Russian Countermeasure Systems for Adverse Effects of Microgravity on Long-Duration ISS Flights

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INTRODUCTION: The system of countermeasures for the adverse effects of microgravity developed in the USSR supported the successful implementation of long-duration spaceflight (LDS) programs on the Salyut and Mir orbital stations and was subsequently adapted for flights on the International Space Station (ISS). From 2000 through 2010, crews completed 26 ISS flight increments ranging in duration from 140 to 216 d, with the participation of 27 Russian cosmonauts. These flights have made it possible to more precisely determine a crewmember's level of conditioning, better assess the advantages and disadvantages of training processes, and determine prospects for future developments.

KEYWORDS: spaceflight, human, history.

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Research performed during long-duration spaceflights (LDS) has shown that those countermeasures which reproduce a distribution of bodily fluids similar to that on Earth prevent or significantly reduce the manifestation of unfavorable changes resulting from exposure to spaceflight factors.[1,2,4,5] These countermeasures typically compensate for microgravity's insufficient loading of the musculoskeletal and cardiovascular systems. The system of microgravity countermeasures developed in Russia to support the safe execution of LDS includes the following:[3,5,8,11,13,16]

1. Physical exercises that create loads on the musculoskeletal, cardiovascular, and other systems stimulate proprioceptive and related sensory systems and thus facilitate normal function of the regulatory systems for posture and locomotion.
2. Physical methods and equipment intended to reduce redistribution of bodily fluids in microgravity and during readaptation to 1 G—occlusion cuffs in the early stages of exposure to microgravity conditions, negative pressure on the lower half of the body (the Chibis suit) during flight, and the Kentavr G-suit during landing and postflight adaptation.
3. Measures facilitating fluid retention—water and salt supplements.
4. Pharmacological preparations intended to prevent possible negative vestibular, cardiovascular, and metabolic effects of microgravity.

Long-Duration Spaceflight Factors and Their Effects on the Body

During spaceflight, a person encounters a new, challenging environment full of unusual sensations and stressful, critical work that is strictly regimented time-wise. Successful execution of a mission is tied to recognition of the fact that errors by the crew or some other causes could lead to unforeseen, dire consequences. The human body responds to this challenge by developing universal adaptive reactions, the intensity and time characteristics of which are individual in nature.[3]

While the environment of outer space is hostile to humans, spaceflight takes place in vehicles that are equipped with pressurized habitation compartments and the necessary life support systems. Ionizing radiation does not have a significant effect on the crewmember's body during flights below the Earth's radiation belts and during periods of low solar activity. Crewmembers may experience adverse effects from nervous and emotional stress related to their critical, stressful work, particularly in the event of off-nominal situations or emergencies. However, during LDS, the most significant factor

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affecting the human body is microgravity, which prompts the development of a broad spectrum of negative changes in various bodily systems: cardiovascular, motor, sensory, musculoskeletal, and others.[3,12]

The main link in the mechanism of the microgravity effect is the removal of bodyweight and, as a consequence, the deformation of key human body structures (including, first of all, the lead gravity receptors—the otoliths, proprioceptors, and support-reference receptors[9,10]) concurrently with the redistribution of bodily fluids caused by the removal of hydrostatic pressure in fluid media. These changes trigger subsequent physiological functional and structural changes in bodily systems that are summarized below:[6,7]

- Demineralization of the skeleton;
- Deconditioning, atrophy, and structural changes in the muscular apparatus;
- Disrupted coordination of movement (posture, locomotion, purposeful movements);
- Deconditioning of the cardiovascular system;
- Reduced orthostatic tolerance;
- Reduced resistance to gravitational loads;
- Reduced overall capability to work.

The typical progression of the aforementioned disorders during LDS has allowed specialists to combine them, according to etiological factors, into a series of syndromes listed in **Table I**.

Physical Training During Long-Duration Spaceflight

The ever-present tendency for deconditioning to rapidly develop in microgravity dictates that LDS must include the systematic performance of physical exercise. According to crewmembers' reports, lapses in exercise over the course of 7 to 10 d during LDS are accompanied by sensations of a "rapid deterioration" of physical functioning, and the time necessary to restore functioning is much longer than the duration of the lapse.[7]

The present system of countermeasures used by Russian International Space Station (ISS) crewmembers is based on the experience of LDS (up to 430 d) on Russian space stations.[9,11] As noted previously, this system includes the following: physical exercises and specialized suits that provide loads, including axial weight loading, on the musculoskeletal and cardiovascular systems and thus activate proprioceptive systems (particularly the sensory input system) that aid in retaining postural and locomotor functions. These physical methods are intended to reproduce in microgravity a distribution of bodily fluids that closely resembles that on Earth. Water and salt supplements, which foster the body's retention of fluid, increase orthostatic stability and tolerance to g loads during descent. Also, a well-balanced diet and medicines are used to correct possible negative vestibular, cardiovascular, and other bodily reactions to the effects of microgravity.[13,18]

