Imaging Photoplethysmography for Monitoring of Vascular Response to Local Heating*

Valery V. Zaytsev, Natalia P. Podolyan, Anzhelika V. Belaventseva, Maxim A. Volynsky, Anastasiia V. Sakovskaia, Roman V. Romashko, Oleg V. Mamontov, and Alexei A. Kamshilin

***Abstract*—In this study, the response of skin blood flow to local heating of subject's forearm was assessed by imaging photoplethysmography. The proposed system is featured by accurate control of the parameters affecting the endothelium during prolonged measurements. It is shown that this method reliably reflects the function of the mechanisms of regulation of peripheral vascular resistance, which is of great prognostic value for the detection of cardiovascular diseases.**

I. Introduction

Blood circulation in human vessels is provided by changes of the vessels resistivity due to regulations by the hormonal and autonomic nervous systems. The resistive function of the vessels is complemented by the interaction between the vascular endothelium and smooth muscle cells [1]. In fact, it regulates vascular tone through the release of vasoactive substances such as nitric oxide (NO), prostacyclin, endothelial hyperpolarizing factors, and vasoconstrictors. In any genesis of cardiovascular diseases, the processes of imbalance of the endothelial system associated with insufficient endothelium-dependent vasodilation in response to vasoactive stimuli due to insufficient NO production are revealed. Therefore, assessing of vasodilating properties caused by NO production can provide information about the integrity and function of the endothelium that has important prognostic value both for the detection of primary cardiovascular events and for subsequent determination of disease outcomes and treatment results. The aim of the present study is to demonstrate feasibility of using imaging photoplethysmography (iPPG) [2] to assess the reaction of the forearm skin microcirculation to moderate local heating.

II. Ethic Statement and Participants

This study was performed in accordance with ethical standards presented in the 2013 Declaration of Helsinki. Approval for the study was obtained through the Interdisciplinary Ethics Committee of the Pacific State Medical University, Vladivostok, Russia, decision No 10 of June 20, 2021. Fourteen volunteers, men 39-55 years old, participated in the study. Volunteers had no medical comorbidities (hypertension, cancer, severe systemic comorbidities, including cardiovascular, respiratory, hepatic and renal failure, skin diseases), drug dependence, or chronic alcohol consumption that could adversely affect the patient's competence in relation to the performance of the procedures and the result of the study. Immediately before the test, the subject underwent a clinical examination, anthropometry, biochemical blood test, echocardiography. The room where the studies were darkened, satisfactory sanitary and hygienic conditions were established, the temperature was stable (22-24 °C). The study was carried out after a fifteen-minutes rest, continuously for 65 minutes in a sitting position, leaning back on chair back, relaxed posture, legs uncrossed, free breathing. Throughout the experiment, an electrocardiogram (ECG) was continuously recorded for each subject. Local heating was applied to an area of the middle third of the subject's forearm as shown in Fig. 1A. The first 5 minutes, the basal recording was carried out. Then, the glass plate of the heating element was heated up to 40-41°C in two minutes, and this temperature was maintained during 20 minutes. At such heating rate, the subject did not experience any discomfort, and a slight warmth was rarely felt at the site of the heating element. Thereafter, the heating was turned off, and the skin temperature relaxed to its original value. The video of the heating region was continuously recorded in all stages. Typical examples of the dynamics of perfusion changes due to subjects' forearm local heating are shown in Fig. 1B.

III. Measuring System

The method is based on illumination of the skin with incoherent green light of invariable intensity, subsequent intensity modulation of a reflected light due to its interaction with red blood cells, and registration of a sequence of images of the area under study. The experimental setup is presented in Fig. 1A. An illuminator is implemented as a set of four rings of 250 light-emitting diodes (LED) operating at the wavelength of 530 ± 25 nm. The incoherent light is linearly polarized with a film polarizer attached in the front of LEDs. Another film polarizer is attached to the camera lens so that the transmission axis is oriented orthogonally to the polarization vector of the illuminating light. Polarization filtering is used to reduce specular reflection and the effect of motion artifacts on the

*Research is supported by the Russian Science Foundation under Grant No. 21-15-00265,

All the authors are with the Institute of Automation and Control Processes of the Far Eastern Branch of the Russian Academy of Sciences, Vladivostok, Russia (e-mail: alexei.kamshilin@yandex.ru; ange202@mail.ru; podolian@iacp.dvo.ru; romashko@iacp.dvo.ru).

V. V. Zaytsev and O. V. Mamontov are also with the Almazov National Medical Research Centre, Saint Petersburg, Russia (e-mail: zaytsevphoto@gmail.com; mamontoffoleg@gmail.com). O. V. Mamontov is also with Department of Departmental Therapy, Pavlov First Saint Petersburg State Medical University, Saint Petersburg, Russia

M. A. Volynsky is also with the School of Physics and Engineering, ITMO University, Saint Petersburg, Russia (e-mail: maxim.volynsky@gmail.com).

