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Interventional infrared thermal diagnostics in medicine and physiology

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Abstract

Up-to-date trend in biomedical infrared thermography is illustrated, discussed and called interventional biomedical infrared thermography. New experimental results obtained with the use of FPA-based infrared camera and applicable to human physiology are presented.

1. Introduction

It is well known that the skin temperature distribution reflects physiological processes progressing in human body. This fact gives infrared thermography (IRT) a great advantage over many other medical diagnostic means and instrumentations because enables IRT to be a very sensitive method capable of detection of changes in the vascular system state, and therefore allows studying different organs, vascular and neurovascular reactions in humans [1–3]. Ground for successful use of IRT in physiology is the fact that in many cases surface temperature represents adequately the blood perfusion, which in turn represents the physiological processes developing in the organism [4, 5]. The modern FPA-based IR camera captures the surface thermal patterns in real time making them accessible to subsequent analysis.

Inexhaustibility of IRT for medical diagnostics is dictated by inexhaustibility of different ways of internal and external influence on the organism, because thermoregulatory processes of the organism normally respond keenly to any intervention. External and internal impacts on the organism provoke different reactions which can be examined by IRT methods with a high degree of accuracy. Usually, healthy and affected organisms respond to stimuli or irritants in different ways that gives grounds to use the IRT results for biomedical diagnostic purposes.

Modern high performance IRT exposes a lot of “reefs” generating a need for examination of many new details that became apparent in the thermograms measured with high accuracy and sharpness in a wide dynamic range. The recognizable new details, consequently, bring forth many tough problems to medical specialists, sending them in search of new IRT-based diagnostic methodologies and criteria. The performance of this task still remains the “problem of today” in medical IRT.

2. Interventional biomedical infrared thermography

Long-term experience gained in medical IRT demonstrates that separate thermograms contain quite scanty information and they usually don’t allow somebody to diagnose. It is necessary to point to elaboration of different tests meant for diagnostics. This approach is realized, in particular, with the help of so-called dynamic or active thermography. Dynamic tests usually include the exposure of the organism to external impacts [4, 6]. The most simple and popular among them is the cold test equipped with the cold water for extremities to be submerged. It should be noted that cooling and moistening are used sometimes to enhance the contrast of surface thermal pattern [7]. The cold stimulus as well as overheating of the organism induce the autonomic vasoconstriction and vasodilatation reflexes in normal structures, thus enhancing the thermal contrast due to differences in the vasculature of the different skin regions [4]. From our point of view, a closer look at the dynamic IRT data is called for. There is a need to pursue this direction in IRT in every possible way because the future of medical infrared diagnostics may well lie with the active methods of examination.

The users of dynamic IRT tests and the authors of corresponding scientific works often reveal from the thermograms the signs of diseases under investigation and thereupon promulgate the relevance of IRT for medical diagnostics. Vulnerability of such an approach consists in the fact that it does not allow to obtain a reliable result when the inverse problem is pending. Namely, it does not place any convincing diagnostic character at practicing physician’s disposal because similar thermograms and thermal manifestations can be obtained also for many other diseases and even for natural physiological deviations of a normal organism.

Interventional infrared thermal diagnostics, or interventional IRT, is the up-to-date version of dynamic IRT. With this approach, the organism is regarded as, in some way, a “blackbox”. In order to reveal the internal features of this object, the external disturbing signals should be let into the organism. In such a case, the obtained different responses are expected in healthy and affected organisms because of the targeted orientation of the executed stimulations.

In former times, the approach with interventional infrared thermal diagnostics was unrealizable, because it requires measurements which are conducted with the frame rate of tens frames per second (to investigate moving individuals, e.g. loaded with a bicycle ergometer), temperature sensitivity of hundredths parts of degree (to investigate the initial phases of physiological reactions), and high spatial resolution. Just the modern FPA-based IRT systems meet all the above-mentioned requirements.

Interventional IRT is concerned mainly with physiological investigations [4, 8]. Here the scientists have no restricted themselves to trivial description of different peculiarities found in thermograms. They endeavor to fit the obtained experimental data to physiological mechanisms responsible for these results. The researchers and medical practitioners try to discover the logic pattern in the observed thermal manifestations by reconciling their data with information taken from anatomy and physiology. With the scientific works of this level we are able both to extract substantial amount of fundamental information about human beings from the IRT data and to lay the groundwork for medical IRT diagnostics.

3. Diagnostic significance of the human thermal pattern heterogeneity

The human organism is a self-regulated physical system, and its principle feature is the maintenance of the mean temperature within a very narrow interval constituting just 2% of the body thermodynamic temperature itself. Interest in thermoregulatory mechanisms responsible for this stability has continued till now [9]. The most fantastic is that such a stability is maintained by a human organism under environmental conditions characterized by much wider than 2% diapason of surrounding temperatures, at the level of about (30–35) %, from cold pole to equatorial heat. At the same time, even in the less aggressive conditions a human organism needs uninterrupted heat exchange with environment. In connection with this fundamental feature, the following new model of surface temperature nonuniformity in homoiothermal organism deserves attention.

