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Analysis of the reaction of cosmonaut's body microcirculatory-tissue systems to postural effects at tilt-table

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ABSTRACT

This study evaluates the peripheral microcirculatory–tissue system (MTS) response of professional cosmonauts to specific postural test, simulating the haemodynamic effects of microgravity. Nineteen Roscosmos cosmonauts underwent a passive tilt-table protocol (−15°, −30°, +70°) at the Yuri A. Gagarin Cosmonaut Training Center while wearing a distributed system of portable multimodal optical analyzers combining laser Doppler flowmetry and fluorescence spectroscopy. Continuous monitoring before, during, and after tilt phases captured changes in average perfusion, oscillatory amplitudes (endothelial, neurogenic, myogenic, respiratory, cardiac), nutritive and shunt blood flow, and normalized NADH fluorescence. Results demonstrate individual adaptation mechanisms: trained cosmonauts maintained metabolic stability (unchanged NADH fluorescence) despite marked microcirculatory rearrangements, with region-specific shifts in perfusion and regulatory oscillations. Cluster analysis of relative parameter changes identified distinct response phenotypes, underscoring intra-and inter-subject variability in microvascular regulation. These findings confirm the high sensitivity of wearable multimodal diagnostics for detecting MTS shifts under orthostatic load and support their use as markers of training efficacy. Personalized information of microhaemodynamic reserves may enhance cosmonaut selection, optimize pre-flight conditioning, and inform countermeasure development for long-duration space missions.

1. Introduction

Space flight (SF) has a complex effect on the human body, causing changes that can adversely affect not only the health and performance of cosmonauts during SF, but also have long-term negative consequences after its completion (Shen and Frishman, 2019). Space medicine is primarily focused not on treating cosmonauts in a narrow sense, but on preventing the development of adverse health changes, maintaining functional status, and working capacity during stages of preparation for SF and during it, as well as during rehabilitation after its completion (Hodkinson et al., 2017).

Space medicine is closely connected with terrestrial medicine. Advanced developments that are introduced into clinical practice on Earth find application in space research. At the same time, diagnostic methods and tools developed for the needs of cosmonautics are gradually being introduced into terrestrial medicine, enhancing its capabilities (Ruyters and Stang, 2016). One of the main trends in the development of modern medicine is personalization. This involves creating strategies for diagnosing, treating, and rehabilitating patients based on their individual characteristics (Pavez Loriè et al., 2021). At the same time, technological advancements are leading to the development of more compact diagnostic devices, which are already commonly used in clinical settings on Earth (Zhou et al., 2025) and are expected to become essential in space medicine.

These new technologies are particularly relevant in the context of preparing for ultra-long interplanetary missions. The autonomy of medical care and the length of SF will be crucial to the safety of cosmonauts. For example, in microgravity conditions, which are different from those on Earth, the mechanisms that the human body's sensory systems that ensure posture and control movement are disrupted (Mergner and Rosemeier, 1998). One of the most significant aspects of long-term spaceflight is the impact it has on the cardiovascular system. This system is particularly vulnerable to the effects of weightlessness, which can lead to various changes (Gazenko et al., 1988; Baevsky et al.,

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2014). The study (Gallo, Ridolfi and Scarsoglio, 2020) found that prolonged exposure to zero gravity causes deconditioning of cardiovascular system in humans, and the physical endurance of cosmonauts after long SF is similar to that of untrained people with a sedentary lifestyle. At the same time, there are changes at the level of blood microcirculation, which manifest as a deterioration in perfusion and supply of nutrients to cells. These findings suggest that spaceflight conditions are similar to those of accelerated aging (Vernikos and Schneider, 2010).

The microcirculatory-tissue system (MTS) is the final link in the circulatory system. It includes the microvascular bed of the CVS, cells of biological tissues and lymph microvessels. In this system, oxygen and nutrients are exchanged across capillaries in this system, cell waste products are removed and tissue metabolism takes place (Krupatkin and Sidorov, 2016). A distinctive feature of MTS is their functional temporal and spatial heterogeneity. The functioning of regulatory mechanisms leads to the fact that MTS are the first to be involved in pathological and adaptive changes in the complex of protective and adaptive 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 research methods for MTS, and the development of portable devices that implement wireless data transmission and are based on multimodal approaches combining various methods of optical non-invasive diagnostics (Dunaev, 2023), it has become possible to assess the condition of human MTS under extreme conditions, particularly under the adverse effects of specific SF factors, which can be studied in detail when they are simulated in ground conditions.

Cosmonauts training for space flights has more than sixty years of history. During this time, as well as currently, various methods of modeling individual SF factors have been actively developed and applied in terrestrial conditions, which include both mathematical (Mohammadyari, Gadda and Taibi, 2021), and experimental, performed using "dry" immersion (Navasiolava, et al., 2011), anti-orthostatic hypokinesia (Watenpaugh, 2016) or during parabolic flights (Ansari et al., 2003).

This work is devoted to the study of the effect on peripheral blood flow and oxidative metabolism of biological tissues of the redistribution of blood volume that occurs during SF. In terrestrial conditions, orthostatic (stand) test (OT) and antiorthostaric (head-down) test are used to simulate hemodynamic changes characteristic of SF. OT is a change in the position of a person's body (or a part of it, for example, an upper or lower limb), which leads to a pressure gradient due to the redistribution of fluid, including blood, from the upper to the lower part of the body (Stewart, 2002). Active actions involve independent change of body position by means of muscular efforts, for example, getting up. In passive orthostatic tests, additional equipment is used, such as a tilt-table, with which body position changes are performed.

A change in body position can be considered a physical stress factor that requires the complete mobilization of reflexes. This triggers a series of adaptive responses from the body, aimed at maintaining homeostasis and regulating cardiovascular function (Stewart, 2012). In the first few seconds after a change in body position, the body adjusts mainly through the sympathetic division of the autonomic nervous system. This division maintains blood pressure by activating mechanisms that regulate microvascular tone and the baroreflex. The baroreflex prevents loss of consciousness by regulating heart rate, constricting arteries, and narrowing veins (La Rovere, Pinna and Raczak, 2008.). Thus, the authors of the article Breit et al. (1993) associate the changes in microvascular blood flow in response to the tilt-test with baroreflex. However, the kinetics of the myogenic response (Loutzenhiser, Bidani and Chilton, 2002) and dilation due to blood flow (Shipley, Kim and Muller-Delp, 2005), are comparable in reaction time (Stewart, 2012). Thus, the normal hemodynamic response to orthostatic stress is conditioned by and largely depends on the sequence of many interrelated mechanisms, including several redundant feedback loops that counteract the underperformance of any of the involved subsystems (Gronwald, Schaffarczyk and Hoos, 2024).

