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THE EFFICIENCY OF LASER RADIATION ABSORPTION BY HEMOGLOBIN AND OXYHEMOGLOBIN IN THE SKIN BLOOD VESSELS

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Abstract. The results of the investigation of the efficiency of light absorption by oxyhemoglobin (HbO_2) and deoxyhemoglobin (Hb) in cutaneous blood vessels in dependence on the radiation wavelength and the optical properties of the tissue is presented. Using the Kubelka-Munk optical model of the tissue the spectral dependence of the efficiency of laser interaction both on HbO_2 and Hb of blood vessels at different depths of the tissue layer are calculated. The obtained results show that for blood vessels located in tissue up to a depth of 2500 μm the efficiency of laser radiation absorption follows the shape of the Q-absorption bands of HbO_2 and Hb.

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1. Introduction

In recent years medicine and biology have attracted the increasing attention of the specialists in Laser Physics, Laser Spectroscopy and Photochemistry. A new branch of science "Lasers in the Life Sciences" has been formed and a significant place in this field belongs to the medical application of lasers. It should be noted that the success of medical application of lasers practically in all areas of modern medicine is caused by two factors: pioneering investigations by enthusiasts, which started practically from the time of discovery of laser, and by modern development of laser technics. One of the significant achievements in recent time is the application of the flashlamp-pumped dye lasers in dermatology for the treatment of vascular cutaneous lesions [1-6]. This achievement is based on theoretical conception of selective photothermolysis [7], which considers two basic optical and thermal properties of pigmented tissue targets. One of the basic requirements is connected with the time of heat generation by chromophores due to selective absorption of high power laser radiation. It is required that this time should be shorter than the thermal relaxation time of the target. In this case the major part of the absorbed energy is concentrated within the target structure and the undesirable thermal damage of the surrounding tissue is minimized [8-10]. Thus, the flashlamp-pumped dye laser with pulse duration up to 450 μs was developed and applied for the treatment of a variety of cutaneous vascular lesions. In particular, significant success has been achieved in the treatment of Portwine stains [4-6].

In the clinical practice, the radiation at wavelength of 577 nm was primarily used, as it correlates with the one of the Q-band maximum of HbO_2 absorption spectrum. Recently, it has been demonstrated that the radiation at 585 nm is also very effective because of its deeper penetration into tissue. It should be noted that most of the efforts today are concentrated on the developing of high power laser systems to reach maximal absorption by HbO_2 at 577 nm and 585 nm.

Unfortunately, the absorption by Hb, which is contained in significant amounts in venous blood, so far has been practically ignored and needs investigation [11]. To consider the treatment of vascular lesions, located in deeper layers of dermas, it is important to investigate the efficiency of laser absorption at IR bands by both HbO_2 and Hb. There is one more interesting aspect of laser-tissue interaction by means of low-energy laser radiation as well as light effect on HbO_2 of human skin blood vessels. It is connected with the laser-induced photodissosiation of HbO_2, which leads to local increase of the molecular oxygen concentration. We propose this phenomenon as a possible primary mechanism of biostimulation and therapeutic effect of low-energy laser radiation. In this paper the result of investigation of the laser interaction efficiency on HbO_2 and Hb of the skin blood vessels in both aspects on selective photothermolysis and biostimulation effect are presented. The efficiency of interaction of laser radiation on HbO_2 and Hb of cutaneous blood vessels in dependence of the wavelength and the depth of penetration in tissue are investigated.

The future development of the practical application of long pulse flashlamp-pumped dye lasers in the treatment of vascular cutaneous lesions is discussed. The phenomenon of laser-induced photodissosiation of HbO_2 in the skin blood vessels as a possible primary mechanism of biostimulation and therapeutic effect of low-energy laser radiation is proposed.

