THE ROLE OF FAST RUNNING IN PREVENTION OF NEGATIVE EFFECTS OF PROLONGED EXPOSURE TO WEIGHTLESSNESS

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The prospects of deep space exploration necessitate modification of the principles and methods underlying the system designed to prevent negative impact of weightlessness on the human body. This work aimed to determine how fast running, as part of locomotor training during a space flight (SF), helps maintain physical ability of a person. The study involved 10 cosmonauts; their physical performance was assessed at all stages of the SF with the help of the Individual Strategies Test (IST). The parameters registered when the participants were doing the IST included heart rate (HR), gas exchange, capillary blood lactate concentration. The cosmonauts were divided into two groups based on the differences in the mean distance covered while fast running on a treadmill (single session). Group A ($n = 4$) run 949 m/day on average, group B ($n = 6$) — 2669 m/day. After SF, HR in group A increased at speeds from 5 to 8 km/h ($p < 0.05$), pulmonary ventilation indicators grew at speeds from 8 to 15 km/h ($p < 0.05$), and the capillary blood lactate concentration measured during the post-test recovery period increased by 37% ($p = 0.03$). Moreover, after SF, the pulse sum recorded under load and during recovery was 14% ($p = 0.02$) and 15% ($p = 0.03$) in group A, respectively, while in group B we registered no differences. Thus, our hypothesis that fast running triggers sensory reactions simulatingEarth conditions for the body, which consequently activates physiological mechanisms counteracting the negative effects of weightlessness, has been confirmed in a space experiment.

Keywords: locomotor training, physical activity test, physical performance, space flight, ergospirometry

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Compliance with ethical standards: the Profilactika-2 experiment was approved by the Ethics Committee of the Institute of Biomedical Problems (Minutes #368 of August 22, 2014). All participants signed a voluntary informed consent form.

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РОЛЬ БЫСТРОГО БЕГА В ПРЕДОТВРАЩЕНИИ НЕГАТИВНЫХ ВЛИЯНИЙ ПРЕБЫВАНИЯ ЧЕЛОВЕКА В НЕВЕСОМОСТИ

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Перспектива освоения дальнего космоса определяет необходимость модификации принципов и методов системы профилактики негативного влияния невесомости на организм человека. Целью исследования было определить роль бега с высокой скоростью во время локомоторных тренировок, выполняемых в ходе космического полета (КП), в сохранении уровня физической работоспособности человека. В исследовании приняли участие 10 космонавтов. Оценка физической работоспособности проводилась на всех этапах КП на основе теста «Индивидуальные стратегии» (ТИС). Во время выполнения ТИС регистрировались частота сердечных сокращений (ЧСС), параметры газообмена, концентрация лактата в капиллярной крови. Космонавты были разделены на две группы на основе различий в среднем объеме бега с высокой скоростью в ходе одной тренировки на дорожке. В группе А ($n = 4$) средняя дистанция быстрого бега составила 949 м/день, в группе Б ($n = 6$) — 2669 м/день. ЧСС в группе А после КП увеличилась на ступенях от 5 до 8 км/ч ($p < 0{,}05$). Повышение легочной вентиляции после КП наблюдалось в группе А на ступенях нагрузки от 8 до 15 км/ч ($p < 0{,}05$). После КП концентрация лактата в капиллярной крови в периоде восстановления после теста в группе А увеличилась на 37% ($p = 0{,}03$). Пульсовая сумма работы и восстановления оказались выше после КП в группе А на 14% ($p = 0{,}02$) и 15% ($p = 0{,}03$) соответственно, в то время как в группе Б различий не обнаружено. Таким образом, наша гипотеза о том, что бег с высокой скоростью воспроизводит сенсорный приток, сопоставимый с условиями Земли, и, как следствие, обеспечивает включение физиологических механизмов, противодействующих негативному влиянию невесомости, подтверждена в космическом эксперименте.