OT has become widespread not only in clinical practice as a functional test, but also in the field of space medicine during the selection and cosmonauts training for SF. There are studies in the literature on the assessment of microcirculatory changes in OT, but most of them were performed on conditionally healthy volunteers (Fedorovich et al., 2021; Tikhonova et al., 2021) or patients with neurological diseases (Coupé et al., 2009).

To study the autonomic regulation and functional state of the cosmonauts' CVS during selection, annual examination and clinical and physiological examination before and after SF, a passive postural test (PPT) is performed on the tilttable. The implementation of the PPT consists in sequentially changing the orthostatic and anti-orthostatic positions. In addition, a series of daily tilt-table hemodynamic workouts is also used at the final stage of SF preparation for a more gentle adaptation of the cardiovascular system to weightlessness. Orthostatic training can reduce the orthostatic intolerance of cosmonauts after the end of the SF (Jordan, Limper and Tank, 2022). Given the high diagnostic potential of the MTS parameters, the assessment of peripheral blood flow and oxidative metabolism during orthostatic effects on the cosmonaut's body can become a potential source of information about the individual reactions of the cardiovascular system and the degree of its fitness. In addition, the assessment of individual functional reserves when exposed to certain adverse factors of space flight will allow us to form a personalized approach to the process of preparing for the SF.

In this regard, the aim of the study was to study the reaction of the microcirculatory-tissue systems of the cosmonaut's body to postural stress, simulating the hemodynamic effects of weightlessness.

2. Materials and methods

2.1. 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 the use of laser radiation in the near-infrared range to probe tissues, followed by analyzing the light reflected from moving red blood cells. This method allows us to measure a parameter called the index of blood microcirculation, which depends on the rate and concentration of red blood cells in the diagnosed volume. LDF also makes it possible to evaluate the functioning of various peripheral blood flow regulation mechanisms. These include endothelial (0.0095–0.02 Hz), neurogenic (0.02–0.06 Hz), myogenic (0.06–0.15 Hz), respiratory (0.15–0.4 Hz), and cardiac (0.6–1.6 Hz) rhythms (Stefanovska, Bracic and Kvernmo, 1999). Based on the parameters of the microcirculatory bed, recorded using the LDF method, it is possible to assess the body's reserve capabilities and adaptive features, as well as identify abnormalities in the functional state of blood microcirculation at the early stages of development.

Spectroscopic methods such as fluorescence spectroscopy 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 and the respiratory chain of electron transport, a change in the concentration of which indicates the intensification or slowing of metabolism (Dunaev et al., 2015).

2.2. The used equipment

The portable microcirculatory blood flow analyzer “LAZMA PF”, (LAZMA Ltd., Moscow, Russia) implements a multimodal approach. It combines the LDF and FS (fluorescence spectroscopy) channels in one device. This allows for comprehensive diagnostic information about the effectiveness and consistency of the cardiovascular system's nutrient delivery and their utilization during metabolism to be obtained. The analyzers also include channels for recording temperature and artifacts from the subject's movements. The mass and size characteristics of these devices, along with wireless data transmission via Bluetooth, make it possible to combine several analyzers into a distributed system. This opens up great prospects for using “LAZMA PF” analyzers in both outpatient and clinical medicine on Earth and in space medicine (Dunaev, 2023).

Thus, the devices have already demonstrated good reproducibility of the recorded data (Loktionova et al., 2025) and their diagnostic potential in endocrinology (Zherebtsov et al., 2023), cardiology (Fedorovich et al., 2022), rehabilitation (Zharkikh et al., 2023), somnology (Loktionova et al., 2024) and extreme physiology (Frolov et al., 2025). For example, the work (Dunaev et al., 2024) shows the use of devices for recording MTS parameters during a real space flight. Analyzers are also actively used in modeling the effects of individual SF factors on the cosmonaut's body, for example, to study the functional state of the microcirculatory bed of the skin under conditions of "dry" immersion (Pashkova, Popova and Fedorovich, 2023) and 21-day antiorthostatic hypokinesia (Pashkova et al., 2025).

2.3. Research protocol

The research was conducted at the Yu. A. Gagarin Research and Test Cosmonaut Training Center, using tilt table with a medical monitoring system for functional diagnostics. The protocol included recording baseline data in a horizontal position, both before and after the PPT. The PPT included consecutively changes in the position of the subject from a horizontal position to an anti–orthostatic or anti–orthostasis (15° and 30° below the horizontal - the head is below the level of the heart), then to an orthostatic or orthostasis (70° above the horizontal - the head is above the level of the heart) and again to a horizontal position. A schematic representation of the protocol is shown in Fig. 1, which includes the duration of each stage.

MTS parameters were continuously recorded at all stages. A distributed system of four "LAZMA PF" analyzers were installed symmetrically on the right and left sides in the basins of the supraorbital arteries and on the inner surface of the upper third of the legs. The studies were conducted at least 2 h after meals and exercise in the laboratory in the morning.

When evaluating the data obtained, parameters such as average perfusion (I_m, PU – perfusion units) for stages 1, 2, 3, and 5, as well as for the first and last 5 min of stage 4, amplitudes(A_i, PU) of endothelial, neurogenic, myogenic, respiratory, and cardiac oscillations, and nutritive ($I_{m\ nutr}$, PU) and the shunt ($I_{m\ shunt}$, PU) component of the total perfusion, as well as the NADH fluorescence amplitude normalized to the back–reflected probing radiation (A_{NADH}, AU – arbitrary units), as shown in work (Loktionova et al., 2025).

2.4. Participants

Data were collected on 19 Russian cosmonauts (18 men and 1 woman), 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 the subjects signed a voluntary informed consent to participate in the study.

3. Results

All 19 subjects subjectively tolerated PPT well. Symptoms of orthostatic instability (discomfort, nausea, dizziness, etc.) were not reported. The CVS response was adequate to the applied loads.

Fig. 2 shows representative curves of the index of blood microcirculation (I_m) and their wavelet spectra for each stage of the PPT.

The LDF grams in Fig. 2a,c demonstrate pronounced shifts in tissue perfusion in response to a change in the position of the subject's body during PPT: an increase in I_m in the head and a decrease in tissue perfusion in the legs during the transition to the anti-orthostasis position (-15° and -30°), reflecting the natural redistribution of blood to the upper part of body (head) caused by changing the body position. When switching to the orthostasis position (+70°), the subject has a decrease in I_m, followed by an increase in oscillatory activity, which reflects an individual microhaemodynamic response in this subject.