Let a certain mankind-average apparently healthy individual presents a typical result of human evolution. Compare this human with that affected by any lesion or physiological change. If the malfunction of the latter person is in active phase, the metabolic processes in his organism would be expected as disturbed, and the altered heat production in the organism should lead to excess (or reduced) heat release into environment as against the amount of heat produced and dissipated by a healthy person, all other factors being the same (environmental conditions, behavior, external loads, food intake, etc.). It will entail overheating (overcooling) of an affected person that cannot be allowed by a homoiothermal organism. While the reflectory conditioned struggle of the organism for recovery necessitates an increased (decreased) metabolism in affected part(s) of body, it might be supposed that, to keep a metabolic balance, the well organized systems of this organism would slacken (intensify) the function of intact parts of the body and reduce (increase) their heat production respectively. Thus, in a sense, the temperature contrast is changed (predominantly, increased) inside a body, and this change becomes apparent on the body surface as on outer boundary of the body volume. This model explains why the recording of surface thermal nonuniformity has a diagnostic significance in human medical examination. The model also generates a need for development of methods and techniques meant for the investigation of spatial nonuniformity of the human body temperature and its transformation with time.

It is valid to say that the use of IRT is the optimal line of attack on the above-formulated problem to date. No method can match IRT in the recognition of diseases or physiological and pathological deviations if diseases and deviations are accompanied by non-uniform body surface increase or decrease in temperature.

The importance for biomedical diagnostics of such a new characteristic of thermal images as heterogeneity were first enunciated and substantiated in [4]. In the above-mentioned work the correlation of the degree of heterogeneity and human physiological status as well as the necessity of elaboration of mathematical and computational methods dedicated to quantitative description of the extent of heterogeneity were highlighted. Human surface thermal heterogeneity is the mirror of a deviation from homeostasis and the characteristic of a neurovascular function of the organism. The extent of thermal heterogeneity is influenced by acute situational reaction, alarm reaction, anxiety reaction, etc.; therefore it may serve as an informative quantitative diagnostic sign in interventional medical infrared thermography.

4. Laboratory equipment for high-precision IRT-based investigation of small animals

Many medical and physiological IRT-based studies are carried out using small laboratory animals (usually rats and mice) [10–14]. In this respect, considerable difficulties are connected with the following factors:

1) small-sized organs that require high spatial resolution of IRT equipment;
2) high mobility of non-narcotized animals that requires the use of IR camera of high operation speed;
3) hair-covered body whose hair is always in a good contact with air and, at high sensitivity of IRT method, it leads to the appearance of considerable temperature artifacts caused by air motion in a laboratory.

Due to the aforesaid, working out the methodology for correct studies of such animals becomes important.

Towards this end, we designed and fabricated a special chamber meant for such investigations (figure 1). It is a box sized 90×60×110 cm^3 with the following built-in components:

1) horizontal revolving table to fix an animal on it; the table may be fixed in several positions;
2) optical-mechanical support of IR camera with a possibility of its vertical movement and rotations in two planes.

The technical requirements for this experimental equipment were meant to provide the maximal possible reliability regarding the results of IRT-based studies. They are as follows:

1) To avoid light spots, the illumination of table's working field in the visible range is realized from the sources, equipped with cut-out filters, radiating outside the IR camera working spectral range.

2) All the walls and the ceiling of the box are fabricated from nontransparent materials to exclude the interference of external thermal sources.
3) A special mounting accompanying the movement of IR camera provides a fixation of additional devices and optical elements (e.g. an additional IR lens) as well as different equipment realizing impacts on an animal.
4) The raised front and back walls of the box open an access to an animal from two sides simultaneously (for example to a surgeon and his assistant).
5) Hermeticity of the box at lowered walls is sufficient to exclude convection inside the chamber caused by air motion in the laboratory.
6) An additional hermetic acrylic dish with walls 24 cm high allows us to study the temperature response of active (non-narcotized) animals.
7) The material from which parts of the revolving table and box are made provides for a multiple sanitary treatment of the item.
8) A special pan of stainless steel is installed under the rotation table to collect liquids flowing down during manipulations with animals.

Using the described chamber, preliminary investigations of fast vascular reactions in narcotized laboratory rats were made with arterial occlusion of one of the paws and creating artificial ischemia in the tail (figure 2).

5. Interventional tests: some implementations in humans

For a time, we are developing the methods for interventional infrared thermal diagnostics of human organisms. Besides high performance IR camera, special accessories are usually necessary for interventional IRT measurements. We tested for this purpose the equipment as follows: setting mechanism for physical loads [4, 15], heated support for feet and palms, electric massager, occlusive tester equipped with a laser Doppler flow meter, etc.