Ключевые слова: локомоторные тренировки, тест с физической нагрузкой, физическая работоспособность, космический полет, эргоспирометрия

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Development of methods of preservation of health and physical ability of cosmonauts during long space flights is a key task for space medicine [1–4]. Preparation for Moon and Mars missions, or survival scenarios in the event the ship lands in an unplanned place, substantiate the quest for ways to maintain high levels of cosmonauts' performance , to support functional reserves and reliability of their bodies, to ensure effectiveness of their actions when discharging complex extravehicular tasks on the surface. Prolonged exposure to weightlessness affects cardiovascular [5–10], respiratory [11], and musculoskeletal [12–14] systems; thus, prevention of the negative effects thereof should be aimed to all of them. Data collected during space flights and from simulations indicate that in axial unloading, translates into sensory deprivation degrading regulation of the support afferentation, which subsequently leads to atony, muscle fiber atrophy, and compromises the vestibular system [14, 15]. Proprioceptive and tactile inputs enable postural control, therefore, activating the respective systems and keeping them "tuned" to maintaining vertical balance with the help of running in zero gravity can help improve the ability to perform functional tasks after the flight [16, 17]. Thus, intensive physical training designed to counteract the weightlessness-induced negative changes in the functioning of gravity-dependent physiological systems is a mandatory component of medical support during long space flights [16, 18–20].

Previously, we determined the values of axial load and the volume of locomotion needed to move treadmill in the passive mode using leg strength, which translates into an effective locomotor training during space flight [21]. This study aimed to assess the role of fast running on a moving treadmill in the context of locomotor training effectiveness. In our opinion, countermeasures to the negative impact of weightlessness can take form of the work that simulates keeping weight elevated or moving it in the conditions of the Earth. It can be said that the preventive efficacy of the method revolves around mechanical work that creates conditions reproducing the effects of gravity and generates the respective sensory inputs. In weightlessness and with lack of mechanical loading, only intensive exercising activates metabolic and functional systems to the levels comparable to those specific to Earth conditions. The purpose of this study was to determine the role of fast running in maintaining a person's physical performance during a long-term space flight.

METHODS

Characteristics of the examined individuals

The article presents results of the Profilaktika-2 experiment conducted during a space flight. The study involved 10 cosmonauts (age 44 ± 6 years, weight 84 ± 6 kg, duration of space flights 173 ± 33 days). The inclusion criteria were gender (male), and space flight duration (about 6 months). The exclusion criteria were incomplete or untimely completion of the experiment sessions, and significant deviations from training protocols designed for the space flight.

Prevention of negative effects of weightlessness during space flight

The method for prevention of the negative effects of weightlessness relies mainly on physical training. During the space flight, they consumed 2.5 hours a day on average, including preparations and hygienic procedures. According to the onboard documentation, the cosmonauts did two physical training sessions every day. BD-2 treadmill (Institute of Biomedical Problems; Russia) was used on a daily basis, and VB-3M ergocycle (Institute of Biomedical Problems; Russia) and ARED exercise device (NASA; USA) were alternated every other day.

Treadmill sessions are a key element of the countermeasures against hypogravity disorders developed for Russian cosmonauts. The on-board treadmill training protocols for a four-day microcycle were compiled based on the simulations run in the Earth conditions [22]. After introduction of the BD-2 treadmill, they were modified slightly, but still suggested alternating intervals of high-intensity running and walking. Strictly speaking, in accordance with the existing classification of training methods, all exercises under the protocols imply a pattern that alternates different maximum running speeds and physical exercise levels conditioned by the proportion of time when the treadmill is in passive-mode, i.e., it is rotated only by the strength of the cosmonaut's legs. BD-2 treadmill can work in active mode, i.e., it is driven by a motor, and in passive mode, when it is rotated by strength of the cosmonaut's legs.

All treadmill training protocols prescribed a warm-up of 4 minutes, which is running at 7 km/h, then — physical loading with the treadmill in passive mode, which is walking and two 2-minute sessions of running at 6-8 km/h.

The final component included 2 minutes of walking at 5 km/h, then running for 2 minutes at 8 km/h with treadmill in the active mode, then walking in the passive mode for 1 minute.

The main partof the treadmill training protocol changed on different days of the microcycle:

Day one — four 1-minute fast running takes (at 14 km/h), alternating with 2-minute walks.

Day two — two 2-minute passive mode running takes (at 8 km/h), one active mode running take (at 12 km/h), alternating with 2-minute walks.

Day three — 4-minute running takes (at up to 13 km/h), alternating with 2-minute walks.

There were no exercises prescribed for day 4, except for individual locomotor training.

