Possibilities of Recording Peripheral Blood Flow and Oxidative Metabolism of Biological Tissues under the Orthostatic Effects during Cosmonaut Training

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2025 Systems and Technologies of the Digital HealthCare (STDH) | 979-8-3315-9739-9/25/$31.00 ©2025 IEEE | DOI: 10.1109/STDH66836.2025.11227517

***Abstract* — The work is devoted to the possibilities of a distributed system of portable analyzers in recording peripheral blood flow and oxidative metabolism of cosmonauts' biological tissues during a passive orthostatic test. The possibility of continuous recording of the microcirculatory-tissue systems parameters of cosmonauts' organisms simultaneously at 4 points (symmetrical areas of the basins of the supraorbital arteries and the upper thirds of the inner surfaces of the shins) was demonstrated. All subjects tolerated the load well and did not experience discomfort. The detected changes in skin perfusion and the normalized amplitude of NADH fluorescence reflect the work of adaptive mechanisms for maintaining homeostasis in response to blood redistribution. After the end of the test, when returning to the horizontal position, there is a general increase in blood microcirculation both in the area of the forehead and shins, that characterizes the recovery of the body. The results obtained show the need for an individual approach to assessing the response of microcirculatory-tissue systems to orthostatic effects as an indicator of the functional reserves of organisms.**

Keywords* — *wearable optical analyzer, microcirculatory-tissue system, peripheral blood flow, oxidative metabolism, orthostatic effects, cosmonaut training, simulated space flight factors

I. Introduction

Space Flight (SF) factors cause shifts in the human body's hemodynamics, which can negatively affect not only cosmonauts' health and productivity during SF, but also have long-term negative impacts after SF [1]. The study of physiological reactions of various organs and body systems to SF factors, preparing for these effects, and developing methods to prevent negative consequences remain important, especially with regard to changes in the cardiovascular system [2,3].

The Microcirculatory-Tissue System (MTS), which includes the microvascular section of the cardiovascular system, cells of biological tissue and lymph vessels, is the final link of the cardiovascular system, where transcapillary exchange of oxygen and nutrientsand the utilization of cell waste products occur, and the processes of tissue metabolism begin [4]. A distinctive feature of MTS is its' functional temporal and spatial heterogeneity. The functioning of regulatory mechanisms leads to the fact that MTS are firstly involved in pathological and adaptive changes in the complex of protective mechanisms for restoring self-regulation of individual organs and the body as a whole. Due to the simplicity of application and high information content of modern MTS research methods and the development of portable devices that implement wireless data transmission and are based on a multimodal approach combining various methods of optical noninvasive diagnostics [5], it has become possible to assess the condition of a person's MTS in extreme conditions, in particular, when exposed to certain adverse SF factors, a detailed study of which is available when their modeling in ground conditions.

In conditions of Earth's gravity, various techniques are used to simulate the individual effects of weightlessness. These include mathematical [6], experimental using "dry" immersion [7] and antiorthostatic hypokinesia [8], as well as parabolic flights [9]. This work is dedicated to the study of the redistribution of blood volume caused by the passive Orthostatic Test (OT), which represents changes in a person's position in space. OT involves changing the position of one's body or part of it (such as an arm or leg) in space. Active OT involve independent change of body position by means of muscular effort, for example by getting up. Equipment such as a tilt table is also used for passive OT. OT has become widely used not only in clinical settings for diagnosing neurological disorders, but also in space medicine for training cosmonauts. The change in position of the body triggers a series of adaptive

Y.L., K.K., E.Zh. and Vy.Y. thank the Russian Science Foundation for supporting the research (grant number 25-25-00546).

responses from the body aimed at maintaining homeostasis. First of all, local tone-forming mechanisms, including microvascular regulation and baroreflex, work to prevent loss of consciousness when the body's position changes.