The wavelet spectra (Fig. 2b, d) demonstrate changes in the amplitudes of the active and passive mechanisms of blood flow regulation in case of PPT. In the forehead skin in the anti-orthostasis position (-30°) and orthostasis position (+70°), the myogenic peak shifts to the border with respiratory oscillations (0.18 Hz), the so-called area of cholinergic oscillations, the appearance of which reflects the activation of parasympathetic centers with a shift in the central regulation of microcirculation in the trophotropic direction. At the same time, during orthostasis, an increase in the amplitude of myogenic oscillations is observed in the forehead skin. This is associated with an increase in the number of functioning capillaries and reflects an enhancement of blood flow through the nutritive pathway, which may represent an individual

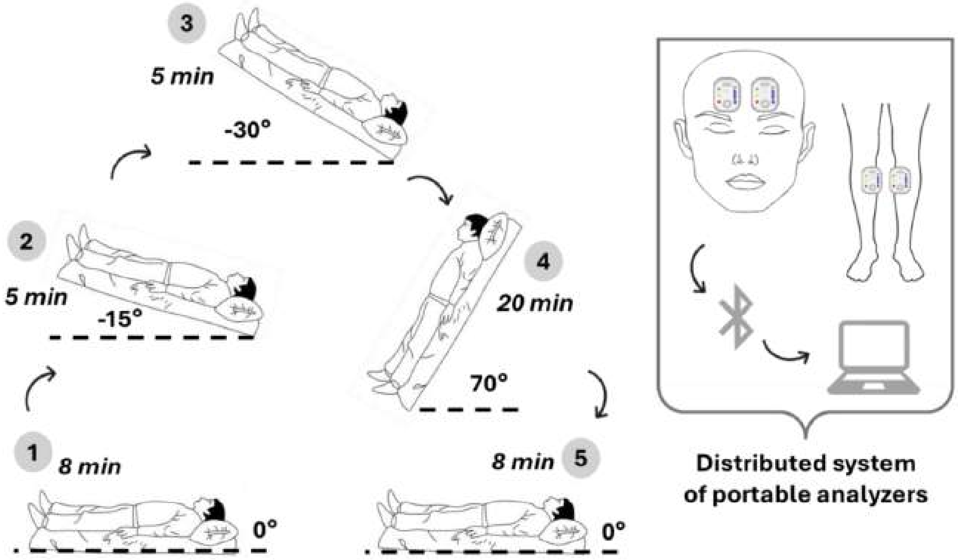
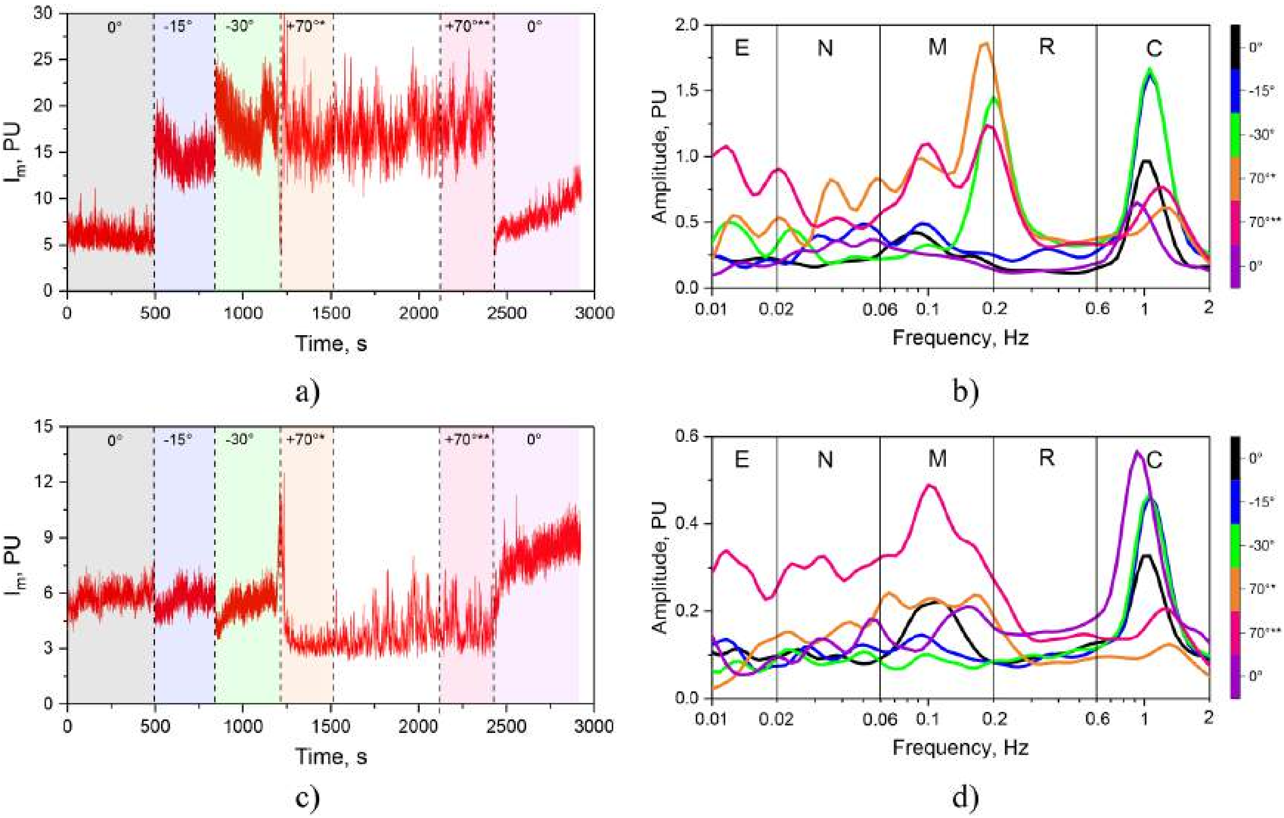


Fig. 1. Study protocol: schematic representation of the subject's body position during the PPT.



a) b)

c) d)

Fig. 2. A typical example of LDF grams (a,c) obtained during PPT and their wavelet spectra (b,d) in the skin of the forehead (a,b) and shins (c,d) at different stages of PPT: 0° – in a horizontal position before PPT; -15° – when tilted 15° below the horizon (head below); -30° – when tilted 30° below the horizon (head below); +70°* – from 1 to 5 min of orthostasis (head at the top); +70°** – from 16 to 20 min of orthostasis (head at the top); 0° – in the horizontal position after PPT.

adaptive mechanism to blood pooling in the lower parts of the body. In contrast, in the shins, a gradual increase in oscillatory activity of the microcirculatory bed is observed throughout the entire orthostatic period.