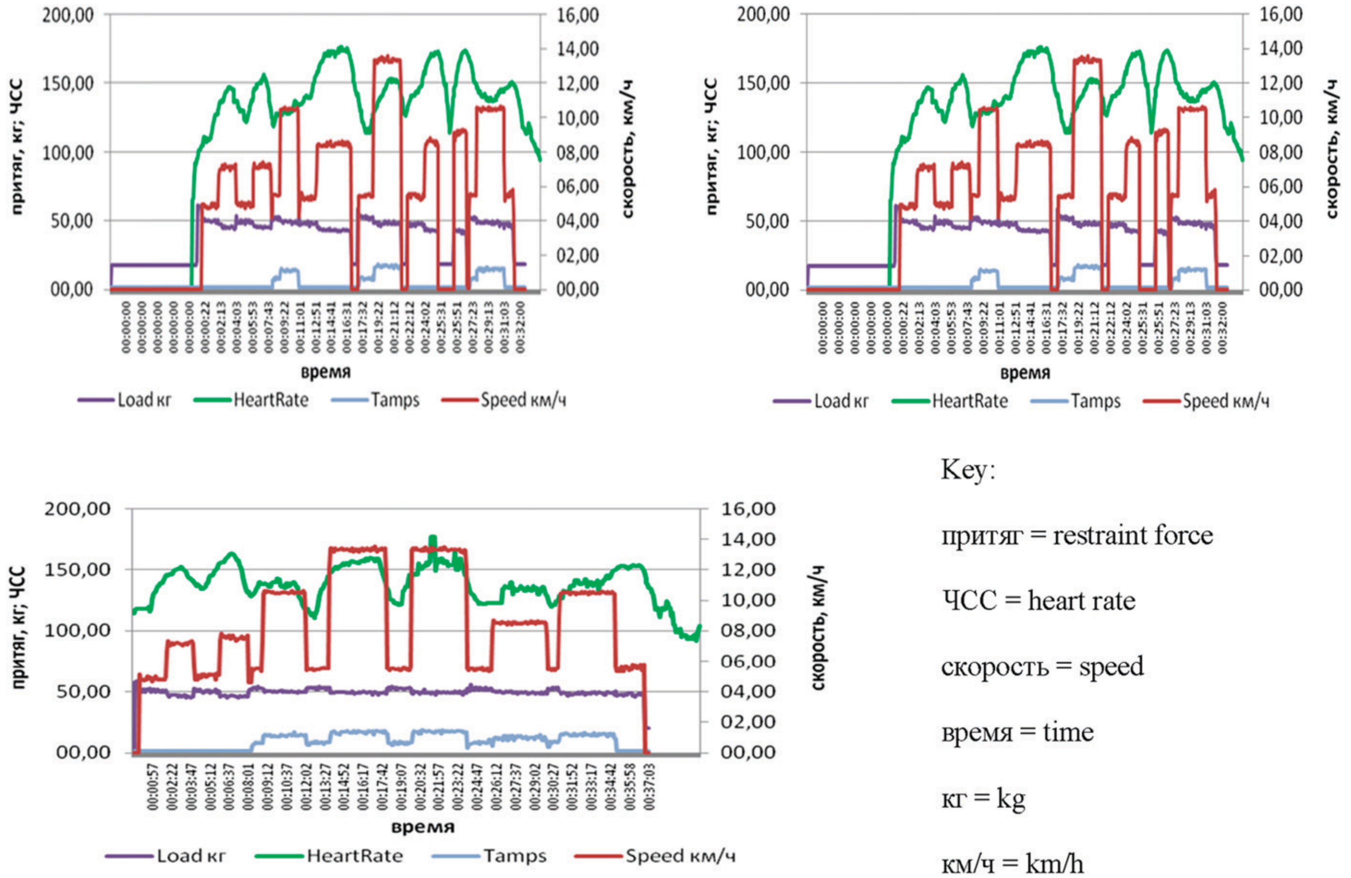
A key element in the countermeasures system for ISS flights, as well as for previous flights on Russian space stations, is the twice-daily physical training that takes place over the course of 2.5 h using all available onboard training equipment. Physical training includes locomotor and cycle ergometer exercise, as well as strength training. The regimen recommended for Russian cosmonauts is set forth in a 4-wk training microcycle protocol, including: 3 loading days and 1 day of active rest. The levels of locomotor loads in the treadmill cycle vary on different days between 3000 to 4400 m with an average intensity of 117–135 $\mathrm{m \cdot min^{-1}}$; on the cycle ergometer they are 19,700 to 23,250 $\mathrm{kg \cdot m^{-1}}$ (3220 to 3800 $\mathrm{W \cdot min^{-1}}$) with an average load of about 800 $\mathrm{kg \cdot m^{-1} \cdot min^{-1}}$ (130 $\mathrm{W \cdot min^{-1}}$). The energy cost of the loads on various days of the microcycle ranges from 380 to 580 kcal (1600 to 2500 kJ).[11,14,17]