2. Basic Concepts

As is well-known, the skin has complex structure with three basic layers: epidermis, derma and hypodermic fatty tissue. The thickness of skin without hypodermic fatty tissue layer can reach 4 mm. The architecture of tissue and the wavelength of the laser radiation determine the peculiarities of laser light interaction with tissue. At first, there is a partial reflection of light from the surface layer of the epidermis. The deeper epidermis layer contains melanin pigment, which is one of the basic chromophore intensively absorbing light in a wide spectral range. The derma contains collagen, which causes strong scattering of incident light. The tissue has a rich net of cutaneous blood vessels containing HbO_2 and Hb chromophores with strong absorption bands in the UV and visible spectral regions. The cutaneous blood vessels are located basically in two layers: in a superficial layer close to the epidermis and the deeper one on the border with hypodermic fatty tissue. These basic components of the tissue determine the depth of penetration of incident light into the skin in dependence on the light wavelength. Thus, the laser radiation incident on the skin is partially reflected by epidermis, partially scattered by collagen of derma, and partially absorbed by pigments of melanin, HbO_2 and Hb. The typical absorption spectra [12] of Q-band and in IR-band of HbO_2 and hemoglobin are presented in Fig. 1.

The absorption of light by HbO_2 and hemoglobin of cutaneous blood vessels allows considering and discussing the following photophysical and photochemical processes. The photophysical processes are connected with nonradiative dissipation of the electronic excitation energy by HbO_2 and Hb. The heat generated in this process is transferred to the blood capillaries, and has characteristic time of thermal relaxation of 0.05–1.2 ms [7]. The mechanism of the laser light influence on the human body is very much dependent on the output

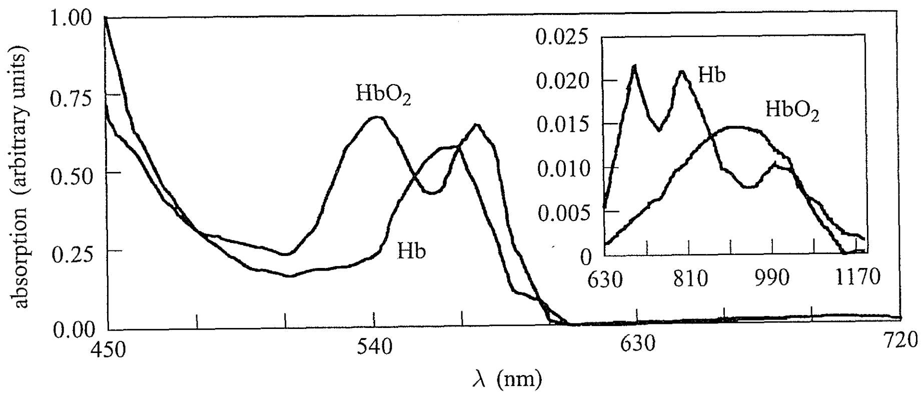

Fig. 1. Absorption spectra of Q-band and in IR spectral range of oxyhemoglobin (HbO_2) and hemoglobin (Hb) of cutaneous blood vessels

laser energy. The effect of high-energy lasers is quite clear and it is based on the photo-thermal processes such as selective photothermolysis. On the contrary to that, the mechanism of biostimulation and therapeutic effect of low energy laser radiation is still not established [15] despite of the numerous publications in this field. As a result the correct interpretation of experimental data obtained in clinical practice remains to be difficult. The absence of quantitative interrelation between the parameters of laser radiation and the object of interaction complicates the search for optimal methods of treatment. From the first experiments till the present time the question of existence of the fundamental differences in the biological effect on human organism of low-energy laser radiation and of conventional light is widely discussed. It is clear that the effect of heating via absorption of low-intensity laser radiation in tissue is not very important. Estimation shows that in typical case a local increase of temperature by 0.1–0.5 °C may be expected [13]. Such a small rise of a local temperature may promote only some improvement in capillary microcirculation of blood and this perhaps somewhat stimulate the metabolism processes. We suppose that in a case of low-intensity lasers the most important process is the laser-induced photodissosiation of HbO_2, whose main biological function is the transport of molecular oxygen. The molecular oxygen is generated due to the light absorption by HbO_2 in blood vessels, which allows controlling the local increase of oxygen concentration at irradiated region. The quantum yield of this process in a spectral range of 300–600 nm is close to 10 % while it seems to drop by a factor of 50 at the wavelength of excitation $\lambda \geq 1060$ nm [14]. It is worth to note that the above reasoning may be equally related to oxymioglobin, the function of which is to accept molecular oxygen from HbO_2. The spectral properties of HbO_2 and oxymioglobin are similar as they are defined by the identical structure of hem. It follows from the above considerations that efficiency of the therapeutic effect of low-intensity lasers must be directly dependent on the efficiency of laser radiation absorption by HbO_2. From this point of view it is important to know the real efficiency of the interaction of the laser radiation on HbO_2 and Hb of cutaneous blood vessels, taking into account both their absorption spectra and the change of the spectrum of the incident light at penetration of beam into the skin. We have calculated the efficiency of interaction of laser radiation on HbO_2 and Hb in dependence on the wavelengths and the location depth of cutaneous blood vessels in tissue. Calculations were carried out by the method of computer modelling using Kubelka-Munk optical model of tissue [12]. This model is based on the optical properties of white tissue and considered reflection, scattering and absorption by melanin and hemoglobin pigments of incident radiation. The efficiency of the absorption of laser radiation by HbO_2 and Hb was calculated in dependence on the wavelengths and the depth of penetration into the tissue.

