Evolution of Russian Microgravity Countermeasures

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INTRODUCTION: Countermeasures to prevent or partially offset the negative physiologic changes that are caused by the effects of microgravity play an important role in supporting the performance of crewmembers in flight and their safe return to Earth. Research conducted in Russia on the orbital stations Salyut and Mir, as well as simulation experiments on the ground, have demonstrated that changes that occur during extended spaceflight in various physiologic systems can be prevented or significantly decreased by using countermeasures. Hardware and techniques used on the ISS have been substantially improved to reflect the experience of previous extended missions on Russian orbital stations. Countermeasures used during early ISS missions consisted of the U.S. treadmill (TVIS), cycle ergometer (ВБ-3), a set of resistance bands, a postural muscle loading suit (Penguin-3), electrical stimulator (Tonus-3), compression thigh cuffs (Braslet-M), a lower body negative pressure (LBNP) suit (Chibis), a lower body g-loading suit (Kentavr), and water/salt supplements. These countermeasures are described in this article.

KEYWORDS: microgravity, International Space Station, exercise, treadmill, cycle ergometer, LBNP, resistance bands, muscle loading, fluid loading.

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Countermeasures to prevent or partially offset the negative physiologic changes that are caused by the effects of microgravity play an important role in supporting the performance of crewmembers in flight and their safe return to Earth.[1,2] Research conducted in Russia on the orbital stations Salyut and Mir, as well as simulation experiments on the ground, have demonstrated that changes that occur during extended spaceflight in various physiologic systems can be prevented or significantly decreased by using countermeasures.[3–7] An important role is to decrease the effects of redistribution of blood and fluids both during microgravity and during the period of readaptation to the Earth's gravity. These countermeasures take the form of negative pressure applied to the lower body during flight, and positive pressure to the lower body during descent with a g-loading suit. Hardware and techniques used on the ISS have been substantially improved to reflect the experience of previous extended missions on Russian orbital stations. Countermeasures used during early ISS missions consisted of the U.S. treadmill (TVIS), cycle ergometer (ВБ-3), a set of resistance bands, a postural muscle loading suit (Penguin-3), electrical stimulator (Tonus-3), compression thigh cuffs (Braslet-M), a lower body negative pressure (LBNP) suit (Chibis), a lower body g-loading suit (Kentavr), and water/salt supplements.[6]

Treadmill (БД-2)

The foundation of the Russian program of onboard countermeasures in long-term spaceflight is exercise on the treadmill. The U.S. treadmill with the vibration isolation system (TVIS) was on the station when the ISS-1 crew arrived. The treadmill had not undergone operational testing, so during the first missions it did not support consistent implementation of the exercise protocol. During increments ISS-1 through ISS-6, the treadmill did not operate for 87 d due to the failure of the VIS system (8 d) and of the treadmill itself (79 d). There were constant constraints on maximum belt speed, longitudinal axial loading on the crewmember's body while running, and on the TVIS modes of operation.

Experts at the Institute of Biomedical Problems (IBMP) were tasked with creating backup means that could be used in the event of TVIS failure. A Russian treadmill was selected for this purpose because it had already been developed, produced, and undergone a complete cycle of ground testing to support

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crews on the Buran space vehicle. Treadmill БД-1 has a small volume and mass, did not require any onboard interfaces, was simple to operate and reliable, and its delivery did not require large financial outlays.[9] БД-1 was composed of the treadmill itself, a built-in restraint system, and a standardized training/loading suit (ТНК-У-1). The ТНК-У-1 was used together with the БД-1 restraint system to create a constant static load (up to 60% of body mass) along the longitudinal axis of the body. The ТНК-У-1 was certified for use with TVIS instead of the U.S. suit and was used on the ISS with TVIS by the Russian crewmembers of ISS-8 through ISS-12.

As TVIS neared the end of its operational life, U.S. and Russian experts grappled with the issue of developing and making new treadmills to replace it. Following an agreement in 2006, U.S. and Russian experts developed unified medical and technical requirements for any new treadmill. The U.S. treadmill T2 was developed and installed in the U.S. module in 2009. The new Russian treadmill was planned for completion in 2012.