Most of the participants followed the above-described protocols in their prevention activities; on the fourth day, four cosmonauts did not abstain from physical activity but started the microcycle anew, two cosmonauts worked out under individual protocols (interval training), and two more preferred to rest. Two cosmonauts who were in space for the fourth time followed a individuallocomotor training program that spanned 7 days, with the last day being Sunday, a day of rest.

The parameters of each training session during the long-term SF were analyzed based on the weekly ergometric and physiological data, the analysis yielding further treadmill training recommendations. The response of the cardiovascular system to locomotor loads was registered as reflected in the heart rate (HR) recorded during training. When the flight was over, we calculated the mean values of each type of locomotion, monthly and overall (entire flight). Among the participating cosmonauts, the main parameters of treadmill training — the magnitude of axial load, the ratio of passive and active treadmill modes, the distance covered in a day — varied only slightly. The recommended axial load value was 70% of the body weight or more, and, for the most part, the participants took this recommendation into account. As for the modes, the share of passive mode varied through the microcycle and amounted to 30% over three days. One cosmonaut, who followed an individual training program, run with the treadmill in passive mode only for 8.2% of the total daily training time, while for all the other participants this value ranged from 23 to 41%. The distance covered during a session also varied through the microcycle and ranged from 3000 to 6000 m on different days.

For the strength training part enabled by ARED, all the cosmonauts had individual protocols. Initially, the load factored in the cosmonaut's body weight before flight, and during the flight it was adjusted to make the training process wavelike. Specialists supervising the program of countermeasures against negative effects of microgravity received information about exercises on ARED every week, and adjusted the workout routines.

As reported by the crew, they trained on the ergocycle following guidance from the on-board documentation, that is, alternating intervals of various intensity. Currently, there are no systems enabling transmission of objective information about the magnitudes of loads and the response of cardiovascular system to physical exercise on the ergocycle.

Experimental groups

The cosmonauts were divided into two groups based on the duration of fast running intervals. Pre-flight, locomotor tests revealed no differences between the groups.

During the flight, in group A (n = 4), the average distance covered while running fast, with treadmill in the active mode, was 949 m per day, while group B (n = 6) covered 2669 m per day under similar conditions.

Test procedures

The cosmonauts' physical performance was assessed on the basis of the IST 30 days before the flight, 3–4 times during the flight (42–68, 83–113, 115–131 and 140–156 days thereof), and 10 ± 2 days after its completion [23]. The IST followed a standard protocol and employed the BD-2 treadmill in active mode; the components thereof were a warm-up with alternating intervals of walking at 3 km/h and 6 km/h in a pseudo-randomized sequence, and an interval of growing load, from 3 km/h to 15 km/h, with the speed increasing for 1 km/h every 30 seconds.

During the test, heart rate was recorded using Polar (Polar; Finland) and Cardiocassette-2010 (Institute of Biomedical Problems; Russia). Ergospirometry (Earth conditions) was enabled by Oxycon Mobile (Jaeger; Germany), "breath-by-breath" method. The lactate content in capillary blood was measured using the Lactate-2 kit (Institute of Biomedical Problems; Russia), at rest before the test, then at the first and fifth minutes of the post-test recovery period.

The functional reserves of the cardiovascular system were assessed based on the total heart rate under load (area under the heart rate curve for the entire IST) and that during the recovery period (area under the heart rate curve reflecting the 5 minutes of recovery after the test). The said totals were sums of the heart rate values, which were registered every 10 seconds during the test and through the 5 minutes of the subsequent recovery.

The "heart rate deficiency" value was calculated as the difference between the number of recovery period heartbeats and that peculiar to relative rest [24]. This indicator reflects the post-exercise physiological and metabolic changes in the body. We also calculated the delta heart rate that shows the difference between maximum heart rate and resting heart rate.

Statistical data processing was performed using Minitab 19.1 (USA); it included checking the distribution in samples with the help of the Shapiro–Wilk test, calculating indicator means and variance (one-way ANOVA). The results were considered significant at $p < 0.05$ under the Fisher test or the Tukey test. We considered only the significant differences in the results.

RESULTS

Before the space flight, the groups were similar in all the studied indicators. Compared to the pre-flight data, heart rate increased significantly in group A at each load increment from 5 km/h to 8 km/h post flight. No such changes were registered in group B (Fig. 1). The post-flight IST did not reveal differences in heart rate between groups A and B.

