figure 3. The structure of the arterial vessel wall.

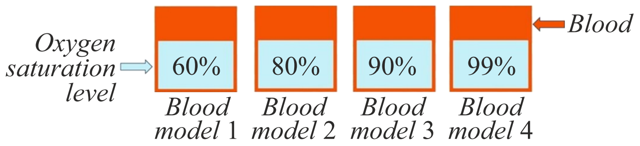

Figure 4. The studied blood models with different oxygen saturation values, where the model 1 corresponds to the blood oxygen saturation value equal to 60, model 2 corresponds to value 80, 3 — 90, 4 — 99%.

saturation using the formula for calculating the absorption coefficient [11]:

$$\mu_{blood}(\lambda) = \vartheta_{blood}\mu_w(\lambda) + (1 - \vartheta_{blood}) \times \left(p^{\mathrm{Oxy}}\mu_{\mathrm{HbO2}}(\lambda) + (1 - p^{\mathrm{Oxy}})\mu_{\mathrm{Hb}}(\lambda)\right), \quad (5)$$

where $\mu_w(\lambda)$ —water absorption coefficient; ϑ_{blood} — volume water content in oxygenated blood; $\mu_{\mathrm{HbO2}}(\lambda)$ — oxyhemoglobin absorption coefficient; $\mu_{\mathrm{Hb}}(\lambda)$ — coefficient of absorption of hemoglobin by oxygen (as a percentage); p^{Oxy} — oxygen saturation of the blood as a percentage.

The value ϑ_{blood} is assumed to be 90% [12]. Different values of blood oxygen saturation were used in these calculations: $p^{\mathrm{Oxy}} = 60, 80, 90, 99\%$. A graphical representation of blood models with different values of blood oxygen saturation is shown in Fig. 4.

The penetration depth of radiation in the model 1–4 was calculated based on the obtained values of the absorption coefficient μ_{blood}. All the results were reflected in Fig. 5 for a comparative characterization.

The graph shows the tendency of the same dynamics of the values of the penetration depth of radiation into oxygenated blood with different degrees of oxygen saturation. The depth differs by 0.2 cm at a wavelength of 700 nm. Blood with an oxygen saturation value of 99% (model 4) absorbs radiation best at a wavelength of 700 nm, where the penetration depth reached 1.4 cm. The radiation is absorbed best at the same wavelength by the blood with an oxygenation value of 80% (model 2), where the depth reached a value of 1 cm, and model 3 (blood oxygenation value is 90%), where the depth is 1.2 cm. Model 1, unlike the previous ones, absorbs radiation best at a wavelength of 940 nm, where the penetration depth of radiation is 0.8 cm.

Next, the values of the coefficient of absorption of radiation by the dermis μ_{a_D} were obtained using the formula

$$\mu_{a\_D}(\lambda) = f_{blood}\mu_{a\_b}(\lambda) + \vartheta_{a\_D}\mu_{a\_w}(\lambda) + (1 - f_{blood} - \vartheta_{a\_D})\mu_{a\_background}, \quad (6)$$

where f_{blood} — the volume content of blood; ϑ_{a_D} — the volume content of water in the dermis; $\mu_{a\_b}(\lambda)$ — the absorption coefficient determined by the content of chromophores in it; $\mu_{a\_w}(\lambda)$ — the water absorption coefficient; $\mu_{a\_background}$ — the dermis absorption coefficient in the absence of chromophores.

The dependence of the absorption coefficient of the dermis for different values of the volumetric blood content f_{blood} (0, 5, 10 and 15%) and a fixed value of the volumetric water content was plotted (Fig. 6). Value $\vartheta_{a\_D} = 65\%$ [13].

The dependences of radiation penetration depth for the model 1 in the absence of absorbing groups of atoms in