A. V. Sakovskaia is also with the Pacific State Medical University, Vladivostok, Russia (e-mail: sakovska86@mail.ru).

978-1-6654-8512-8/22/$31.00 ©2022 IEEE

recorded signals. Digital video camera, assembled together with an LED illuminator, provides video recording of the heating area at the rate of 36 frames per second and a resolution of 340 x 286 pixels. Video data are transferred to a personal computer and recorded on a solid-state hard drive. The video camera is equipped with objective, which ensures the formation of a sharp image of the object on the video camera matrix at a distance of ~20 cm from the examined skin area. The digital electrocardiograph records the electrocardiogram of the subject in two leads with a frequency of 1 kHz. Additionally, the electrocardiograph records a signal from the video camera containing information about the time of registration of each video frame. Thus, the recorded video frames and ECG are synchronized in time. The electrocardiograph transmits all the data to a personal computer via the USB 2.0 interface. The block of controlled temperature exposure is a glass plate with dimensions 70 × 20 × 2 mm^3 in a plastic frame. A resistive ITO (Indium-tin-oxide) coating with a resistance of 20 Ohm is sprayed onto the plate, transparent to green light and providing local heating of the subject's skin area. To ensure thermal conductivity between the glass plate and the skin, liquid petrolatum is applied. Voltage control on the ITO layer is carried out using a custom-made control unit. Temperature control is carried out using a K-type thermocouple (chromel-alumel) located between the glass with a resistive layer and the subject's skin. Additionally, for the convenience of the operator and the safety of the subject, the data on the recorded temperature and the operating modes of the heating element are displayed on the liquid crystal display on the control unit. A personal computer is used to control the data recording unit and the controlled temperature exposure unit. All data are recorded on a hard disk, and then subjected to offline processing using specially developed software on the MATLAB platform.

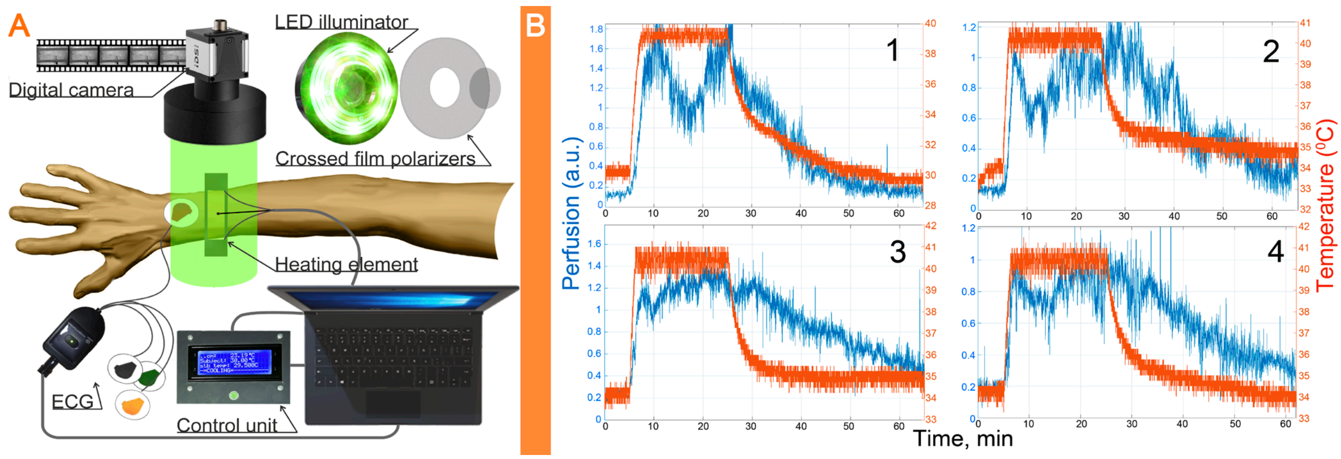

Figure 1. Schematic of measuring system and an experimental result. A - Layout of the measuring system consisted of three computer-controlled modules (iPPG, heating, and ECG), B - Dynamics of perfusion changes due to subjects' forearm local heating. Blue curves show changes in the perfusion index, whereas red curves show changes in local skin temperature.

IV. Results

Variable reactions in response to skin heating, which apparently reflects differences in the regulation of local blood flow, were observed. Figure 1B shows typical perfusion index dynamics for four representative subjects. As seen, the perfusion response to the local heating is biphasic. First increase in perfusion occurs in a few minutes, followed by a brief nadir, and then a secondary prolonged increase. This reaction is similar to that observed by the popular laser Doppler flowmetry technique [3]. The first phase is due to the axon reflex [4], which leads to a strong increase in perfusion for all subjects. It was observed that the increase in perfusion linearly decreases with the basal skin temperature, and increases with the temperature difference between the baseline and heating stage. The second phase is associated with activation of the endothelial component of NO vasodilation and an increase in blood flow, and leads to the following increase in perfusion and the appearance of a second maximum. In some cases, the perfusion increase in the second phase is continuing even after switching off the heating in spite of decreasing skin temperature.

V. Conclusion

The proposed multimodal system based on the iPPG method is suitable for reliable studying the mechanisms of regulation of peripheral vascular resistance in response to local heating, which opens up wide opportunities for its use to study various physiological disorders caused by endothelial dysfunction.

References

[1] M. Gimbrone and G. Garcia-Cardena, "Endothelial cell dysfunction and the pathobiology of atherosclerosis," *Circ. Res.,* vol. 118, no. 4, pp. 620–636, 2016.

[2] M. A.Volynsky, N. B. Margaryants, O. V. Mamontov, and A. A. Kamshilin, "Contactless monitoring of microcirculation reaction on local temperature changes," *Appl. Sci.,* vol. 9, no. 22, p. 49472019, 2019.

[3] J.-L. Cracowski, C. T. Minson, M. Salvat-Melis, and J. R. Halliwill, "Methodological issues in the assessment of skin microvascular endothelial function in humans," *Trends Pharmacol. Sci.*, vol. 27, no. 9, pp. 503–508, 2006.

[4] C. T. Minson, L. T. Berry, and M. J. Joyner, "Nitric oxide and neurally mediated regulation of skin blood flow during local heating," *J. Appl. Physiol.*, vol. 91, no. 4, pp. 1619–1626, 2001.