The scientific literature presents studies on the assessment of microcirculatory changes during OT, but most of them were performed on conditionally healthy volunteers [10, 11] or patients with neurological diseases [12]. However, OT is essential for the annual Russian cosmonauts clinical examination. Series of daily OT is also used before SF to improve the adaptation of cosmonauts to the redistribution of blood in zero gravity. Given the high diagnostic potential of MTS parameters, the assessment of peripheral blood flow and oxidative metabolism during orthostatic effects on the cosmonaut's body will allow us to form a personalized approach to the training process by assessing individual functional reserves when exposed to certain adverse SF factors.

In this regard, the aim of the research was to show the capabilities of a distributed system of portable laser analyzers for recording of microcirculatory-tissue systems parameters of cosmonauts body during their orthostatic stability training.

II. Methods And Materials

A. Diagnostic methods

Optical noninvasive diagnostic methods are actively used to evaluate MTS parameters, which make it possible to safely obtain information about blood flow and metabolism in real time. Such methods include Laser Doppler Flowmetry (LDF) and Fluorescence Spectroscopy (FS).

The LDF method is based on probing tissues with laser radiation in the near infrared range, followed by analysis of the light reflected and scattered back from moving red blood cells. The recorded parameter, an index of blood microcirculation, reflects the volumetric velocity of capillary blood flow and depends on the rate and concentration of red blood cells in the diagnosed volume. LDF also makes it possible to evaluate the functioning of peripheral blood flow regulation mechanisms [13]. Based on the parameters of the microcirculatory bed recorded by the LDF method, it is possible to assess the reserve capabilities and adaptive features of the body, as well as identify violations of the functional state of blood microcirculation in the early stages of development.

Spectroscopic methods such as FS are used to evaluate metabolic processes. The FS method is based on the excitation and registration of the fluorescence of endogenous fluorophores, for example NADH, involved in the Krebs cycle, a change in the amount of which indicates the intensification or slowing of metabolism [14].

B. Analyzers for Recording MTS Parameters

Thanks to the advent of vertically emitting lasers, a portable modification of the microcirculatory-tissue system analyzers “LAZMA PF” has been developed (SPE LAZMA Ltd., Russia), which implements a multimodal approach – the LDF and FS channels are presented in one device, which makes it possible to obtain comprehensive diagnostic information on the effectiveness and consistency of the nutrient delivery system (cardiovascular system) and their utilization through metabolism [5]. The analyzers also have channels for recording the temperature and movements of the subject, while the data is transmitted to a personal computer via a Bluetooth channel. The data obtained show good reproducibility indicators [15], which creates a wide range of possibilities for their use.

Thus, the devices have already shown their diagnostic potential in endocrinology to detect peripheral blood flow disorders in patients with type 2 diabetes mellitus [16], in cardiology to detect functional disorders of vasomotor activity of resistive skin microvessels in newly diagnosed hypertension [17], in the field of rehabilitation to assess disorders caused by COVID-19 [18] and to evaluate the effectiveness of various breathing exercises [19], as well as in the field of somnology [20].

Compact size of the analyzers, their weight characteristics, the use of optical non-invasive diagnostic methods, ease of use and wireless data transmission with the ability to combine several analyzers into a common distributed system for simultaneous remote registration of MTS parameters in various areas of the body opens up great prospects for the use of “LAZMA PF” analyzers not only in outpatient and clinical medicine on Earth, but also in space medicine.

For example, work [21] shows the use of devices for recording MTS parameters during a real SF. Analyzers are also actively used in simulations of individual SF factors influence on an cosmonaut's body, for example, to study the functional state of the microcirculatory bed of the skin under conditions of “dry” immersion [7] and 21-day antiorthostatic hypokinesia [22].

