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WEIGHTLESSNESS (MEDICAL AND BIOLOGICAL RESEARCH)

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16. Abstract The book gives data and much discussion on physiological aspects of space flight, emphasizing weightlessness as the primary unfavorable factor. Experiments and studies with simulated weightlessness on the ground, brief weightlessness in parabolic aircraft flights and all space flights with man and animals participating, including numerous aspects of vestibular-sensory, vegetative and motor reactions in weightlessness, are discussed at length. The last half of the book is devoted to discussion and documentation of pathogenesis and prophylaxis of the unfavorable effects of weightlessness and the performance capacity of man in weightlessness, concluding with presentation of results of Gemini and Apollo program biomedical studies.

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ANNOTATION

The book presents materials of experimental physiological studies or the effect of weightlessness on animals and observations of people during brief weightlessness (parabolic laboratory-aircraft flights), as well as the results of observations during flights of astronauts in various flight vehicles. Particular attention is given to physiological studies, conducted during the flights of the Vostok, Voskhod, Soyuz, Salyut orbital station, as well as of the American Gemini and Apollo spacecraft.

Data are presented on the sensorimotor reactions in weightlessness, and condition of the cardiovascular, respiratory and other systems of the body.

Questions of performance capacity of man under weightless conditions are examined, an analysis is made of the activities of astronauts in performing various operations, an estimate of the psychophysiological capabilities of man, in control of a craft and its systems in orbital flights, is given.

For the first time, the pathogenesis of the "weightlessness syndrome" is examined, from the classical viewpoint of modern pathological physiology and, on this basis, methods and means of prophylaxis of the unfavorable effects of weightless on the human body are discussed.

The book may be of interest, not only to physicians, biologists and engineers working in the field of space medicine, but to persons occupied with working out various allied problems.

FOREWORD

Weightlessness is one of the most important biomedical problems in the study of the effect of extreme space flight factors on living organisms.

The first domestic book devoted to examination of this problem was Mediko-biologi-cheskie issledovaniva v nevesomosti [Biomedical Studies in Weightlessness], which was written under the guidance and with the active participation of academician V. V. Parin. It was widely acclaimed by the reading public. This encouraged us to generalize accumulated data and to write what is essentially a new book. V. V. Parin inspired this idea. To our great chagrin, however, it befell us to complete our work on this book only after the death of V. V. Parin, who had contributed so much to the development of domestic space biology and medicine. In working on this book, we bore constantly in mind what the reader expects from authors and made every effort for the new book to be worthy of V. V. Parin's respectful memory.

The present book includes a considerable amount of data obtained since the publication of Biomedical Studies in Weightlessness: experimental data and theoretical and synoptic studies, as well as the results obtained during orbital flights by astronauts on the Vostok, Voskhod and Soyuz spacecraft and the Salyut orbital station. Also discussed in the monograph are the basic biomedical findings of the American Gemini and Apollo spacecraft flights.

The most voluminous material is presented in Chapters 2, 3 and 4, with investigation of vestibulosensory, vegetative and motor reactions during short-term weightlessness and orbital flight. Particular attention is paid to the question of man's work capacity in the weightless condition, to analysis of his activity in performing different tasks and his psychophysiological resources in controlling his spacecraft and its systems during orbital flights of the Vostok and Soyuz spacecraft and the Salyut orbital station. Also assayed is the efficiency of the space performances of aviators and astronauts A. A. Leonov, Ye. V. Khrunov and A. S. Yeliseyev upon emerging into empty space and upon transferring from one craft to another.

Elucidated for the first time is the pathogenesis of the "weightlessness syndrome," which is discussed from the classical position of modern pathological physiology. A number of authors have attempted to present in the form of schema the mechanisms of the weightlessness effect on living organisms. In singling out the most prominent links in the pathogenetic chain and their interconnections, their specific significance and the sequence of their inclusion in different phases of flight, different authors have different points of view and ideas, which have inevitable repercussions on the structure of the proposed schema. They have proved to be convenient for elucidation of the different positions examined in Chapter 1. But it is quite clear that it is still too early to construct a unified pathogenetic schema that would apply to all cases. To construct such a schema, it is necessary to accumulate new data obtained first of all on protracted space flights. There can be no doubt that the mechanism of action and the physiological effects of weightlessness observed in man differ in a number of particulars from the effects observed in animals, so that extrapolation to man of the results obtained in experiments on animals is in need of certain corrections. On the basis of the pathogenesis of the weightlessness syndrome, the prophylaxis of the unfavorable effect of weightlessness on the human organism is analyzed: ways and means of physical conditioning, the effect of drugs, the utilization of artificial gravitation, etc.

We hope that the data in this book will be of interest not only to specialists working in the field of space medicine, but also to persons dealing with related problems.

The editors and authors will be grateful for any critical comments by readers interested in improving the book's structure and content.

--Editorial Staff

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CHAPTER 1

PHYSIOLOGICAL ASPECTS OF SPACE FLIGHTS

1. Physiological Problems of Weightlessness

The conquest of space is connected with an inevitable increase /7* in man's staying times under extraordinary missions of existence. Directly dependent on the duration of these staying times is the effect on the organism of all space flight factors, first and foremost of which is weightlessness. But about the concrete characteristics of this dependence little is as yet known. Moreover, one of the most urgent issues of astronautics is the question of how long a man can stay in space to no detriment of his health and performance capacity.

At the present time we can summarize the data on the flights of Soviet astronauts on the Vostok, Voskhod and Soyuz spacecraft that are shown in Table 1, and of American astronauts on the Mercury, Gemini, Apollo and Skylab spacecraft (see Chapter 7 of the present book). These data, as well as those obtained in experiments with the simulation of weightlessness by means of hypokinesia in the horizontal position or by means of a stay in immersion media, make it possible to draw some general conclusions from physiological investigations and to chart the course of future research.

By now it has been established that we can distinguish three groups of people by the nature and degree of manifestation of their sensory reactions to weightlessness. To the first group belong people who endure weightlessness with no appreciable deterioration of their general condition or reduction of their work capacity. The second group consists of persons who during weightlessness generally experience a sensation of freely floating the air, illusions of their body rotating in an indeterminate position and of being suspended upside-down, general discomfort, etc. To the third group belong those in /11
whom the space analog of motionsickness develops in a comparatively short time, with serious and prolonged disturbances of performance capacity and with vegetative changes.

Contradictory data are encountered in the literature about the distribution of examinees in terms of the seriousness of their sensory disturbances (Ye. M. Yuganov, et al., 1961; L. A. Kitayev-Smyk, 1964, etc.). As is well known, G. S. Titov and V. V. Tereshkova in flight developed a space analog of motionsickness (V. V. Parin et al., 1964; V. I. Kopanev, 1964, etc.). Illusional effects were

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*Numbers in the margin indicate pagination in the foreign text.

TABLE 1
DATA ON SOVIET SPACECRAFT FLIGHTS

Craft and Crew Members	Launch Data	Flight Duration	Medical Research Methods	Comments
Vostok, Yu. A. Gagarin	12 Apr 1961	1 hr 48 min	EKG, pneumogram	First manned orbital flight in history
Vostok, G. S. Titov	6 Aug 1961	25 " 18 "	EKG, pneumogram, seismocardiogram, kinetocardiogram	
Vostok-3, A. G. Nikolayev	11 Aug 1962	94 " 22 "	EKG, pneumogram, seismocardiogram, electrooculogram	First group spacecraft flight in history
Vostok-4, P. R. Popovich	12 Aug 1962	70 " 58 "		
Vostok-5, V. F. Bykovsk'iy	14 June 1963	118 " 57 "	EKG, pneumogram, seismocardiogram, EEG, galvanic skin reflex (GSR)	
Vostok-6, V. V. Tereshkova	16 June 1963	70 " 41 "		
Voskhod, V. M. Komarov, K. P. Feoktistov, B. B. Yegorov	12 Oct 1964	24 " 17 "	EKG, pneumogram, seismocardiogram, arterial blood pressure, coordination tests, vestibulometric studies, blood study, vital capacity, pulmonary ventilation	First crew launch in history. The crew included a scientist and a physician
Voskhod-2, P. I. Belyayev A. A. Leonov	18 Mar 1965	26 " 02 "	EKG, pneumogram, seismocardiogram, pulmonary ventilation, respiratory metabolism, vital capacity, body temperature	Astronaut A. A. Leonov was the first man in history to take a space walk

TABLE 1 (continued)

Craft and Crew Members	Launch Data	Flight Duration	Medical Research Methods	Comments
Soyuz-1, V. M. Komarov	23 Apr 1967	More than a day	EKG, pneumogram, seismocardiogram	Test of a new spacecraft, which crashed on landing. V. M. Komarov died
Soyuz-3, G. T. Beregovoy	26 Oct 1968	94 hr 51 min	Same	
Soyuz-4, V. A. Shatalov	14 Jan 1969	71 " 14 "	EKG, pneumogram, seismocardiogram, pulmonary ventilation, respiratory metabolism, vital capacity, arterial blood pressure	On January 15, 1969 the Soyuz 4 and Soyuz 5 spacecraft coupled, forming an experimental space station. In the course of the flight, A. S. Yeliseyev and Ye. V. Khrunov transferred from the one craft to the other through empty space. The craft were coupled in orbit for 4 hr 35 min
Soyuz-5, B. V. Volynov, A. S Yeliseyev, Ye. V. Khrunov	15 Jan 1969			
Soyuz-6, G. S. Shonin, V. H. Kubasov	11 Oct 1969	118 " 42 "	EKG, pneumogram, seismocardiogram, pulmonary ventilation, respiratory metabolism, vital capacity, arterial blood pressure	The Soyuz 6, Soyuz 7 and Soyuz 8 spacecraft were in a group orbital flight for about 3 days. Aboard Soyuz 6 spacecraft a unique experiment was conducted: welding in space
Soyuz-7, A. V. Filipchenko, V. H. Volkov, V. V. Gorbatko	12 Oct 1969	118 " 41 "		

TABLE 1 (continued)

Craft and Crew Members	Launch Data	Flight Duration	Medical Research Methods	Comment
Soyuz 8, V. A. Shatalov, A. C. Yeliseyev	13 Oct 1969	118 hr 41 min	EKG, pneumogram, seismocardiogram	
Soyuz 9, A. G. Nikolayev, V. I. Sevast'yanov	1 Jun 1970	424 "	EKG, pneumogram, seismocardiogram, kinesthetic sensitivity, arterial blood pressure, pulmonary ventilation, respiratory metabolism, vital capacity, musculojoint feeling, muscle strength of hand	Astronauts A. G. Nikolayev and V. I. Sevast'yanov were the first men in history to be in weightless condition for 18 days
Soyuz 10, V. A. Shatalov, A. S. Yelise N. N. Rukavishnikov	23 Apr 1971	71 "	EKG, pneumogram, seismocardiogram	The Soyuz 10 crew mastered important elements of the flight program needed for subsequent coupling with the Salyut station
Soyuz 11 and Salyut orbital station G. T. Dobroyol'skiy, V. H. Volkov, V. I. Patsayev	6 Jun 1971	About 24 days	EKG, pneumogram, seismocardiogram, kinetocardiogram, tachooscillogram, distal-perimetric oscillogram of the brachial artery, pulse of the femoral artery, arterial blood pressure, respiratory metabolism, vital capacity, musculojoint feeling, kinesthetic sensitivity, muscle strength of hand	World's first piloted orbital station (Salyut). The astronauts died during descent

TABLE 1 (continued)

Craft and Crew Members	Launch Data	Flight Duration	Medical Research Methods	Comment
Soyuz 12, V. G. Lazarev, O. G. Makarov	27 Sep 1973	48 hr	Seismocardiogram, electrocardiogram, pneumogram	Testing of improved on-board systems. Optimization of manual and automatic control processes under different flight conditions
Soyuz 13, P. I. Klimuk, V. V. Lebedev	8 Dec 1973	8 days	Rheoencephalogram, seismocardiogram, electrocardiogram pneumogram	

experienced by B. B. Yegorov and K. P. Feoktistov (B. B. Yegorov, 1964; P. V. Vasil'ev, Yu. M. Volynkin, 1964), as well as by F. Borman and D. Lovell (Berry, 1966). Apparently weightlessness is conducive to the development of motionsickness. This condition was especially striking in the second Skylab crew. For the first few days of the flight, all three astronauts (A. Bean, D. Lousma and O. Garriott) experienced vertigo and nausea, and D. Lousma even had three vomiting spells. At first the astronauts refrained from food and partook only of juices inasmuch as immediately after eating, these symptoms intensified. After a few days aboard the orbital station, these effects disappeared. It is still difficult to explain the nature of these manisfestations of discomfort, but many American specialists feel that this sickly condition of the astronauts was the result of certain changes of their position inside this station with sharp head movements. To discover the nature of the vestibulovegetative disorders, it is important to establish accurately the functional connection between the vestibular apparatus itself and its vegetative components, which have not yet been definitively studied down to the present time.

An important part in the genesis of sensory reactions is played by altered afferentation of the vestibular, cutaneous, proprioceptive interoceptive and other analyzers (V. V. Baranovskiy, et al., 1962; I. D. Pestov, 1965; R. A. Vartbaronov, 1965; Brown, 1961), as well as by typological peculiarities of higher nervous activity, too.

Very pronounced are the individual differences in subjective sensations and behavioral reactions reflecting changes in man's condition under the action of prolonged weightlessness. This has raised the problem of working out adequate methods of so selecting astronauts as to reduce the likelihood of unfavorable reactions under prolonged flight conditions.

The important fact has been established that with conditioning, most persons of the second group became adapted to the weightless condition (L. A. Kitayev-Smyk, 1964; I. I. Kas'yan, et al., 1965, etc.). It became necessary to study the fundamental natural laws in conformity with which adaptation develops, optimum conditioning conditions, the potentialities of accumulation and the conditions under which it arises, the effect of weightlessness on the state of higher nervous activity and of physical and intellectual efficiency (see Chapters 5 and 6).

A great number of studies under different conditions of reproducing weightlessness (high-speed elevators, parabolic aircraft flights, suborbital and orbital flights) were devoted to investigation of its effect on the sensorimotor function of animals and man. In the process it was clearly shown that while serious disturbances of the correctness of movements and coordination do not take place with open eyes, their accuracy, the time necessary for their execution and the muscle strength, especially at the start of staying in the weightless condition, did undergo certain deviations from their initial values (see Chapter 4). Thus, during short /12 periods of weightlessness on aircraft flights, L. A. Kitayev-Smyk [1963] established a reduction in firing accuracy, an increase in the time required to switch on toggle switches and an increase in the number of errors when determining indicator pointers by approximately a factor of 3-4 as compared with initial values.