During LDF signals wavelet analysis for reliable statistics one should ideally include 10 cycles for each of the frequencies under investigation. In our measurement protocol, due to the large number of positions studied and the overall long duration of the studies, we were limited to 5 min of recording in antiorthostatic positions, that is why the reliable results can be obtained only for frequencies higher than 0.03 Hz, for lower frequencies we show results obtained, but only to demonstrate the tendency qualitative.

Examples of the data obtained show the sensitivity of MTS parameters to postural effects. This, in turn, indicates the high informational value of using a distributed system of wearable sensors to study the response of the MTS of cosmonauts' bodies to postural changes.

Fig. 3 illustrates the dynamics of changes in the index of blood microcirculation during PPT. In the forehead area, there is an increase in skin perfusion during anti-orthostasis (-15° and -30°) compared to the horizontal position before the start of PPT. These alterations are a natural result of the redistribution of blood flow to the head region. It is worth noting that at the -30° stage, the median is at the level of the I_m of the horizontal position, which indicates the activation of adaptive mechanisms, however, a large spread 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°), a stable level of perfusion is observed, which may be a reflection of the high reaction rate of microhemodynamic parameters to maintain brain homeostasis.

No significant changes were found in the shin area during the PPT, however, when returning to the horizontal position, there is an increase in the perfusion level above the initial one. A similar increase in I_m in the horizontal position after PPT compared to the stage before it is observed in the skin of the forehead. Perhaps this is how the compensatory mechanisms of blood flow work after an irritating effect. In Breit et al. (1993) 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.

A statistically significant increase in nutritve blood flow in the skin of the supraorbital artery basins during orthostasis is most likely a reflection of the work of compensatory mechanisms to restore the pressure gradient and homeostasis during blood outflow to the lower extremities, which is confirmed by an increase in M_{nutr} in the skin of the legs.

The absence of statistically significant changes in the A_{NADH} at all stages of PPT may indicate the constancy of metabolism, which is a consequence of maintaining homeostasis due to the microcirculatory part of the circulatory system, characteristic of a trained organism.

Fig. 4 shows the range diagrams for the values of the amplitudes of blood flow oscillation for each stage of the study. In the area of the forehead skin, in anti-orthostasis positions, there is a dominance of cardiac oscillations, which, together with an increased level of perfusion, indicates an increase in the flow of arterial blood into the microcirculatory system. When switching to the orthostasis position (+70°), arterial blood flow decreases, but there is an increase in the amplitudes of active rhythms (endothelial, neurogenic, myogenic), which indicates vasodilation and is a mechanism for compensating blood outflow to the lower body. Interestingly, in the leg area at +70°, vasodilation also occurs, accompanied by an increase in the number of functioning capillaries, which is confirmed by an increase in the amplitudes of endothelial, neurogenic, and myogenic oscillations.

In studies conducted with the participation of untrained volunteers, there were significant differences in limb microcirculation parameters between each stage of the study (Fedorovich et al., 2021). These differences reflect the redistribution of fluid in the body when body

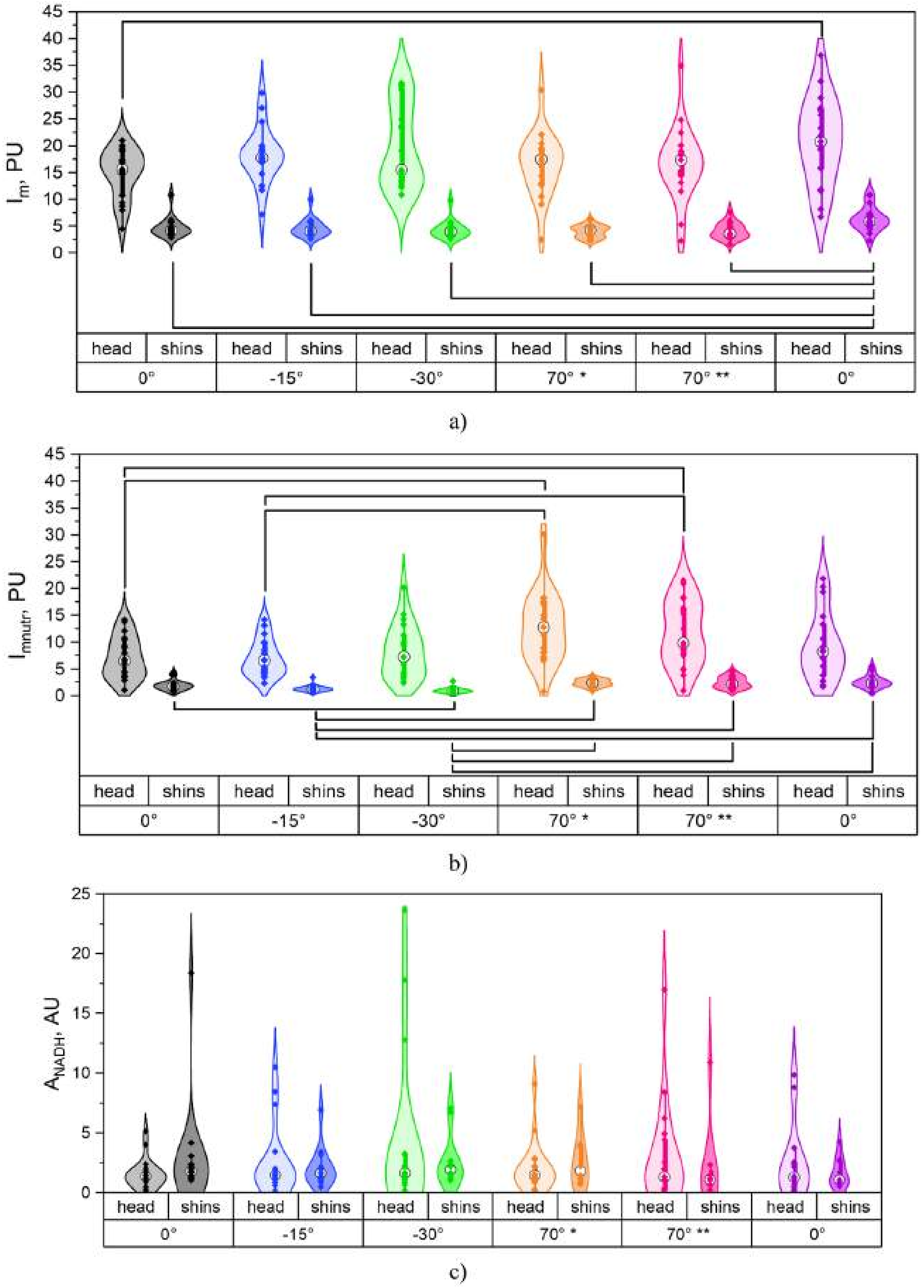


Fig. 3. Index of blood microcirculation (a), nutritive blood flow (b), and normalized amplitude of NADH fluorescence (c) in the forehead and shins skin areas at different stages of PPT: 0° – in a horizontal position before PPT; -15° – when tilted 15° below the horizon (head below); -30° – when tilted 30° below the horizon (head below); +70°* – from 1 to 5 min of orthostasis (head at the top); +70°** – from 16 to 20 min of orthostasis (head at the top); 0° – in the horizontal position after PPT.
Statistically significant differences were confirmed by the paired ANOVA test ($p < 0.05$) and shown using statistical comparison markers. The Tukey test was used for a posteriori analysis.