The ISS physical training program was created taking into account universal principles of human adaptation to physical loads,[7,14] including: systematic physical training throughout the entire flight, including variety, with the primary objective being to maintain specific physical parameters and prevent functional and structural changes in the body's main systems. Activities include static (loading suits), dynamic (walking, running, jumping, strength training), and inertial-impact actions in the physical training program. In-flight physical training is characterized by its high intensity, interval-based structure and precise focus of each day of the cycle on training various physical parameters (**Fig. 1**).

The exercises on the first day of the microcycle are aimed at maintaining speed and load-bearing endurance and include, along with walking and running at a rate of 120 to 140 steps/min, sessions of high-speed running at a rate of 200 to 300 steps/min [12 to 14 km/h (7.5 to 8.7 mph)], which promotes the maintenance of speed and strength properties of the skeletal muscles and the anaerobic mechanisms of the cardiovascular system. Pulse rate upon completion of

Table I. Weightlessness Syndromes.

PHENOMENON OR SYNDROME	SYMPTOMS	ACTING FACTORS
Motion sickness	Illusions, dizziness, disorientation, body orientation disturbance, complex vegetative disorders – nausea, vomiting	Disruption of the activity of normal gravity receptor entries and intersensory interactions
Gravitational ataxia	Disordered posture, locomotion, metrics of all types of fine voluntary movements (locomotor, postural), atonia, hyperreflexia, and other disruptions of motor control system activity	Removal of support, reduction of proprioceptive activity, change in motion biomechanics
Muscular hypogravity syndrome	Atonia, atrophy, reduced speed and strength properties, and reduced endurance, with the greatest manifestation of the aforementioned in the system of extensor muscles	Reduced physical loads and body weight, change in motion biomechanics; removal/reduction of activity in gravity receptor systems – support, vestibular
Orthostatic deficiency syndrome	Increased heart rate, lowering of the arterial pressure, and, in severe cases, collapse when transitioning to the upright position and under g loads	Extended period spent in conditions that do not require maintenance of an upright posture in a gravitational field



Key:

притяг = restraint force

ЧСС = heart rate

скорость = speed

время = time

кг = kg

км/ч = km/h

Fig. 1. Chart of locomotor training in the microcycle of Cosmonaut K.

physical training on the first day averages 140 to 160 bpm, peaking during high-intensity exercise at 180 bpm and higher. The exercise structure is based on the principle of interval training.

The second day of the cycle focuses mainly on load-bearing endurance training. To achieve this goal, the amount of locomotion performed in the treadmill's passive motion mode increases (Fig. 1). Accordingly, the load on that day is medium; the intensity is medium to above medium. The total energy cost of two exercise sessions reaches 1882 to 2092 kJ (450 to 500 kcal) [versus 1590 to 1757 kJ (380 to 420 kcal) on the first day]. The structure for the third day's training session consists of relatively slow and medium-speed steady-state running over the course of relatively long time intervals—up to 4 to 6 min—and pedaling on the cycle ergometer in a similar mode, which helps stabilize the oxygen consumption in tissues and increases their blood supply (aerobic modes).

Analysis of data obtained during long-duration spaceflights on Russian stations and from ground studies show that, in microgravity, high-intensity interval training is much more effective than aerobic training. The modes for studying countermeasures during LDS differ in accordance with the tasks in the five stages of LDS (**Table II**). Monitoring and control of the crewmembers' training process during flight on the ISS include systematically monitoring the level of conditioning, determining the efficacy and correctness of the physical training being performed by crewmembers, and also providing, if necessary, recommendations for corrections.

The exercise quantity and intensity of loads during physical training on the treadmill were monitored as well as the qualitative features of these exercises and their correspondence to recommended methods of execution. Data from daily records of treadmill with vibration isolation system (TVIS) training sessions were analyzed after being copied to storage media with subsequent downlink to the ground via telemetry

Table II. Application of the Russian System of Countermeasures at Various Flight Stages.