In analyzing data on motor disorders during weightlessness, we must bear in mind that their nature depends on the degree of fixation of the pilot or cosmonaut in space (Henry, et al., 1952; Clark, et al., 1960; I. I. Kas'yan, et al., 1964). K. E. Tsiolkovskiy has pointed out that in the absence of fixation, a man's slightest movements (even the act of breathing) can cause involuntary changes in his body's position in space.

Gradually, new relations between the body and space conditions arise and a new motor stereotype is created. Thus, the sensorimotor coordination of the astronauts on the Soyuz 9 flight underwent some change in the first 3-4 days, which was expressed in a disproportion of movement. Subsequently, however, the astronauts found the necessary accuracy of movements (Ye. I. Vorob'ev, et al., 1970), though the process of orientation in space with closed eyes was troubled for the entire period of weightlessness in the case of A. G. Nikolayev, as well as V. I. Sevast'yanov (O. G. Gazenko, P. V. Vasil'ev, 1970).

With open eyes, most astronauts experienced no disturbances of spatial orientation. Thus, during Skylab's 28-day flight, Commander C. Conrad noted that with open eyes, they could more easily move about the station in any direction.

It has been brought out that the purposefulness of motor acts in the weightless condition depends in many respects on individual differences among people.

It has been established that the motor activity of astronauts in flight was not substantially disturbed. They steered their spacecraft, effected its manual orientation in space, corrected the automatic ground position indicator, kept records in the log, photographed the earth's surface and the sky, maintained radiotelephone contact with the earth, took psychological and vestibular tests and ate regularly (N. M. Sisakyan, 1965, etc.). A. A. Leonov moved away from and back toward the craft five times in space. Analysis of motion picture frames showed that in his first steps away from the craft, "twists" of his body took place, but his subsequent movements were executed correctly and with assurance, which attests not only to the astronaut's good adaptability to the weightless condition, but also to the high quality of the motor skills that he mastered under parabolic flight conditions (A. Ivanov, et al., 1968). Finding himself in the

weightless condition, A. A. Leonov did not become disoriented in space; his movements were quite coordinated. He had no difficulty in inspecting the outer surface of the craft, switching on the motion picture camera or dismantling it before returning to the craft and carried out a visual observation of earth and near-earth space. The 90° turns around his body's vertical axis that was specified by the flight program, A. A. Leonov generally performed quite accurately. This was achieved as the result of the skill that he had acquired beforehand in controlling his own movement by using the moment of force arising incident to tightening of his lead. Nor did the American Gemini and Apollo astronauts display any serious disturbances of spacial orientation or coordination of movements upon emerging into empty space, though the performance of some tasks upon emerging into empty space turned out, according to Berry's /13
communication (1966), to be more difficult than under terrestrial conditions. An especially great physical effort was required of astronauts D. Lousma and O. Garriot when they emerged into empty space to set up the "canopy" screen. It took the astronauts three hours longer to set up the screen than had been scheduled. The astronauts encountered great difficulties in assembling the boom, as well as in fastening the panel to its special frame.

It will be obvious that movement in the weightless condition will on the whole require considerably less effort than on earth. Movements which are executed easily and frequently recall swimming motions. But in connection with this characteristic of movement in the weightless condition, it is necessary to acquire new skills and to master new biomedical principles, the working out of which must be entrusted to the competent specialists. As Berry [1971] points out, the ability to move about freely and to displace objects at no great energy cost from one end of the spacecraft cabin to the other must be taken into account in solving general problems of habitability, especially on prolonged flights.

Vision under space flight conditions was good. Specially displayed terrestrial targets and signals were identified accurately enough.

It follows from the foregoing that when astronauts are adequately secured, they will be able to perform simple tasks with no particular difficulty. Of course, with increasing complexity of the task, serious difficulties requiring special procedures, skills and instruments may be encountered.

Also of great significance in the organism's reactions is the level of the working setting. The dominant idea behind the task is an important normalizing factor -- at least under certain conditions. But physical stress during weightlessness differs appreciably from what it is under terrestrial conditions.

As new data are accumulated, we shall come up against new problems. One of the most interesting of these problems will undoubtedly involve the efficiency of man's performance on space flights (see Chapter 6).

Of course, the level of the astronaut's activity will be determined to a considerable extent not only by the kind and degree of impairment of sensorimotor functions, but also by the organism's vegetative reactions. In studying the vegetative functions, attention has been paid for the most part to the cardiovascular and respiratory systems (see Chapter 3). The results of these studies have appeared in numerous publications here (O. G. Gazenko, 1962; I. I. Kas'yan, 1962; V. V. Parin, et al., 1964; N. M. Sisakyan, V. I. Yazdovskiy, 1963, 1964; I. I. Kas'yan, et al., 1965; I. I. Kas'yan, V. I. Kopanev, 1965), as well as abroad (Lawton, 1962; Dietlein, 1969; Berry, 1971, etc.).

The change in gravitation on space flights can lead to deconditioning of those mechanisms which, under terrestrial conditions, counteract the effect of the force of gravity on the hemodynamics when the body is in a vertical position. If we regard the constant strain on these mechanisms as the norm so far as man spends two-thirds of his time in an upright position, we should expect prolonged weightlessness to be accompanied by specific active processes of functional reorganization of the cardiovascular and other systems.

The cessation of hydrostatic blood pressure against the walls of the blood vessels leads to redistribution of the blood. This redistribution of the blood and increase in the volume of blood in /14 the venae cavae, pulmonary heart, vessels of the pulmonary circulation system and left atrium can cause serious disturbances of the usually well-balanced interaction of cardiac and vascular reflexes. In particular, when the venae cavae are engorged, a considerable increase in the reflex component of the Bainbridge reflex may occur in the overall complex of reflex and afferent effects of the vascular system. Of very great significance can be a certain change in the classical reflex of the sinocarotid zones, due to the unusual, long-changed effect of redistribution of the blood in the upper half of the body. The relative decrease in pulse rate and slight drop in arterial blood pressure observed in almost all astronauts in the first few hours of experiencing weightlessness compel us to ponder this reflex mechanism, too. It is interesting to note that during the Soyuz 4 and Soyuz 9 flights, the astronauts felt a rush of blood to their heads similar to that experienced by a man in an upside-down position (Ye. I. Vorob'ev, et al., 1969, 1970). In the weightless condition, moreover, it is obvious that additional stimulation of the volumoreceptors may also occur, leading to an increase in diuresis. Unfortunately, to this day no experimental data are available about the localization of these formations in the organism. It has been suggested that they are situated in the walls of the vessels and arteries, inside the brain, etc. (A. G. Ginetsinskiy, 1963). Engorgement of the atria, depressed production of the antidiuretic hormone (Henry-Gauer reflex) and increased urination -- all this can lead to disturbance of the water metabolism and dehydration of the organism, with plasma loss and the subsequent decrease in the number of formed elements and, in the final analysis, to a drop in the total volume of circulating blood (Gauer, et al., 1965, 1971). The restriction of muscular activity that accompanies weightlessness is in turn an extremely important factor, with a direct as well as indirect effect on the functional state of the cardiovascular system (L. I. Kakurin, 1972; Lamb, et al., 1964, 65).

On prolonged flights, nonspecific deconditioning of the cardiovascular system to work loads can also take place as a consequence of the inevitable restriction of mobility in the confined space of spacecraft cabins and a sharp reduction in activity of the musculature. It is therefore clear that prolonged weightlessness, in combination with hypokinesia, must exert an unfavorable effect on the functional resources of the cardiovascular system, reducing man's overload endurance and orthostatic tolerance.

This is confirmed by experiments in which the effect of weightlessness on the cardiovascular system was simulated by means of prolonged bed rest (A. R. Kotovskaya, et al., 1964; Graveline, 1962; Miller, 1964, etc.) or water immersion (Graveline, 1962; Vogt, 1965, etc.). These experiments clearly showed a reduction of orthostatic tolerance and overload endurance. (A more detailed analysis of the possible mechanisms involved in the unfavorable effect of weightlessness is presented in the first section of Chapter 5.)

The astronauts' subjective impressions of the effect of accelerations on the descent flight leg generally turned out to be more distressing, and the increase in pulse rate more considerable, than in the case of centrifuge rotations (P. V. Vasil'ev, A. R. Kotovskaya, 1965, etc.).

Domestic, as well as American authors have reported on signs of deterioration of the state of the cardiovascular system of astronauts on the basis of data from functional tests lasting several days after /15
the flight. These signs are expressed in a more accelerated pulse, a drop in blood pressure and dizziness under orthostatic loads (N. M. Sisakyan, 1965; Berry, 1966, 1971; Dietlein, 1969). Thus, for example, upon taking an active orthostatic test 1.5-2 hours after landing, A. G. Nikolayev and V. I. Sevast'yanov showed a pronounced drop in tolerance. In the standing position, the increase in heart rate attained 50 beats per minute. By palpation, there was little filling of the pulse; at inspiration, it could not be detected. Korotkov's sounds could not be heard in A. G. Nikolayev in the erect posture. In the second minute of orthostasis, the arterial blood pressure of V. I. Sevast'yanov was 120/100 mm Hg, and subsequently no sounds were heard. In performing passive orthostatic tasks beginning with the second day after the flight, disturbances were noted in a number of hemodynamic indices (pulse rate, arterial blood pressure, stroke volume, volumetric rate, etc.) and the respiratory function. The reaction to an orthostatic load was normalized only 10 days after landing (V. V. Kalinichenko, et al., 1970).

It is obvious that one of the mechanisms involved in reduced tolerance to orthostatic loads must consist in deconditioning of the vessels and muscles of the lower extremities. As a matter of fact, plethysmographic measurements of the legs conducted during tilt table studies after the Gemini flights pointed to an increase in engorgement of the extremities by from 12 to 82% of preflight values. True, no such changes were recorded incident to the Apollo flights. At the same time, I. D. Pestov (1968) established plethysmographically that under the effect of 70 days of bed rest, the vessels of the lower extremities become relatively rigid and lose some of their distensibility and contractility. This the author regards as a biologically justified reaction on the part of the organism, aimed at increasing its resistance to orthostatic effects. The mechanism involved in the organism's increased adaptibility to the effect of increased gravitation along the longitudinal axis of the body after bed rest and space flights has not been fully disclosed and is in need of further study. It is especially important to elucidate the role and significance of disturbances in the neurohumoral regulatory system and changes in the blood composition and tonus of the smooth and striated musculature.

The most characteristic feature of the reaction of the cardiovascular system in the first week of flight is considerable fluctuation in the pulse rate within physiological limits. The fluctuation in the R-R intervals are most pronounced in the first 4 days of flight, and then they gradually decrease. The EKG and seismocardiogram indices correspond on average to the pulse rate and attest to the absence of pathologic disturbances of cardiac activity. As has repeatedly been noted earlier, restoration of the rate of cardiac contractions after the overloading represented by putting a spacecraft into orbit, occurs in the weightless condition 2-3 times more slowly than after analogous accelerations by centrifuge rotation under terrestrial conditions.

Thus, in analyzing the indices of cardiac activity, the most distinct and unusual changes come to light in the regulation of cardiac rhythm, the observed changes being connected with the time structure of the respiratory cycle. These facts give grounds to suppose that during weightlessness, the central apparatus that regulates the vegetative functions develop lability, with predominance of now adrenergic systems, now cholinergic systems. /16
According to Berry (1966), in the second week of flight the regulatory mechanisms of the hemodynamics undergo a considerable adaptation to the weightless condition. The author comes to the daring conclusion that the effect of weightlessness on the cardiovascular system cannot be the limiting factor on future prolonged flights. In our opinion, even after the successful flight of the Skylab crew, there are insufficient grounds for drawing a definitive conclusion about this question. Thus, it is well known that after 18 days of flight A. G. Nikolayev and V. I. Sevast'yanov showed pronounced disturbances involving regulation of the hemodynamics and of the motor sphere, which hampered the astronauts' activities.

In them, a complete restoration of physiological functions set in only on the 10-12th day after the flight (Ye. I. Vorob'ev, 1970; O. G. Gazenko, P. V. Vasil'ev, 1970).

It should be noted that while we have some idea about the respiratory rate and rhythm, as well as the structure of the respiratory cycle, we possess very few data about the intensity of the respiratory metabolism and the level of energy consumption under different conditions of activity during weightlessness, and those data we do have are in need of more careful study.

In the weightless condition, certain types of activity that are connected with overcoming the force of gravity must be accompanied by reduced energy costs and decreased oxygen consumption. Types of work that are aimed at supporting the body, moving the hands and feet, moving the thorax and diaphragm -- i.e., all types of human muscular activity including a component of overcoming terrestrial gravity, are much less important. There arises the need for accurate determination of energy costs in the weightless condition and reconsideration of very many calculations of energy losses that have already been established for organisms. In connection with this, it is necessary to reconsider the calorie value of the existing food ration. Conducting a study with a simulated decrease in gravity (one-sixth of body weight), A. V. Yeremin, et al. (1970) found that the energy costs incident to walking at a speed of 4-4.5 km/hour decreased by 24%, and incident to running at a speed of 9-9.5 km/hour, by 28%. As can be seen, the changes are very considerable and with decreasing gravitation, energy costs decrease. On the moon, where gravity amounts to one-sixth of that on earth, it is clear that the reduction of energy costs may be considerable. The first studies of the respiratory metabolism under real space flight conditions were carried out by P. I. Belyayev and A. A. Leonov (I. I. Kas'yan, V. I. Kopanev, 1967). It turned out that the oxygen consumption of A. A. Leonov increased by 206 ml/min, which is easy to understand in connection with great nervous and emotional stress and performance of a number of tasks upon emerging into empty space. The oxygen consumption of P. I. Belyayev decreased by 72 ml/min as compared with initial preflight values. Subsequently, the respiratory metabolism was investigated in three other astronauts. Here, too, ambiguous changes were noted. A. G. Nikolayev and Ye. V. Khrunov showed some increase in oxygen consumption for the same load, while G. S. Shonin showed some decrease. The impression is created that with increasing flight length, decreasing nervous and emotional stress and adaptation of the organism to the weightless condition, the metabolic processes may become stabilized at a lower level. Thus, for example, the energy costs of astronaut V. N. Volkov during the flight of the Salyut orbital station amounted on the fifth day to 2.49 kcal/min, and on the 18-21st day, it dropped 2.16 and 2.23 kcal/min, respectively (as against an initial value of 2.35 kcal/min).