C. Research Protocol

Experimental studies were carried out in the Yu.A. Gagarin Research and Test Cosmonaut Training Center (GCTC) using an orthostatic table with an electric drive. The study protocol included recording background data in a horizontal position before and after the OT. The OT included successive changes in the position of the subject from horizontal to anti–orthostatic (15 and 30 degrees below the horizontal – the head is below the level of the heart), then orthostatic (70 degrees above the horizontal – the head is above the level of the heart) and again horizontal positions. A schematic representation of the OT with the duration of the stages is shown in Fig. 1.

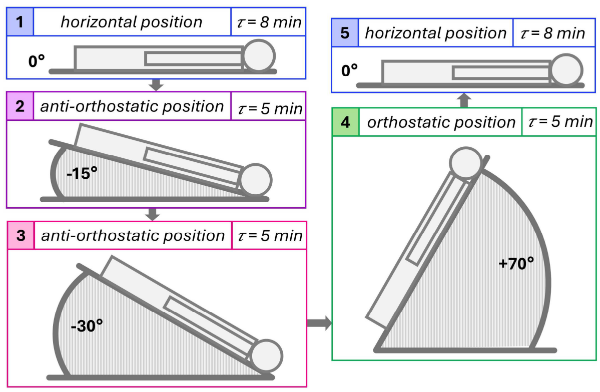

Fig. 1. Research protocol: schematic representation of the subject's body position during the OT

MTS parameters were recorded continuously at all stages. A distributed system of 4 “LAZMA PF” analyzers was mounted symmetrically on the right and left sides in the basins of the supraorbital arteries and the inner surface of the upper third of the shins. The studies were conducted no earlier than 2 hours after eating and exercising in the laboratory conditions in the morning.

When evaluating the data obtained, such parameters as the average perfusion (I_m, PU) for stages 1, 2, 3, and 5, as well as for the first and last 5 min of stage 4 and the normalized to the back-reflected probing radiation amplitude of NADH fluorescence (A_{NADH}, AU) were calculated.

D. Sample of Subjects

The sample included 19 cosmonauts of the Roscosmos, whose average age was 41±7 years. All the subjects were healthy, had no bad habits, and did not take any medications on a regular basis.

Before conducting the study, all subjects filled out a voluntary informed consent to participate in the study and process personal data.

III. Experimental Results And Discussion

All 19 subjects underwent OT well. No manifestations of orthostatic instability (discomfort, nausea, dizziness, etc.) were recorded.

Fig. 2 shows the dynamics of blood microcirculation during OT. In the area of the forehead skin, there is an increase in blood perfusion during anti-orthostatic positions (-15 and -30) compared with the horizontal position before OT. These changes are a natural consequence of the redistribution of blood to the head area. It is worth noting that at the -30 stage, the median is at the I_m level of the horizontal position, which indicates the activation of adaptive mechanisms, however, a large variance of data in the upper part of the box indicates the existence of an individual reaction time and/or threshold of changes in the body necessary to activate compensatory mechanisms. When moving to the orthostasis position (+70), we observe a stable level of perfusion, which may be a reflection of the reaction rate of microhemodynamic parameters for maintaining brain homeostasis.

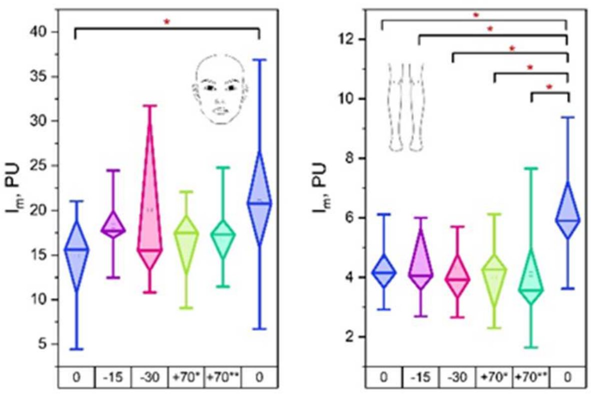

Fig. 2. The index of blood microcirculation in the area of the skin of the forehead and shins at different stages of OT: 0 – in a horizontal position before OT: -15 – when tilted 15 degrees below the horizon (head below leg-30 – at an inclination of 30 degrees below the horizon (head below leg); +70* – from 1 to 5 minutes of orthostasis (head above legs); +70** – from 16 to 20 minutes of orthostasis (head above legs); 0 – in a horizontal position after OT.

