

Thermal-vision monitoring of processes of heating and microcirculation of blood accompanying low-intensity laser therapeutic procedures

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Temperature fields on the surface of skin and the parameters of the microcirculation of blood in the skin accompanying various procedures of low-intensity laser therapy have been investigated by means of an IRTIS-2000ME digital thermograph and a LAKK-M spectrophotometric diagnostic complex. It is shown that changes of the parameters of the microcirculation of the blood in the skin accompanying both surface laser procedures and intravenous laser irradiation of the blood, if they were observed, were always accompanied by changes of the temperature of the skin surface. © 2011 Optical Society of America.

INTRODUCTION

Biostimulation mechanisms of low-intensity laser therapy (LILT) have been discussed for many years.^{1–5} However, they largely remain controversial, even though such therapy has developed in a comparatively short time into a relatively autonomous, fashionable, and fairly effective (judging from medical primary sources) section of physiotherapy in Russia and a number of other countries of northern Europe and Asia.⁶ According to the data of a large number of papers, the best-substantiated mechanism by which low-intensity laser radiation (LILR) acts on soft cellular tissues and blood is by stimulating microcirculatory processes in the irradiation zone.^{2,4,7,8} This shows up especially clearly when there is intravenous laser irradiation of the blood (ILIB), which is widely used in Russia in virtually all regions of medicine.⁹ Most authors are confident in this case that no substantial heating of the tissues occurs in the process of LILT,^{1,4,7,9} while the temperature of the irradiated tissues does not increase by more than 0.1 °C.

These conclusions as a whole were obtained about 10–15 years ago on the basis of ordinary clinical observations and the results of laboratory and morphological studies.^{1,2,7,8} There were no devices available to physicians at that time that could record microcirculation processes and the dynamics of the surface temperature of biological tissues with sufficient accuracy and in real time. Today such devices have appeared. These include, most importantly, noninvasive spectrometric instruments that make it possible to monitor tissue respiration and the perfusion of tissues with blood,⁹ as well as apparatus for digital IR thermography and thermal-vision monitoring devices that record the temperature over a large surface area of the body to within ± 0.05 °C.¹⁰ All this opens up the prospect of direct on-line checking of the conclusions made earlier and some of the most controversial and interesting results of earlier papers (as is well known, only results that are independently verified in different laboratories of the world can be regarded as reliable in science).

It must be said that such papers have recently begun to appear. Reference 11 undertook a fairly professional attempt to detect the reaction of the blood microcirculatory system, in particular the parameters of hypervolemia (V_b) and tissue saturation of oxyhemoglobin in mixed blood of the microcirculatory system (S_rO_2) to the LILT procedure immediately during irradiation and right after it. According to the author's data, such a reaction was observed, but only under two conditions: either with fairly large irradiation power densities (1–5 W/cm²), causing substantial heating of the tissues, or with intravenous introduction of exogenous photosensitizers into the subject. In the latter version, S_rO_2 decreased at lower power densities (50 mW/cm²). However, it is well known that any photosensitizer increases the absorption coefficient of radiation in tissues; it consequently can be assumed that the total thermal effect from LILR remained the same (true, the temperature of the tissue was not measured). The reactions of the blood microcirculatory system to LILT and to ordinary thermal heating (thermal probe) were compared in the same paper. It was shown that these reactions are identical. The paper's authors could detect no reaction to LILR (in particular, the measurements were clearly made with large errors, since the parameter S_rO_2 in the subject fell below the zero mark on one of the graphs during occlusion). They therefore concluded that their method of oximetry is very crude and assumed that this reaction could be detected by more sensitive methods—for example, laser Doppler fluorimetry (LDF)—and with lower LILR power densities.

Similar measurements were made by pulse oximetry to estimate how a laser affects the saturation of arterial blood (S_aO_2).¹² No S_aO_2 dynamics were observed for wavelength $\lambda = 632$ nm (a He–Ne laser) and power $P < 5$ mW at the irradiation focus. Variations at a level of $\pm 2\%$ were recorded at $P = 5$ mW, but the authors did not disclose the metrological aspects of such high-accuracy measurements.¹⁾ They recorded a reliable decrease of S_aO_2 by about 4–5% only for $\lambda = 532$ nm and an irradiation power of 2 W.