It is convincingly shown by domestic (Ye. I. Vorob'ev, et al., /17
1970; I. S. Balakhovskiy, et al., 1971, etc.) and foreign (Gauer,

1971; Berry, 1971, etc.) authors that after their flights, almost all astronauts showed to one extent or another pronounced signs of disturbance of the water-salt equilibrium and of different types of metabolism. Thus, a reduction of muscular activity and gravitational load on the bony apparatus causes serious changes in the bone metabolism: the protein bone matrix becomes damaged, the osteoclast function is reduced and calcium is washed out. This destructive process in the bones is patently progressive. Just how far it will go is unknown.

Astronauts F. Borman and D. Lovell after 14 days of flight, as well as the crew members of Apollos 7 and 8, showed an increase in calcium excretion with the urine. Densitometric studies brought out a loss of bony mass of the heel bone and terminal phalanx of the fifth finger of the left hand because of calcium removal (Berry, 1966, 1969). Similar results were obtained in animals after the 22-day Kosmos-110 flight, in studies with 70- and 100-day hypokinesia in people (I. G. Krasnykh, 1969) and in A. G. Nikolayev and V. I. Sevast'yanov on their flight (Ye. N. Biryukov, I. G. Krasnykh, 1970). On the other hand, after the Apollo 14 flight, when the monoenergetic light absorption method was employed to determine calcium content in the bones, no appreciable bone impoverishment was detected. These contradictory data point to the need for more careful study of this important question.

Berry (1971) presents convincing data attesting to a considerable drop in the total content of potassium, which plays an important part in the function of the heart and is combined with the intracellular water, in the bodies of the Apollos 13 through 15 astronauts (see Fig. 129). A considerable decrease in the potassium excreted with the urine in the first few days after flight is noted by I. S. Balakhovskiy, et al. (1971). The results of these observations served as the basis for the recommendations to increase the potassium preparations introduced into the food of the Apollos 16 and 17 astronauts for prophylaxis of the unfavorable effects of weightlessness, in particular on the function of the cardiovascular system.

In the postflight period, the loss of body weight attracts our attention; in some cases, hemoconcentration is noted, and a sharp drop in the excretion of chlorine and sodium with urine; in some astronauts, the urea content in the blood was high (I. S. Balakhovskiy, et al., 1971). Regarding the catecholamine and 17-oxycorticosteroid content, the data are contradictory. In connection with the important role of these hormones in regulating many physiological processes, it is important to pay more attention to studying their content at different stages of space flight.

As Berry (1971) asserts, about 60-70% of the loss of body weight is restored in the course of the first 12-24 hours after return to terrestrial gravitation. This points to the fact that water losses are an important component in total weight deficit. Interesting observations were conducted during the Apollo 14 flight. It was established that the intracellular fluid constitutes the greatest percentage in the water deficit. A definitive solution of this question is not only of great theoretical interest, but is also of great practical importance for working out prophylactic measures.

Our attention is attracted by the results obtained by I. S. Balakhovskiy et al. with water loads. They established that in the course of the first two weeks after his flight, V. M. Komarov showed changes in excretion of drinking water, which attests to some disturbance in the system that regulates the water metabolism. In later studies, these results were fully confirmed. What is more, in addition to the earlier described slowing down of water excretion after its intake, the authors noted a considerable increase in electrolyte and 17-oxycorticosteroid excretion (I. S. Balakhovskiy, et al., 1971). The increase in the urea indices in the blood may put us in mind of intensification of the nitrogen metabolism. In most cases, these results, which were obtained with astronauts in the postflight period, are confirmed by experiments with weightlessness simulated by means of hypokinesia in bed or by means of water immersion, as well as by experiments on animals (I. V. Fedorov, L. A. Grishanina 1967; Vogt, Johnson, 1965). /18

The repeatedly described reactions of the blood to the effect of space flight factors attests to their transient character. They are a neutrophil leukocytosis and some reduction in the number of monocytes and eosinopenia. As V. I Legen'kov, et al. (1973) correctly pointed out, a decrease in number of thrombocytes and hemoglobin content, capable of progressing with increase in flight duration, gives rise to a certain alertness.

Thus, even a brief review of the problem shows that, in a prolonged space flight, a number of significant readjustments in functions of various systems of the body is observed. In flights lasting no more than 24 hours, the changes observed, as a rule, were compensatory-adjusting. However, the possibility might be surmised from individual indicators, of the possibility of disruption of compensation and development of pathological disturbances, especially in the case of increased functional loads, as, for example, in returning to conditions of terrestrial gravitation. From this point of view, particular attention must be given to the function of the cardiovascular system and the state of the skeletomuscular apparatus and nervous and hormonal systems. The state of these systems in flights lasting more than 3 weeks must be under special medical control of the investigators, for the purpose of finding out the mechanisms of disturbances in flight and the peculiarities of reactions in the postflight period. There is no doubt that, in subsequent development, a number of other questions are required, since knowledge of the pathogenesis of disturbances caused by hypokinesia and weightlessness results in more rapidly finding effective means of preserving high efficiency on prolonged space flights and of preventing the unfavorable aftereffects of these flights.

At the present time, on the basis of the mechanisms of disorders studied, a series of means and methods of increasing the resistance of the body to the effects of weightlessness have been proposed, which are examined in Chapter 5.

2. Reactions of Astronauts under Weightless Conditions

N75 23108

We have attempted to analyze a series of physiological reactions of astronauts, which have occurred under conditions of brief (familiarization flights along a Kepler parabola in an aircraft) and prolonged weightlessness (flights in Vostok, Voskhod and Soyuz type spacecraft and the Salyut orbital station).

Some Reactions of Astronauts During Brief Weightlessness

Brief weightlessness has been reproduced during flight of an aircraft along a Kepler parabolic trajectory. The duration of the state of weightlessness was 35 ±5 sec. In each flight, the astronauts underwent from 3 to 6 periods of weightlessness ("humps"). During a flight, the astronauts were either immobilized in the working seat with restraining straps or were in the free state. /19

The biocurrents of the heart muscles (electrocardiogram), blood pressure and pulse and respiration rates were recorded in flight. Besides, coordination of movement was studied, by means of "writing tests" and work on a special coordinograph.

The state of health of the astronauts under weightless conditions did not change significantly, and there were no symptoms of spatial disorientation. In the words of P. R. Popovich, "During the transition to the state of weightlessness, the feelings were different. The body lost its weight, an unusual lightness in movement was felt . . The state of well-being under weightless conditions was outstanding . . . . We oriented ourselves normally in the cabin and in space." Approximately the same thing has been noted by other astronauts. They all were tense and agitated during the first "humps," but, under the repeated effects of weightlessness, they became more peaceful. /20

The accuracy of execution of coordinated movements depended greatly on immobilization of the astronauts. If they were immobiized in the work place, they executed the "writing test" and assignments on the coordinograph without particular difficulties (Table 2). Under conditions of weightlessness, as on earth, the

TABLE 2

SOME DATA ON MOTOR ACTIVITY OF ASTRONAUTS DURING FLIGHT ALONG A KEPLER PARABOLA (average figures and maximum deviations)

Astronaut	Total time of execution of program on coordinograph		Duration of contact of "pencil" with coordinograph contact, sec	
	On Earth	In weightlessness	On Earth	In Weightlessness
Yu. A. Gagarin	5.50 4.8—5.96	5.85 5.32—6.78	0.36	0.37
G. S. Titov	6.0 5.88—6.12	5.82 4.52—5.88	0.40	0.38
A. G. Nikolayev	7.18 7.0—7.36	6.83 6.34—7.32	0.40	0.38
P. R. Popovich	9.32 8.16—10.48	9.05 8.32—9.78	0.85	0.86
V. F. Bykovskiy	3.16 3.04—3.28	3.83 3.52—4.14	0.18	0.21
V. M. Komarov	5.65 5.52—5.76	5.72 5.60—5.84	0.41	0.38
P. I. Belyayev	4.8 4.72—4.88	4.29 4.08—4.50	0.56	0.34
A. A. Leonov	4.08 3.56—4.30	5.16 4.44—5.92	0.25	0.36
B. V. Volynov	6.39 5.80—7.36	7.81 5.76—10.04	0.46	0.54
V. V. Gorbatko	5.42	5.76 5.28—6.48	0.43	0.36
G. S. Shonin	4.90 4.52—5.20	5.27 4.94—6.24	0.38	0.39
Ye. V. Khrunov	4.73 4.58—4.88	5.29 4.88—5.96	0.26	0.21

astronauts worked rhythmically. The differences in time indicators were insignificant. It was determined by visual monitoring that movements of the astronauts were coordinated, smooth and quite distinct. The same was revealed in analysis of the movements, which the astronauts performed under weightless conditions, in eating and drinking: removal from the pocket of tubes with water, food packets, opening them and eating. The tests showed that astronauts successfully ate foodstuffs in various forms -- liquid, semiliquid and solid. The exact opposite was noted during their free movement in the spacecraft cabin. The astronauts could not perform the "writing test," since the movement of the extremities caused displacement of the entire body in space. However, experience showed in this case, that, under the repeated effect of weightlessness, the astronauts worked out the skills, which permitted them to retain some stability.

TABLE 3

RESULTS OF HAND DYNAMETRY OF ASTRONAUTS (kilograms) BEFORE AND DURING "FREE FLOATING" UNDER WEIGHTLESS CONDITIONS

Astronaut	Right Hand				Left Hand			
	Horizontal Flight	Humps			Horizontal Flight	Humps		
		1st	2nd	3rd		1st	2nd	3rd
A. G. Nikolayev	56	54	52	48	54	52	50	47
P. R. Popovich	54	48	50	49	50	48	48	46
V. F. Bykovskiy	58	48	46	48	56	44	46	47
V. M. Komarov	68	66	64	64	68	48	50	48
A. A. Leonov	74	70	72	70	58	56	58	56
B. V. Volynov	90	70	76	72	76	70	72	70
Ye. V. Khrunov	48	46	--	--	48	42	--	--

The muscular strength of the hands was evaluated by means of a dynamometer. The results of the investigation are presented in Table 3, from which it is evident that the maximum muscular force decreased considerably in weightlessness: by 6-12 kg for the right hand and 4-12 kg for the left. In all likelihood, one of the causes of the decrease in muscle strength is a reduction in tonic stress on the skeletal musculature.

As was pointed out above, certain physiological indicators were recorded during the flight. Pulse rate data are presented in Table 4. Before flight, in the initial condition, the pulse rate of the astronauts was 60-84 beats per minute. In horizontal flight, in the majority of the astronauts, the pulse speeded up by 6-36 beats, which apparantly was caused by neuroemotional stress. Individual /21
singularities were distinctly revealed in the reactions of the astronauts. Thus, the pulse of P. R. Popovich increased considerably (by 26-34%), of G. S. Titov (by 20.8%) and of V. V. Tereshkova (by 16.6%), and it did not change in V. F. Bykovskiy, A. A. Leonov or V. V. Gorbatko. Under weightless conditions, the frequency of

TABLE 4

CHANGE IN PULSE RATE (beats per minute) OF ASTRONAUTS DURING FAMILIARIZATION FLIGHTS ALONG WEIGHTLESSNESS PARABOLA

Astronaut	Earth Base Data	"Hump"	Horizontal Flight	Weightlessness, (duration), sec 10	20	30	40	Horizontal Flight
Yu. A. Gagarin	62	1st	75	66	54	54	60	76
		2nd	68	66	60	60	66	78
		3rd	72	78	54	60	66	70
G. S. Titov	77	1st	93	72	66	66	—	—
		2nd	—	—	66	72	—	—
		3rd	—	—	66	72	72	84
A. G. Nikolayev	70	1st	80	84	72	72	72	84
		2nd	80	78	66	66	72	82
		3rd	88	72	66	72	72	88
P. R. Popovich	70	1st	94	72	78	[illegible]	—	80
		2nd	88	78	72	78	—	92
		3rd	92	78	72	74	84	84
V. F. Bykovskiy	66	1st	66	72	66	72	—	66
		2nd	66	66	60	60	—	—
		3rd	—	60	60	60	—	—
V. V. Tereshkova	72	1st	84	96	96	84	—	—
		2nd	—	78	78	—	—	—
		3rd	—	78	84	90	—	72
V. M. Komarov	60	1st	70	72	54	54	—	60
		2nd	78	54	60	60	—	66
		3rd	78	54	54	60	—	60
K. P. Feoktistov	68	1st	—	90	90	84	—	90
		2nd	90	—	—	—	—	84
		3rd	84	90	86	76	—	78
B. B. Yegorov	72	1st	108	98	98	102	—	100
		2nd	100	96	84	90	—	90
		3rd	90	84	84	84	—	—
P. I. Belyayev	84	1st	96	—	—	84	—	84
		2nd	90	60	—	—	—	90
		3rd	96	96	72	78	—	[illegible]
A. A. Leonov	66	1st	66	—	66	72	—	66
		2nd	66	66	66	72	—	66
		3rd	66	72	60	72	—	54
A. V. Filipchenko	60	1st	90	54	54	72	—	78
		2nd	78	60	60	72	—	84
		3rd	84	66	54	72	—	66
V. V. Gorbatko	76	1st	78	72	78	—	—	—
		2nd	—	72	—	—	—	—
		3rd	—	72	72	74	—	—

cardiac contractions decreased, as a rule, uniformly from "hump" to "hump," in the majority of cases (see Table 4). In all likelihood, /22 this is explained by the development of adaptation-compensatory processes and, to some extent, by a decrease in orienting reactions.

It should be noted that, in performing with measured physical loads (18 tests) under weightless conditions, more pronounced quickening of the pulse rate was observed, by 18-26 beats per minute, compared with the data obtained during performance under similar loads in horizontal flight.

With change in heart rate, the blood pressure also changed: It increased during horizontal flight and decreased during the weightless period, remaining a little above the initial level. A. G. Nikolayev is an exception. His blood pressure dropped even below the initial level, during the second and third "humps."