3. Results and Discussions

The calculated efficiency of laser radiation interaction on HbO_2 and Hb in dependence on the wavelengths and the depth of penetration are presented in Figs 2 and 3. These spectral distributions are normalized to the maximum of the correlated absorption bands in order to demonstrate their transformation at penetration of radiation into tissue.

As it is seen from Figs 2 and 3 the efficiency of laser radiation interaction on HbO_2 and Hb in deeper layers of tissue shifts to the long wavelengths with maximum at $\lambda = 585$ nm and $\lambda = 570$ nm, respectively, and becomes very narrow ($\Delta\lambda \approx 25$–30 nm). These results are consistent with experimental data on low efficiency of argon laser radiation at wavelengths 488 and 514 nm and predict the high efficiency of application of Rhodamine 6G dye laser.

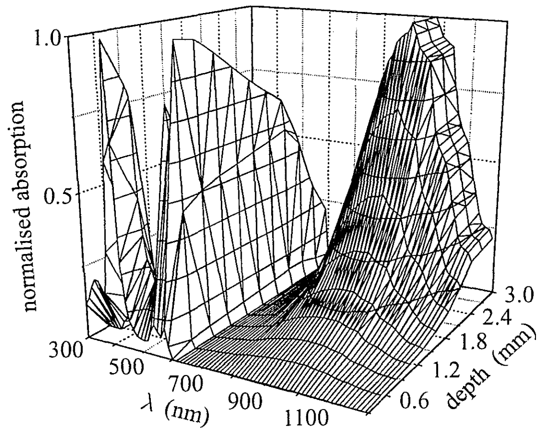

Fig. 2. Efficiency of laser radiation interaction on HbO_2 normalized to the maximum absorption in dependence on the wavelength and the depth of penetration into tissue

The efficiency of laser radiation interaction in the near IR range covers a rather broad spectral region from 600 nm up to 1200 nm. The obtained results show that these bands must play a dominant role in the absorption of laser radiation by HbO_2 and Hb in deep layers of tissue.

Thus, there are two preferable wavelengths in the infrared spectral region for irradiation of Hb ($\lambda \approx 800$ nm and $\lambda \approx 1000$ nm) and one at $\lambda \approx 960$ nm for HbO_2. The efficiency of laser radiation absorption by HbO_2 at the widely used in clinical practice wavelength 585 nm as compared to the absorption at $\lambda = 960$ nm at different depths of tissue is shown in Fig. 4.