5.1. "Dry"-manner heating of upper and lower extremities

With the aim of extremities "dry"-manner heating, the production version of "InTermo GreenStone" heating support (manufacturer and seller – LLC "Sibirskaya Zvezda", Russia) was used in our investigations. The flat upper panel of this equipment is made of natural mineral jade. These supports are assigned for medioprophylactic and relaxational heating of feet in physiotherapeutic rooms and domiciliary. The voltage regulator provides a change of the support's effective area temperature.

Measurement manipulations were as follows. When sitting, a volunteer or patient placed his naked feet or palms on a polished stone surface of the support heated to about 41 °C and was keeping to this position during 10–30 minutes. Thermal patterns of backs of the feet (or hands), as well as front surfaces of lower legs (or forearms) falling within an IR camera view, were continuously measured and saved in the computer memory. The extent of thermal effect in the extremities exposed by heating was determined from the change of the vascular pattern revealed within parts of the body under examination.

A set of the thermograms obtained during heating of a volunteer's hands (woman, aged 40) is demonstrated in figure 3. IR camera makes it possible to represent and objectively map the characteristic features of temperature changes. First of all, it is easily observable that, in initial state, the intensity of superficial blood supply in fingers was quite scanty. As a result, the fingers skin was rather cold. The origin of this cooling is heat dissipation from fingers into the environment without gaining compensatory heat from deep tissues and warm arterial blood.

Figure 3 offers a clearer view of how the blood penetrates through the hands in question. It is seen that, initially, the blood flow washing cooled distal parts of the upper extremities was sufficiently intensive. This hypothesis is corroborated by the fact that the cooled blood flowing off from fingers and from the surrounding tissues uninterruptedly cools great surface veins leading this blood away from hands. The latter is exhibited in the thermograms as dark "cords" in forearms going towards proximal parts of limbs. In case the blood velocity in great vessels is low, the surface thermal contrast between the great veins and surrounding tissues in the forearms should be gradually disappeared.

Even the simplest quantitative analysis of the thermograms represented in figure 3, namely, the comparison of temperature profiles plotted in the same places of the thermograms along the hand under investigation makes it possible to discover phenomena that go unheeded at ordinary external visual examination. A series of the profiles mentioned above is presented in figure 4. The result, interesting and unobvious in advance, here is the fact that, in response to external heating, thermal effect in the limb is progressing only within the hand area while the skin temperature in the forearm (except for areas above the great surface veins) remains rather unchanged. It can point to the fact that the hand heating does not lead to reflectory enhancement of arterial blood flow in the great vessels, at least proximally of the hand. The intensified warm arterial blood circulation in the whole limb increases the temperature within the forearm what it otherwise would be.

Of interest is the fact that the results obtained in lower extremities, when feet were placed on the heated support were, in many respects, similar to those obtained in hands.

5.2. Occlusive test and systemic organismal reaction

In addition to a standard registration of vascular reactions in human hands as a response to arterial occlusion (commonly employed method here is laser Doppler flowmetry (LDF)), the temperature measured in contralateral hand became of interest in the middle of the 90's of the 20-th century [16]. During and after occlusion, thermal pattern of the free upper limb showed that the blood flow in it was responsive to external intervention. Unfortunately, the review of literary sources did no allow us to find new reports of the recited authors on this point. Thereof, it may follow that the work begun in [16] was not continued.

In our investigations, IR camera field of view involved either both hands (arms and forearms) or both hands and both feet of volunteers simultaneously. The latter differed the measurements from those described in [16] and provided to extract more information about systemic organismal reactivity. Separate results were presented by us in [17].

The temperature decrease of limbs distal parts free from the blood pressure cuff at the onset of occlusion was typical of the test (n>25 out of 40). Besides possible alternative explanations of this fact, it is reasonable to hypothesize [18] that cold receptors of the occluded hand transmit along the afferent channels the signal alerting the organism to exposure to cold, and the command "to constrict the vessels of all fingers", as efficient thermal exchangers with the environment, follows from the central nervous system (CNS) to avoid general over-cooling. One cannot exclude the role of adrenaline generated in response to external intervention, though it is noteworthy that we did not see any general organismal effect of blood efflux from skin: face and other parts of body did not react to the cuff-test. The expressed reaction was observed only in distal limbs parts. Note that a number of volunteers were examined from 3 to 5 times with intervals of several months to prove the reproducibility of their results.