Under weightless conditions, together with decrease in heart rate, the electrocardiogram becomes normal: The P and T spike amplitudes and lengths of intervals approximated the initial data. The respiration rates of four astronauts were practically unchanged during horizontal flight. Respiration speeded up somewhat in four astronauts (P. R. Popovich, V. F. Bykovskiy, K. P. Feoktistov and B. B. Yegorov). In the first 10 sec of weightlessness, the number of respiratory movements of the majority of the astronauts /23 increased. Respiration became shallower. Subsequently, despite the lasting effect of weightlessness, respiration was curtailed, decreasing to the level observed during horizontal flight (Table 5). Pulmonary ventilation, vital capacity of the lungs (VCL) and energy expenditure under weightless conditions (state of rest) and in performing measured workloads in unsupported space increased noticeably over the data obtained in horizontal flight (Table 6).

Data on the sensory, motor and vegetative reactions of the astronauts, during the time of action of brief weightlessness on them, coincide, to a certain extent, with the results of the studies of other authors under the same conditions, with testers participating.

In this manner, it follows from the test results, that, under conditions of brief weightlessness, specific functional changes were observed in the astronaut, on the part of a number of body systems, with a tendency towards their return to the initial level. Individual singularities in the nature of the physiological reactions of the astronauts were revealed by the degree of expression of vegetative changes.

TABLE 5

CHANGE IN RESPIRATION RATE OF ASTRONAUTS DURING FAMILIARIZATION FLIGHTS ON WEIGHTLESSNESS PARABOLA

Astronauts	Earth Base Data	"Hump"	Horizontal Flight	Weightlessness, (duration), sec				Horizontal Flight
				10	20	30	40	
Yu. A. Gagarin	10	1st	17	15	15	12	—	18
		2nd	18	15	18	15	—	18
		3rd	19	24	24	18	—	18
G. S. Titov	20	1st	18	15	15	18	—	18
		2nd	14	16	18	12	18	18
		3rd	19	30	18	18	24	19
A. G. Nikolayev	14	1st	15	21	18	18	—	14
		2nd	14	15	18	15	—	14
		3rd	14	15	15	14	—	14
P. R. Popovich	16	1st	18	18	21	15	—	22
		2nd	20	24	18	18	24	20
		3rd	17	18	24	24	—	18
V. F. Bykovskiy	18	1st	21	21	21	27	22	18
		2nd	24	24	24	27	—	18
		3rd	24	27	24	21	24	18
V. M. Komarov	14	1st	14	16	14	16	—	14
		2nd	14	14	14	14	—	16
		3rd	16	14	16	16	—	16
K. P. Feoktistov	14	1st	—	21	18	18	—	18
		2nd	18	18	16	18	—	18
		3rd	18	20	18	16	—	16
B. B. Yegorov	16	1st	—	24	24	24	—	18
		2nd	22	—	—	—	—	—
		3rd	22	—	—	—	—	—

TABLE 6

CHANGE IN EXTERNAL RESPIRATION INDICATORS AND ENERGY CONSUMPTION OF SUBJECTS DURING PERFORMANCE OF MEASURED PHYSICAL WORKLOADS (with ED-3 expander) IN UNSUPPORTED SPACE

Section of Flight	Respiration Rate, cycles/min	Pulmonary Ventilation, l/min	Energy Expenditure, kcal/min
Horizontal flight, M ±m	25.4±0.9	20.22±0.8	3.94±0.14
Weightlessness, M ±m	29.0±1.5	25.42±0.8	4.82±0.16

Physiological Reactions of Astronauts in Prolonged Weightlessness

A particularly unfavorable factor in orbital flight is weightlessness. Cosmic radiation and other factors have insignificant effects, since their physical quantities were small, and they were practically the same as the values observed under normal earth conditions.

In evaluation of the physiological reactions to weightlessness, it must be taken into account that the astronauts experienced considerable neuroemotional stress. It increased particularly distinctly in the prelaunch period (Table 7). This character of the physiological shifts is nothing specific for space flight. They are observed in parachutists before a jump, in sportsmen before a competition, etc. Three types of prestart condition are distinguished in the psychology of sports: "combat readiness," "starting fever" and "starting apathy." Analysis of radioconversation, television and astronaut activity data results in placing their neuroemotional condition in the first category, "combat readiness." It is caused by the effect of secondary and primary stimuli (high level of motivation, readiness commands, fitting out, etc.). In the transition from increased weight to weightlessness and in the first few seconds of /24 orbital flight, the reactions of people had very marked individual singularities. Of 25 astronauts completing orbital flights in various flight vehicles, the state of health and efficiency of 15 was not disrupted in flight, 8 noted spatial illusions and the "space /25 form of seasickness," with marked vegetative shifts and reduction of efficiency in flight, developed in two. Thus, for example, P. R. Popovich wrote in the log: "In the state of weightlessness, I experienced a feeling of hanging in the head down and forward position, which lasted for several minutes. Subsequently, with sharp inclination of the trunk, the illusion of counterrotation arose." The expression of reactions under weightless conditions depended mainly on the individual singularities of the body, the nature and level of ground training, and also on the number of flights performed in a laboratory-aircraft, under conditions of brief weightlessness.

It also was learned that, in the absence of expressed vestibular reactions and discomfort in the weightless state, the astronauts of the Soyuz spacecraft and of the Salyut orbital station, noted a feeling of "blood rushing to the head," which was most pronounced in the first orbits of the flight, and which continued for several hours in some cases and for several days in others. During this time, hyperemia of the mucous membranes, puffiness of the face, smoothing of wrinkles and the like were observed in the crew members. Thus, the astronauts wrote in the log: "During the first hours in the state of weightlessness, rushing of blood to the head was noted. The impression is that I am standing on my head" (V. A. Shatalov). /26 "Under weightless conditions, I observed the constant feeling of blood rushing to the head. This is actually so, if you please, because our faces have a somewhat 'swollen' appearance" (G. S. Shonin). Nevertheless, efficiency was not significantly disrupted

TABLE 7

CHANGE IN PULSE RATE (beats per minute) OF ASTRONAUTS IN PRELAUNCH PERIOD (average data)

Time Before Launch	Astronauts					
	Yu. A. Gagarin	G. S. Titov	A. G. Nikolayev	P. R. Popovich	V. F. Bykovskiy	V. V. Tereshkova
Several Days	64	69	64	68	69	70
4 Hours	65	69	72	56	68	84
5-Minute Readiness*						
5 min	102	104	108	111	133	127
4 "	106	105	106	114	122	124
3 "	109	107	113	114	121	144
2 "	101	107	121	128	126	142
1 "	123	110	120	124	137	139

*This means that 5 minutes remain before startup of the rocket system.

during this time. The astronauts carried out observations of external reference points and equipment operations and maintained radiocommunications.

Analysis of the biomechanical effects under prolonged weightlessness leads to the conclusion that the sensorimotor coordination of the majority of the astronauts, when immobilized in the seat and working with varied equipment, was not significantly disrupted. Also, noticeable disruptions of orientation in space and coordination of movement in the extravehicular activity of A. A. Leonov and in the transfer of Ye. V. Khrunov and A. S. Yeliseyev from one craft to the other, were not disclosed. Similar results (during extravehicular activity) were obtained in the flights of American astronauts in the Gemini spacecraft (Berry, 1966) and the Skylab orbital station, during the extravehicular activities of D. Lousma and O. Garriott.

A large amount of information on the state of the vegetative functions also has been obtained in space experiments. It has been determined that the heart rates of the astronauts decreased regularly in orbital flight, to the values recorded a few minutes before launch, in some cases. The pulse of G. S. Titov was 69 beats per minute on the average 4 hours before launch, of A. G. Nikolayev, 72 beats per minute, of P. R. Popovich, 56 beats per minute, of V. F. Bykovskiy, 68 beats per minute and of V. V. Tereshkova, 81 beats per minute. The pulse rate of A. G. Nikolayev and V. V. Tereshkova reached the initial level approximately in the middle of the second day of the flight and those of P. R. Popovich and V. F. Bykovskiy, by the end of the first day. The pulse of G. S. Titov remained higher than the initial level for the entire flight, which is explained by the conditions of the experiment and vestibular-vegetative disturbances.

However, recovery of the pulse rate to initial values still is not evidence of complete well-being. This indicator changed considerably under weightless conditions. The pulse rate fluctuated within ±10-15 beats per minute and more in short intervals of time (without visible cause). This was expressed particularly in G. S. Titov, P. R. Popovich and V. V. Tereshkova. Thus, the pulse of V. V. Tereshkova quickened on the 20th, 29-31st, and 35-37th orbits and slowed down considerably on the 23rd, 34th and 39th orbits.

Statistical processing of the results of examination of the astronauts (Table 8) has also showed that, during orbital flight, as a rule, their root mean deviation (σ) and coefficient of variation (C) increased considerably over the initial level. Thus, the oscillations of the pulse rate of A. G. Nikolayev 4 hours before launch was characterized by the following indicators: root mean deviation 3.02, coefficient of variation 4.25%; P. R. Popovich, V. F. Bykovskiy and V. V. Tereshkova, 1.97 and 3.52%, 2.15 and 4.63%, 2.52 and 3.11%, respectively. During the time of the prelaunch wait and under weightless conditions, these indicators were higher in all astronauts, as a rule.

TABLE 8

CHANGE IN PULSE RATE (beats per minute) OF ASTRONAUTS AT SEPARATE STAGES OF FLIGHT UNDER WEIGHTLESS CONDITIONS

Flight Stage	Orbit	G. S. Titov				A.G. Nikolayev				P. R. Popovich				V. F. Bykovskiy				V.V. Tereshkova			
		M	σ	C	In % of PL-2	M	σ	C	In % of PL-2	M	σ	C	In % of PL-2	M	σ	C	In % of PL-2	M	σ	C	In % of PL-2
5-min readiness (period PL-2)		106.0	7.31	6.88	100.0	112.0	7.10	6.34	100 0	117.0	7.55	6.45	100.0	132.0	12.39	9.37	100.0	133.0	8.52	6.41	100.0
End Day 1	1	104.0	9.89	9.47	100.0	127.0	6.27	4.94	113.4	104.0	5.36	5.15	88.9	101.0	9.22	9.13	76 5	114.0	6.37	5.61	85.7
	7	82.0	8.72	10.63	77.4	78.0	3.20	4.10	69 6	—	—	—	—	63.0	3.99	6.30	47.7	78.0	3.63	4.65	58.6
" 2	13	89.0	9.74	10.92	84.0	88.0	8.30	9.43	78.6	62.0	2.40	3.87	52.9	63.0	2.58	4 08	47.7	95.0	11.03	11.67	71.1
" 3	17	97.0	12.24	12.62	91.5	79.0 (16)	11.30	14.30	70.5	60.0	5 65	9.42	51.3	70.0	7.30	10.32	53.0	68.0	6.47	9.56	51.1
	23	—	—	—	—	65.0	7.73	11.89	58.0	50.0	4.07	8.14	42.7	64.0	4.72	7.33	48.4	61.0	3.92	6.35	45.9
	29	—	—	—	—	65.0 (30)	2.88	4.43	58.0	59.0	7.44	12.61	50.4	50.0	5,66	11.31	37.9	78.0	9.32	11.96	58.6
Weightlessness	33	—	—	—	—	68 (32)	6.51	9.57	60.7	53.0 (34)	2.70	5.09	45.2	56.0 (35)	3.42	6.07	42.4	69.0	4.09	5.94	51 9
" 4	39	—	—	—	—	73.0	8.25	11.30	65.2	56.0	2.98	5.32	47.9	62.0	3.91	6.25	47.0	64.0	11.78	18.43	48.1
	45	—	—	—	—	72 0	2.70	3.75	64.3	61.0 (46)	1.22	2.00	52.1	58.0	2.49	4.31	43.9	70.0	2.82	4.04	52 6
	51	—	—	—	—	67.0	3.74	5.58	59,8	—	—	—	—	58.0	3.96	6.85	43.9	—	—	—	—
" 5	55	—	—	—	—	64.0	2.55	3.98	57.1	—	—	—	—	70	5.19	7.48	53.0	—	—	—	—
	61	—	—	—	—	71.0 (62)	5.66	7.97	63.4	—	—	—	—	57.0	5 66	9.92	43.2	—	—	—	—
Start Day 6	67	—	—	—	—	—	—	—	—	—	—	—	—	61.0	4.86	8.01	46.2	—	—	—	—
	71	—	—	—	—	—	—	—	—	—	—	—	—	61.0	4.85	7.95	46 2	—	—	—	—
	78	—	—											61.0	4.44	7.32	46.2	—	—	—	—
	81													77.0	5.95	7.77	58.3				

Notes: 1. M, arithmetic mean; σ, root mean deviation; C, coefficient of variation ($\frac{\sigma}{M}100\%$).

2. If there is no information on individual orbits, the data of the neighboring orbits are presented. Their numbers are indicated in parentheses.

TABLE 9

CHANGE IN BLOOD PRESSURE, PULSE RATE AND RESPIRATION RATE OF ASTRONAUTS IN ORBITAL FLIGHT BEFORE AND AFTER MEASURED WORKLOADS

Statistical Indicator	Before Physical Load			15-20 sec After Load			2 min After Measured Load		
	A	B	C	A	B	C	A	B	C
M	117.7/78.1	63.9	11.0	122.8/73.1	71.4	13.9	118.2/76.3	63.94	11.12
σ	8.8/5.93	6.31	1.66	9.60/4.46	9.92	3.54	5.81/6.01	6.41	2.38
C	7.47/7.60	9.87	15.12	7.82/6.10	13.89	25.53	4.91/7.88	10.02	21.41
m	1.07/0.72	0.82	0.22	1.62/0.76	1.68	0.59	1.02/1.06	1.11	0.41
t	—	—	—	2.57/4.81	4.0	4.49	0.27/1.38	0	0.25
n	67/67	58	53	35/35	35	35	32/32	33	33

Key: A Blood pressure, mm Hg
B Pulse rate, beat/min
C Respiration rate, cycle/min

In performing measured workloads of moderate severity (the work performed was 100.8 kgm), the pulse rate and blood pressure of the astronauts under weightless conditions for up to 5 days, changed negligibly (Table 9). However, a tendency was observed towards some increase in pulse pressure. Such oscillations of the physiological /27 indicators is evidence of imperfection of the neuroreflex regulation mechanisms (Ye. M. Yuganov, et al., 1961; V. I. Yazdovskiy et al., 1963, 1964). It is difficult now to explain what caused the regulatory disturbances: neuroemotional stresses or the effect of weightlessness. It apparently is the result of the effects of weightlessness, since, during prolonged orbital flights, when the neuroemotional stress gradually decreased, fluctuations in the pulse rate even increased somewhat.