The Russian treadmill БД-2 (**Fig. 1**) operates in the following modes: active (moving), passive (idle and braking), and with mechanical lock of the treadmill belt. Running speed on the treadmill can reach 20 kph (12 mph). The operating area of the treadmill belt is 400 mm (16 in) wide and 1080 mm (43 in) long. A passive vibration isolation system, comprised of a frame and eight shock absorbers (four main and four auxiliary) is used to isolate forces while walking and running. The treadmill's restraint system is capable of exerting longitudinal axial loading of 40 to 70 kg (88 to 154 lb) on the exerciser's body. A pressure plate was included with the design of БД-2 to measure the load-bearing reactions during running and walking, and to measure the initially set longitudinal load.

The control panel of the treadmill is a tablet computer with a touch screen. Software was developed to enable not only the typical running timelines indicated in crew procedures, but also the creation and tracking of individualized exercise protocols. The БД-2 provided the capability to measure and downlink the following parameters:

Fig. 1. Ground testing of treadmill БД-2 on a vertically-mounted test stand.

- heart rate, using the compatible heart rate monitor with an accuracy of ± 1 bpm;
- mode of exercise (active, passive, mechanical belt lock);
- treadmill belt speed with an accuracy of ± 0.1 kph, distance with an accuracy of ± 1 m, and total exercise time ranging from 0 to 99 min with an accuracy of ± 1 min;
- exercise time in active and passive modes with an accuracy of ± 10 s;
- longitudinal axial load (0 to 70 kgf) exerted by the restraint system on the crewmember, with an accuracy of ± 0.2 kgf; and
- load-bearing reaction forces and moments in the three axes (Fx, Fy, Fz; Mx, My, Mz) that occur during walking and running (0 to 300 kgf with an accuracy of ± 0.5 kgf and 0-100 N-m, with an accuracy of ± 0.3 N-m).

Cycle Ergometer

The Russian countermeasures program on the ISS also includes exercise on the cycle ergometer (ВБ-3). The ВБ-3 is composed of a seat with restraints for the crewmember, a control panel, and a generator assembly on the pedal shaft. The cycle ergometer has 3 modes of operation: idle, operating, and free movement.

Idle is operation of the generator without loading. In this case, power exerted on the pedal shaft is spent in overcoming the resistance of the gears, loss in the generator, and the small amount of electrical power needed to power the device's electrical circuit. Operating mode corresponds to operation of the generator under loading and is set on the control panel. Free movement corresponds to rotation of the pedal shaft in the direction opposite its rotation during idle mode and under loading, and is enabled using a free movement coupler.

The ВБ-3 provided the necessary load on the pedal shaft and measured operating time and theoretical distance cycled. Telemetry downlinked the load that was set and pedal rotation speed. A unique, important aspect of the ВБ-3 is that the loading is without inertia; in other words, the load remains constant and equal throughout the entire pedaling cycle.

Power on the cycle ergometer pedal shaft can be set incrementally: 50 (idle), 100, 125, 150, 175, 200, 225, and 250 W with a consistent accuracy of ± 5% throughout a range of rotation speeds starting at 40 rpm. When using the ВБ-3, its control panel displays the following parameters: pedal shaft rotation speed, rpm; set load power, W; total exercise operating time, hours/minutes/seconds; operating time at a given load, hours/minutes/seconds; work output during exercise, $W \cdot h^{-1}$; and theoretical distance cycled, km. The accuracy of measuring time intervals was at least ± 0.5%; for work and theoretical distance, it was at least ± 10%. The cycle ergometer ВБ-3 operates on autonomous power and its mass is less than 25 kg (55 lb).

At the onset of ISS operations, the cycle ergometer control panel had a liquid crystal display, whose use during low ambient lighting led to constant complaints from crewmembers that the display was not readable. In response, a new panel was subsequently developed with a button for switching loads but without a display of pedal shaft rotation speed. The new panel and the control unit required to support its operation were delivered to the ISS in 2004. However, this upgrade did not resolve the issue of the constant malfunctioning of the cycle ergometer, so in 2010 the modified ВБ-3М (**Fig. 2**) was delivered to the ISS. The output specifications were retained, while a series of changes were made: contact pedals were added to the cycle ergometer to attach cycling shoes, two fans were installed to cool the loading unit on the cycle ergometer frame during operation, and a display of pedal shaft rotation speed was added to the control panel.