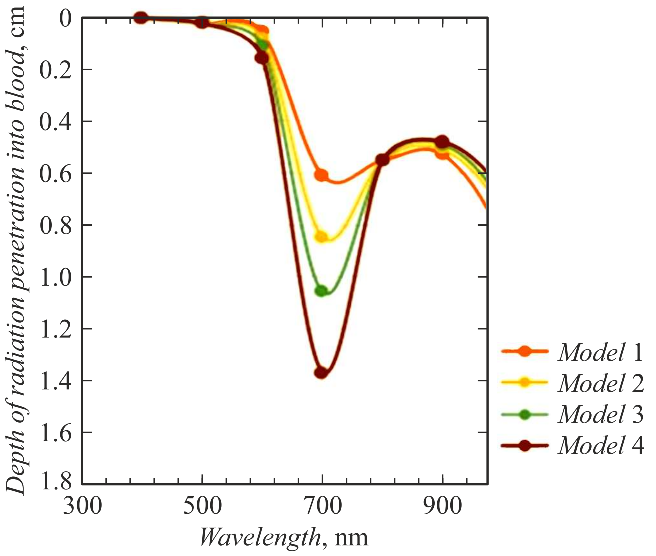

Figure 5. Theoretically calculated dependences of the depth of radiation penetration into the blood at different wavelengths at different values of the degree of oxygen saturation.

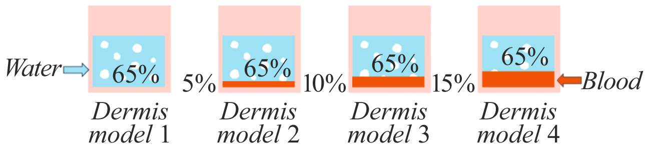

Figure 6. Studied dermis models with different values of blood volume content, where model 1 corresponds to the value of 0, model 2 corresponds to the value of 5, model 3 corresponds to the value of 10, model 4 corresponds to the value of 15%.

the wavelength range from 400 to 900 nm were the first to be theoretically calculated. The results of theoretical calculations of the depth of radiation penetration into the dermis, taking into account different models, were visualized and collected in the graph below (Fig. 7).

The graph shows a trend: the optical radiation loses its ability to penetrate into its deep layers as the saturation of the dermis with blood increases. Also, the depth of radiation penetration into biological tissue increase with the increase of the wavelength.

The dependence of the depth of penetration of optical radiation into the arterial vessel wall was considered for the theoretical calculation of the interaction of radiation with blood arterial vessels.

The value of the volumetric water content in the arterial vessel wall is approximately 80%. The following formula was used for the theoretical calculation of the depth of radiation penetration into this tissue:

$$h = \frac{1}{\mu_w} \cdot 0.8. \tag{7}$$

The dependences of the depth of light penetration into the artery wall at wavelengths of 400–940 nm were calculated based on the obtained values (Fig. 8).

The graphs show the ability of light to penetrate only in adventitia regardless of wavelength (in the range of 400–940 nm). At the same time, the light has the deepest into the artery wall at a wavelength of 400 nm. The ability of blood to absorb light makes it possible to evaluate its various properties, such as saturation, by optical methods. However, theoretical calculations showed that the upper layer of the wall of the circulatory artery absorbs optical radiation much more strongly than the rest of its constituent layers. This complicates the study of large arteries and arterial blood, respectively, in medical practice because of the occurrence of strong interference in measurements.

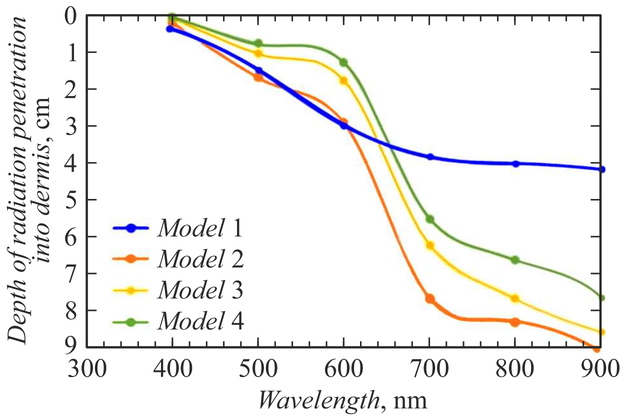

Figure 7. Theoretically calculated dependences of the depth of penetration of radiation into the dermis at different wavelengths with different values of the volume content of blood in it.