Korolevich *et al.*¹³ used LDF to observe how much the perfusion of the tissues with blood increased in the zone of action of LILR at $\lambda = 632 \text{ nm}$ even at $P = 1.1 \text{ mW}$ (laser beam 2.5 mm in diameter, power density 22 mW/cm^2). The graphs in their paper show that the perfusion in the subject's skin increases from about 35 to 75 perfusion units in an irradiation time of 5 min (!). However, even the physiological possibility itself of such an increase of the perfusion when the initial value is 35 perf. units is doubtful (it is not impossible, for example, that the device operated incorrectly). Moreover, according to the authors' information, a simultaneous increase of the perfusion from 35 to 50 perf. units was recorded on the unirradiated symmetric zone on the other side of the subject's body. They see heating of the tissues as the leading mechanism of such action of the LILR: according to the authors' calculations, with these irradiation parameters, the temperature can increase to $41.7 \text{ }^\circ\text{C}$ (!). However, the symmetric section of the body was not subjected to irradiation, and consequently the strengthening of the microcirculation in it can have only a reflector nature (no temperature measurements were made in the experiment).

As can be seen, these data are contradictory and disagree not only with each other but with earlier conclusions concerning the mechanisms by which LILT acts (strengthening of the microcirculation in the absence of heating). A substantial drawback of all these papers was that there were no direct measurements of the surface temperature of the biological tissue during the LILT. A goal of our studies was to make combined measurements of the temperature and the blood microcirculation parameters for various regimes and regions of LILR action, including the most "potent" ILIB, by different methods simultaneously: high-accuracy IR thermography, LDF, and optical tissue oximetry (OTO). Simultaneously recording various parameters by different methods, in our opinion, should eliminate the situation in which one of the devices or methods is insensitive, should reveal the advantages of temperature measurements, and should also make it possible to obtain a clear dependence between the blood microcirculation dynamics and the surface temperature of biological tissue in the zone where the LILR acts.

MATERIALS AND METHODS

Twenty-eight people took part in the studies. They included nominally healthy volunteers (including two of the authors of this article) and patients of the Moniki Clinic suffering from various diseases, who, according to various indicators, had been prescribed to receive planned procedures of cutaneous LILT or ILIB. All the subjects of this study were chosen with a normal or spastic type of blood microcirculation, in order to prevent a hyperemic type of microcirculation from affecting the experimental results.²⁾ Of the total number, ten of the subjects were treated with LILR on the surface of the skin of different zones of the upper extremities (the forearm, palm, and wrist), and fifteen patients received ILIB. Three volunteers were also tested using ordinary contact thermoelectric methods of heating the skin. Nine "quasi-placebo" measurements were made, with no irradiation, to obtain a set of data on the parameters of the microcirculation and oxygenation of blood in a state of

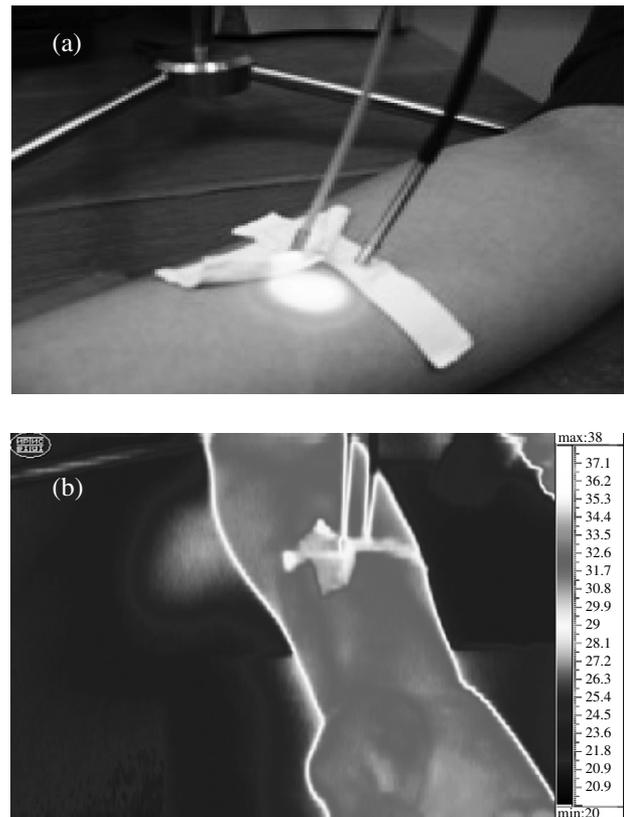


FIG. 1. Experimental design for irradiating the skin by laser. Photograph in the visible region (a) and thermal image (b).

rest [both for healthy volunteers (seven) and for patients with diseases (two)].