In group A, compared to the pre-flight values, we registered a significant growth of pulmonary ventilation at each load increment from 8 km/h to 15 km/h (Fig. 2). In group B, this parameter was higher than before the flight only at the load increments of 9 km/h and 10 km/h. Compared at each load increment, the groups exhibited no differences in terms of pulmonary ventilation post-flight.

Comparing the respective pre-flight and post-flight data, we registered increased capillary blood lactate concentration

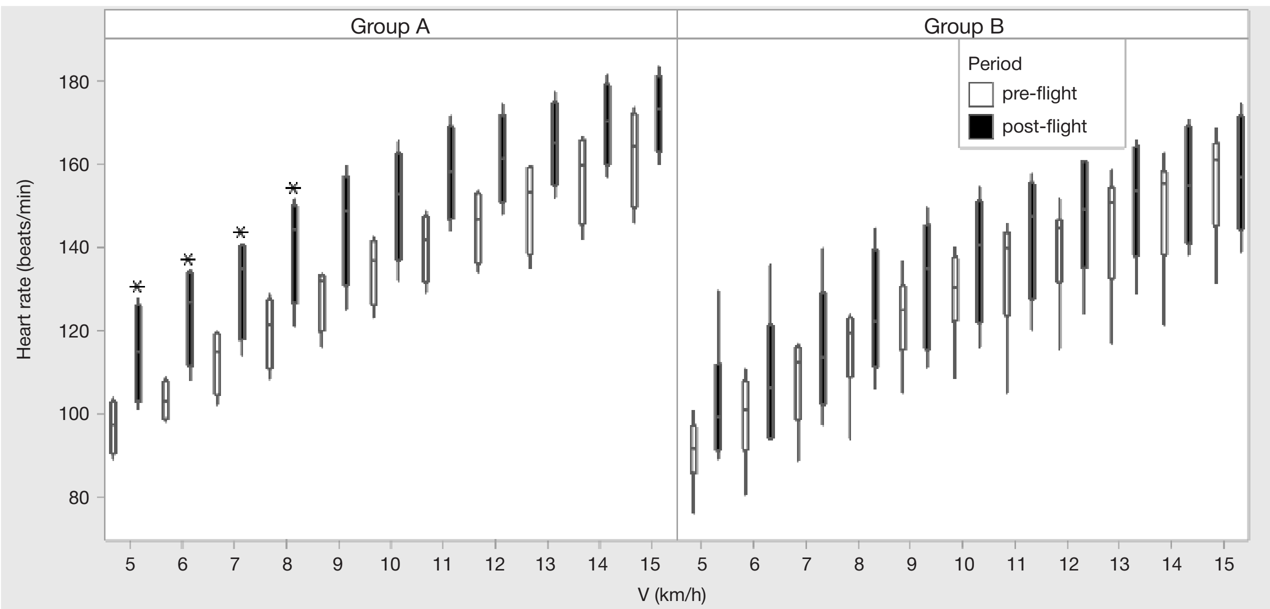

Fig. 1. Heart rate as registered with the IST before and after the space flight. * — compared to the preflight level in the group, $p < 0.05$