STAGE	APPLICATION
1	Initial stage (FD1–10). Occlusion cuffs ($P < 50$ mmHg for 20 to 30 min) and physical training with a load of up to 50% of that recommended. If necessary, pharmacological remedies to relieve space motion sickness.
2	Condition stabilization stage. Physical training twice a day for 1 and 1.5 h (2.5 h/d) using the treadmill, cycle ergometer, and bungee cords; if desired or necessary, use of passive alternative measures.
3	Pre-EVA. Same training, with emphasis on the cycle ergometry using the arms.
4	Final stage (R-30 d). Two sessions per day on the treadmill; LBNP for two to four preliminary sessions and two final sessions; water and salt supplements (0.9% NaCl, 18 to 20 ml • kg^{-1} of body mass three to four times over the course of the last 12 to 20 h before landing).
5	Descent stage and the first few days of readaptation: g suit.

systems. These analyses allowed specialists to determine the intensity, scope, and structure of training sessions, as well as the cosmonauts' level of conditioning. It is known that the load intensity selected by the cosmonauts, the scope of work they perform, the duration of high-intensity work periods, and the breaks after completing them fairly accurately reflect total work capacity. Individual recommendations for improving the training process were created and uplinked to the station once a week. Determining the level of physical training was significantly easier when information on heart rate during exercise was available. Unfortunately, a number of cosmonauts did not use a heart rate monitor in flight, which reduced the accuracy of assessing the physiological costs of the work being performed and, by extension, the creation of individual recommendations. It must be noted that the capability to register each training session was first implemented during ISS operations. Previously on Russian stations, physical training and conditioning levels were monitored by a system that involved the monthly recording of 3 d of the training cycle on the treadmill and cycle ergometer, then downlinking data for analysis, evaluation of the crewmember's conditioning level, determination of his compliance with physical training and crew procedures, and finally development of recommendations for future training.

The level of conditioning and, consequently, the effectiveness of the training sessions performed by crewmembers on ISS flights were also determined through evaluation of results from tests with graded increasing locomotor and cycle ergometer loads, which were performed once a month in accordance with crew procedures. The duration of the locomotor test (test [MO]-3) is 11 min with an energy cost of about 4184 kJ (100 kcal). The test, which is performed on TVIS in passive mode with axial loading comprising at least 60% of bodyweight, involves 3 min of warm-up walking, 2 min of slow running, 2 min of middle-range running, 1 min of running at maximum speed, and 3 min of cool-down walking (**Fig. 2**). The distinguishing feature of the test is the standardization of the sequence and the duration of each of the three loading stages and the cosmonaut's voluntary selection of intensity at each stage. The intensity of the speeds selected by crewmembers served as an additional indicator of the cosmonaut's conditioning level. Data from the locomotor parameters on the treadmill and heart rate were recorded on special cards and returned to the ground.[19]

The overall work capacity of cosmonauts was also assessed according to readings from the 3-step cycle ergometer test ([MO]-3) with loads of 125, 150, and 175 W with a standard 3 min duration for each step; the last step corresponds to approximately 75% of maximum capability. The total duration of work in the test was, thus, 9 min. During the test, a DS lead ECG reading was obtained and arterial pressure was measured according to the Korotkov method in real time at each load step for test safety.[18]

Before extravehicular activity (EVA) in Russian spacesuits, cosmonauts performed a test on the cycle ergometer involving hand pedaling "towards oneself." The work level was set at 150 W, then total work time to exhaustion and heart rate at the end of each minute were recorded. Heart rate was also recorded during the 3-min recovery period.

Crew messages about the status of training equipment and the performance of physical training, as well as the results of the tests performed, were clarified and supplemented during cosmonauts' private radio conferences, which were held on a regular basis once a month with participation by the flight surgeon and countermeasures specialists. The effectiveness of the equipment and countermeasures regimens used by cosmonauts was determined after the flight using data from a broad postflight clinical and physiological examination of the status of the main bodily systems (**Table III**).

Cosmonauts' Use of Countermeasures During Long-Duration Flights on the ISS

All Russian ISS crewmembers used the recommended system of countermeasures as a baseline; however, wide variability in the implementation of some elements of the system resulted due to the operational conditions of life and work aboard the station, as well as the functional status of the training equipment. In light of the heavy workload and the significant duration of preparatory operations for exercising, more than half of Russian crewmembers preferred to follow (up to 80% of the flight time) a once-daily training regimen, despite the fact that long-duration flights on Russian stations had provided convincing proof of the significantly greater efficacy of twice-daily training.[7] Cosmonauts performed locomotor training sessions daily; the rare omissions were generally related to the crew's heavy workload. The training regimens, however, varied widely