The parameters of the microcirculation and oxygenation of blood were experimentally recorded by means of the LAKK-M multifunctional laser noninvasive diagnostic complex (MLNDC), which makes it possible to use the LDF method *in vivo* to simultaneously measure in the section of the skin being studied the perfusion of the tissues with blood (I_m), as well as parameters S_tO_2 and V_b by the OTO method.¹⁴ The experimental design for cutaneous LILT and the method of fixing the fiber probes of the MLNDC are shown in Fig. 1, along with a thermal-vision image of the test region.

The thermal-vision image, from which the temperature was subsequently automatically calculated, covered the entire area of the irradiated surface and the surrounding region in which the LILR acted on the tissues. This made it possible subsequently to analyze the dynamics of the temperature changes not only directly at the center of the irradiation spot but also along its periphery and the unirradiated tissues that surround it. An IRTIS-2000ME digital medical thermograph (Institute of Radio Engineering and Electronics, Russian Academy of Sciences) was used to measure the surface temperature and to obtain thermal images. The thermal probe (heating) was carried out by means of an external thermal heater from the LAKK-01 apparatus, with the possibility of stabilization and independent monitoring of the heater temperature during the procedure. The heater temperature in the experiment was set and maintained at a level of $41.5\text{--}42 \text{ }^\circ\text{C}$. The time of heating was 3.5 min. The skin

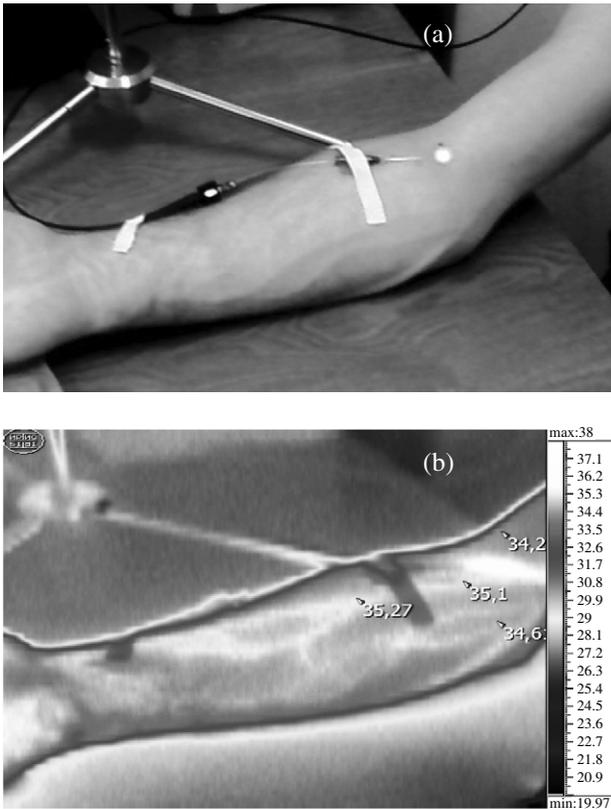


FIG. 2. Experimental design for intravenous laser irradiation of the blood. Photograph in the visible region (a) and thermal image (b).

temperature in this case was determined on the image next to the edge of the heater.