Force Loader

The ban on using the TVIS belt for exercise with resistance bands to load various muscle groups required development of a separate force loader for Russian cosmonauts. This force loader (HC)-1 was installed in July 2002 on the ВБ-3. The (HC)-1 made it possible to exercise by loading the arms, legs, and back concentrically (overcoming resistance). The loader is composed of a control panel, power unit, loaders 1 and 2, four removable rollers, and a support plate, which were delivered to the ISS in December 2005. Each of the two loaders on this device provides maximum loading of 30 kg (66 lb) and minimum loading of 5 kg (11 lb). The operating principle is to create resistance to the force of movement against a set load on the control panel. The control panel displayed the set load during exercise, the number of repetitions, and operating time in the given mode. All components of the force loader (HC)-1 were installed on the cycle ergometer ВБ-3.

The force loader supports the following exercises: rowing, hammer throw, "the saw," forearm curls, and trunk flexion and extension. The loader is powered from the station network.

Following crew comments on the lack of smoothness and significant asymmetry of loading, the (HC)-1 was upgraded to the (HC-1M). The main output specifications of the loaders were retained but the following changes were made: the dimensions of the control unit and panel were decreased, the control panel display was replaced with a touch screen, the loading asymmetry and lack of smoothness during exercise were eliminated, a holder bar was added, and the capability to record exercise results and downlink them was provided. The new force loader (HC-1M) is planned for delivery to the ISS.

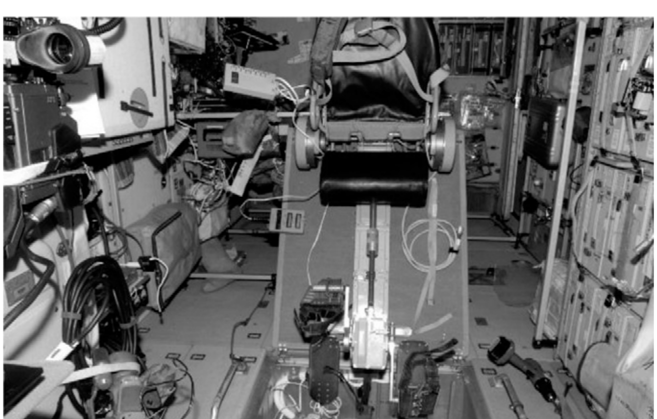

Fig. 2. Cycle ergometer ВБ-3М.

Resistance Bands

In accordance with the requirements of the Russian countermeasures program, a set of resistance bands was sent to the ISS for the purposes of strength training on the mechanically locked treadmill belt. However, as previously noted, starting with ISS-1, using resistance bands on TVIS was prohibited due to safety concerns. As a result, crewmembers began to use the resistance bands by attaching them to ISS structural elements.

The set contained three short bands to load the shoulder muscles, medium ones to load the muscles of the torso, and long ones to load the muscles of the torso and legs. When the working part is extended to its maximum length, the band's design provides the following forces: in the short band (length 1050 ± 50 mm) a maximum 18 kgf; in the medium band (length 1315 ± 50 mm) a maximum 22 kgf; and in the long band (length 2665 mm) a maximum 25 kgf. A new set of resistance bands was developed in 2010 due to the need to replace materials; and instructions for performing exercises with the crewmember secured to ISS interior structural elements were supplied with that set.

In addition to active physical training, the Russian countermeasures system includes the capability for crewmembers to use passive means, making it possible to supplement active countermeasures or replace them in the event of equipment breakdown, deterioration in crewmember health status, or other reasons hindering physical training.

Loading Suit (Penguin-3)

The purpose of the Penguin-3 suit is to compensate for the lack of loading on the skeleton and musculature to guarantee the stipulated level of safety during crew deorbit on the Soyuz vehicle. Elastic components in the suit's design generate a compression force along the longitudinal axis of the body (from shoulders to feet) to load the skeleton and muscles over extended periods of time. The amount of loading of the Penguin-3 suit worn for 6 to 8 h per day at maximum tension of the elastic bands can approach 50% of the crewmember's weight on the ground.