Less distinct data were obtained in recording the respiration rate (Table 10). An increase in number of respiratory movements, especially at the start of the experiment, over the data of the 5-minute readiness examination, was observed in all astronauts. This kind of change apparently is caused by neuroemotional stress.

TABLE 10

CHANGE IN RESPIRATION RATE (cycles per minute) OF ASTRONAUTS AT SEPARATE STATES OF FLIGHTS UNDER WEIGHTLESS CONDITIONS (average data)

Flight State	Orbit	G. S. Titov				A.G. Nikolayev				P. R. Popovich				V.F. Bykovskiy				V.V. Tereshkova			
		M	σ	C	In % of PL-2	M	σ	C	In % of PL-2	M	σ	C	In % of PL-2	M	σ	C	In % of PL-2	M	σ	C	In % of PL-2
5-min readiness (period PL-2)		19.61	4.00	20.38	100.0	9.67	1 34	13.86	100.0	15.17	2 65	17 47	100.0	16,83	4.88	28 97	100.0	17.28	2 22	12 85	100 0
End Day 1	1					13.71	2 86	20.86	141.8	19.14	3.18	16.61	126.2	24.25	5.36	22.12	144.0	20.50	3.11	15 20	118 6
		13.60	2.22	16.33	69.4	11.44	2.00	17 48	118.3	—	—	—	—	16.60	2.07	12.49	98.6	21.28	2.63	12 38	123.1
" 2	13	16.17	5.34	33 01	82.4	11.00	1.80	16.36	113.8	18.20	2.06	11.32	120.0	18.00	2.71	15.04	107.0	22.50	3 10	13.82	130.2
	17	16.61	3.01	18.14	84.7	11.28 (16)	1.58	14.01	116.6	17.38	3.69	21.23	114.6	19.90	2.08	10.45	118.2	21.88	2 99	13 70	126.5
" 3	23	—	—	—	—	10.88	3.14	28 86	112.5	16.38	0.82	5.01	108.0	21.25	2.63	12.38	126.3	21.00	1.19	5.69	121.5
Weightlessness	29	—	—	—	—	7.5 (30)	1.73	23.01	77.56	16.00	3.46	23.07	98.9	14 00	2.83	20.20	83.2	21.80	1 48	6.80	126.1
	33					11.1 (32)	2.89	26.00	114.79	15.25 (34)	2.83	18.56	100.5	19.0 (35)	3.26	16.79	112.9	21.81	2.69	12.35	126.22
" 4	39					12.40	2 84	22.90	128.2	14 86	2.70	18.17	98.0	18.54	1.62	8.73	110.2	21.54	1 97	9.16	124.6
	45					10.6	2.41	22.74	109.6	16.33 (46)	2.60	15.92	107.6	18.43	2.48	35.57	109.5	19.67	5.86	29.81	113.4
	51					13.0	3.24	24.92	134.4	—	—	—	—	18.30	2 83	15.46	108.7	—	—	—	—
" 5	55					11.7	2.78	23.75	120.0	—	—	—	—	18.25	1.25	6.82	108.4	—	—	—	—
	61					9.75 (62)	2.51	25.74	100.8				—	17.00	1,41	8,31	101.0	—	—	—	—
	67												—	18.86	2.54	13 46	112.0	—	—	—	—
Start " 6	71												—	19.17	1.48	7 73	113.9	—	—	—	—
	78												—	13.05	2.52	18 64	80.2	—	—	—	—
	81												—	17,54	2.44	13 91	104.2	—	—	—	—

Notes: Same as Table 8.

At the start of a period of weightlessness, the astronauts reacted quickly to any external stimulus, since they still had not mastered weightlessness and the conditions of living in the spacecraft. Moreover, the respiration rate was determined to a great extent by the rhythm of the radioconversations, which were carried out at a very high rate during the entire flight.

The respiration rates of the astronauts changed especially noticeably during extravehicular activity. Thus, in the first extravehicular activity, the respiration rate of A. A. Leonov was 26-36 cycles/min and, of Ye. V. Khrunov, 49 cycle/min. Performing measured workload (using the expander-dynamometer) in the first five days of the orbital flight led to more noticeable change in external indicators of respiration, compared with the data obtained in a relatively peaceful state. After a functional test, pulmonary ventilation increased by 4.74 l/min, the vital capacity of the lungs, by 171.1 ml and energy loss by 0.67 kcal/min (Table 11). Three types of reactions of the astronauts can be distinguished, by nature of change in respiration rate. In the first type, the respiration rate increases noticeably under weightless conditions over the initial data. This was observed in a number of persons, both in the state of rest and 10-15 sec after performing measured physical workloads. Some decrease in respiration rate immediately after performing a measured workload under weightless conditions is inherent in the second type. In the third type of reaction, a periodicity is noted in the change in /28 respiration rate during orbital flight (both in state of rest and in performing measured workloads).

TABLE 11

CHANGE IN RESPIRATION RATE, PULMONARY VENTILATION, VITAL CAPACITY OF THE LUNGS AND ENERGY LOSS OF ASTRONAUTS UNDER ORBITAL WEIGHTLESS CONDITIONS BEFORE AND AFTER PHYSICAL LOADING (average data)

Statistical Indicator	Before Physical Load				15-20 sec After Measured Workload			
	A	B	C	D	A	B	C	D
M	9.9	12.07	4516.7	2.32	10.7	16.81	4687.8	2.99
σ	2.56	2.36	538.7	0.33	3.15	3.13	429.5	0.44
C	25.9	19.56	11.9	14.39	29.45	18.64	9.16	14.7
m	0.53	0.49	139.09	0 07	0.74	0.72	98.5	0.10
t	—	—	—	—	0.87	5.43	1.02	5.39
n	23	23	15	23	18	19	19	19

Key: A Respiration rate, cycle/min
B Pulmonary ventilation, l/min
C Vital capacity of lungs, ml
D Energy loss, kcal/min

Some changes also were observed in the electrocardiograms: The Q-T interval was shortened during the 5-minute readiness, at the beginning and end of the period of weightlessness and somewhat increased in the middle of it; the P-Q interval changed approximately the same, but less distinctly. Change in the time indicators of the electrocardiograms, as usual, was closely connected with pulse rate: with curtailment of it, the intervals increased, and vice versa.

The T-spike amplitude of all astronauts increased under weightless conditions, over the 5-minute readiness examination data, and the R-spike increased only in A. G. Nikolayev and, in the first half of the flight, in V. F. Bykovskiy. It was reduced in astronauts P. R. Popovich and V. V. Tereshkova, as well as in the second half of the flight of V. F. Bykovskiy. The cause of the changes is not clear, since, even for terrestrial conditions, there is not now clear information on the causes of change in the amplitudes of the electrocardiograms. It is possible that they are a consequence of change in the electrical axis of the heart and, to a certain extent, a result of disturbance of metabolic processes in the myocardium. Differences in the direction of change in amplitudes, in all likelihood, are /29
explained to a certain extent by the singularities of telemetric recording of the biomedical information.

The systolic index gradually decreased under weightless conditions; just as in analysis of the pulse and respiration rates, these indicators of the P-Q and Q-T intervals, T- and R-spike amplitudes and the systolic index fluctuated considerably.

There is a certain interest in data on change in bioelectric activity of the cerebral cortex during a space flight. Under weightless conditions, a tendency was noted in A. G. Nikolayev and V. F. Bykovskiy of predominant replacement of the low-frequency oscillations (below 8 Hz) by high-frequency, with a gradual decrease in bioelectric rhythm amplitudes. As a rule, there was an increase in low-frequency potential in V. V. Tereshkova. If it is considered that, according to the data of P. I. Shpil'berg (1949), P. I. Gulyayev (1960) and others, the exitation process is characterized by depression of the low-frequency and activation of the high-frequency oscillations and an inhibiting process, by exaltation of the α-rhythm and appearance of slow waves, excitation was increased under weightless conditions in A. G. Nikolayev and V. F. Bykovskiy and, in V. V. Tereshkova, inhibition. In all likelihood, the /30
great variability of the pulse rate of V. V. Tereshkova stems from this. It might be supposed that, because of development of an inhibiting process, the cortical control of the vegetative functions was disrupted, as a result of which, more significant shifts arose in the pulse rate. The nature of the physiological reactions of the astronauts under weightless conditions is evidence of their great adaptability to the unusual living conditions. While the vegetative shifts were expressed more significantly initially, they decreased subsequently.

There was definite interest in data from study of the cutaneogalvanic reactions (CGR) under weightless conditions. Experiments were carried out on four astronauts, during the flights of the Vostok 3 and Vostok 6 spacecraft. 254 measurements of the cutaneogalvanic reaction were recorded in all. Special proportioned stimuli were not used in the flight. The appearance of cutaneogalvanic reactions was caused only by various occupational stimuli (radioconversations, commands from earth, signal indications, etc.). Slow changes in the electrical resistance of the skin were recorded in A. G. Nikolayev and P. R. Popovich and, rapid oscillations of the CGR were investigated in V. F. Bykovskiy and V. V. Tereshkova. Three types of reactions can be distinguished on the curves recorded: a) slow single-phase, b) fast two-phase (duration less than 2 sec), c) combined. Analysis of the data showed that the CGR of astronauts A. G. Nikolayev and P. R. Popovich under weightless conditions were in different directions. Thus, in proportion to his stay under weightless conditions, the cutaneogalvanic resistance of A. G. Nikolayev increased and that of P. R. Popovich, being increased initially, decreased somewhat, beginning with the 24th orbit; the resistance was higher in the morning in this case than in the evening. In analysis of individual measurements, a definite cyclic nature is successfully noted in changes in the indices, which apparently is explained by the circadian rhythm. Moreover, an appreciable tendency towards reduction in the cutaneogalvanic resistance was noted during periods of marked emotional stress.

The cutaneogalvanic reactions of astronauts V. F. Bykovskiy and V. V. Tereshkova under orbital weightlessness conditions was studied more completely (I. T. Akulinichev, A. Ye. Baykov, et al., 1963). As a result of the study, it was determined that, at the start of /31
a flight, as well as before descent of the craft to earth, an increase in number of CGR oscillations was observed in V. F. Bykovskiy and V. V. Tereshkova which was caused by higher neuroemotional stresses (Table 12).

TABLE 12

AVERAGE NUMBER OF CGR OSCILLATIONS IN ASTRONAUTS V. F. BYKOVSKIY AND V. V. TERESHKOVA PER MIN IN DIFFERENT SECTIONS OF THE SPACE FLIGHT

Astronaut	5 min Before Launch	Start of Weightlessness	Weightlessness (flight orbits) 2	18	38	45	48	78	81
V. F. Bykovskiy	6	11	8	5	1	2	--	5	6
V. V. Tereshkova	8	12	8	2	2	3	6	--	-

Cutaneogalvanic reactions were interpreted by A. Ye. Baykov

The average CGR duration of both astronauts, in the 5-minute readiness period, varied from 4.1 to 20.5 sec. Under weightless conditions, during the greater portion of the flight orbits, the average duration of the reaction of V. F. Bykovskiy and, in orbits 1-7 of the flight of V. V. Tereshkova, were considerably less than in the 5-minute readiness period (Table 13). This decrease was particularly significant in V. V. Tereshkova in the 4th orbit, during a conversation with the flight leader. In proportion to the stay of V. V. Tereshkova under weightless conditions (13-23rd orbits), the average duration of the reaction increased considerably (to 18.1 sec), in which it was higher in the first half of the day than before sleep.

TABLE 13

CHANGE IN BASIC INDICATORS OF CUTANEOGALVANIC REACTION OF ASTRONAUTS V. F. BYKOVSKIY AND V. V. TERESHKOVA DURING ORBITAL FLIGHT (from data of I. T. Akulinichev and A. Ye. Baykov)

Flight Period		Duration of Reaction, sec			Positive Phase Amplitude, %			Negative Phase Amplitude, %			
		Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	
V. F. Bykovskiy											
5-min readiness period		14.6	20.5	4.1	1.3	1.7	0.8	3.4	5.1	1.6	9
Weight-lessness	1	8.1	13.0	4.5	1.6	2.6	0.6	3.2	5.0	2.5	13
	2	7.6	14.4	2.7	2.0	3.4	1.0	2.8	4.1	1.2	17
	3	8.7	16.1	4.4	1.3	1.4	1.1	3.7	5.0	2.0	30
	4	7.4	16.0	3.2	1.1	1.1	1.1	3.3	5.2	1.4	17
	7	8.9	11.5	6.0	—	—	—	2.0	3.4	1.3	3
	13	8.9	14.3	4.2	—	—	—	3.4	4.8	1.6	11
	17	10.9	16.0	5.5	3.4	3.9	2.8	2.5	4.6	1.8	10
	23	—	—	—	—	—	—	—	—	—	—
	29	6.2	8.0	3.7	—	—	—	2.4	1.2	1.2	6
	45	13.7	23.2	6.7	2.2	2.9	1.4	3.3	5.0	2.5	3
	55	6.6	10.0	3.2	—	—	—	3.1	3.1	[illegible]	2
	78	11.8	22.6	3.4	2.8	3.8	1.6	3.4	5.0	1.6	11
	80	7.2	8.8	4.3	2.2	2.7	1.7	3.7	4.8	2.0	4
	81	15.1	22.2	7.4	—	—	—	4.2	7.0	3.4	4
V. V. Tereshkova											
5-min readiness period		13.5	17.5	5.5	2.0	4.7	0.6	2.5	5.0	1.6	11
Weight-lessness	1	11.2	27.2	4.4	1.7	2.4	0.6	2.4	5.0	1.2	13
	4	9.2	14.0	5.3	0.8	1.1	0.7	2.7	4.6	1.4	12
	7	12.1	26.0	4.2	0.9	1.2	0.6	3.0	5.0	2.2	8
	[illegible]	17.1	23.8	11.5	0.8	1.3	0.3	2.3	2.7	2.0	3
	17	18.1	30.0	9.4	1.2	1.3	1.0	2.8	4.1	2.0	4
	23	13.6	23.8	5.2	0.4	0.6	0.3	2.6	3.4	1.0	6
	[illegible]	7.3	12.3	4.6	2.0	2.7	1.3	—	—	—	3
	[illegible]	9.6	14.3	5.0	0.9	1.3	0.4	2.6	2.9	2.1	3
	[illegible]	9.5	17.0	3.3	2.3	1.2	0.4	2.9	[illegible]	1.2	6
	47	14.3	15.0	13.5	1.3	1.3	1.3	2.2	2.3	2.0	2
	48	17.0	28.0	10.4	1.5	2.5	0.6	2.8	3.4	[illegible]	10

Note: n is number of measurements.