As is seen, the efficiency of absorption at $\lambda = 585$ nm remains higher than at $\lambda = 960$ nm up to 2 mm of tissue depth and at the depth of about 2.5 mm they become equal. In the deeper layers of tissue the IR band of HbO_2 plays a dominant role in the absorption of laser radiation. So the wavelength 585 nm

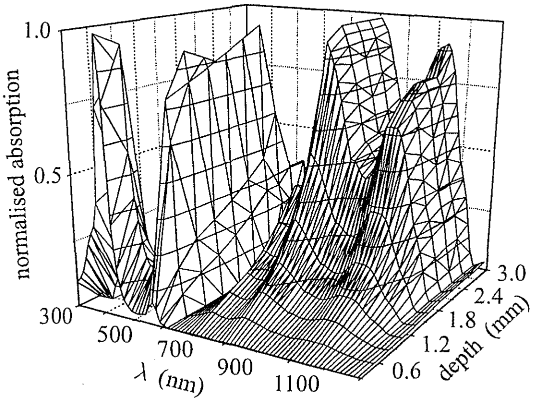

Fig. 3. Efficiency of laser radiation interaction on Hb normalized to the maximum absorption in dependence on the wavelength and the depth of penetration into tissue

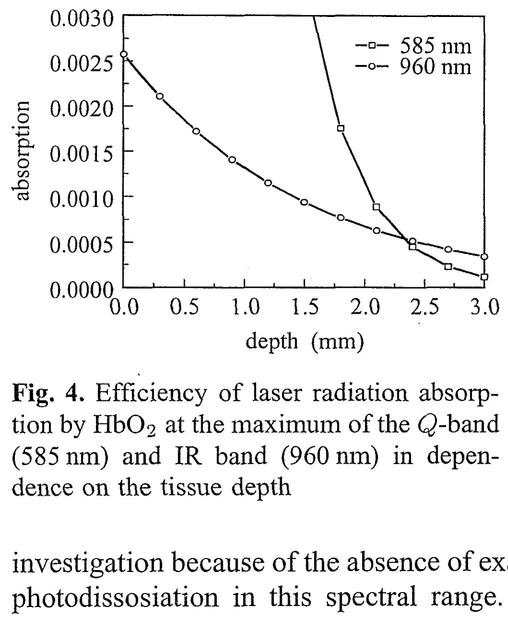

Fig. 4. Efficiency of laser radiation absorption by HbO_2 at the maximum of the Q-band (585 nm) and IR band (960 nm) in dependence on the tissue depth

may be recommended as the most efficient for the treatment of vascular lesion located at the depth of tissue down to 2.5 mm while for the deeper layers of tissue the most suitable wavelength is 960 nm. In practice different semi-conductor lasers (820 nm, 870 nm, 880 nm, 904 nm) are widely used for wound healing and treatment of various diseases. As is seen from Fig. 2, all these wavelengths are well correlated with the IR band of HbO_2 action spectrum. As to the He-Ne laser, the role of HbO_2 photodissosiation under irradiation at 632.8 nm needs an additional investigation because of the absence of exact data on the quantum yield of HbO_2 photodissosiation in this spectral range. He-Ne laser was evidently chosen because of its simplicity, reliability and low cost. At the same time it must be stressed once again that the wavelength 585 nm is expected to be the most effective in its effect on the blood. It should be noted in this respect that the improvement of efficiency and photostability of flashlamp pumped dye lasers, producing radiation at 585 nm, still remains an important practical problem to be solved. We hope that application of new water-soluble laser dyes on the basis of inclusion of complexes of organic molecules with cyclodextrines [16] may significantly improve the above mentioned parameters.

4. Conclusion

The results obtained demonstrate the necessity of binding of parameters of the laser to effect on the cutaneous blood vessels in consideration of laser therapeutic effect. The high spectral selectivity of the laser action on HbO_2 and Hb of cutaneous blood vessels is determined mainly by the absorption of melanin in epidermis. Thus, the efficiency of laser-tissue interaction depends on the degree of skin pigmentation. Some important conclusions may be drawn from the analysis of the spectra of laser action on HbO_2. First, one may expect the increase of therapeutic effect under irradiation directly at the maximum ($\lambda = 585\,\text{nm}$) of HbO_2 action spectrum. Second, considerable therapeutic effects are expected under laser irradiation directly at the maximum of Hb and HbO_2 action spectra in the IR spectral region. More definite conclusion on the role of HbO_2 photodissosiation in mechanism of biostimulation could be drawn only after comparative experimental investigations of the effect of low intensity laser radiation at various wavelengths.

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