Two types of therapeutic apparatus with different designs were used for cutaneous LILT: the ULAN-BL-20 (pulsed regime, $\lambda = 890$ nm, pulse-repetition rate 30 kHz) and the ULF-01 (continuous regime, $\lambda = 632$ nm, output power 20 mW). Only the continuous irradiation regime with the ULF-01 was used for ILIB. The area of the irradiated zone for cutaneous irradiation was varied within the limits $0.3\text{--}4$ cm². To attempt to find how the thermal effect depends on the power density, part of the experiments on two volunteers were especially done with three different irradiation gradations along the spot diameter (0.3, 1.5, and 3 cm). The output power of the LILR from the needle during ILIB was 2 mW. In this case, a needle with a lightguide was introduced into an ulnar vein of the patient (Fig. 2), while a sensor from the MLNDC for measuring the blood microcirculation and oxygenation parameters was fixed on the distal phalange of the third finger of the same arm. This region is chosen as having the richest network of capillaries and arteriovenous shunts, and it quickly and strongly reacts to any changes in the ambient conditions.¹⁵

The duration of the irradiation accompanying LILT was varied from 5–10 min for cutaneous procedures to 20 min for ILIB. In this case, all the parameters were recorded both before beginning the irradiation (background recording) and simultaneously with the laser irradiation and then for several minutes after it ended. All the measurements were made in the same office at room temperature (21–23 °C) by the same group of researchers. Before any procedure was begun, the subject was made to sit still for 5–7 min to normalize the blood flow.

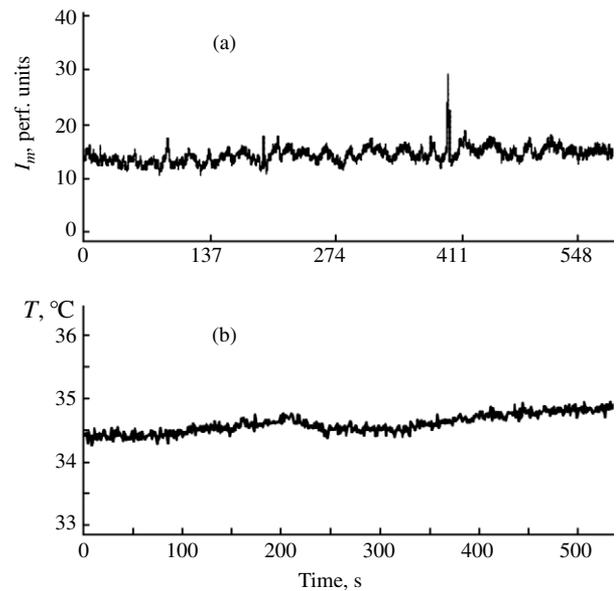


FIG. 3. The absence of visible dynamics in the microcirculation index (a) and in the temperature (b) with normal physiology in the process of cutaneous irradiation by laser for 8 min. Beginning of irradiation: 60 s.

In all, about fifty different experiments were carried out as part of the studies described here.

RESULTS

Examining the correlation of the blood-microcirculation parameters (the perfusion index I_m) and the surface temperature of the tissues (T), all the trends obtained in the different experiments can be conventionally divided in their dynamics into three groups:

- I. The fact that, within the limits of accuracy of the measurements, there are no visible dynamics and no changes in either index during the entire experiment, aside from the dependence on the presence or absence of external action in the form of LILR (Fig. 3).
- II. The differently directed drift (oscillations) of the values of the indices I_m within its variations of $\pm 10\%$ from the mean and of T within ± 0.5 °C during the entire experiment, with no unambiguous or coordinated dynamics on one side or the other, also aside from the dependence on the presence or absence of external action in the form of LILR (Fig. 4).
- III. An assured simultaneous increase of I_m and T during the entire experiment when there is external action (irradiation by LILR or thermal probing) and a latent period and/or subsequent falloff after the action ends (Fig. 5).

For the first of the two indicated groups of dependences, it was impossible during the experiment to detect any unambiguous correlation in the behavior of the oximetric parameters S_rO_2 and V_b with the dynamics of parameters I_m and T . This was independent of whether a sick or healthy subject participated in the experiment, whether or