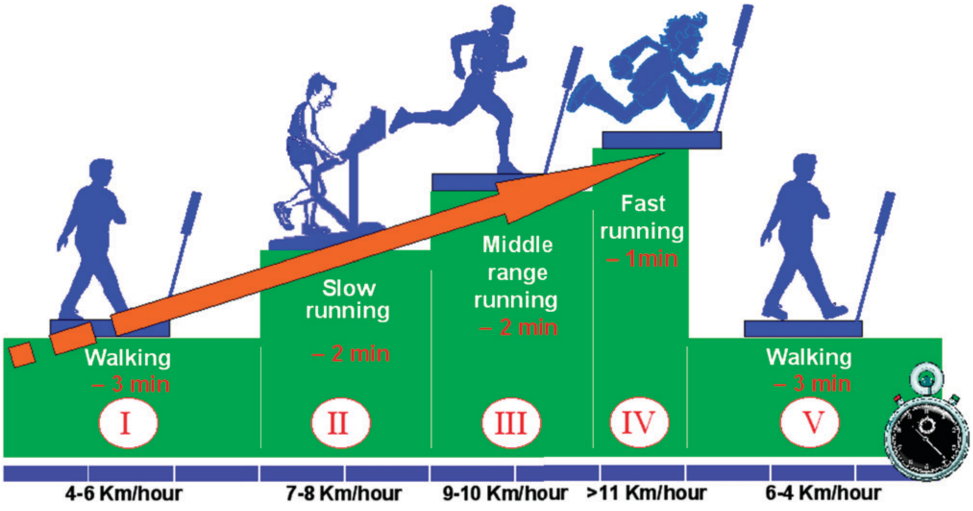


Fig. 2. Diagram of graded locomotor test [MO]-3.

Table III. List of Sensory and Motor Clinical and Physiological Studies Performed on Russian ISS Crewmembers Pre- and Post-Spaceflight.

CHARACTERISTICS STUDIED	RESEARCH METHODS
Mineral density of bone tissue	Osteodensitometry
Muscle properties	Isokinetic dynamometry of the thigh and calf muscles Tension measurements of induced tetanic contractions of the calf muscles Biopsy of the soleus muscle
Motor control system	Tendon (Achilles) reflex Equilibrium (corrective responses) Strength gradation test Head and eye motor coordination Locomotion
Vestibular system	Battery of sensory adaptation tests

and, as a rule, differed significantly from the recommendations. The locomotor training protocols of only six cosmonauts corresponded to the recommendations over the course of the entire flight.

The main alternative to the recommended high-intensity interval regimen on ISS flights consisted of jogging-type locomotion aimed at training aerobic endurance, which is notable for its lower intensity and energy cost and significantly lower prevention efficacy. The choice of this as the primary form of exercise seemed to be because it was less difficult to perform, and because it was possible to combine steady-state running with watching movies, listening to music, etc. To compensate for the insufficient efficacy of this exercise, some cosmonauts significantly increased their locomotor loading.

Between 30 to 40 d before completing their flights, all Russian ISS crewmembers, with rare exceptions, switched to the recommended training protocols for the final phase, according to which locomotor training sessions were to be performed twice a day per the regimen of the first day of the microcycle. To illustrate the wide distribution of locomotor training sessions accomplished during LDS, **Fig. 3** shows a diagram of one cosmonaut who was part of the group of Russian ISS crewmembers with the best postflight health and conditioning indicators. Analysis of LDS data from the Russian stations, which included 28 crews on the Mir station, showed that an intensive physical training regimen assured increased orthostatic tolerance and normalization of vascular tone postflight.

Cosmonauts also varied significantly in their use of the passive treadmill belt mode versus the active or motorized mode. It was recommended that approximately 25–30% of exercise should be in passive belt mode, as the belt resistance in this mode is greater and the mode itself provides greater loading. However, for ISS cosmonauts, the overall amount of locomotor exercise in passive mode varied from 13 to 30%.

ISS cosmonauts devoted significantly less time and attention to exercising on the cycle ergometer than was the case on Mir. As a rule, the cycle ergometer saw intensive use only before monthly testing of general work capacity and in the preparatory period for EVA as hand pedaling for training the arms. Only two cosmonauts used the cycle ergometer "nominally" in strict compliance with the recommended protocols as a necessary addition to TVIS training sessions, even during the final flight phase.

In the first ISS increments, cosmonauts performed resistive exercises using the Russian strength trainer, bungees, and resistance bands; starting with ISS-19, they used two U.S. devices, the Interim Resistive Exercise Device and the Advanced Resistive Exercise Device (ARED), according to the protocols recommended by the U.S. side. These protocols included squats and a number of other exercises. In accordance with the recommendations of Russian specialists, the majority of Russian cosmonauts performed resistance training 2 to 3 times per week, alternating it with cycle ergometer training. In reality, the degree of use of the ARED varied significantly, depending on the cosmonauts' individual preferences.* It was used most intensively by three Russian crewmembers; one spent more time exercising on ARED than on locomotor training. Meanwhile, a number of other cosmonauts used it less while some did not use it at all.

Passive countermeasures have been used rarely on ISS flights. This occurred, as a rule, only in cases when their use was dictated by limited opportunities to perform locomotor training for one reason or another. The Penguin-3 loading suit, regularly used by Mir crewmembers, has been used much more rarely on the ISS. The exceptions have been cosmonauts whose relatively large size prompted the need to prevent the expansion intrinsic to microgravity (particularly in the vertebral column) to maintain their fit into the Kazbek protective seats used during landing. All Russian cosmonauts who were tall periodically wore the Penguin suit, using it particularly during the last month of flight. The Chibis pneumatic vacuum suit, the Kentavr G-Suit, and water and salt supplements, which ensure safe landing and greater tolerance to g loads during the descent phase, were used by all Russian crewmembers precisely in accordance with crew procedures.