* – statistically significant differences were confirmed by the Anova test ($p<0.05$)

No significant changes were found in the shin area during the OT, however, when returning to the horizontal position, there is an increase in the perfusion level above the initial one. Similar increase of I_m in horizontal position after OT compared to the stage before it is observed in the skin of the forehead. These changes may indicate compensatory mechanisms of blood flow regulation after an irritating effect. In [23], the authors explain a similar increase in perfusion during the transition from a vertical to a horizontal position by vasodilation, provided by the work of baroreceptors.

Fig. 3 shows diagrams of the normalized amplitude of NADH fluorescence. No statistically significant differences were found between the study stages, however, there is an increase in the data dispersion in the position of antiorthostasis -30 and orthostasis +70, which persists after the end of OT. In the shins during the last 5 minutes of orthostasis, there is a tendency to decrease A_{NADH}, which may indicate an increase in the intensity of metabolic processes due to prolonged irritant effects.

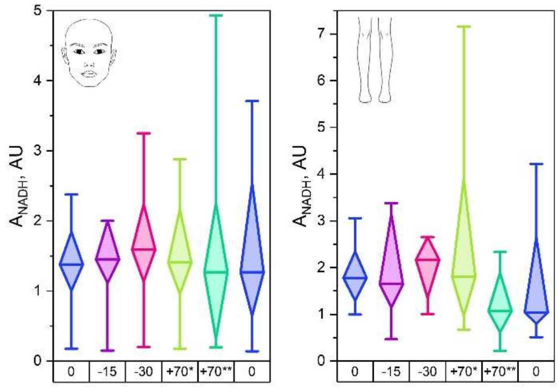

Fig. 3. Normalized amplitude of NADH fluorescence in the skin of the forehead and shins at different successive stages of OT: -15 – when tilted 15 degrees below the horizon (head below leg); -30 – at an inclination of 30 degrees below the horizon (head below leg); +70* – from 1 to 5 minutes of orthostasis (head above legs); +70** – from 16 to 20 minutes of orthostasis (head above legs); 0 – in a horizontal position after OT.

In studies performed with the participation of untrained volunteers, significant differences in the microcirculatory parameters of the extremities were observed between each stage of the study [11], reflecting the redistribution of fluid in the body with a change in body position. The absence of significant changes in the I_m level in subjects in our study during OT, as well as general significant changes in the normalized amplitude of NADH fluorescence, may be a consequence of the high level of physical preparation of cosmonauts and large functional reserves of the body, which means that when the body's position in space changes, the work of tone-forming mechanisms quickly adjusts, which is sufficient to maintain the optimal level of perfusion for stable provision of metabolic needs of biological tissues.

In the group of conditionally healthy volunteers, as a rule, there is a similarity of reactions to functional tests. Similarly, in our study, all the subjects underwent the OT well. However, a promising direction is to evaluate the individual response of each subject, which will make it possible to assess the individual characteristics of the organism and can serve as a diagnostic criterion for borderline states and an indicator of adaptation failure, since each organism has different needs to maintain homeostasis.

IV. Conclusion

Thus, in this work, the possibilities of recording peripheral blood flow and oxidative metabolism parameters of the biological tissues of the comonaut's body under the influence of orthostatic effects during the training process are demonstrated.

This direction can become the basis for a personalized approach to the training process and will allow both improving it and evaluating the effectiveness of the cosmonaut training process, as well as predicting the adaptation of cosmonauts to SF based on the diagnosis of hidden functional reserves of the body.

Acknowledgment

The researchers would like to express their gratitude towards the cosmonauts who took part in the study.

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