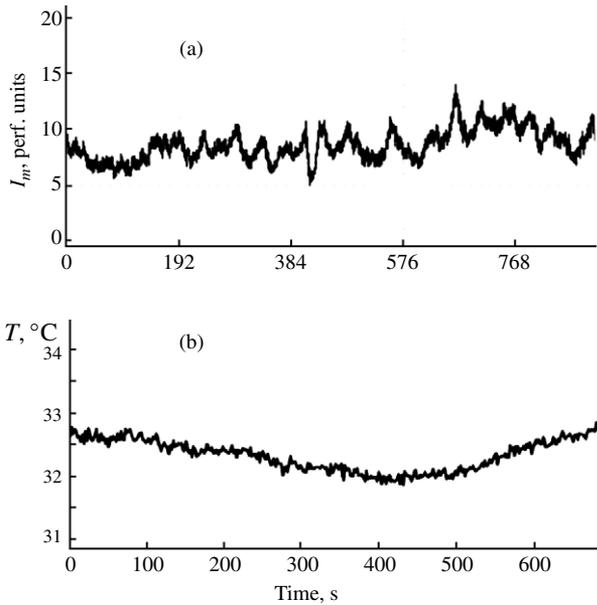


FIG. 4. Natural oscillations of the microcirculation index (a) and of the temperature (b) in the absence of action in the norm.

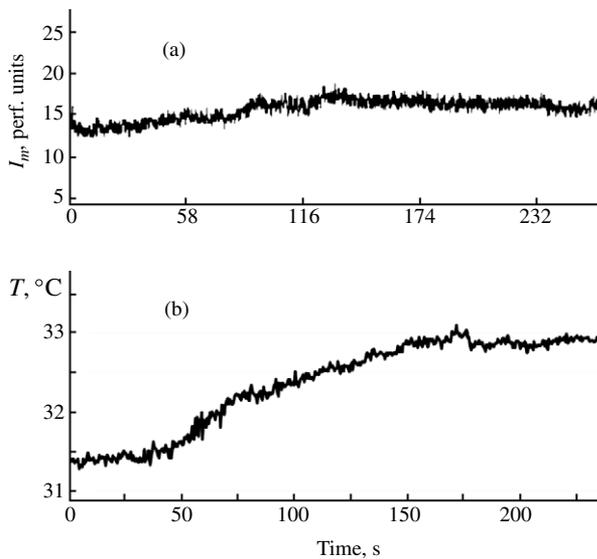


FIG. 5. Visible simultaneous dynamics of the microcirculation index (a) and of the temperature (b) accompanying intravenous laser irradiation of the blood of an oncological patient for 240 s. Beginning of procedure: 10 s.

not there was LILR irradiation in the experiment, whether there was cutaneous irradiation or ILIB, and whether it was continuous or pulsed. Each of the parameters (S_tO_2 and V_b) in all the experiments most likely behaved independently of I_m and T in the type of manifestation of fluctuations of the values of the parameters in group II. All these changes (or their absence) are probably caused not by external action—cutaneous LILR irradiation or ILIB—but were determined by ordinary physiological rhythms and the background physiological variability of the living system, since it is precisely this variability that was observed in six of the nine cases of experiments with no LILR irradiation, i.e., “quasi-placebo” experiments (one case for a sick subject and five for healthy subjects).

On the average, although some prominence of the reaction of the microcirculatory system and the skin temperature was observed in the zone of cutaneous laser irradiation and during ILIB (Fig. 5), this was true in no more than 20% of the cases of LILT with ordinary therapeutic doses of irradiation. In 80% of the cases, it was impossible in general to detect changes of the temperature or of the blood microcirculation and oxygenation parameters accompanying LILT procedures on the background of natural physiological fluctuations of the type of Fig. 4, although the evidence was manifested in a wide range of power densities and irradiation times by means of the thermographic technique and spectrophotometric apparatus used here. Even in the 20% of the cases indicated above, although there were some variations during recording, they were all just barely noticeable on a background of strong physiological fluctuations. However, everywhere that the perfusion I_m varied during LILT, the surface temperature in the irradiation zone changed at the same time and in the same direction. The opposite was not observed. In several cases, the increase and falloff of the skin temperature were not accompanied by corresponding changes of index I_m (Fig. 4). That is, when the changes are small, on the level of physiological variations or a little higher, changes of the surface temperature of the skin do not always correlate with a change of the perfusion of the tissues with blood. This can be evidence that not all thermal processes in the skin are determined only by the blood-microcirculation parameters. Some thermal fluctuations apparently depend on other processes—for example, on the process of diffusion and evaporation of moisture from the skin surface.