The Russian countermeasures system has confirmed its high efficacy in long-duration ISS increments. Despite the frequent failures of exercise equipment (particularly during the first 10 increments) and the individual variations noted in the use of countermeasures, the health of Russian crewmembers during flight and postflight was evaluated as good, or more rarely, only satisfactory. The crew of ISS-6, whose spacecraft performed a ballistic descent and landed 500 km (310 mi) from the calculated site, was forced to wait for the rescue team for several hours. Even in those conditions, a Russian crewmember was able to exit the descent module without help and assist the others.

Similar to long-duration expeditions on other Russian space stations, crewmembers on the ISS demonstrated varying degrees of reduced physical performance, orthostatic tolerance, coordination, sensory, and vestibular-vegetative dysfunction postflight.[11] Moreover, the extent of the changes in the activity of the cosmonauts' various bodily systems during flight and in the postflight period exhibited a direct

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* It should be noted that monitoring the fulfillment of this part of the countermeasures program still poses great difficulty in light of the fact that the training equipment does not have a reliable system for downlinking data to the ground about the real loads created by the training device.

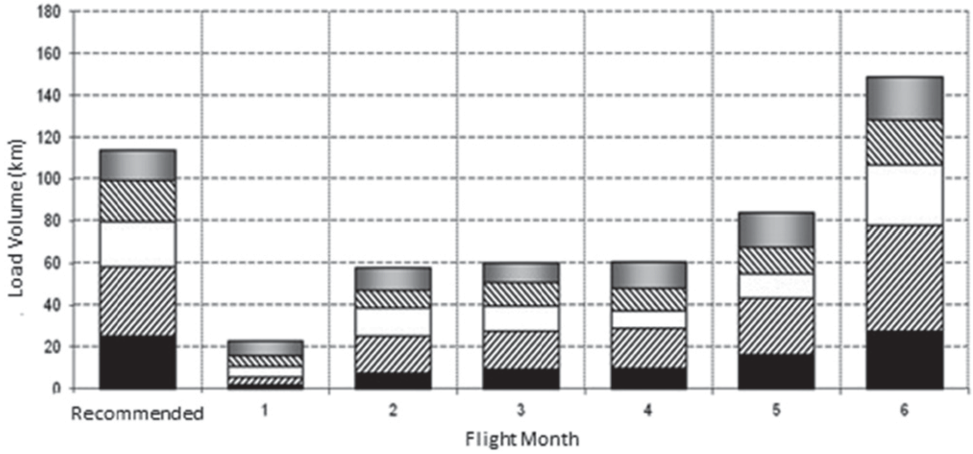


Fig. 3. Distribution of the scope of locomotion in various periods of flight. Black sections = active run, V = 5.5-9.0 km/h; sections with left-hand stripes = active run, V = 9.0-15 km/h; white sections = passive run, V = 6.0-8.0 km/h; sections with right-hand stripes = active walk, V = 4.0-5.5 km/h; grey sections = active walk, V = 4.0-5.5 km/h.

correlation with how fully and closely they respected the countermeasures program.

The experimental rationale for the varying effectiveness of the locomotor exercise regimens used by cosmonauts in flight was developed during the Profilaktika experiment on board the ISS, in which 14 Russian cosmonauts from 12 expeditions participated.[19] The cosmonauts split into two distinct groups (A and B), with roughly the same number of members, according to the type of locomotor training. Group A consisted of cosmonauts performing intensive training with a large number of transitions from walking to high-speed running (interval training). Group B consisted of cosmonauts who performed steady-state aerobic exercise in the moderate intensity zone. The effectiveness of each exercise regimen was assessed using a test program based on the tests described above with increasing loads on TVIS ([MO]-3) and the cycle ergometer ([MO]-5). Heart rate and ventilation volume were recorded at rest, when performing work, and in the recovery period. At the first and fifth minute of recovery, the presence of lactate in capillary blood was also determined. In the locomotor test, the maximum running speed and the coefficients of the ratio of maximum heart rate, maximum ventilation volume, and lactate at 1 min of recovery after maximum running speed were taken as the performance criteria. The use of these coefficients was dictated by the requirements for standardizing the cost of loading, as the [MO]-3 test allowed cosmonauts to select their speed of locomotion; consequently, they varied from one to another. Tests were performed on LDS crewmen once before launch and four times during flight at intervals from FD 30 to 40, FD 60 to 80, FD 110 to 120, and 30 d before the flight ended (R-30). After the flight, testing was performed on R+8 through R+11, depending on the cosmonaut's condition.