Figure 5 experimentally confirms the assumption that sensitivity of cardiovascular system to local ischaemia may vary between subjects. Two typical examples given in figure 5 represent two kinds of human population regarding responsiveness to transient local ischaemia. It is seen that, in some individuals (figure 5a), the temperature of contralateral hand not subjected to ischaemia, as well as the temperature of feet, alter almost synchronously and quite similarly to that of compressed hand both during and after cuff inflation. The changes in the vacant upper extremity and in lower extremities may be induced by autonomous nervous reflexes stimulated by the compressed hand brief ischaemic state and post ischaemic vascular relaxation. The bilateral manner of organismal reactions (coincident vascular manifestations) to unilateral external impacts is based on the segmental arrangement of the nervous system and on humoral and hormonal systemic regulations. Figure 5a can be considered as an example of high sensitivity to remote ischemic preconditioning (RIPC) as was hypothesized in [17]. Figure 5b is a typical example demonstrating minor sensitivity to RIPC. Replications of the described IRT-based test in the same persons with time intervals of several months showed the results qualitative reproducibility.

In a number of cases (n>15), the temperature of limbs not subjected to occlusion began increase definitely earlier than cuff loosening showing that the organism has "come to its senses", possibly having "realized" that the alarm signal was false.

It is worth indicating that the curves analogous to those in figure 5 are highly informative [18]. Such parameters as time delay of hyperemia onset in free limbs, interval duration of "delayed reperfusion", character and ratio of the amplitudes of bilateral reaction effect in upper and lower limbs, and some other quantitative characteristics are interesting for physiology and are apt to be of diagnostic value for medicine. Studying this phenomenon at the quantitative level is a practically important and interesting scientific task which is necessary to solve.

5.3. Synchronous use of IRT and laser Doppler flowmetry

Attempts were made to observe the above-described phenomenon (figure 5) using simultaneously two methods of measurement – IRT and LDF. A standard LAKK-01 device with two optical fiber channels for visible (0.63 μm) and IR (0.81 μm) radiation was used for LDF. Optical fiber outputs were mounted in the thermo-insulating support, on which the testee's arms were put, so that the same fingers of the left and right arms were irradiated. To increase the stability (exclusion of accidental movements during continuous examination), these fingers were fixed with an adhesive plaster under which cotton wool was layered for air circulation (figure 6).

The signal, proportional to micro-circulatory perfusion in each measured finger, was entered in the computer through the COM-port in real time. Simultaneously, the continuous (non-stop) "thermofilm" – a succession of thermograms coming from the FPA-based IR camera – was recorded. After saving the "thermofilm", there was a possibility of making up temperature dependencies on time in any frame points. Such were usually four points chosen: two of arm fingers and two of feet's fingers.

In figure 7 there is a typical example to demonstrate a group of curves obtained synchronously using IRT and LDF methods in the volunteer (a 46-year-old woman). The site of curves that corresponds to the left upper limb subjected to three-minute occlusion is most clearly interpreted. In LDF characteristics, a sharp decrease of perfusion is connected with the blood flow limitation in great vessels, and the increase – with reactive hyperemia after the cuff deflation. The skin temperature during occlusion almost linearly decreases due to normal physical cooling of the arm (thermal exchange with cool air with the absence of thermal influxes from circulating blood); after occlusion there proceeds temperature restoration.

The effect of synchronous temperature fall is quite notable in all the rest limbs after the onset of occlusion, although it is expressed not so strongly in this individual as it is presented in figure 5a. The following fact is noteworthy. LDF method is known to be highly sensitive. At the same time, the perfusion level remains practically inactive to the processes causing temperature fall and its further increase in the right limb not subjected to occlusion. There is an impression that temperature changes in the right arm proceed independently from the circulation level and can be partially controlled, e. g., by perspiration mechanisms. The detailed study of the true origin of the observed manifestations is the subject of further scientific investigations.

6. Conclusion

Unfortunately, overwhelming majority of physicians are grateful for small favors and content themselves just with the most trivial and entry-level information taken from the total store of opportunities presented by IRT. This simplistic approach does without mathematical analysis of thermal patterns as well as without anything but the qualitative examination of thermograms supplemented with local temperatures measured in several points.

The future of medical thermal diagnostics may well lie with all-round use of interventional IRT methods based on real-time measurements of surface temperature changes and mathematical treatments of the obtained primary data. Unfortunately, a lot of attractive nonstandard approaches which the modern computerized FPA-based IRT makes possible to realize in medicine with high sensitivity and operating speed still remain without due attention. Among them are integrated, mathematics- and computer-assisted quantitative analysis of human surface thermal patterns, search for a correlation between the results of this analysis and homeostasis state with regard to different systems of the organism, precise study of objective laws responsible for quantitative changes of heat production at different diseases, as well as those at normal and abnormal states of the organism when arisen in response to external loads, etc. Consequently, medical diagnostics misses the exceptionally important information that might be provided by a unique channel delivering regular diagnostically significant data which concern the local and integral thermoregulatory characteristics of a human organism. The main objective for the immediate future is to correct cardinally this situation.