Unambiguous and correlated dynamics of all four indices S_tO_2 , V_b , I_m , and T were stably detected only with strong enough action, associated either with large LILR power densities (for example, starting from 250 mW/cm^2 for cutaneous irradiation at $\lambda = 632 \text{ nm}$), or when the tissues are directly heated with a thermal heater (Figs. 6 and 7). Moreover, it was identical for LILT procedures and for ordinary heating. The term “low-intensity” here is evidently no longer quite correct. In all cases of obvious, visible reaction of the microvascular system to external action, the temperature in the region of action had increased from the initial level by at least $0.8\text{--}1 \text{ }^\circ\text{C}$. Similar dynamics with lower LILR power densities were observed only with external irradiation of the skin by continuous laser radiation in areas having increased thermal sensitivity. For instance, the dorsal side of the radiocarpal joint of one of the subjects began to heat up and responded to the action by obvious vasodilation at a power density of about 50 mW/cm^2 . Consequently, the leading mechanism of LILR action is also a thermal mechanism in this case.

DISCUSSION

The results of our studies on the whole thus confirmed the latest experimental results of Refs. 11 and 12, that variations of the parameters of the microcirculation and oxygenation of the blood under LILT occur much less often and are less clearly expressed (if they are there at all) than reported by purely medical primary sources. The use here of more sensitive methods of the type of LDF by comparison with OTO, as was assumed,¹¹ has no substantial significance. A pronounced

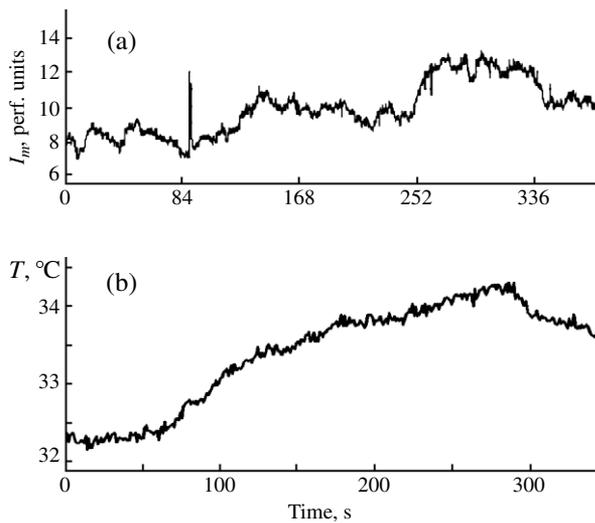


FIG. 6. Obvious simultaneous dynamics of the microcirculation index (a) and of the temperature (b) accompanying contact heating of the wrist in the norm. Beginning of heating: 60 s; end: 270 s.

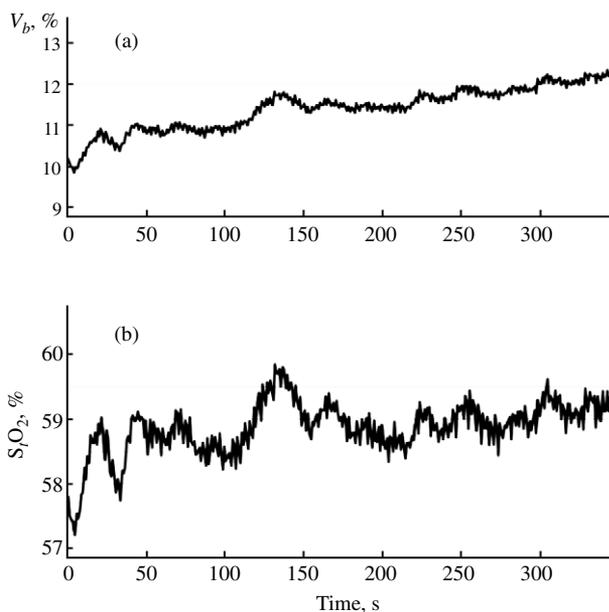


FIG. 7. Simultaneous dynamics of the oximetry index accompanying contact heating of the wrist in addition to Fig. 6 in the same experiment. (a) Hypervolemia index, (b) mean cellular saturation of the oxyhemoglobin of the blood in the skin.