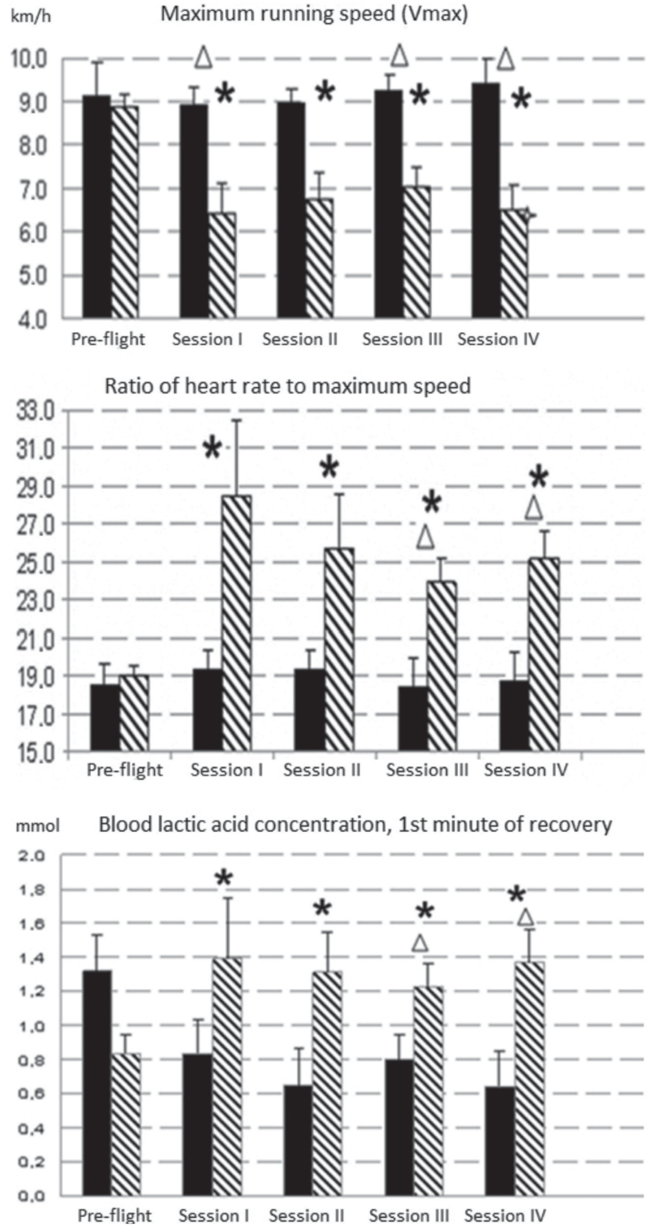
As shown in **Fig. 4**, before flight, maximum running speed in the groups did not differ significantly. Yet during flight, Group A's maximum running speed did not change throughout the flight, while this indicator for Group B was lower, differing significantly from both the baseline speed and the speed in Group A (Fig. 4). In all in-flight sessions, in the first, third, and fourth sessions, this indicator for Group B was significantly lower than in Group A.

The coefficients of heart rate/maximum running speed during the in-flight testing of Group A did not differ from baseline values. Meanwhile, in Group B, throughout the flight, they were significantly ($P < 0.03$) higher than baseline, which evidenced the increased physiological cost of locomotion (Fig. 4). The difference in the coefficients of heart rate/maximum running speed between the two groups of cosmonauts, which did not exist in the baseline, reached a significant level.

There was an interesting dynamic in the level of lactate in capillary blood during the course of the flight. Before flight, both groups had levels of about 1.0 ± 0.1 mmol $\cdot$ L^{-1} in the first minute of the recovery period after the locomotor test. For all in-flight testing sessions, Group B's blood lactate levels, normalized for speed, were significantly elevated, while Group A's levels were lower (Fig. 4). The difference between the groups for this indicator in the third and fourth in-flight sessions was statistically significant, which indicates that Group B exhibited a greater proportion of anaerobic processes during test loading and, consequently, their level of physical performance was lower. Postflight, only three of the eight cosmonauts in Group B were capable of performing the locomotor tests on R+5 through R+8, which demonstrated the significant decrease in the performance level in the "aerobic" group, and also significantly hampered comparisons of the postflight test results between the groups.

The results of the cycle ergometer test matched the data from the locomotor test: the differences between the two groups' indicators of the physiological cost of work and ventilation volume increased over the course of the flight, reaching a level of significance by the final in-flight sessions. Moreover, a comparison of data from the two tests distinctly demonstrated the greater sensitivity of the locomotor test. Analogous results were obtained in tests with graded physical loading on the cycle ergometer ([MO]-5 test). In Group A, out of 70 tests, only 21 (i.e., 30%) were evaluated as "satisfactory," while 70% of test results were "good." In Group B, whose members used aerobic locomotor training, the percentage of tests with "satisfactory" evaluations was 86%, and only 14% were rated as "good."