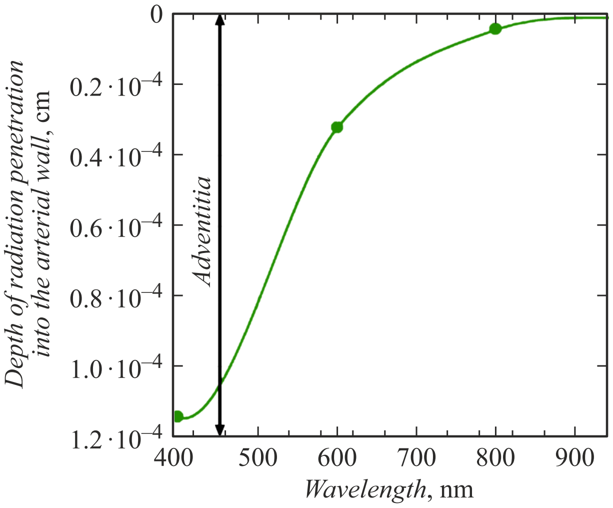

Figure 8. Theoretically calculated dependences of the depth of light penetration into the artery wall in the range of $2 \cdot 10^{-5}$–10^{-4} cm.

2. Experimental research

The Institute of Analytical Instrumentation of the Russian Academy of Sciences (St. Petersburg) developed a hardware and software complex for experimental studies of the interaction of radiation and biological tissue and this complex includes two modules: information and optoelectronic. The information module controls the device, collects, processes and analyzes the results. The optoelectronic module comprises an 18-channel analyzer of optical spectra of the visible and near infrared wavelength ranges, having an array of 18 photosensitive elements operating at wavelengths of 410–940 nm, and three radiation sources. The spectral optical characteristic of the 18-channel optical spectrum analyzer is shown in Fig. 9.

Each channel has a spectral bandwidth (full width at half maximum, FWHM) equal to 20 nm. The system has a built-in battery with a capacity of 500 mA/h enabling operation for 5 hours without recharging. There are operation modes of both pulsed illumination of the studied material and continuous illumination. Data are transmitted via wireless personal networks to a personal computer [14]. A hardware and software package was developed in two configurations for measuring the parameters of the studied biological tissue at different depths. The system configurations differ in the distance between the radiation source and the multichannel spectrum analyzer. Both configurations perform measurements in the „reflection“ mode, in which the connected sources and detectors are located on the same side of the biological tissue at a certain distance from each other. The nature of the optical path from the source-detector pair corresponds to an arc-shaped curve with such an arrangement of the elements of the optical system, as shown in Fig. 3 [15], while the depth of penetration of radiation into biological tissue is approximately half the

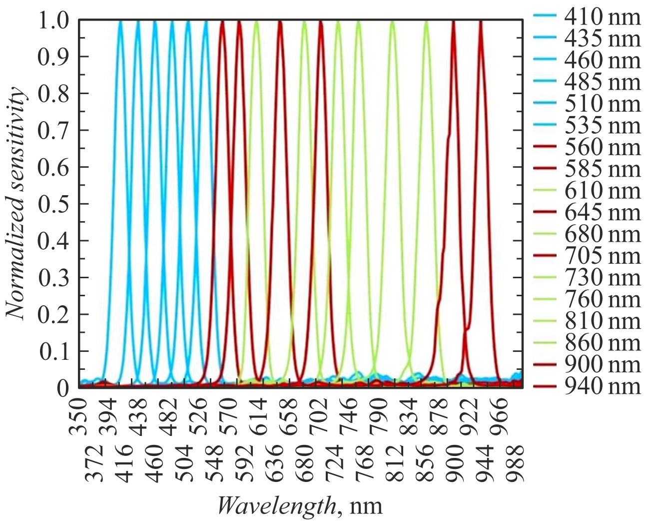

Figure 9. Spectral optical characteristics of the 18-channel analyzer of optical spectra of visible and near infrared wavelengths.

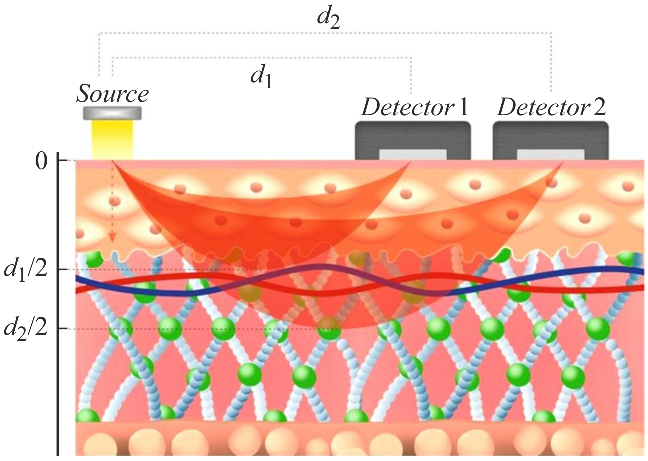

Figure 10. The scheme of operation of the hardware and software complex in the „reflection“ mode with the trajectories of propagation of the detected radiation at different source-detector distances.