The Penguin-3 is a suit containing a tension system and boots. The belt and straps on the legs of the suit are made of elastic banding. Rubber cords (bungees) are used for the flexible components; the tension is adjusted with buckles. The gastrocnemius muscles are additionally loaded with a special short strap (stirrup) attached to the toe of the boot. The extent of tension in the elastic components, i.e., the amount of loading of the bones and muscles, is adjusted at the crewmember's discretion. The belt (the lower edge is attached to the leg straps; the upper part is attached to the torso bungees) performs an important function of the suit. When tightened, the belt makes it possible to individually adjust the amount of tension for each component, up to completely removing loading from the torso while maximally loading the legs over a broad range. It also allows separate adjustments for flexor and extensor muscles.

In 2007, Yuri Malenchenko used the Penguin-3 suit with the load measuring system (СИН) for the first time on the ISS (**Fig. 3**). The load measuring system in the Penguin suit

Fig. 3. Cosmonaut Yuri Malenchenko using the Penguin-3 loading suit with load measuring system on the ISS.

Fig. 4. Cosmonaut Pavel Vinogradov using the Stimul-01 LF set on the ISS.

provided objective monitoring of longitudinal axial loading of the vertebral column, skeleton, and main muscle groups of the crewmember's lower extremities and torso. The СИН is composed of 20 tension dynamometers, a distribution unit, and a kit that contains a power cable, analog-to-digital converter, and electronic storage device to record data. The tension dynamometers are connected to the suit's bungees and are located inside the distribution unit, which is secured with Velcro to the outside of the Penguin-3 suit. The distribution unit contains the power unit, converting voltage at 27V DC from a station power source into stabilized voltage at 5V DC, thus powering the dynamometers. The station computer has software that processes input signals, calibrating, scaling, and recording them in the form of forces (in kilograms) acting on the crewmember while wearing the suit. The station PC software supports the following: load sensor polling at a given frequency (10 to 50 Hz); output on the computer's display of a table containing the current loading of all straps, individually and totals by group (Fig. 3); placing brief comments on the experiment on the computer screen; and archiving results.

Electrical Muscle Stimulator (Tonus-3)

The Tonus-3 electrical muscle stimulator is used to stimulate the skeletal muscles of crewmembers to prevent muscle atrophy on the ISS (**Fig. 4**). It is composed of an impulse generator and set of electrodes in a bag. The electrical muscle stimulator operates in four programs: Program 1 – stimulation of calf and quadriceps muscles, Program 2 – calf and hamstring muscles, Program 3 – calf, abdominal, and back muscles, and Program 4 – shoulder muscles.

The Tonus-3 simulation output signals are in the form of "packets" of electrical impulses, which are harmonic signals at a frequency of 10 $\pm$ 1.5 kHz. The pulse repetition frequency in the packet is 60 $\pm$ 6 Hz. The maximum current amplitude of output signals for an equivalent load is 300 $\pm$ 45 mA. The pulse envelope has a steep leading edge and an exponential tail. Pulse duration at 0.1 of the amplitude value is 1 $\pm$ 0.2 ms. Pulse amplitude in the packet increased to 0.9 of the maximum value in 0.5 s. Each stimulation channel supports two operating modes: 1) generating impulses in packets at durations of 0.5 $\pm$ 0.05 s and 1.5 $\pm$ 0.15 s with pauses between packets of 1.5 $\pm$ 0.15 s; and 2) generating impulses in packets at a duration of 10 $\pm$ 1 s with a pause of 50 $\pm$ 5 s. This electrical muscle stimulator supports phased alternation of impulse packets and pauses at channel outputs 1 and 4, 2 and 5, and 6 and 3. The electrical muscle stimulator receives power from the station network. Its power requirement is 8 W. Stimul-01 HF Set, like Tonus-3, is designed for the targeted high frequency stimulation of skeletal muscles of the legs, back, shoulders, arms, and neck. In addition to electrical muscle stimulation for the purposes of training, the system also supports stimulation for the purposes of rehabilitation.[8] The amplitude of the stimulation signal in the Stimul-01 HF system does not exceed 60 V; its form is an alternating sinusoidal electrical signal at an audio frequency of 2500 Hz, modulated rectangular pulses at a frequency of 50 Hz, and at a duration of 10 ms.