The results of postflight research correlated well with the in-flight data. For example, during moderately paced locomotor testing (90 steps/min), the amplitude of the EMG for the three main muscles of the lower leg—the tibialis anterior, gastrocnemius, and soleus—increased markedly in the aerobic training group (Group B), which indicated a reduction in the strength of the locomotive muscles, both for the flexors (tibialis) and


Maximum running speed (Vmax)

Ratio of heart rate to maximum speed

Blood lactic acid concentration, 1st minute of recovery

Fig. 4. Pattern of changes in [MO]-3 test parameters, top to bottom: maximum running speed, heart rate, and lactate level in the capillary blood of cosmonauts in Groups A (black columns) and B (striped columns) during flight, where * is the difference from baseline, $P < 0.01$, and the white triangle is the difference between the two groups of cosmonauts, $P < 0.05$.

extensors (soleus). These changes were distinctly evident in Group B both on R+5 and R+8. Meanwhile, in the interval running group (Group A), the changes in the electromyographic cost of locomotion were not significant on R+5; on R+7 they were completely absent.

According to osteodensitometry data, the mineral density losses in the area of maximum losses were significantly greater in the aerobic locomotion group.[**] This finding implies that the locomotor protocol (i.e., treadmill) protected skeletal integrity better than cycle ergometer exercise.

Development of Countermeasures Equipment and Methods

Flights on the ISS also served as a platform for future development of Russian countermeasures. First and foremost, this concerns both the improvement and expansion of the assortment of exercise equipment. Specialists from IBMP developed the Stimul-01 M low-frequency electrical muscle stimulator and delivered it to the station, having previously received a positive evaluation in a pilot experiment performed by cosmonauts G. Padalka and S. Avdeyev on the Mir station (Padalka G, Avdeyev S. Unpublished experiment, August 1999). Comparative evaluation of the effectiveness of low-frequency stimulation of the muscles in the lower extremities versus high-frequency myostimulation in 7-d “dry immersion” and strength training on the “MDS” multifunction trainer during a 105-d isolation also showed superiority of the Stimul-01 M for prevention of motor dysfunctions.

Work has continued on improving the design and methodology of the “support unloading compensator,” which provides mechanical stimulation to the support areas of the soles of the feet in natural locomotion modes. Physiological tests of various modifications of the apparatus and modes for its use during dry immersion have demonstrated its high effectiveness for preventing the negative effects resulting from unloading of the locomotor system. The device has passed all technical tests and is being prepared for testing on board the ISS.

A modified version of the Penguin axial loading suit, which is equipped with a system for the objective registration of forces, has passed testing on board the ISS and been included in the onboard equipment. Evaluation included assessing the effects of loads that varied in both magnitude and direction. In particular, it was demonstrated that when using the asymmetric loading mode, with a greater load on the front half of the body, the crewmember attempts to maintain a vertical position and voluntarily exerts the muscles of the back, the backs of the thighs, and the calves, which creates a significant training effect in them.

The creation of a new treadmill, the БД-2, is complete; its technical specifications were developed jointly by Russian and U.S. specialists, taking into account all the comments and requirements that arose during TVIS operation, and the results of a comprehensive search for new technical approaches and solutions. The IBMP staff, together with Austrian specialists from the University of Vienna's Centre for Sport Science and the Vienna University of Technology, developed a resistive training device that provides the capability for exercises that load the legs, back, and arms eccentrically, concentrically, and isometrically.[15] The maximum load generated on the training device is 250 kgf (550 lbf). In concentric and eccentric modes of operation, the device can be controlled by speed: 0.15, 0.3, and 0.6 $m \cdot s^{-1}$, with the control panel displaying all necessary training parameters: operating mode, load, type of exercise, number of repetitions, rate of performing the exercise, duration of training session for each exercise, and current time. Significant changes have been made to the system to enable the tracking of training.

[**] Study data kindly provided to us by V. S. Oganov.

As indicated previously onboard the ISS, locomotor speed and heart rate during exercise on the treadmill were recorded on a daily basis for the first time. Daily monitoring has made it possible to more precisely determine the crewmembers' levels of conditioning and better assess the advantages and disadvantages of the training process. Flights on the ISS have also made it possible to determine prospects for future developments, chief among which are optimizing the conditions for physical training (volumes, temperature, air environment, humidity), improving training equipment, expanding the assortment of countermeasures equipment and methods, and increasing their convenience. One important task for improving the countermeasures system is to further automate the processes that control physical training; at its heart lies the development of an expert computerized system for the assessment of crewmembers' physical parameters to guide modification of exercise protocols, taking into account the capabilities of the training equipment available on the station.

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