reaction in which microcirculation increases under the action of LILR shows up only in the case of fairly powerful and prolonged irradiation, when ordinary thermal heating of the tissues becomes the leading cause, and the reaction itself of the microvascular system becomes identical to the reaction to a contact thermal probe. Less pronounced reactions within the limits of 1–10% of the initial values of the indices, if they occur, are fundamentally “drowned” in the natural physiological fluctuations of these parameters and cannot be reliably recorded nor be taken seriously in the aspects of the mechanisms of LILR action or the objectivation parameters of the reaction of the microvascular system to LILR. This reaction probably does not exist in most cases,

while the experimentally observed 20% of cases in which such a reaction occurs can be assigned to a situation with increased photo- or thermal sensitivity, as well as to the psychosomatic effect of a placebo.

Can this be true in principle in the numerous existing publications on the stimulation of microcirculation accompanying LILT? Apparently it can. This conclusion, by the way, does not strongly conflict with the latest literature and the data of the authors of this paper, which they have already reported more than once (see, for example, Ref. 16). Reactions in which hypervolemia increases in the zone of LILR irradiation have not been experimentally recorded by devices that are even less sensitive than they are today as often as has been reported by many medical specialists. Quite recently, Plavskii *et al.*¹⁷ indicated that LILT was most widely used only in Russia and the countries of the former USSR, whereas, abroad, in particular, in the USA, Great Britain, Canada, and many other countries, there is extremely cool reception to it, especially to ILIB. The authors analyzed about 3000 professional publications on LILT, but they found methods of conducting the studies that satisfy criteria convincing to a physician (randomized clinical tests) in only about 140 of them. Only a few individual publications contained a description of an experimental technique with double-blind control, in which neither the physician nor the patient knew whether the laser was operating. In this case, in half of the papers that report such monitoring (all foreign, listed in the cited primary source), it is pointed out that the results of LILT are indistinguishable from the placebo effect.

A Japanese publication¹⁸ is instructive in this sense and has existed for a long time but has apparently remained unnoticed by medical specialists. It reported the action of LILR of different wavelengths and power densities on the vascular tone in an experiment with individual segments of the vessels. For comparison, the reaction of the vessel to ordinary heating was also tracked. The fundamental conclusion of that article is that the vascular tone reacts only to heating, regardless of by what method it is obtained—by contact heating or by means of LILR. In all cases of irradiation and contact heating, a reaction of the vessels was observed in this experiment only when the temperature in the zone of action increased by about 1 °C from the initial level. Neither contact heating nor LILR below this threshold produced an appreciable change of the vascular tone, and this is consistent with the results of this paper.

Nevertheless, aside from the presence or absence of a threshold and aside from the nature of the vascular reaction to LILR, the studies carried out and reported here showed that, along with noninvasive spectrophotometry, the methods of thermography can be successfully used as a highly accurate and fairly sensitive method for monitoring the parameters of microcirculation and temperature of the skin surface when carrying out LILT procedures. In all the experiments in which the microcirculation in the skin clearly varied during LILT, the thermograph also clearly recorded changes of its temperature greater than ± 0.8 °C. That is, both of these methods give similar diagnostic results and show changes of the microcirculation parameters under the action of LILT in real time. This conclusion from the experimental results presented in this study, in the authors’ opinion, is indisputable.

CONCLUSION

In this study, for various procedures of low-intensity laser therapy, the temperature fields on the skin surface and the blood microcirculation parameters in the skin were simultaneously measured by means of the IRTIS-2000ME digital thermograph and the LAKK-M spectrophotometric diagnostic complex. The results of this work showed that, with both surface laser LILT procedures and internal laser irradiation of the blood, if changes of the blood microcirculation parameters in the skin were observed on the background of strong natural physiological fluctuations, they were always accompanied by temperature changes of the skin surface. Thus, the methods of thermal vision and IR thermography allow the physician to successfully investigate the reaction of the microcirculatory system to the action of LILT in the same way as modern methods of spectrophotometry.

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¹⁾According to GOST [State Standard] P ISO 9919-99, "Pulsed medical oximeters. Technical requirements and test methods," (2000), all measurements by pulse oximetry have an error of at least 2–3%.

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