The maximum duration of high frequency stimulation is 40 min; stimulation is powered from the station. Stimulation data are relayed to the station computer and then downlinked.

Stimul-01 LF Set, is a wearable electrical muscle stimulator that provides low-frequency and relatively low-amplitude electrical muscle stimulation of the quadriceps and hamstrings, front and back calf muscles, long muscles of the back, chest and lumbar spine. It was delivered to the ISS in 2006. This electrical muscle stimulation, unlike high frequency, can be used over long periods of time (up to 6 h per day) without distracting the crewmember from work performance (Fig. 4). According to the results of ground testing, low-frequency electrical-muscle stimulation is an effective countermeasure for gravitational muscular unloading.[4,8] The Stimul-01 LF set is comprised of a personal suit with electrodes, two electrical muscle stimulation units and a charging unit for the rechargeable battery. Leg and back muscles are electrically stimulated at the same time by two electrical muscle stimulators on the right and left of a belt attached to the crewmember's body. The electrical muscle stimulation signal amplitude is 0 to 45 V and controlled by buttons, one for each of the 6 channels, located on the front panel of the device.

The stimulator operates in cycles: 1 $\pm$ 0.1 s of stimulation alternating with a pause of 2 $\pm$ 0.1 s. Treatment is in the form of a bipolar symmetrical rectangular impulse, with a duration of 1 $\pm$ 0.05 ms at a pulse rate of 25 $\pm$ 1 Hz. The maximum duration of low frequency electrical muscle stimulation without recharging the battery is 6 h.

The Stimul-01 LF set collects data on individual, crewmember-selected values for electrical muscle-stimulation signals, plus date and time of the stimulation, and relays these data to the station computer via an RS-232 interface, with subsequent downlink. In 2011, the personal suit with electrodes was replaced with a set of electrode attachment devices.

Lower Body Negative Pressure Suit (Chibis)

The Chibis suit supports the procedure for creating negative pressure to the lower part of the crewmember's torso (LBNP). The Chibis suit consists of the following: a vacuum suit (ПВК-1), a pump unit ПВК-Д, a bundle of hoses, and a power cable. Just as in prior units on Russian orbital stations, the ПВК-1 is designed in the form of corrugated pants with a corrugated shell made of air-tight fabric. Metal rings on the shells prevent compression upon unloading. The corrugations also enabled the axial compression of the shell. There are aluminum alloy boots at the bottom of the shell. There is a waist-sealing band on the belt of the Chibis suit and shoulder attachment straps. The suit has a vacuum regulator (throttle), a vacuum (safety) valve, and a vacuum indicator. The suit is depressurized using the ПВК-Д unit, which contains a mini pump. Air from the surrounding environment is drawn into the suit through the throttle, enters the pump, and is released externally, creating a vacuum within the suit and providing ventilation. When the cap on the throttle is turned, the vacuum within the suit increases. The Chibis suit was designed for maximum differential pressure of 60 $\pm$ 5 mm Hg. The manually adjustable vacuum level within the Chibis suit when using the ПВК-Д control unit is within the range of 10 to 60 mm Hg. The Chibis suit vacuum pump is powered from the station. Vacuum levels in the suit are downlinked by telemetry.

The long-term operation of the Chibis suit, which was developed by Russian designers in the 1970s, brought to light a number of deficiencies, such as unreliable pressurization, discrepancies between its structure and the anthropometric parameters of the ISS operators, the presence of a long air hose, and the need for space to set up the pump unit in direct proximity to the suit. As a result, a new Chibis-M suit was developed that included the vacuum suit ПВК-2, a Granat tablet computer and on-station kits.