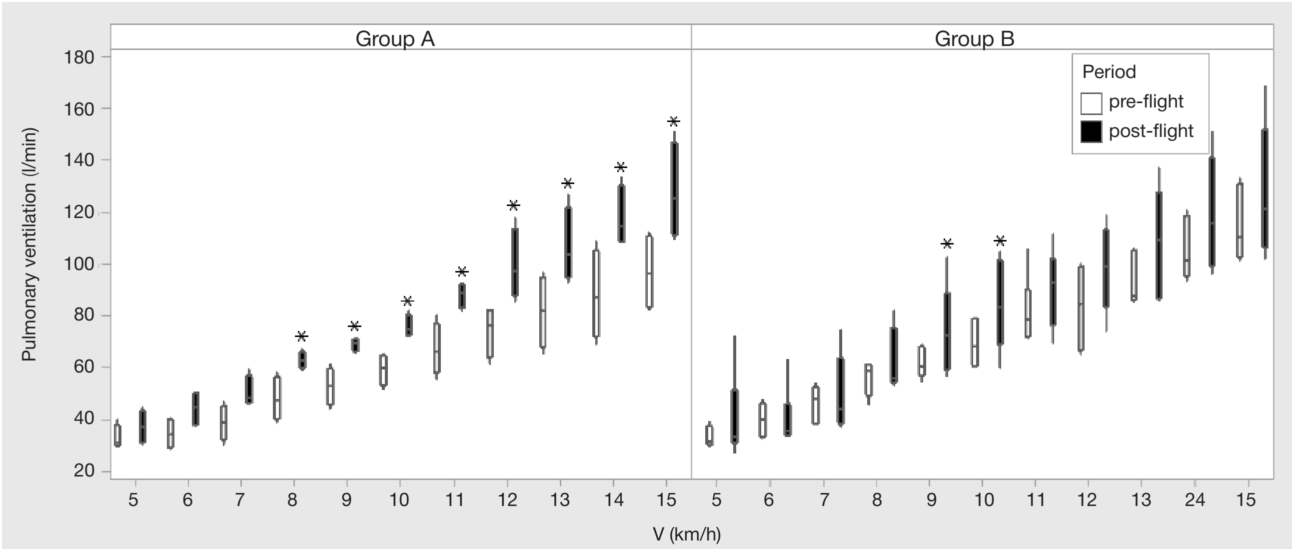

Fig. 2. Pulmonary ventilation before and after the space flight, as registered with the IST. * — compared to the preflight level in the group, $p < 0.05$

during the first minute of recovery (5.3 ± 1.6 before flight and 8.5 ± 3.4 mmol/L after flight, $p = 0.03$) in group A, and in group B these values did not differ significantly (5.3 ± 2.7 before flight and 6.7 ± 3.4 mmol/l after flight). We believe that higher capillary blood lactate concentration indicates flaws in utilization of this metabolite during exercise in group A, which means their level of physical ability was lower after the flight (Fig. 3).

At the final stage of the flight (days 140–156), we registered intergroup differences in the total heart rate values: they were 19.4% (17,897 ± 529) higher in group A than in group B (14,678 ± 3148) ($p = 0.009$).

Post-flight, the total heart rate value in group A was higher than the background value recorded before the space mission: 16,475 ± 1257 and 19,143 ± 1972, respectively ($p = 0.02$). In group B, the differences in this indicator were insignificant: 14,983 ± 1572 before the flight and 16,148 ± 2651 after the flight (Fig. 4).

At the final stage of the flight, the total recovery heart rate value was higher in group A than in group B: 2838 ± 188 and 2181 ± 490, respectively ($p = 0.009$) (Fig. 5).

Post-flight, the total recovery heart rate value in group A was 3027 ± 405, which is higher than what was registered in this group before the flight (2575 ± 326, $p = 0.03$) and more than seen in group B after the flight (2599 ± 350, $p = 0.02$).

Analysis of the heart rate deficiency, oxygen consumption, carbon dioxide release and maximum respiratory rate before and after the flight revealed no significant differences between the groups and within them.

DISCUSSION

We hypothesized that the effectiveness of prevention of the negative effects of weightlessness depends on the degree of reproduction of action of gravity. If the preventive measures bring around internal and external sensory inputs comparable to those peculiar to the Earth conditions, the body's gravity-dependent systems function nearly as if it had weight. The respective effects are reproduced most accurately when a cosmonaut is running on a treadmill in the special training suit that simulates 60-70% of his Earth body weight, exerting the load along the vertical axis. A person standing or performing locomotions on a treadmill works out, but the intensity of this training in space flight conditions is significantly lower than on Earth, mainly because the magnitude of axial load usually does