distance between the emitter and the optical sensor [16]. Hardware and software complexes with different „source-detector“ distances d_1 and d_2, equal to 5 and 10 mm, respectively, were created for experimental studies. This makes it possible to measure the parameters of biological tissues at a depth of about 2.5 mm (epidermis and upper layer of dermis — surface layer of the skin) and 5 mm (epidermis and dermis — deeper layer), expanding the possibilities of studying various layers of biological tissues (Fig. 10).

An experimental study of the spectral characteristics of biological tissues at different radiation penetration depths was conducted using the developed hardware-software package. The study was conducted with the participation of 14 subjects who participated in physical activity with the device described above fixed on their forearms (Fig. 11).

Physical activity had three stages: warm-up, exercise, and recovery. The spectral characteristics of backscattered radiation in the visible, near-infrared wavelength ranges in the biological tissue of the forearm were obtained according to the results of the experimental study. Figure 12 shows the spread of intensity values for each wavelength.

Figure 11. Experimental study process.

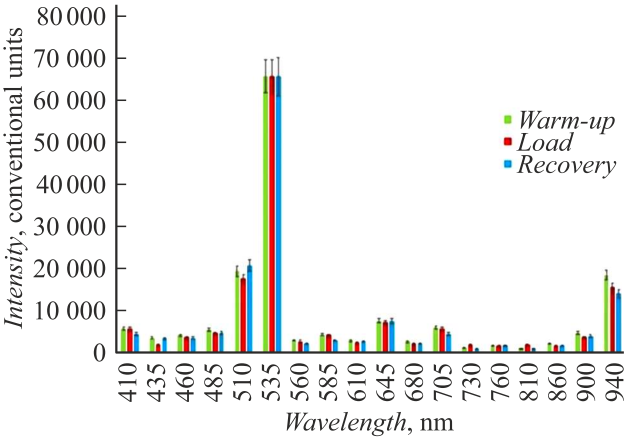

Figure 12. Measured spectral response under load and recovery for a typical test subject in the surface layer of biological forearm tissue.

In the case of measuring the spectral characteristics of biological tissue in the surface layer, signals were recorded using a sensor in a configuration with a source-detector distance d_1 equal to 5 mm, at which the penetration depth of radiation is approximately 2.5 mm. The radiation intensity has a maximum intensity at the wavelength of 535 nm and reaches a value of 65 thous. c.u. The following trend can be traced: a high intensity of radiation was observed at the warm-up stage for the majority of subjects, among the three stages of physical activity. This may be attributable to a decrease of the density and diameter of functioning capillaries [17].

The experimentally obtained intensities of backscattered radiation in deeper layers have slightly different values. Figure 13 shows the spread of intensity values for each wavelength.

Measurements in deeper layers of biological tissue were obtained using a system with a source-detector distance d_2 equal to 10 mm, at which the penetration depth of radiation h_2 is approximately equal to 5 mm. The maximum radiation intensity can be traced at a wavelength of 535 nm like in the previous chart. Its maximum value is 20 thous. c.u. Also, a regular decrease of the intensity value is seen at each wavelength with each subsequent stage of physical activity. As in the case of the surface layer, such a pattern may be attributable to changes of the density and diameter of blood vessels, as well as changes of the rheological properties of blood, morphofunctional restructuring of the cardiovascular system and changes of the parameters of systemic hemodynamics due to physical exertion [18].

The experimental dependences of the intensity of backscattered radiation in the superficial and deeper layers of biological tissue of the forearm show the difference of the maximum values of the intensity of the recorded backscattered radiation in biological tissues. It reaches the maximum value of 20 000 c. u. from the depth of 5 mm, while its maximum value is 65 000 c. u. from a depth of 2.5 mm. This may be attributable to the greatest absorption of light by chromophores in deeper layers of biological tissue. Thus, the main chromophores absorbing optical radiation were considered for further estimation of the „source-detector“ distance of the hardware-software complex for obtaining more detailed information about the functional state of human biological tissue. Such theoretical studies of the depth of radiation penetration into biological tissue and the absorbing properties of its main chromophores are important for the creation of diagnostic complexes.