An increase in average duration of the reaction of V. F. Bykovskiy, to 13.7 sec in the 4th-5th orbit, coincided with injection into orbit of the Vostok 6 spacecraft and with subsequent conversations with V. V. Tereshkova.

Before launch of the Vostok 5 and Vostok 6 spacecraft, the average duration of the reaction of both astronauts increased noticeably, to 15.1-17 sec. The heart rates of the astronauts speeded up considerably during this time. The average amplitude of the CGR positive phase of the astronauts differed: The amplitude had a tendency to decrease during the entire flight in V. F. Bykovskiy and in V. V. Tereshkova, to decrease, compared with the 5-minute readiness period. Thus, the average amplitude of the CGR positive phase of V. F. Bykovskiy, under orbital weightlessness conditions, was 1.1-3.4%; for V. V. Tereshkova, it had a phase nature during the entire flight. Initially, during the first 1-1/2 orbits of the flight, the amplitude had a tendency to decrease, it increased in the 29th-30th orbits (2nd day of the flight), reaching the initial value and, before descent, it again became less in orbits 47 and 48.

It was determined that a range of fluctuation of positive phase amplitudes under flight conditions was considerably larger for V. F. Bykovskiy than for V. V. Tereshkova. A particularly noticeable increase in CGR amplitude of V. F. Bykovskiy was observed in the 2nd, 45th and 78th orbits of the flight. During this time, the astronaut carried on conversations with ground stations and awaited descent of the spacecraft to earth.

The average negative phase amplitude of both astronauts did not have a marked tendency to change, and it fluctuated between 2.2 and 3% in V. V. Tereshkova and 2-4.2% in V. F. Bykovskiy. In those cases, when positive phase amplitude increased, the negative /32
phase amplitude most often decreased.

Thus, it is evident from the data presented that the dynamics of change in the individual indicators of the cutaneogalvanic reaction of both astronauts was connected mainly with their neuroemotional state. Undoubtedly, on longer space flights, especially when using special proportioned stimuli, investigation of these reactions will have important scientific and practical value, for judgments on the state of the vegetative sphere of an astronaut and for prognostic purposes.

The experimental data allow the conclusion to be drawn that, /33
under weightless conditions lasting 5 days and more (18-24), there are no significant disturbances, with the exception of some singularities in functioning of the cardiovascular system: a reduction in heart rate, sometimes even greater than values recorded under ground conditions; large fluctuations in the physiological indicators; a slow increase in some indicators to the initial level under weightless conditions, after the powered phase of the flight.

The results of comparison of experimental data obtained during the action of brief and prolonged weightlessness on the astronauts gives a basis for concluding that there are individual resistances of the astronauts to weightlessness and that there is prognostic value in the results of examination during familiarization flights along a Kepler parabola in aircraft. Thus, in astronauts G. S. Titov, P. R. Popovich and V. V. Tereshkova, increased fluctuation of the physiological indicators were observed during brief weightlessness, and the same was noted during orbital flights. The necessity for obligatory conduct of familiarization flights on the Kepler parabola and consideration of experimental data in selection and training of astronauts flows from this.

3. Physiological Mechanisms of the Effect of Weightlessness on the Body

N75 23109

Serious attention is now being given to study of the effect of weightlessness on the bodies of animals and man, since this factor apparently is a definite obstacle to the conquest of space by man.

The experimental way of solving problems of weightlessness is extremely difficult, because of the impossibility of full-scale ground modeling of this state. Nevertheless, definite successes have been achieved in recent years. Direct data on the state of people under weightless conditions have been obtained during flights in aircraft along a Kepler parabola, ballistic rockets and satellite spacecraft and indirect, by partial modeling of the state of weightlessness while submerging subjects in immersion media, being under conditions of relative isolation, hypodynamia, etc.

Generalized works on the change in the individual functional systems of the body under weightlessness have appeared in the literature in recent years (V. I. Yazdovskiy, et al., 1964a; I. I. Kas'yan, et al., 1964a; R. M. Bayevskiy, O. G. Gazenko, 1964 and others) and, therefore, we have limited ourselves only to a description of the pecularities of physiological reactions, since they permit a closer approach to understanding the mechanisms of the effect of weightlessness on the human body.

In analysis of experimental data, it has been ascertained that, under these conditions, there have been some changes in development of the sensory, motor and vegetative components of the overall reaction of the body, as well as individual differences in adaptation-compensatory reactions. Thus, under weightless conditions, persons being examined frequently have felt, especially during the first minutes, the illusion of flight in the upside-down position ("legs upward" flight), a feeling of falling downward, rising upwards, etc. The illusory disturbances have disappeared with continuation of the flight, in the majority of cases; however, they easily arise again during rapid movements of the head, fatigue, and movements in /34
space. The spatial illusions were observed in a portion of the people in all parabolic flights (Ye. M. Yuganov, et al., 1961; G. L. Komendantov, V. N. Kopanev, 1962; V. V. Baranovskiy, et al.,

1962; I. I. Kas'yan, V. I. Kopanev, 1963: L. A. Kitayev-Smyk, 1963, 1964; N. M. Sisakyan, V. I. Yazdovski, 1963, 1964; Yazdovski, et al., 1964b; Gerathewohl, 1954, 1956; Ogle, 1957; Hauty, 1960).

According to the data of L. A. Kitayev-Smyk (1963), the perception of light signals changed under conditions of brief weightlessness: The appearance of a violet halo around bright objects, heightened color perception (mainly yellow), distortion and diffusness of visible objects. Besides the sensory disturbances, certain changes in the motor sphere also were observed in the state of brief weightlessness. In the majority of subjects, accuracy in hitting a target decreased, motor coordination was disrupted (missing the target), the muscular strength of the arms decreased, the rate of performance of motor acts and the precision of maintaining fixed muscle efforts decreased, the time necessary for turning off toggle switches and the number of errors in setting indicator needles increased (V. S. Gurfinkel', et al., 1959; Ye. M. Yuganov, et al., 1962, 1963; Ye. M. Yuganov, 1963; L. A. Kitayev-Smyk, 1963; I. I. Kas'yan, 1963a; I. I. Kas'yan, et al., 1964a; Beck, 1954, 1956; Lomonaco, et al., 1957; Gerathewohl, et al., 1957).

The motor activity of astronauts was not significantly disrupted during orbital flights. They controlled the craft, performed various work operations, in accordance with the flight cyclogram, and carried out medical observations and experiments (O. Gazenko, 1962; N. M. Sisakyan, V. I. Yazdovskiy, 1963; V. I. Yazdovskiy, et al., 1963, 1964a; N. L. Delone, et al., 1963, 1964). Nevertheless, these data still do not permit it to be concluded that the motor activity of the astronauts is unchanged, since the accuracy necessary for executing these movements was low and fully commensurable with possible disturbances of the movement indicators (I. I. Kas'yan, 1964a).

There now are data showing that, under weightless conditions, fine coordinated acts are disrupted. Thus, A. I. Mantsvetova, I. P. Neumyvakin and colleagues (1965), analyzing the handwriting of astronauts A. G. Nikolayev and P. R. Popovich, found that coordination of movement at the start of a flight changed considerably; these changes subsequently were smaller.

Extensive biomedical information on the vegetative functions under weightless conditions has now been obtained. Under both brief and prolonged weightlessness, the heart rates of persons and animals examined have decreased, in the majority of cases (sometimes it was even below the level recorded under ground conditions), and the blood pressure has decreased; some indicators slowly recovered (pulse rate, blood pressure, respiration rate, etc.) to the initial level under weightless conditions, after an increase in them during the powered phase of the flight; the physiological indicators changed strongly. The root mean deviations, coefficients of variation of the pulse rate and certain other physiological indicators of all astronauts were higher than the values calculated in ground examinations (V. N. Chernov, V. I. Yakovlev, 1958; O. G. Gazenko, 1962; I. I. Kas'yan, 1962; N. M. Sisakyan, V. I. Yazdovskiy, 1963-1964; I. I. Kas'yan, et al., 1964b; R. M. Bayevskiy, O. G. Gazenko, 1962; O. G. Gazenko, et al., 1964).

Weightlessness apparently also favors development of seasickness (see Chapter 3). /35

By generalizing the data on reactions of people in the state of weightlessness, it can be concluded that, under these conditions, a disruption of the sensory component of the total reaction of the organism (illusory perceptions of spatial relationships, changed perceptions of color signals, etc.), disruptions of the motor component of the total reaction of the body (disruption of motor coordination, decrease in muscle tonus, decrease in muscle strength, etc.), disruptions of the vegetative component of the total reaction of the body (increased vegetative lability, reduction in some physiological indicators below the ground level, delay in adaptation, etc.), and development of space forms of seasickness (increased salivation, hyperhidrosis, nausea, vomiting, etc.) are observed in some people.

There still is no theory at this time, explaining the effect of weightlessness on the body. There are only individual opinions of both Soviet and foreign investigators, on the mechanisms of one change or another. Thus, Burch and Gerathewold (1960) considered the reduction in arterial pressure under weightless conditions to be functional adaptations of the heart to a decrease in the mechanical load. G. Von Beck (1958) considers that disruptions (or shifts) of the complex synergism of the autonomous cardiovascular pressoreceptors and pressoregulators can be expected in the state of weightlessness. Graybiel and colleagues (1959) attempt to explain the slowing of the pulse in monkeys under weightless conditions by the fright of the animals. One can scarcely agree with this, since a similar reaction is observed during a long stay under these conditions. R. M. Bayevskiy and O. G. Gazenko (1964), studying the reactions of the cardiovascular system, concluded that there was a phase nature of the adaptation of the circulatory system to the new physical conditions, and they expressed predominance of the vagus nerve system. Slowing down of adaptation processes under weightless conditions is explained by Gerathewohl and Ward (1960) by the "contrast aspect" of the transition of the body from one state to another, and V. N. Chernov and V. I. Yakovlev (1958) evaluate it as a consequence of change in the functional state of the nerve centers regulating blood circulation and respiration. The latter explanation apparently corresponds more to reality. A number of investigators prove that the sensory disturbances are caused by change in the afferent impulses from the labyrinth apparatus (V. V. Parin, et al., 1962, and others), etc.

According to Ye. M. Yuganov (1963), weightlessness does not lead to functional switching off of the otolith apparatus, but is an unusual minus-stimulus for the otoliths. The author thinks that, if weightlessness has a cumulative property, in all likelihood, the summation of the nerve processes arising here can lead to appearance of spacesickness symptoms.

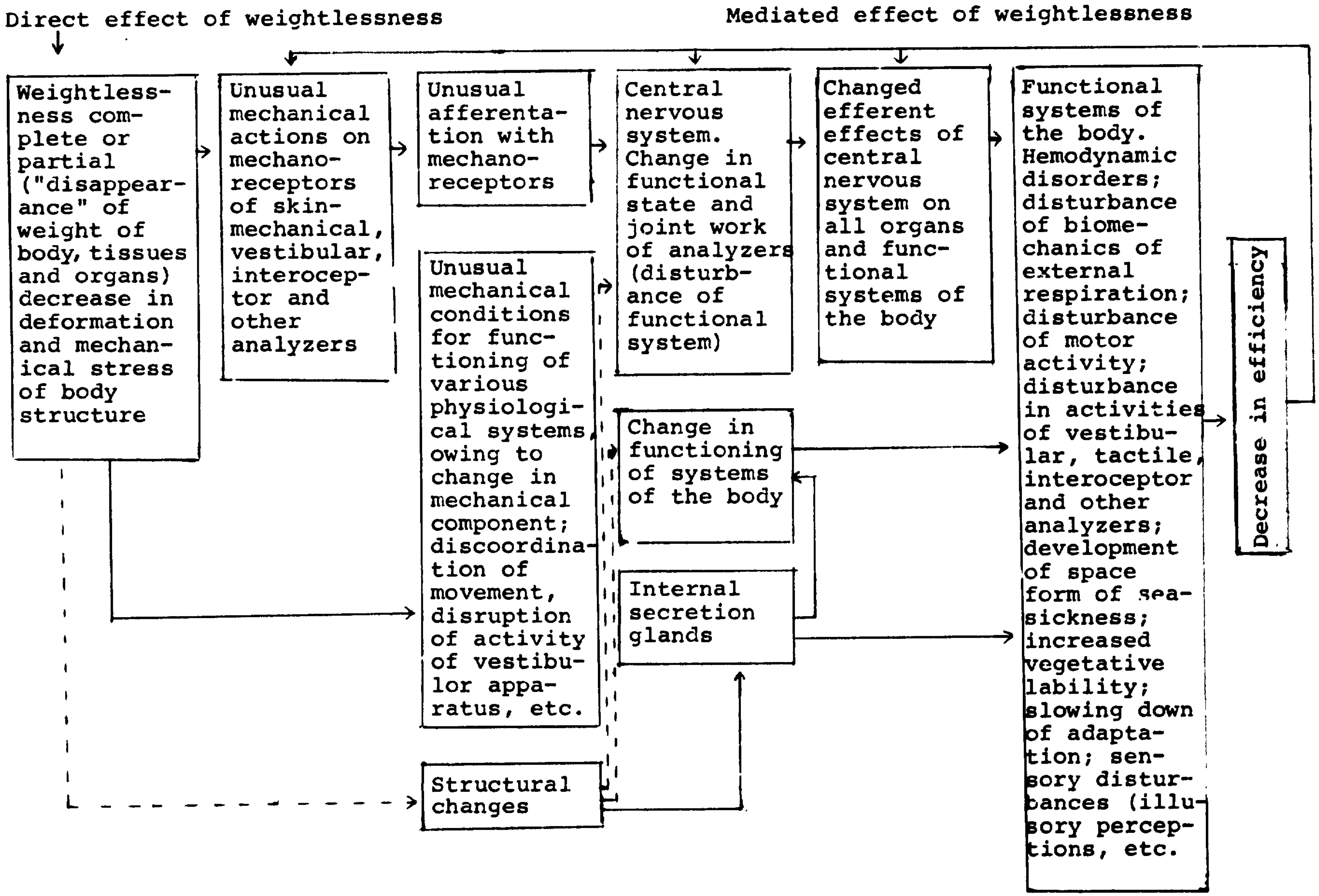
Experimental material and data in the literature have permitted us to state that there is a direct and mediated effect of weightlessness on the functional state of the cardiovascular system (Kas'yan, et al., 1964). In our opinion, it is completely competent to explain the sensory, motor and vegetative disruptions, which are observed under weightlessness conditions, on these grounds. The effect of weightlessness on the body is shown in the diagram. As is evident, the direct effect is understood to be the entire complex of reactions caused by decrease ("disappearance") of the weight of body tissues and organs and, consequently, the change in signals from the receptors, which are sensitive to mechanical actions. As a result, the blood pressure (arterial and venous) decreases, and accumulation /37 of blood takes place in the veins, in all likelihood, the venous flow from the upper part of the body is hindered, the biomechanics of external respiration change (under ground conditions, the act of exhaling takes place passively and the respiratory muscles participate under weightless conditions), and movement coordination is disrupted (missing the target), since movements are accomplished by the accustomed terrestrial stereotype, allowing for the weight of the extremities. Apparently, changes take place in the secretations of the glands of the gastrointestinal tract, afferentation changes, because of decrease in weight of the otoliths, and conditions for sensory disturbances are created. It might be supposed that urination could be disrupted to a certain extent, during prolonged weightlessness, although the astronauts examined noted no pecularities in urination. If the number of urinations and amount of urine eliminated are compared, some differences are possible, compared with terrestrial conditions (it is evident that the urges will be more infrequent in weightlessness, and elimination of urine more abundant, since a larger amount of urine is necessary, considering the "disappearance" of its weight, to cause the urination reflex).