position changes. The absence of significant changes in perfusion level in our sample of subjects during PPT, as well as the general significant changes in normalized amplitude of NADH fluorescence, can be explained by the high level of physical fitness and significant functional reserves of cosmonauts. This means that when body position changes, tone-forming mechanisms quickly adjust their work to maintain optimal perfusion levels and ensure stable provision of metabolic needs for biological tissues.

3.1. *Assessment of individual reactions to PPT*

The assessment of the individual responses of the MTS participants will allow us to study the characteristics of each organism and can serve as a diagnostic criterion for borderline conditions and an indicator of adaptive failure. Therefore, considering the individual variations in MTS parameters during the PPT, we observed multidirectional responses in peripheral blood flow and metabolism among different participants. The overall good tolerability of the sample by each individual suggests that each organism, especially a trained one, has its own adaptive

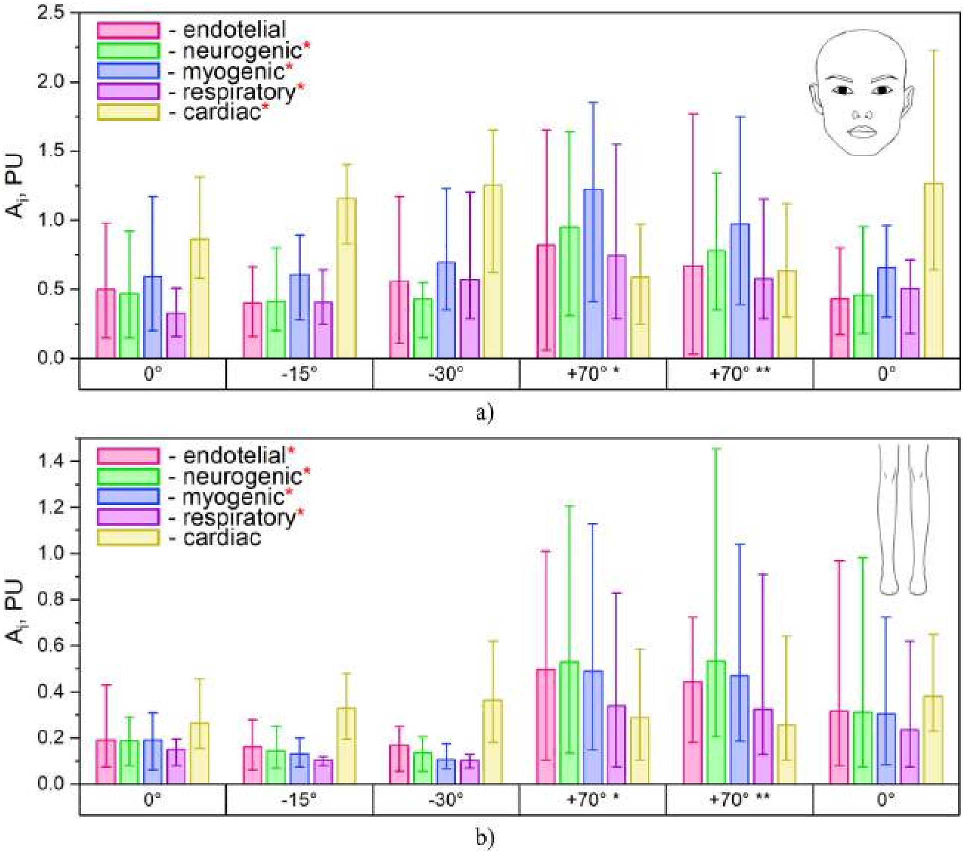


Fig. 4. Amplitudes of blood flow oscillation caused by active and passive regulatory mechanisms in the skin of the forehead (a) and shins (b) at different stages of PPT: 0° – in a horizontal position before PPT; -15° – when tilted 15° below the horizon (head below); -30° – when tilted 30° below the horizon (head below); +70°* – from 1 to 5 min of orthostasis (head at the top); +70°** – from 16 to 20 min of orthostasis (head at the top); 0° – in the horizontal position after PPT.
* – statistically significant differences in this parameter at the stages of the PPT were confirmed by the paired ANOVA test ($p < 0.05$). The low frequency part of the spectra (below 0.03 Hz) has insufficient statistics and is shown just to demonstrate the tendency. The diagrams are presented for mean values and the range 10–90.

mechanism to changing conditions, particularly to postural influences, which maintains the needs of biological tissues under such loads by preserving homeostasis.