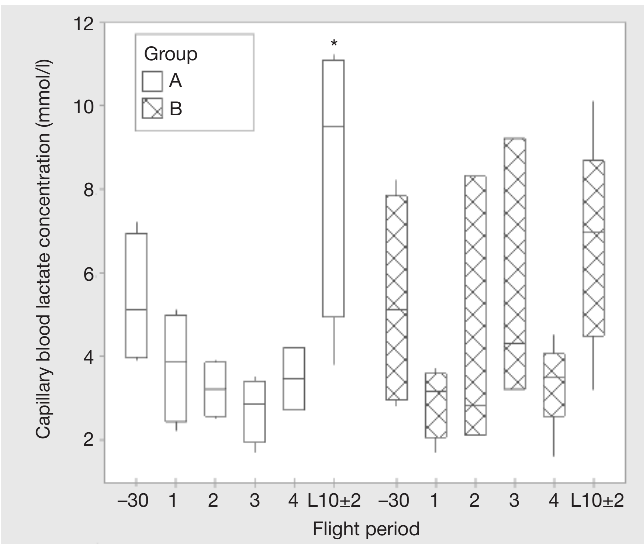

Fig. 3. Capillary blood lactate concentration, first minute of recovery after the IST. * — compared to the pre-flight level in the group, $p < 0.05$; 1 — days 42–68, 2 — days 83–113, 3 — days 115–131, and 4 — days 140–156

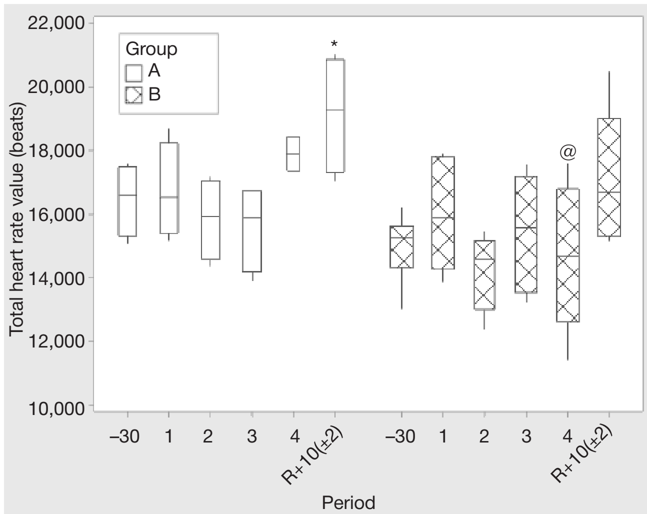

Fig. 4. Total heart rate value registered during the IST. * — $p < 0.05$ compared to the background value in the group; @ — $p < 0.05$ in comparison with the value of the same flight period in group A; 1 — days 42–68, 2 — days 83–113, 3 — days 115–131, and 4 — days 140–156 of the flight

not exceed 70% of that person's body weight on Earth. We have previously shown that running at the speed of 7 km/h in space triggers response from the body's support systems consistent with its weight at 1G [21]. Thus, in order to launch the physiological mechanisms governing muscular activity, and to have the respective vegetative system functioning in the mode resembling that peculiar to the Earth conditions, it is necessary to run at high speed. Obviously, the greater the physical load, the higher the physiological load. If a person's body is not only held upright, countering gravity simulated with the training suit, but also moves, then the physiological load increases, and the preventive effect is more pronounced. Based on the above, it was suggested that the proportion of fast running will play a role in maintaining the cosmonauts' physical performance after a long exposure to weightlessness.

Earlier, we have shown that alternating intensity in a training session (intervals of fast running and walking) is more effective from the prevention standpoint than running at a constant speed [25], the result consistent with a study that involved cosmonauts [26] and the present study, which registered a higher level of capillary blood lactate concentration at the 1st recovery minute after a locomotor load in the group that had fewer fast running intervals during the space flight. The mentioned higher lactate concentration indicates that the subject is in an unstable metabolic state that shifts the acid-base balance, which may be associated disruptions of operation of nerve centers, lower level of activity of enzyme systems, and, consequentially, inhibition of muscles [27–29]. In the group that had more fast running spans in the protocols, concentration of lactate in the capillary blood during the post-test recovery period was at the pre-flight level, which, according to the concepts of sports physiology, means healthy functioning of the aerobic mechanisms supplying energy to muscles, and retention of the ability to utilize lactate [30]. Protocols with a greater proportion of fast running launched physiological mechanisms that preserve the aerobic system supplying energy to the muscles, and, as a result, anaerobic mechanisms were triggered at the later stages of the incremental loading test. Accordingly, there was no significant accumulation of lactate, which is a product of the glycolytic system supporting muscle activity.