In all likelihood, the functioning of the auditory and visual analyzers changes to a certain extent, in connection with the fact that, in weightlessness, the weight of the tympanic bones, eyeballs, etc. decreases ("disappears"). However, all these changes apparently are quite negligible; they were not felt by the people and astronauts examined.

The mediated effect of weightlessness is understood to be the entire set of physiological reactions, arising as a result of changes in the functional state of the central nervous system and the cooperative work of the analyzers, under the unusual afferent impulses from the mechanoreceptors of the vestibular, interoceptor, motor and other analyzers. As a result, the functional system of the analyzers, participating in analysis of spatial relationships, in the setting of the body in space, is disrupted (G. L. Komendantov, 1959, 1963), the space form of seasickness develops (G. L. Komendantov, V. I. Kopanev, 1962) and instability of a number of vegetative indicators is manifested.

DIAGRAM 1

EFFECT OF WEIGHTLESSNESS ON THE BODY



The principles of the functional system in the work of the analyzers is being confirmed more and more recently, in experimental research. Thus, V. V. Baranovskiy and colleagues (1962) have established that the vestibular-vegetative reactions were reinforced by stimulation of the proprioceptors and the visual analyzer. The same thing was demonstrated by V. N. Barnatskiy (1964). In seasickness of experimental animals, vegetative disorders were reinforced or weakened, by means of change in the functional state of the visual, proprioceptive and interoceptive analyzers.

There now are data showing that, in some persons under weightless conditions, an inhibiting process is strengthened in the central nervous system. Thus, with V. V. Tereshkova (V. I. Yazdovskiy, et al., 1964b), an increase in the low-frequency potentials took place during orbital flight, which indicates development of inhibition. From this, the observed instability of her pulse rate is understandable. Apparently, because of development of the inhibiting process, cortical control of the vegetative functions was disrupted, as a result of which, more pronounced vegetative shifts were displayed. The impression is created that, under weightless conditions, the tonus of the parasympathetic section of the central nervous system begins to predominate, since the pulse rate and blood pressure decrease, and a state of seasickness develops. To a /38
certain extent, the functional state of the cerebral cortex is determined by the tonic influences of the subcortical formations, mainly by the reticular formations, which also are not insensitive to unusual afferent effects (G. Megun, 1964; T. S. Naumova, 1963). It is possible that changes in afferentation from the mechanoreceptors changes the interference of the reticular substance and the cerebral cortex, as a result of which the cortex tonus decreases. In an actual space flight, weightlessness acts on the body, on a background of other factors (noises, vibrations). However, apparently, the main and, to a considerable extent, determining reaction of the body is the neuroemotional stress, caused by peculiarities of the flight, which must always be taken into account in analysis of the data (V. I. Yazdovskiy, et al., 1964), the more so that, as is thought, it favors strengthening of the sympathetic influences.

As is well known, in proportion to the length of time in weightlessness, a certain adaptation of the body to these unusual conditions develops. Considering knowledge of the physiological mechanisms, the effect of weightlessness on the human body and the physiological reactions, several periods of adaptation can be distinguished under these conditions and means of prophylaxis can be planned (Diagram 1a).

The first period[1] is a transitional process from the action of g-forces to the state of weightlessness. Its duration is from 1 to

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[1]A somewhat different and more detailed interpretation of the adaptation phase is discussed in Chapter 5.

DIAGRAM 1a

PERIODS OF ACTION OF WEIGHTLESSNESS ON THE BODY

	I	II	III	IV
Launch	Group 1 Good health, vegetative reactions adequate to unusual conditions of weightlessness. Preservation of efficiency at high level.	Partial adaptation. Physiological functions of body become normal.	Steady adaptation. High level of efficiency.	Group I Stable adaptation. High level of efficiency.
	Group II Static-kinetic disorders (seasickness, illusions, etc.). Reduction in efficiency.			Group II "Imbalance" of certain functions and systems of the body. Reduction in efficiency.
	1st day	2nd day	3rd-7th-8th days	9th-10th, up to 24 days and more

24 hours. Individual changes in the physiological indicators of the cardiovascular system and respiration appear during this time (pulse rate, blood pressure, pulmonary ventilation, vital capacity of the lungs, etc.), and different illusory sensations (illusions of the upside-down position of the body, falling, banking, etc.) and symptoms of discomfort (salivation, nausea, etc.) also are observed, which can lead to a decrease in the level of efficiency. The physiological basis of these changes should apparently be considered to be a mismatch of the functional system of the analyzers reflecting ·pace, predominantly because of the direct effect of weightlessness and, to a lesser extent, because of the mediated effect. In this connection, in the first period of weightlessness, with vestibular-vegetative disorders, it is advisable to use pharmacological preparations as indicated. It can also be assumed that the use of pharmacologicals in this period accelerates adaptation of the body and permits more efficient accomplishment of work in the first orbits of an orbital

flight. The use of pharmacologicals with such disorders has been dealt with in the periodical literature (P. V. Vasil'yev, V. E. Belay, G. D. Glod, 1971).

The second period is the initial adaptation to the unusual conditions and readjustment of the state of the cardiovascular and other systems of the body to a lower level of functioning. The duration of this period is 25-48 hours. Partial adaptation of the body to the state of weightlessness takes place (turning on of adaptation-compensatory mechanisms, etc.), some indicators of physiological functions of the body become normal, but there is not yet sufficient stability. The physiological basis of adaptation is formation of new functional systems and functioning of the central nervous system at a level, adequate to the unusual conditions of existence in the state of weightlessness. However, the new level of the functional system is extremely unstable, and it can be dis- /39
rupted by the action of unfavorable factors. This must be taken into consideration in organizing the work and rest of the astronauts in this period, and to ensure the optimum physiological-hygienic conditions in the spacecraft cabin.

The third period is a process of temporary adaptation of the functional systems of the body to the effect of weightlessness. The duration of the period is 3-8 days and more. As a rule, the more pronounced adaptation of the body to the state of weightlessness in this period than in the second period, and stabilization of the physiological indicators to the prelaunch level and a steady level of normal efficiency are noted. Therefore, it is advisable to perform critical operations in the third period.

The fourth period (from days 9-10 or more) can develop in two directions. The first is characterized by further adaptation of the body to weightless conditions. In this case, no functional shifts in the body are observed, and a high level of efficiency is preserved. In essence, this period is a continuation of the functional symptoms noted in the third period. The second direction is characterized by "imbalance" of some functions and systems of the body, as a result of the prolonged effect of weightlessness, hypokinesia and other flight factors. However, it is encountered considerably more rarely. In this case, a more pronounced reaction of the cardiovascular, /40
muscular and other systems of the body to measured physical loads and various work operations is observed.

The pulse quickens to a greater extent, the systolic and pulse pressure increase, the muscle strength of the hands decreases and, in a number of cases, asthenization, fatigue and reduction in efficiency of man can set in. In this case, the use of complex prophylactic means is fully substantiated (trainers, special suits, electrical stimulation of the muscles, pharmacological preparations, etc.), to increase the resistance of the body to the effects of weightlessness.

It might be thought that more pronounced shifts in the physiological functions after performing physical workloads under weightless conditions (fourth period) would be observed most often, when sufficiently effective prophylactic measures and protection were not used. As is shown by the results of the flights of the American astronauts in the Skylab orbital station, the employment of adequate physical loads (bicycle ergometer for a period of 1.5 hours per day, etc.) has turned out to be a very effective method of protection in active work of the astronauts, for a period of 56 days of flight.

In this manner, on the basis of study of experimental data, it can be concluded that the physiological reactions observed under weightless conditions are caused by: 1) the direct effect of weightlessness, as a consequence of decrease ("disappearance") of the weight of body tissues and organs; 2) the mediated effect of weightlessness, as a result of changes in the functional state of the central nervous system and the cooperative work of the analyzers. The human body adopts to weightless conditions under the prolonged effects of it. In this case, four periods can be distinguished: the first period, a transitional process lasting from 1 to 24 hours; second period, initial adaptation to conditions of weightlessness and readjustment of all functional systems of the body, the third period, adaptation to the unusual mechanical conditions of the external environment, lasting from 3 to 8 days and more; and the fourth period, the stage of possible "imbalance" of the functions and the systems of some astronauts, as a result of the prolonged effect of weightlessness.

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CHAPTER 2

VESTIBULAR-SENSORY REACTIONS UNDER WEIGHTLESS CONDITIONS

1. Reactions of Animals and People Under Conditions of Brief Weightlessness

Experiments during brief weightlessness in aircraft and rocket /41 flights permit the reactions of the organism to be studied in the initial period of its action. An intense readjustment of the majority of functional systems takes place in this period. Physiological reactions arise, which affect the well-being and efficiency of a man under these conditions.

Any maneuver of a spacecraft flight is accompanied by accelerations on the crew, after disappearance of which, weightlessness again sets in. The adaptation arising here apparently is similar in nature to the processes occurring in the initial period of the effect of weightlessness, i.e., the "initial" period of weightlessness can be repeated many times in a space flight. Weightlessness, precisely the initial period of it, is characteristic, not only of space, but of aviation flight. A pilot is in this condition in performing such maneuvers as "diving," "hanging loop," "tail slide," "parabolic flight," etc. The so-called reduced weightiness frequently arises in aircraft flights, for example, during the rapid loss of altitude in a landing approach. It should be noted that special precision in work is required in the initial period of weightlessness. At this time, an abundance of varied information is noted, coming in to the astronaut or pilot.

The importance of parabolic flights in aircraft, for familiarizing future astronauts with the conditions of weightlessness, as well as for working out various procedures and skills, applicable to space flight, is generally acknowledged. All this, as well as the relative simplicity of creating brief weightlessness and the possibility of /42 use of persons without special prior training and, even, with some health defects, as subjects in these experiments, make flights along a parabola an important procedure for biomedical studies of weightlessness.

Weightless conditions have been created in an aircraft, during flight along a trajectory, which is close to parabolic. Weightlessness preceded (as well as followed) g-forces. Under separate, controlled conditions, weightlessness has been created, without the preceding g-forces. During a single flight, 6-10 cycles of weightlessness have been executed. The parameters of the gravitational-inertial factors generated in establishing weightlessness, in the course of this work, are presented in Table 14 (compiled by Ye. T. Berezkin).

During the flights, the temperature, pressure and chemical composition of the air and the level and spectral composition of the noise in the aircraft cabins were maintained, in accordance with the standards adopted for passenger aircraft of the civil aviation fleet. 2,920 weightless cycles were executed during the course of this work.

Reactions of Animals During Brief Weightlessness

Adaptation to repeated effect of brief weightlessness, from the evolutionary point of view

The task of this investigation was to study the behavioral reactions of various animals used in the laboratory, in the initial period of action of weightlessness, and to determine the duration of their adaptation to the repeated effects of brief weightlessness.

In the brief weightlessness experiments, the behavioral reactions of goldfish, frogs, lizards, pigeons, white mice, white rats, guinea pigs, rabbits, cats and dogs were studied. Ten animals of each species, of random age and sex, were used. Special cubicles were arranged in the aircraft cabin, and containers were installed, in which the animals could soar freely during weightlessness. The containers were filled with water in the experiments with fish. The frogs were studied under weightlessness, in water and air environments. The behavior of the animals was recorded by use of motion picture photography, with subsequent frame-by-frame interpretation. The number and nature of motions of the animals, as well as the positions of the animals, relative to "up" and "down" of the aircraft cabin, were determined in different flight modes.

No significant change was noted in motor activity of fish and amphibians in a water environment during weightlessness. Loss of orientation of "up" and "down" in the cabin was characteristic of this state. Extension of the rear extremities predominated in the frog under weightlessness, while hovering in the air environment; on the other hand, in the water environment, flexor reactions arose and motor activity decreased. While soaring under weightlessness, reptiles performed frequent movements of the feet and motions of the trunk, in the form of "coiling." /43

In birds, at disappearance of the force of gravity, wing flapping began, in the form of continuous upward flight. As a result, they flew "up" to the ceiling, turned around and flew to the floor and, further, again to the ceiling, etc. With the 2nd or 3rd cycle, this reaction was extinguished, and the birds hung in the air in an unusual posture, with the wings extended behind the back and with the tail feathers spread. They could cling to the cabin upholstery, retaining the posture with extended wings. Beginning in the 18-20th

TABLE 14

PARAMETERS OF GRAVITATIONAL-INERTIAL FACTORS

Parameters of Effective Factors	Hori-zontal Flight	Transi-tional Mode	"Steep Climb"	Transi-tional Mode	Pa-rabo-la	Transi-tional Mode	Diving	Transi-tional Mode	Hori-zontal Flight
Duration of Mode, sec	at least 60	1.5-2	15	2-3	28	2-3	15	1.5-2	at least 60
Linear acceleration, n_y	1	from +1 to +1.8	1.8	from +1.8 to 0	0	from 0 to 1.8	1.8	from 1.8 to 1	1
Angular velocity, °/sec	0	from +0 to +2.6	+2.6	from 2.6 to -2.8	-2.8	from -2.8 to +2.6	+2.6	from +2.6 to 0	0
Angular acceleration, °/sec^2	0	+1.7 +1.3	0	-2.7 -1.8	0	+2.7 +1.8	0	+1.7 -1.3	--

cycle, the birds hung in weightlessness, with folded wings and tail.