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REFERENCES

[1] Oosterlinck W., De Sy WA. “Avascular nephrotomy by means of thermography”. Eur. Urol., vol. 7, pp. 25–26, 1981.
[2] Sigal V. L., Shumakova T. E. “Thermophysical models for evaluation of the activity of the functioning kidney by means of infrared thermography”. J. Eng. Phys. Thermophys., vol. 69, pp. 496–501, 1996.
[3] Unger J. K., Lemke A.-J., Grosse-Siestrup C. “Thermography as potential real-time technique to assess changes in flow distribution in hemofiltration”. Kidney International, vol. 69, pp. 520–525, 2006.
[4] Vainer B. G. “FPA-based infrared thermography as applied to the study of cutaneous perspiration, and stimulated vascular response in humans”. Phys. Med. Biol., vol. 50, pp. R63–R94, 2005.
[5] Stoner H. B., Barker P., Riding G. S., Hazlehurst D. E., Taylor L., Marcuson R. W. “Relationships between skin temperature, and perfusion in the arm, and leg”. Clin. Physiol., vol. 11, pp. 27–40, 1991.
[6] Kaczmarek M., Nowakowski A. “Analysis of transient thermal processes for improved visualization of breast cancer using IR imaging”. In: 25-th Annual Internatianal Conference of the IEEE EMBS, pp. 1113–1116, 2003.
[7] Vainer B. G. “Treated skin temperature regularities revealed by IR thermography”. Proc. SPIE, vol. 4360, pp. 470–481, 2001.
[8] Savastano D. M., Gorbach A. M., Eden H. S., Brady S. M., Reynolds J. C., Yanovski J. A.. “Adiposity, and human regional body temperature”. Am. J. Clin. Nutr., vol. 90, pp. 1124–1131,2009.
[9] Cisneros A. B. and Goins B. L., editors. “Body Temperature Regulation”. New York: Nova Science Publishers, Inc.; 2009.
[10] Tamura T. “Investigation of the antiallergic activity of olopatadine on rhinitis induced by intranasal instillation of antigen in sensitized rats using thermography”. Asia Pac. Allergy, vol. 1, pp. 138–144, 2011.
[11] Carrive P., Churyukanov M., Le Bars D. “A reassessment of stress-induced "analgesia" in the rat using an unbiased method”. Pain, vol. 152, pp. 676–686, 2011.
[12] Besio W., Sharma V., Spaulding J. “The effects of concentric ring electrode electrical stimulation on rat skin”. Ann. Biomed. Eng. vol. 38, pp. 1111–1118, 2010.
[13] Vianna D.M., Allen C., Carrive P. “Cardiovascular and behavioral responses to conditioned fear after medullary raphe neuronal blockade”. Neuroscience, vol. 153, pp. 1344–1353, 2008.
[14] Song C., Appleyard V., Murray K., Frank T., Sibbett W., Cuschieri A., Thompson A. “Thermographic assessment of tumor growth in mouse xenografts”. Int. J. Cancer, vol. 121, pp. 1055–1058, 2007.
[15] Vainer B. G. *FPA-based infrared thermography in physiology: Investigation of vascular response, perspiration, and thermoregulation in humans*. Novosibirsk: Publishing House SB RAS, 2004. – 96 pp. (in Russian)
[16] Gulyaev Yu. V., Markov A. G., Koreneva L. G., Zakharov P. V. “Dynamical infrared thermography in humans”. IEEE Eng. Med. Biol., vol. Nov./Dec., pp. 766–771, 1995.

[17] Vainer B. G., Markel A. L. “Imaging and quantitative characterization of bilateral vasomotor reactions in humans using high-performance thermography”. In: QIRT10: Proceedings/July 27-30, 2010, Quebec City (Canada)/ X.P.V. Maldague, Ed. – Canada: Universite Laval, 2010, pp. 91–94.

[18] Vainer B. G. “Systemic response of the organism to local break of the blood flow: finding and quantitative characterization using infrared thermography”. In: High Tech, Basic and Applied Studies in Physiology and Medicine: Proc. Intern. Sci.-Pract. Conf., 23–26.11.2010, St.-Petersburg, Russia. Vol. 2/ A.P.Kudinov, B.V.Krilov, Editors. St.-Petersburg: Publishing House Politechn. Univ., 2010, pp. 165–167.