For example, Fig. 5 illustrates the relative changes in skin perfusion

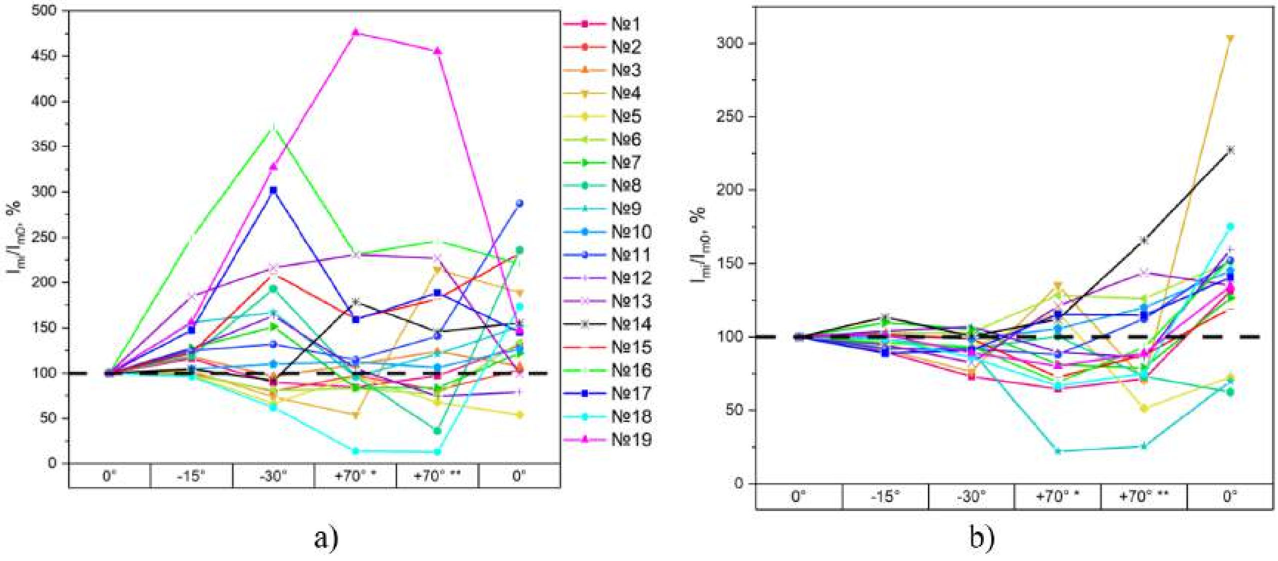


Fig. 5. Tissue perfusion of the basin of the supraorbital arteries (a) and the skin of the inner surface of the shins (b) normalized to the baseline value of the first stage at different stages of PPT: 0° – in a horizontal position before PPT; -15° – when tilted 15° below the horizon (head below); -30° – when tilted 30° below the horizon (head below); +70°* – from 1 to 5 min of orthostasis (head at the top); +70°** – from 16 to 20 min of orthostasis (head at the top); 0° – in the horizontal position after PPT.

in the basins of the supraorbital arteries and the upper third of the shins. I_m values were normalized to the average perfusion value from stage 1 and are presented as a percentage. This calculation method enables us to estimate changes relative to a baseline level of the parameter.

An increase in I_m in the forehead skin area was observed in the anti-orthostatic position compared to the horizontal position in 13 out of 19 subjects, which represents 68.4% of the total sample. This dynamic of parameters reflects a redistribution of blood flow in the head region. However, upon transition to the orthostatic position, 9 out of 21 subjects showed an increase in I_m. In contrast, 4 subjects experienced a decrease in perfusion, which persisted throughout the 20 min period. In 2 other subjects, I_m decreased during anti-orthostasis and increased during orthostasis, followed by a return to baseline values in the horizontal position. At the same time, the decrease in I_m during anti-orthostasis continued in the upright position for 4 other subjects. Finally, on the last stage of the study, I_m significantly increased for 3 out of these 4 subjects (up to 270% of baseline level). For the shins area, 73.7% of the subjects (14 out of 19) had a decrease in blood pressure in the anti-orthostatic position compared to the horizontal position. This was due to blood outflow from the upper body, which paradoxically remained in 47% of them during the transition to the orthostatic position.

It is worth noting that all the participants underwent PPT without any discomfort, which indicates that there are individual mechanisms in place to ensure an optimal level of the body's functional state, despite the different directions of these actions in each participant. Perhaps this sensitivity of the MTS to the needs of the biological tissues is a result of the high fitness and functional reserves of the body.

3.2. *Clustering (dividing subjects into groups depending on the dynamics of parameters)*

During further data processing, it was decided to simplify the protocol to the conditional 4 stages: horizontal position (the initial position before the beginning of changes in the body position of the subjects), antiorthostasis (averaging the tilt stages of -15° and -30°), orthostasis (the average between the first and last 5 min of the stage of +70°), horizontal position (after the end of the position changes the bodies of the subjects). For each of the 4 conditional stages, the parameters of the microcirculatory and tissue systems were also calculated, as indicated in the materials and methods section, and the average values between the right and left sides of the body were found for further analysis.

Clustering is performed based on the parameter ΔX_N, which shows the relative change in the parameter X between two adjacent stages and is calculated using the formula:

$$\Delta X_N = \frac{X_i}{X_{i-1}} * 100 - 100, \ \%$$

where X_i – is the value of parameter X for stage i, X_{i-1} – is the value of parameter X for the stage preceding stage i.

Clustering was performed according to a two-variant scheme, namely, all subjects for whom ΔX_N turned out to be greater than 0 belonged to the group with a positive reaction, that is, the parameter X for them increased at the subsequent stage compared with the previous one. Accordingly, all subjects for whom ΔX_N turned out to be negative belonged to the group with a negative reaction, which means that the parameter X for them decreased at the subsequent stage compared to the previous one. If ΔX_Nassumed a zero value, then the subject was also assigned to the 2nd group (with a negative reaction), which generally did not affect the clustering results because zero values were obtained only twice.

The data was divided into groups for each parameter for each research area. Clustering was performed alternately according to the reactions to each of the protocol steps in the measurement sequence. Thus, for 3 body position changes with this type of clustering, 8 types of reactions could potentially be formed. It is worth noting that since the described clustering method requires the presence of registered MTS parameters for each stage of the study in symmetrical areas of the body, when clustering for the shin area, 16 out of 19 subjects were included in the sample, which is due to the lack of a full amount of data from 3 subjects due to the devices being turned off during measurements.

Clustering performed in this way showed different results for each parameter. For example, when analyzing the types of index of blood microcirculation reactions in the forehead, the subjects were divided into 7 groups, for each of which a step-by-step change in $\Delta I_{m\ N}$ is shown in Fig. 6a. The group №13 became the most numerous of them – it included 7 subjects or 36.8% of the total participants. This group is characterized by an increase in I_m during the transition to the anti-orthostasis position after the horizontal position; during the transition to orthostasis, I_m decreases and increases again upon return to the horizontal position, which can be the most expected microhemodynamic response to PPT. When clustering based on the dynamics of I_m, 5 groups were identified for the shin area, the most numerous of which was the group with 5 subjects (31.2%). They are characterized by a decrease in I_m during the transition to antiorthostasis and orthostasis, followed by an increase in perfusion upon return to the horizontal position.