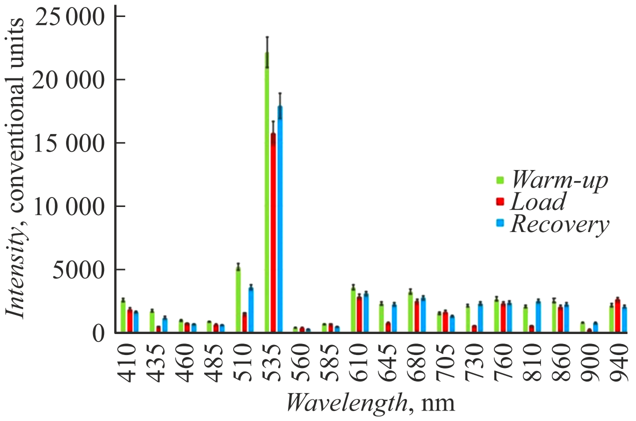

Figure 13. Spectral characteristics of backscattered and reflected radiation in the visible, near-infrared wavelength range in deeper layers.

A noticeable difference of the behavior of signals at different depths carries valuable information about the state of the human microcirculatory system, since microcirculation in the surface layers of the skin ensures heat exchange and cell nutrition and participates in the regulation of body temperature. Microcirculation plays a key role in delivering oxygen and nutrients to cells in deeper tissues such as muscles and internal organs. Microcirculation may be more or less active at different depths in tissues, depending on the oxygen and nutrient demand of cells. Microcirculation in the muscles increases with physical exertion for providing additional oxygen and energy [19].

Conclusions

A study of the penetration depth of optical radiation on theoretical models of heterogeneous biological media is presented. The understanding of the depth of radiation penetration can serve as a basis for the development of fast, non-invasive methods for monitoring the state of parameters of heterogeneous biological media. An experimental study of the penetration depth of radiation for human biological tissues with different modifications of the position of the radiation source and receiver was carried out. The obtained theoretical calculations in combination with experimental data make it possible to develop an optimal design solution and indicate the prospects of using spectrophotometric methods for analyzing the state of the biological environment and, in particular, the microcirculatory bed.

The study of the depth of radiation penetration into biological tissue plays a critical role in medical and biological studies. The importance of such studies is attributable to the fact that the depth of radiation penetration into the tissue is directly related to the effectiveness of treatment and the accuracy of diagnosis. This is especially important in laser therapy and in the diagnosis of various diseases, where an accurate assessment of the condition of tissues plays a key role.

Various models describing the interaction of radiation with tissues were considered in this study. Calculations of the penetration depth of radiation into such biological media as derma, blood and arterial vessel were carried out enhancing the understanding of the nature of interaction and the penetration depth of radiation into different types of tissues.

The results obtained during the study can be used in medical imaging systems, laser therapy and other applications where understanding the interaction of radiation is important. They can also help in the qualitative and quantitative assessment of various parameters, for example, the water content in the skin.

To the authors' knowledge, similar models have not been considered in the literature. However, the data obtained are in good agreement with the results of a number of similar theoretical studies published in foreign literature, which show that the depth of light penetration into the skin increases with the wavelength from UV to visible light before decreasing again in the IR range in accordance with the selected optical properties [20–22]. In addition, experimental studies confirm the possibility of measuring the functional parameters of biological tissues at a depth of 2–5 mm (for example, tissue oxygen saturation).

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Compliance with ethical standards

All procedures performed within the human subject research were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and later amendments or comparable ethical standards.

Informed voluntary consent was obtained from all participants involved in the research.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] P.K. Anokhin. *Uzlovye voprosy teorii funkcional'noj sistemy* (Nauka, M., 1980) (in Russian); Yu.S. Vanyushin, R.R. Khairullin. Teoriya i praktika fizicheskoj kul'tury, **7**, 11 (2015) (in Russian).

[2] N.A. Tishutin. *Podhod k ocenke funkcional'nogo sostoyaniya organizma* (in Russian). In sb. N.A. Tishutin, E.S. Pitkevich. Nauka — obrazovaniyu, proizvodstvu, ekonomike: materialy 72-j Reg. nauch.-praktich. konferencii prepodavatelej, nauchnyh sotrudnikov i aspirantov, (VGU im. P.M. Masherova, Vitebsk, 2020), s. 329–331 (in Russian).