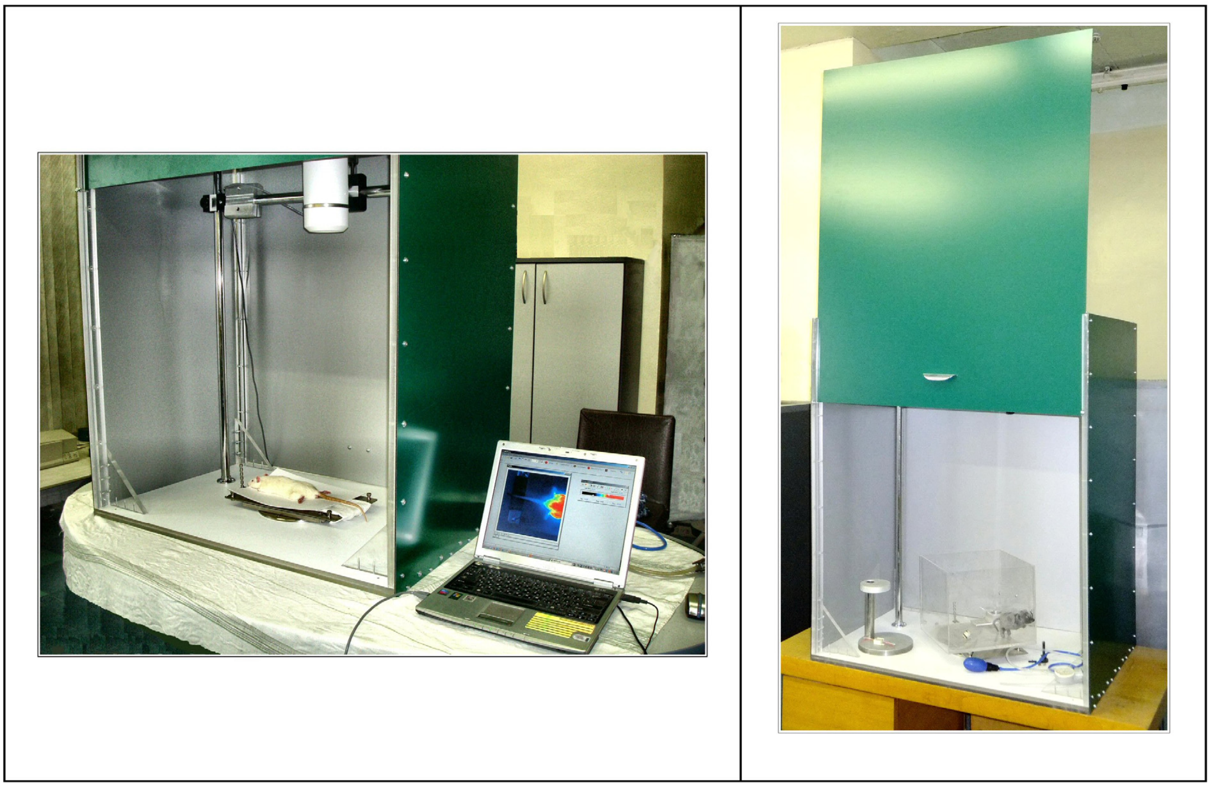

Fig. 1. *Special chamber for IRT-based investigation of small animals.*

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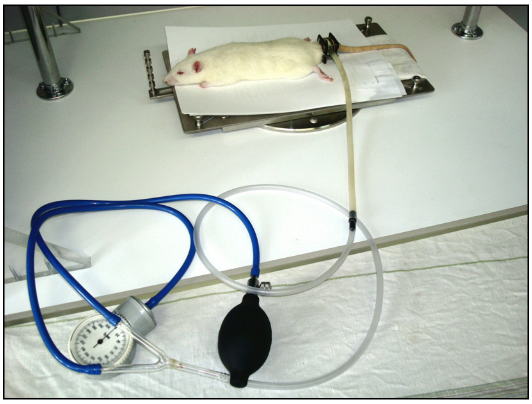