When using changes in the amplitudes of endothelial oscillations to cluster cosmonauts by reaction type, 5 groups were obtained for the forehead area and 4 groups for the shins area. In each region, the most numerous group was the one that showed a decrease in A_e during the transition to antiorthostasis and horizontal position after PPT, along with an increase during the transition to orthostasis ($n = 9$ subjects or 47.4% for the supraorbital artery basins and $n = 7$ or 43.8% for the shins). Groups with the same dynamics were distinguished for the amplitudes of neurogenic and myogenic oscillations for both the forehead ($n = 11$ or 57.9% for A_n and $n = 8$ or 42.1% for A_m) and the shins ($n = 9$ or 56.2% for A_n and $n = 8$ or 50.0% for A_m). The described dynamics of the amplitudes of active regulatory mechanisms may be a reflection of an adaptive response to the redistribution of fluid in the body by changing microvascular tone. The greatest consistency in reactions among the amplitudes of the active blood flow regulation circuit is found in the amplitudes of neurogenic oscillations: all subjects were divided into 3 groups, examples of reactions for which are shown in Fig. 6b and d.

The most numerous groups of subjects, when clustering according to the amplitudes of oscillations of the cardiac mechanism ($n = 14$ subjects or 73.7% for the forehead and $n = 7$ or 43.8% for the shins), showed a counter–directional dynamics - an increase in A_c during the transition to antiorthostasis and a horizontal position with a decrease in A_c in orthostasis. Of interest is the fact that when clustering according to the shunt blood flow parameter, the most numerous groups of subjects ($n = 11$ or 57.9% for the forehead and 68.8% for the shins) demonstrate a reaction opposite to active rhythms and similar to the amplitudes of cardiac oscillations: a decrease in M_{shunt} during the transition to anti-orthostasis and horizontal position after PPT, as well as an increase in shunt blood flow during the transition to orthostasis.

Clustering by the parameter of nutritive blood flow revealed the presence of 4 types of reactions, two of which included 7 subjects (43.8%) – groups with subjects №11 and №9, shown in Fig. 6b. Both groups are characterized by a decrease in M_{nutr} during the transition to the antiorthostasis position and its increase during the transition to the orthostasis position, which most likely reflects the redistribution of body fluid when the body position changes. However, when returning to the horizontal position after the end of the PPT, 7 subjects showed an increase in nutritive blood flow and 7 showed a decrease, which indicates an individualization of the adaptation process.

The dynamics of A_{NADH} in the forehead skin in the most numerous clustering group is as follows: an increase during the transition to antiorthostasis and horizontal position and a decrease in orthostasis, which indicates the activation of metabolic processes in orthostasis and their slowdown with a decrease in the level of the head relative to the heart.

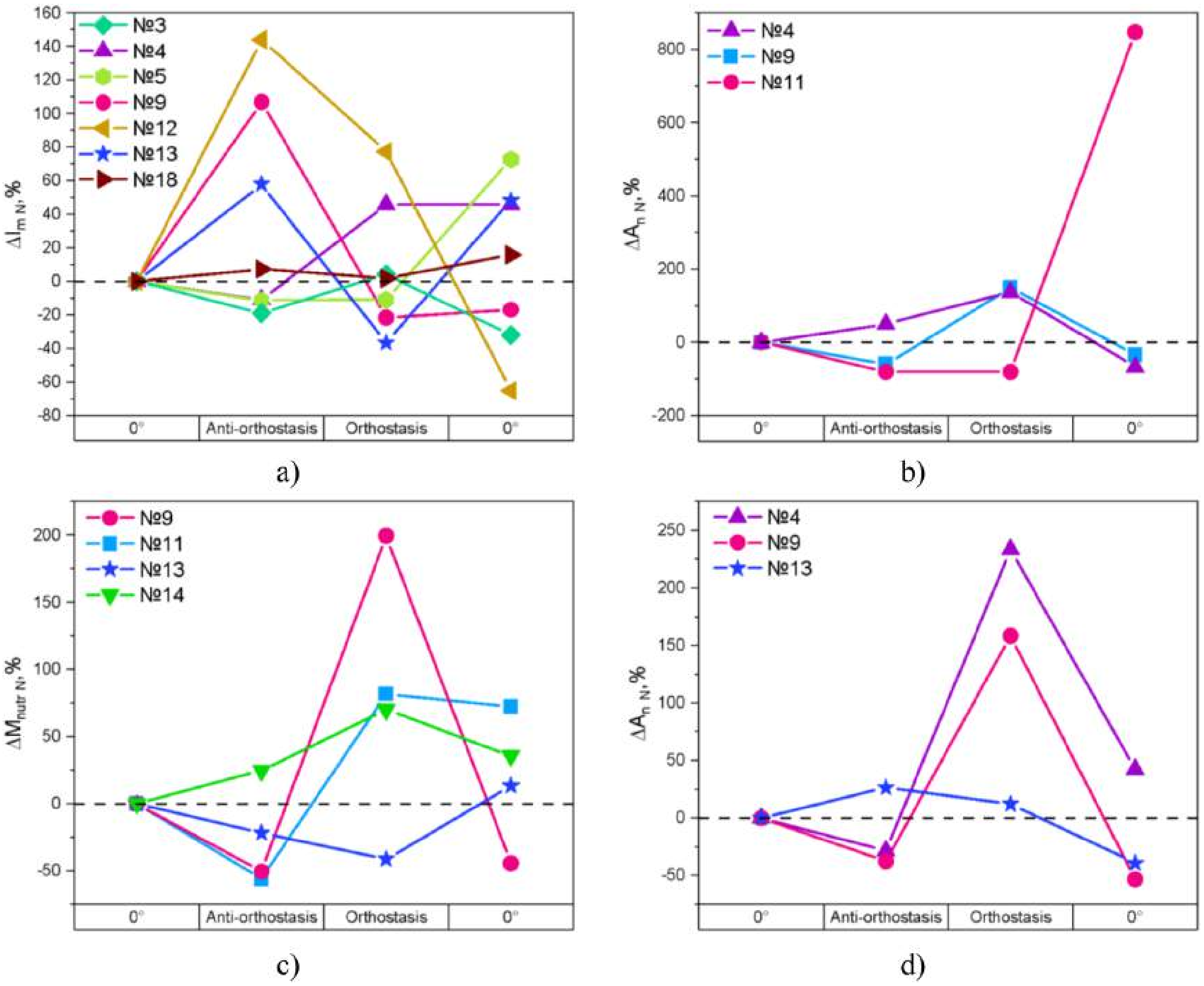


Fig. 6. Representative graphs of the types of dynamics of the index of blood microcirculation (a) and the amplitudes of neurogenic oscillations (b) in the forehead and nutritive blood flow (c) and the amplitudes of neurogenic oscillations (d) in the shins of the subjects when the body position on the tilt table change.