Like ПВК-1, ПВК-2 was designed in the form of corrugated pants with 3 sealing bands on the belt that supported a broader range of crewmember anthropometric parameters. The shell of the new Chibis suit contained an MP2-2Г-1 mini pump, a Granat tablet computer, a vacuum regulator, a pressure-measuring unit, and the ПВК-2 control panel. The manual control of pressure in the Chibis-M suit was supplemented with automatic control hardware using a touch keyboard on the tablet computer. The tablet computer checks the readiness of the automatic pressure control system for operation and provides reference materials and troubleshooting recommendations. There are 13 fixed programs in the PC's memory. The crewmember simply enters the number to select a program. The system also operates according to random, flexible programs. Parameters are entered on the computer's touch keyboard, respecting the following constraints: pressure cannot exceed 60 mm Hg and the total session time cannot exceed 60 min. All information on the set and the actual program parameters are downlinked via telemetry and displayed on the PC's screen, presented in graphic (more user-friendly) or numerical format as selected by the crewmember. The crewmember can also temporarily pause the session time counter while keeping the given level of pressure, can stop the session early and exit the program at a controlled rate of 1 mm $\text{Hg} \cdot \text{s}^{-1}$, and can stop the session on an emergency basis, with the highest possible repressurization speed while exiting the program.

The Chibis-M LBNP suit (ПВК-2) was also designed for a pressure differential of 60 $\pm$ 5 mm Hg. The strap that connected the ПВК-1 version of the suit to the permanently installed ПВК-Д unit and the ПВК-Д unit itself was removed from the modified Chibis suit with the introduction of the mini pump MP2-2Г-1. The system is powered from the station.

It is important to note that the Russian LBNP Chibis suit differs from the U.S. LBNP suits in that there is no support saddle and the presence of the Chibis corrugated pants creates a force that must be opposed by muscular contraction of the lower extremities, resulting in a different response to LBNP between the two suits. The Russian suit will likely not elicit as much fluid shifting or as much stress on the cardiovascular system as the

U.S. suit, but probably does provide more countermeasure protection by stimulating the lower extremity vasculature.

Braslet-M

During the initial flight period, some crewmembers use the Braslet-M thigh cuffs to decrease the intensity of the cephalad redistribution of blood that occurs as a result of microgravity. The cuffs contained in the Braslet set are worn on the crewmember's thighs over flight clothing or undergarments. Pulling on special straps generates compression of the cuffs. Crewmembers are given recommended levels and durations of compression during test calibrations on the ground. While Braslet-M is for personal use, it is custom made for each crewmember preflight according to their size (thigh circumference).

Water-Salt Supplements

Saline loading is used before landing as a countermeasure to quickly replenish intravascular fluid volume and increase hydration, by additional intake of fluid and sodium chloride. Crew procedures stipulate taking three to four doses of three sodium chloride tablets (0.9 g each) with 300 mL of fluids (water or juice) 1 d before the end of a flight. The Servak pack of sodium chloride tablets is located in the nutritional supplements kit.

Kentavr G-Suit

All Russian cosmonauts use the Kentavr G-suit in the final stage of flight during descent in the Soyuz vehicle. The Kentavr device generates pressure in the lower part of the body, limiting the redistribution of blood that occurs with g-loading during the descent phase. The Kentavr is custom fitted individually for each crewmember, and is made of a highly elastic woven material that consists of long shorts, a pair of leggings, a hygiene undergarment, and Camelia-A underwear. Before leaving the ISS and entering the Soyuz, the crewmember adjusts the suit fit using the straps to generate compression on the lower body. The Kentavr suit's effectiveness in countering g-loads is achieved at a pressure of 30 mm Hg.

Summary

The Penguin-3 countermeasures loading suit with the load measuring system, the Stimul-01 low frequency electrical muscle stimulator in a set with the electrode attachment devices, the upgraded Chibis-M suit, and the cycle ergometer ВБ-3М have recently been delivered to the ISS. The treadmill БД-2, the force loader (HC-1M), and the Stimul-01 high frequency set are ready for delivery to the ISS soon. As a part of the Mars-500 experiment, a new resistive training device (MDS) has undergone ground testing to support the strength training of crewmembers and to monitor the status of their muscles on the station. In conclusion, it can be stated that over the course of ISS operations, all Russian countermeasures have been significantly upgraded or new ones have been developed.

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