Fig. 2. *Narcotized albino rat under investigation in the chamber.*

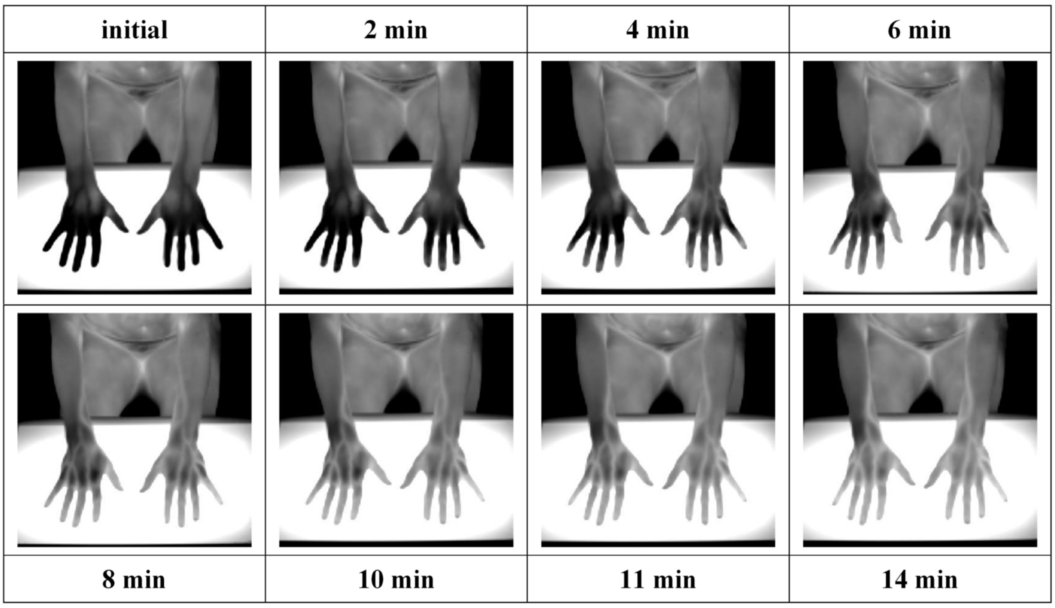

Fig. 3. *Thermograms of a woman's hands placed on the heated stone surface of "InTermo GreenStone" support. The time elapsed after the palms had been placed on the support is indicated near each thermogram.*

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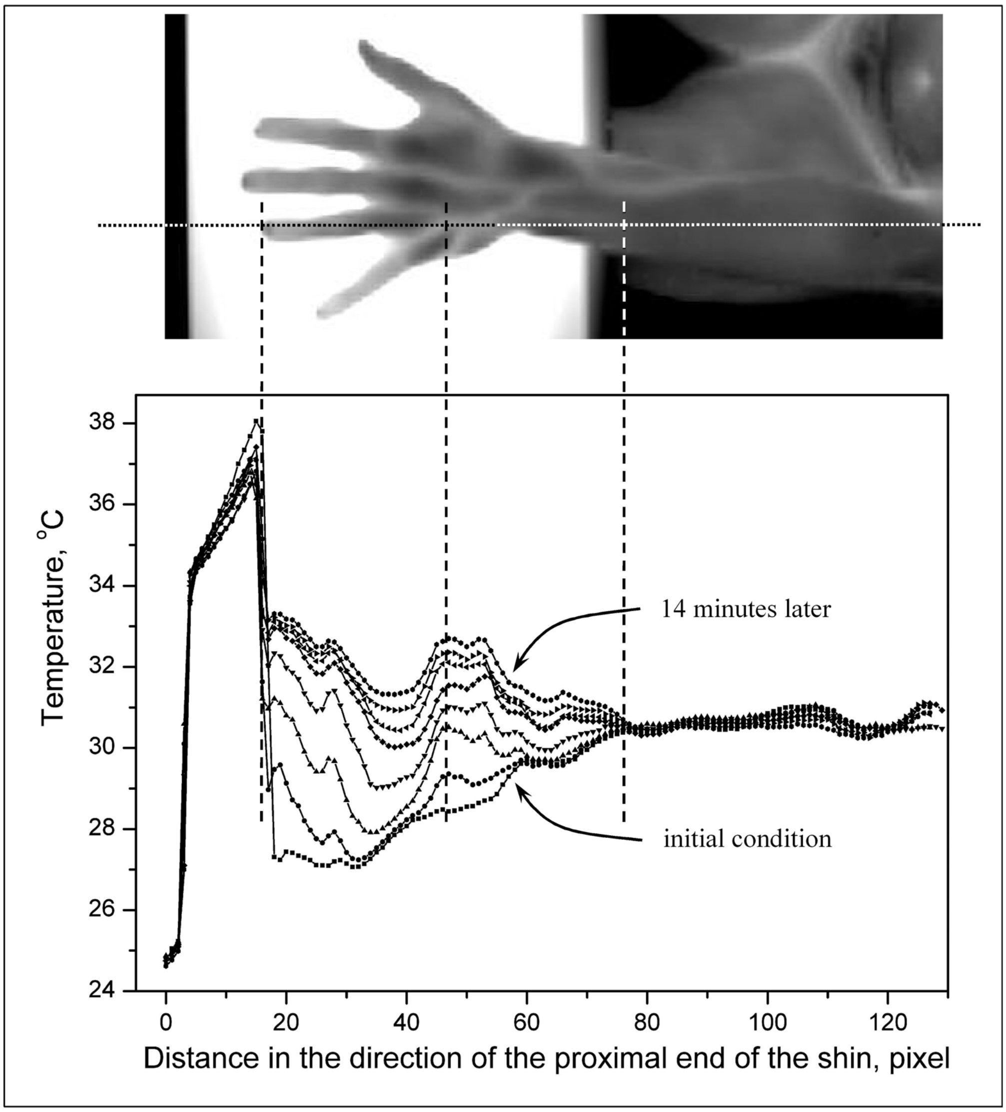

Fig. 4. *Assemblage of temperature profiles plotted along the horizontal dotted line shown on top and crossing in the same places (along the left hand) all the thermograms represented in figure 3.*