An attempt was also made to perform clustering simultaneously for 2 signs:for relative changes in blood microcirculation in the skin of the forehead and shins between consecutively stages of the protocol. With this approach, at each stage of clustering of populations potentially formed 4 subgroups: subgroup 1 – $\Delta I_{m\ N}$ greater than 0 in the forehead and shins; group 2 – $\Delta I_{m\ N}$ greater than 0 in the forehead and not greater than 0 in legs; group 3 – $\Delta I_{m\ N}$ not greater than 0 in the forehead and greater than 0 in legs; group 4 – $\Delta I_{m\ N}$ not greater than 0 in the forehead and shins. With this approach, 64 combinations of values of ΔX_{N}0can be obtained for 3 levels of nodes. The dendrogram obtained in the described way is shown in Fig. 7.

The resulting dendrogram shows that, despite the general trends in the dynamics of I_m in several groups of subjects for the forehead and legs, there is an individual response to PPT among the current sample. This distribution may be due to the body's high fitness and readiness for postural influences, leading to a high sensitivity to the local needs of biological tissues and corresponding changes in microhemodynamics. The results confirm the need for an individual approach when training cosmonauts for spaceflight by assessing their microhemodynamic reserves through the use of a distributed system of portable optical analyzers to measure parameters of the microcirculatory and tissue systems.

4. Conclusion

Thus, this paper presents, for the first time, a developed approach to the registration of MTS parameters using a distributed system of compact, multimodal optical analyzers during postural changes in cosmonauts' bodies.

It has been demonstrated that a trained group of subjects may react differently to functional tests, particularly to passive postural test, than untrained volunteers. This may be due to the higher functional reserves of their bodies. The study shows that a high level of physical and physiological fitness allows cosmonauts to adapt to changes in blood distribution when body position is altered through microcirculatory adjustments. This is achieved by changing the mechanisms of vascular tone regulation without significant changes in metabolic processes.

The registration of MTS parameters using a distributed system of portable multimodal analyzers during functional tests as part of the cosmonauts biomedical training for space flights allows to record individual changes in peripheral blood flow and oxidative metabolism of biological tissues. This can be the basis for a personalized approach to training, allowing us to both improve and evaluate its effectiveness. It also allows us to predict the adaptation of the cardiovascular system of cosmonauts to weightlessness by diagnosing hidden functional reserves of the body.

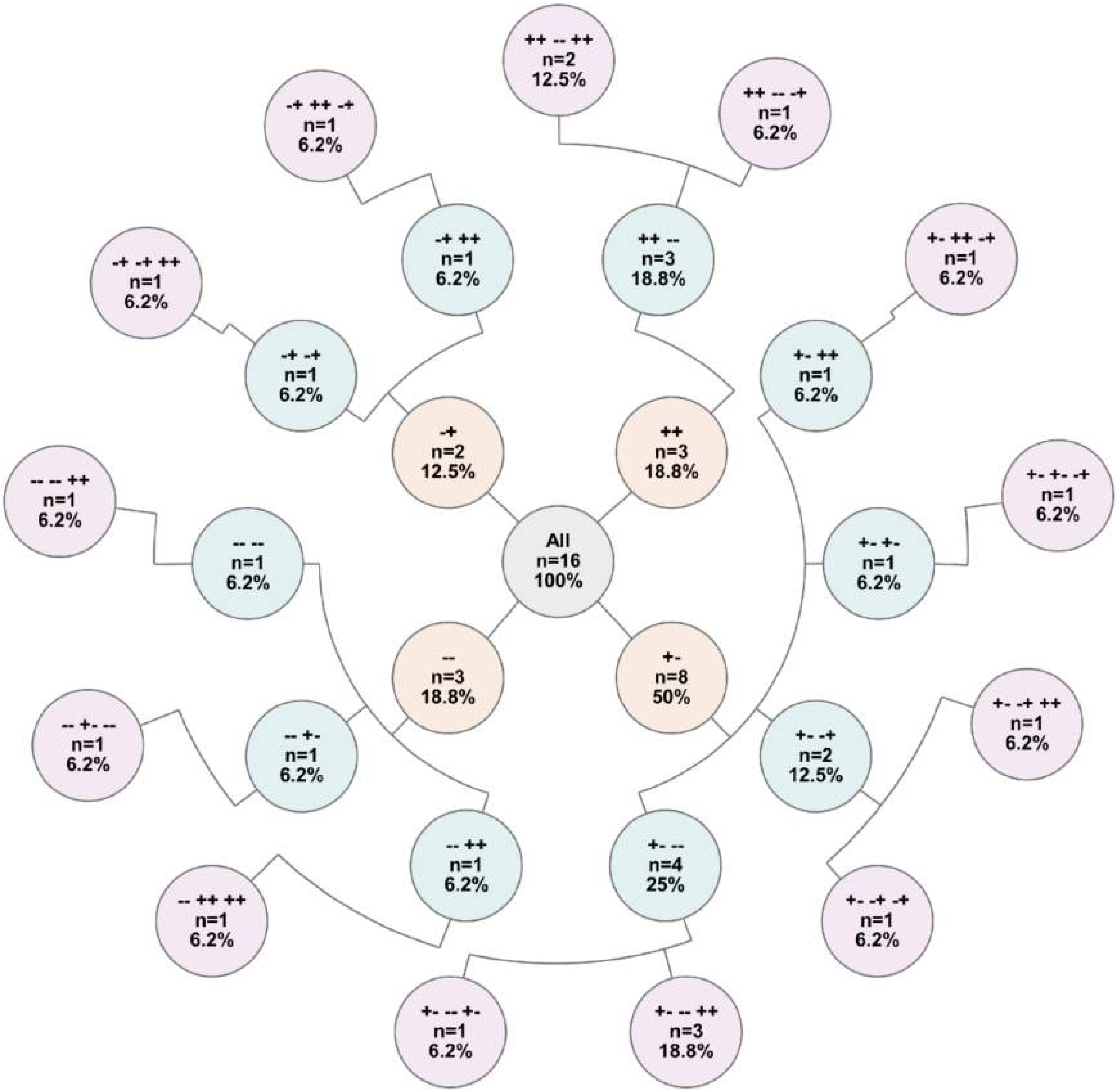


Fig. 7. Dendrogram of clustering of subjects according to the types of dynamics of the index of blood microcirculation in the basins of the supraorbital arteries and the inner surface of the shins when the body position changes on the tilt table.

CRediT authorship contribution statement

Yulia Loktionova: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Kirill Kireev:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Elena Zharkikh:** Writing – review & editing, Writing – original draft, Software, Investigation, Formal analysis. **Dmitry Lutsevich:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Vyacheslav Yanusnin:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis. **Victor Sidorov:** Writing – review & editing, Writing – original draft, Software, Methodology. **Andrey Dunaev:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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