[3] M.V. Alyushin, L.V. Kolobashkina, Y.N. Rozhanskaya. *Measurement of Static and Dynamic Bio-Parameters of a Person in Remote Systems for Current Psycho-Emotional and Functional State Monitoring.* 2018 Third Intern. Conf. Human Factors in Complex Technical Systems and Environments (ERGO)s and Environments (ERGO), IEEE, 2018, p. 161–165.

[4] A. Pantelopoulos, N.G. Bourbakis. IEEE Transactions on Information Technol. Biomed., **14** (3), 613 (2010).

[5] A.E. Pushkareva. *Metody matematicheskogo modelirovaniya v optike biotkani*: uchebnoe posobie (SPbGU ITMO, SPb, 2008), t. 103 (in Russian).

[6] C.F. Guimarães, L. Gasperini, A.P. Marques, R.L. Reis. Nature Rev. Mater., **5** (5), 351 (2020).

[7] T.M. Brown, K. Krishnamurthy. *Histology, Dermis*, StatPearls [Internet] (StatPearls Publishing, 2022)

[8] K. Almezhghwi, S. Serte. *Improved Classification of White Blood Cells with the Generative Adversarial Network and Deep Convolutional Neural Network* (Computational Intelligence and Neuroscience, 2020)

[9] P.E. Dolotov. *Zakon pogloshcheniya sveta dlya zhidkih sred* (Dni nauki, 2022), s. 295–297 (in Russian).

[10] A.E. Pushkareva. *Metody matematicheskogo modelirovaniya v optike biotkani*: uchebnoe posobie (SPbGU ITMO, SPb, 2008), t. 103 (in Russian).

[11] I.J. Bigio, S. Fantini. *Quantitative Biomedical Optics: Theory, Methods, and Applications* (Cambridge University Press, 2016)

[12] V.A. Firago, V.S. Radchikova. *Opredelenie gidratacii poverhnostnyh tkanej cheloveka i parametrov ih mikrocirkulyatornogo rusla sistemy krovoobrashcheniya* (in Russian). In sb. *Prikladnye problemy optiki, informatiki, radiofiziki i fiziki kondensirovannogo sostoyaniya: materialy VII Mezhdunar. nauch.-prakt. konferencii, posvyashchennoj 120-letiyu so dnya rozhdeniya akademika Antona Nikiforovicha Sevchenko* (18–19 maya 2023 g., Minsk. NIU „Int priklad. fiz. problem im. A.N. Sevchenko" BGU, Minsk, 2023), s. 103–104 (in Russian).

[13] V.T. Kondratov. Vimiryuval'na ta obchislyuval'na tekhnika v tekhnologichnih processah, **2**, 116 (2012) (in Russian).

[14] A.Yu. Zaitseva, M.S. Mazing, Yu.Ya. Kislyakov. Nauchn. Priborostr., **30** (4), 106 (2020) (in Ukrainian).

[15] V.A. Alekseev, A.S. Perminov, S.I. Yuran. Pribory i metody izmerenij, **1** (2), 5 (2011) (in Russian).

[16] T. Hamaoka, K.K. McCully. J. Physiolog. Sci., **69**, 799 (2019).

[17] P.V. Mikhailov, A.M. Telnova, I.A. Osetrov, Y.L. Maslennikova, L.G. Zaitsev. Yaroslavskij pedagogicheskij vestnik, **3** (1), 121 (2012) (in Russian).

[18] M.E. Grigorieva, S.M. Sorokoletov, A.V. Korobovsky, L.A. Lyapina. Sportivnaya medicina: nauka i praktika, **12** (4), 45 (2023) (in Russian).

[19] S.A. Borisevich. Sovremennye problemy nauki i obrazovaniya, **3**, 305 (2012) (in Russian).

[20] M. Niwayama, N. Unno. Sensors, **21** (16), 5573 (2021).

[21] H. Arimoto, M. Egawa. Skin Res. Technol., **21** (1), 94 (2015).

[22] L. Finlayson, I.R.M. Barnard, L. McMillan, S.H. Ibbotson, C.T.A. Brown, E. Eadie, K. Wood. Photochem. Photobiol., **98** (4), 974 (2022).

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