Increased pulmonary ventilation registered at days 10 ± 2 post-flight during the test at increments from 8 km/h to 15 km/h, compared to the pre-flight data, accords with higher capillary blood lactate concentration and indicates an overstrain of the oxygen transport system in the group that had fewer fast running intervals during the space flight. Other studies have also reported increased pulmonary ventilation registered with an ergocycle test in astronauts on the 10th day after a long-term space flight [18, 31].

The results of this study clarify the concepts of mechanisms countering the negative effects of weightlessness. Fast transition from low- to high-intensity locomotor training activates the vegetative systems supporting muscle activity, which underpins the efficacy of the alternating load method described previously [25]. In this study, we factored in only the distance traveled at a speed of more than 9 km/h, and the transitions from low-intensity to high-intensity activity were disregarded. We assume that fast running with an axial load of about 70% of the Earth body weight effectively prevents the adverse influence of weightlessness, since this load, in terms of energy consumption and sensory inputs, is comparable with maintaining the body in an upright position or walking slowly under the Earth's gravity. Thus, running at a speed of more than 9 km/h, as we believe, triggers gravity-dependent physiological mechanisms by simulating the Earth weight conditions.

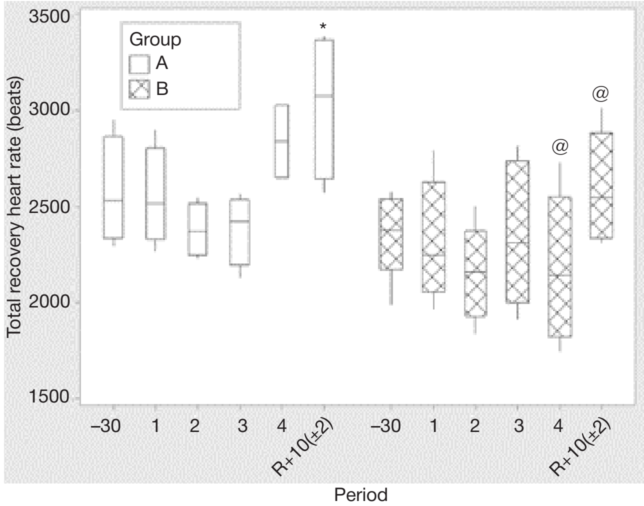

Fig. 5. Total recovery heart rate value registered during the IST. * — $p < 0.05$ compared to the background value in the group; @ — $p < 0.05$ in comparison with the value of the respective flight period in group A; 1 — days 42–68, 2 — days 83–113, 3 — days 115–131, and 4 — days 140–156 of the flight

There is a number of obvious limitations to a comparative analysis of the efficacy of countermeasures against adverse effects of weightlessness. It is possible to conduct a retrospective analysis of the effectiveness of training machines that were used earlier; such knowledge valuable, since some of them are still kept in the ISS as backups [32]. Earth-side simulations reproducing some effects of a space flight offer more extensive opportunities. One of such simulations is antiorthostatic hypokinesia (ANOG), which implies a supine position with the subject's head tilted down by 6°; ANOG simulations yield data on prevention of the negative effects of hypokinesia [33, 34]. A 90-day ANOG simulation experiment has shown that the most effective training program includes treadmill sessions with a vertical axial load of about 80% of the body weight and 80-90% of the maximum oxygen consumption, combined with high-intensity resistance training [34], which is consistent with results of our space experiment.

Our study identified new prognostic indicators in the IST, namely, the total heart rate value under load and the total recovery heart rate value; when these values were high during the space flight, the cosmonaut's physical ability post-flight was hindered. Countermeasures against negative effects of weightlessness will be more effective if these indicators are taken into account in the context of training supervision. In the interests of deep space exploration missions, it is planned to conduct studies investigating readaptation to Earth conditions in the earlier post-flight period and identifying the degree of applicability of the prevention methods used for an orbital flight.

CONCLUSIONS

Countermeasures against negative effects of prolonged exposure to weightlessness may be more effective if the cosmonaut has more sessions of fast running (speed of 9 km/h or faster).

The standard incrementally increasing locomotor load with the treadmill in active mode that allows registering the cardiorespiratory system's parameters provides data enabling prediction of the level of physical ability post-flight.

New predictors of the cosmonaut's physical ability after a long-term space flight are suggested, namely, the total heart rate value under load and the total recovery heart rate value, as registered with the help of a standard incrementally increasing locomotor load test.

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