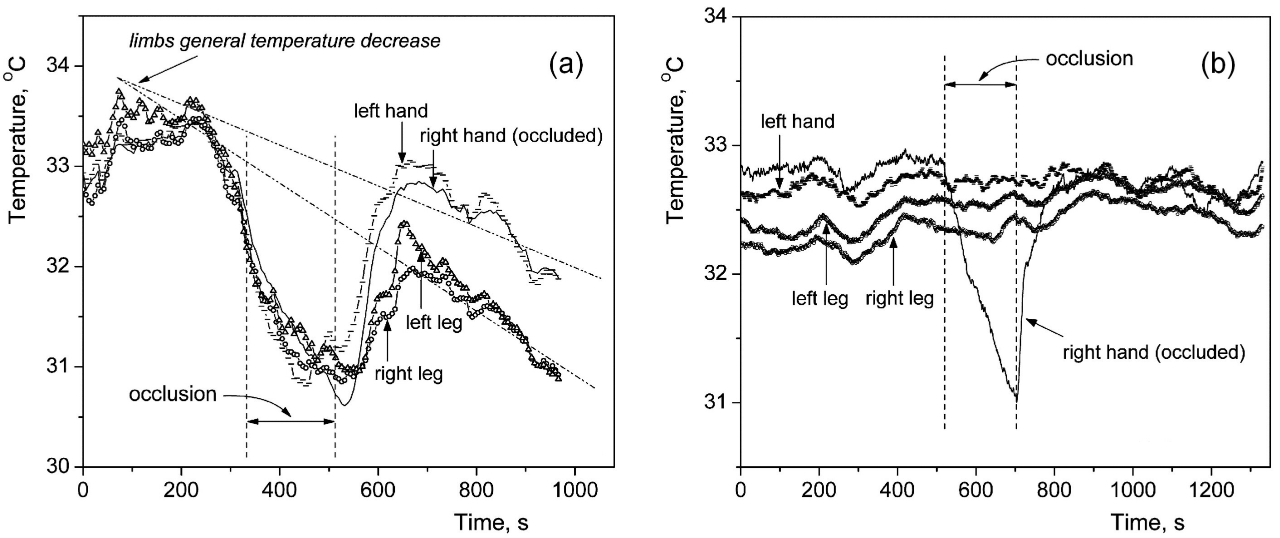

Fig. 5. *Time dependence of cutaneous temperature determined in fingers and toes of two individuals (a and b). These volunteers demonstrate different vascular reactivities during arterial occlusion and after deflation of cuff wrapped around their right upper arms.*

Fig.6. *Volunteer's hands made ready for IRT- and LDF-based synchronous investigation.*

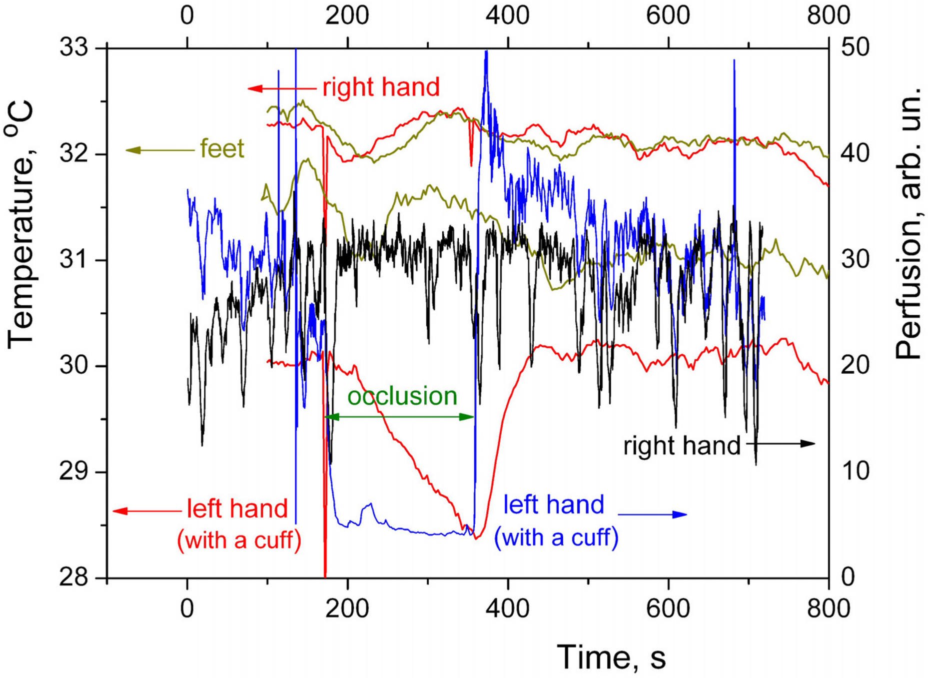

Fig.7. *Experimental results obtained using two measuring methods simultaneously: IRT and LDF.*