The motor activity of <u>mammals</u> increased under weightlessness. Motions initially arose, similar to running of the animals: in the mice and rats, "drumming," reciprocating motions of straightened extremities; in all the other animals, "jumps" (alternating bending and straightening of the trunk) and "drumming" motions of the extremities. Simultaneously, rotating motions of the straightened tail was noted in the mammals, except for the guinea pigs and rabbits; as a result of the torque reaction, the trunks began to rotate in the opposite direction. An increase in motor activity was always accompanied by psychic excitement of the animals: with cries, dilation of the eye slits and marked grasping reactions in the cats. All these reactions took place, from the very start of weightlessness, on a background of marked extension of the extremities and throwing back of the head. Activation of some vegetative functions of mammals was noted in the experiments: an increase in salivation, urination and defecation (which began under weightlessness) and perspiration in the cats; there were no cases of vomiting. With multiple repetition of weightlessness (Table 15), the "jumps" disappeared initially and, then, the "drumming" motions with the paws The psychic excitement of the animals decreased simultaneously: They began to turn with the tail, continuing to hold it extended in the dorsal direction under weightlessness. After disappearance of the motor reactions, extension of the extremities and trunk began to be more noticeable. In proportion to adaptation of the animals, the extensor reaction disappeared. Under weightlessness, they hung in the air, clasping the paws to the abdomen, straightening them only to grasp some object near at hand. The behavior of the cats and dogs differed from the behavior of the other animals, by more rapid onset of adaptation to weightlessness and a greater diversity of individual reactions.

Despite such a sharp reaction of the different animals to weightlessness, it cannot be stated that this state is completely unknown to terrestrial creatures. Cessation of the effect of the force of gravity is experienced comparatively often by various organisms under conditions of life on the ground. Arising only during free fall, weightlessness apparently signals the danger of a possible impact on the earth and, as a rule, it does not last more than 2-3 sec. It seems to us that the mechanisms of the physiological reactions caused by weightlessness should be analyzed, based on a concept of /45
the dynamics of the processes, which arise in the organism during free fall. It is well known that falling causes extensor ("lifting") reactions of the extremities and trunk of an animal, rotating motions of the tail (they stabilize the animal in the oncoming air stream) and activation of grasping reflexes. The biological meaning of these motor acts consists of preparation of the posture ensuring the safest landing.

TABLE 15

DURATION OF ADAPTATION TO REPEATED ACTION OF WEIGHTLESSNESS OF VARIOUS TYPES OF ANIMALS

Class and Species of Animal	Motor Reactions: Reaction	Motor Reactions: Period of weightlessness in which extinction of reaction takes place	Tonic Reactions: Reaction	Tonic Reactions: Period of weightlessness in which extinction of reaction takes place
Fish	None	--	None	--
Amphibians in water environment	"	--	Flexing of extremities	At least 15
In air environment	Jerking of rear extremities	10-15	Extension of extremities and trunk	same
Reptiles	Motions similar to "running"	5-8	same	"
	"Coiling"	5-8		
Birds	"Continuous upward flight"	2-3	Wings spread out behind back	At least 10
Mammals: White mice	"Running"	15-25	Extension of extremities and trunk	20-30
	Rotation of tail	20-30		
White rat	"Running"	6-8	same	6-8
	Rotation of tail	6-8		
Guinea pigs	"Jumps"	3-5	"	6-8
	"Running"	6-10	"	
Rabbits	"Jumps"	6-8	"	15-20
	"Running"	8-12		
Cats	Motion of entire trunk and paws	3-8	"	8-12
	Rotation of tail	6-15		
Dogs	Motion with paws	1-3	"	3-5
	Rotation of tail	3-5		

Similar reactions have been noted (O. G. Gazenko et al., 1968; Henry et al., 1952; Beckh,1954) in animals, in the initial period of weightlessness in flights in aircraft and satellites. In motor excitation, tonic (extensor) reactions of the extremities and trunk and motor reactions (prehensile motions with the tail, reciprocal "drumming" motions of the extremities, motions in the form of jumps) can be distinguished (L. A. Kitayev-Smyk, 1963b). The similarity of the motor reactions in the initial period of weightlessness and in falling indicate that the animals apparently perceive this period as falling. Weightlessness lasting more than 2-3 sec has no phylogenetic or ontogenetic precedents. And, becoming a signal of extreme danger, causes elements of a defensive "running away" reaction (motion, in the form of jumps and running, cries, dilation of the eye slits, etc.). G. Megun (1965) indicates that the reciprocal flexing of the extremities, combined with straightening the back, continually arises in direct stimulation of the reticular formations, in which the impossibility of inducing reticulospinal inhibition is explained by the functions of the cortex, reducing the excitability of the medulla oblongata. Removal of the regions of vestibular representation to the cortex prevents development of motor excitation of cats under weightlessness (Schock, 1961).

In weightlessness, created in closed aircraft cabins, satellites, etc., information coming from the gravireceptors (vestibular, musculocutaneous) and a number of interoceptors is evidence of disappearance of the reactions of defense, of falling, i.e., of danger for the body of the animal or man of disruption of stability of the surroundings. At the same time, vision signals the absence of changes in space: the same walls, floor and ceiling of the cabin are visible. In this manner, two contradictory information flows arise. In analyzing the functioning of various sensory systems, Holst (1951) proposed that, in the case when contradictory reports come from different receptors "neutralization," "extinction" of them takes place in the lower brain centers and only the "residue of the predominant signal" reaches the higher centers.

The results of experiments with animals under brief weightlessness confirm the opinions expressed. Evidently, by virtue of the predominant importance of the vestibular and motor analyzers over the visual in spatial perception (E. Sh. Ayrapetyants, 1960; I. S. Beritov, 1961), after disappearance of the force of gravity, motor reactions arose in the animals, characteristic of free fall under natural conditions, in conformance with the gravireceptor information. The motor activity of the animals decreased, in proportion to advance of adaptation to weightlessness.

It might be thought that the duration of adaptation to repeated weightlessness depends, not so much on the evolutionary level of the animal, as on its ecological pecularities. Fish and amphibians, living in an immersion environment, are practically devoid of defense reactions. Moreover, they can move in three dimensions, which creates natural adaptation to small changes in the force of gravity. Obviously, all this caused the absence of motor excitation in them under weightlessness, while in the immersion environment. The differences in motor activities of the amphibians, under weightlessness in the water and the air environment, are evidence of the importance of tactile signals in forming motor reactions to weightlessness. The relatively short period of adaptation of birds to weightlessness, in all likelihood, also was caused by their natural adaptation to decreases and increases in the force of gravity, frequently arising in flight. The period of adaptation to weightlessness of cats and dogs is shorter than that of mice and rabbits, certainly because the visual analyzers of carnivores is more highly developed than that of rodents (D. A. Biryukov, 1960). /46

Interaction of analyzers in animals during brief weightlessness

For the purpose of analysis of the interaction of the visual and vestibular analyzers after disappearance of the force of gravity, experiments were performed in parabolic flights, with the vision and vestibular apparatus of the animals disengaged.

The experiments were performed with 24 rabbits, 8-10 months old, of both sexes, and with 18 cats of random age and sex. Disengagement of the vision of the animals was accomplished, by means of special light-impermeable masks placed over the eyes of the animals. The vestibular apparatus was disengaged in rabbits, by the method of Tsipin and Grigor'yev (1959) and, in the cats, by the method of De Klein, 1812).

The investigation carried out showed that, with the vision cut off, the motor activity of the animals increases sharply under weightlessness and the period of adaptation to it is lengthened (Table 16). While motor excitation of intact rabbits disappeared in the 5-8th cycle of weightlessness, the "jumps" and "drumming" motions of the paws was retained in the 36th cycle in animals, the vision of which was cut off during the flight. In flight, beginning with the 37th cycle, their eyes were opened; in the 40th cycle of weightlessness, the motor reactions of these rabbits disappeared. Subsequently, the masks were then placed on them again, cutting off the vision, but the motor excitation under weightlessness did not again arise. Cutting off the vision of rabbits, staying 6-8 times under weightlessness with open eyes, also either did not cause an increase in motor activity upon disappearance of the force of gravity, or vague, quickly disappearing motions arose.

In animals with the bony labyrinth removed, in the absence of visual compensation for the lost functions, when the flight experiments were carried out on the 2nd or 3rd day after the operation, the motor activity in weightlessness arose; however, there was no extension of the extremities and trunk. Cutting off the vision had no significant effect on the behavior of these animals under weightless conditions.

TABLE 16

DURATION OF ADAPTATION TO WEIGHTLESSNESS OF RABBITS AND CATS, WITH THEIR VISION AND VESTIBULAR APPARATUS DISENGAGED

State of Animal	No. of Animals		Motor Reaction		Tonic Reaction	
	Rabbit	Cat	Rabbit	Cat	Rabbit	Cat
Intact	6	3	Disappears in 6-8th cycle of weightlessness	Disappears in 3-8th cycle of weightlessness	Disappears in 15-20th cycle of weightlessness	Disappears in 6-12th cycle of weightlessness
With vision cut-off	6	3	Does not disappear in 36 cycles*	Does not disappear in 24 cycles*	Disappears in 20th cycle	Disappears in 10th cycle
Bony labyrinth removed without ground visual compensation	3	3	Does not disappear in 24 cycles*		Absent	
Bony labyrinth removed with ground visual compensation	3	3	Absent		same	
Unilateral removal of bony labyrinth	3	3	Does not disappear in 36 cycles, accompanied by rotation*		Does not disappear in 36 cycles, asymmetric	
Bony labyrinth removed with ground visual compensation and vision cutoff	3	3	Does not disappear in 36 cycles*		Absent	

*Observations were not carried out in subsequent cycles.

Animals with the bony labyrinth removed, in which compensation for the lost functions was formed to a considerable extent, hung peacefully in the air, without motion, with intact vision. If the vision of these animals was cut off, as a rule, 1.5 sec after the onset of weightlessness, they began vigorous motions, in the form of "jumps," with adaptation to weightlessness not arising during multiple repetitions of the experimental cycles.

In unilaterally labyrinthectomized animals, regardless of the time after the operation, both with vision intact and cut off, vigorous motion, in the form of asymmetrical "jumps," began under weightlessness. As a result, quite rapid rotation of the animals in the air arose (1-1/2 - 2 revolutions per second). Adaptation to weightlessness was not observed in repetition of it, in animals with one bony labyrinth. /47

Thus, it might be supposed that the impulses from the gravireceptors, signaling falling, causes formation of the behavioral reactions described above (motor excitation of the animals, on a background of hypertension of the extensors of the extremities and the trunk). Visual information as to the stability of the environment facilitates disappearance of these reactions and adaptation to weightlessness. Upon cutting off the vision, as these experiments have demonstrated, the process of adaptation to the new gravitational conditions is disrupted. /48

In the absence of visual compensation (substitution) of the labyrinth functions in labyrinthectomized animals, the behavior was formed, in conformance with information entering from the musculocutaneous analyzer and, possibly, from visceroreceptors. Signaling the disappearance of the force of gravity, this information caused motor excitation of the animal. In this case, the visual analyzer did not have a decisive effect on the process of behavior formation: not being dominant in animals, it possibly even lost its importance in development of adaptation, because of destruction of the integrity of the analyzer system, in connection with cutting out the labyrinths.

With visual compensation after labyrinthectomy and with intact vision, motor excitation of the animals did not arise under weightlessness.

This phenomenon has been described by a number of authors (Henry, et al., 1952; Schock, 1961, and others). In this version of the test, it might be thought that vision, becoming predominant over the spatial analyzer, provided information on stability of the surroundings under weightlessness, and that this prevented the formation of motor excitation.

The experiments with unilaterally labyrinthectomized animals give evidence in favor of the opinion stated, on the nature of the interaction of the analyzers under weightlessness. As a consequence of the rotation generated in them, in the absence of support under weightlessness, vision could not signal stability of the surroundings. During the experiment, the asymmetry of the body served as an additional source of signals on spatial distortions. As a result, vigorous motor reaction arose in these animals, after the disappearance of the force of gravity, without any signs of adaptation in repeated cycles of weightlessness.

It should be noted that cutting out the vision of intact animals which had been under weightlessness with open eyes, did not cause the same degree of motor excitation upon disappearance of the force of gravity, as in animals, which were always under these conditions with the bandages on the eyes. Consequently, not only visual signals, but visual memory of the stability of the surrounding situation, may favor adaptation to weightlessness.

Bioelectric activity of the brain in brief weightlessness[2]

Bioelectric activity can be an indicator of participation of various sections of the brain in formation of physiological reactions. Study of it, in flights along a parabolic trajectory, was the purpose of this section of the work.

The experiments were conducted on two cats and one rabbit adapted to weightlessness, with permanently implanted surface and buried electrodes. The biopotentials were taken by the unipolar and bipolar methods. During the test, the animals were in a shielded cage, in a fixed position. The tests were performed primarily on unanethetized animals, and, only in isolated tests, the cats were /49 under light nembutal narcosis.

The electrical activity was recorded in the following sections of the brain: 1) the anterior section of the suprasylvian and ectosylvian gyrus (three points), which is considered to be the location of the cortical projection of the vestibular analyzer (Anderson, Gernandt, 1954; Mickle, Ades, 1954); 2) the optic area; 3) the auditory area; 4) the orbital area (projection IX and chorda timpani). In the subcortical regions, the electrical activity was recorded in the anterior-lateral section of the hypothalamus and the inner and outer geniculate bodies.

The most characteristic and marked changes were revealed in the anterior section of the suprasylvian and ectosylvian gyrus. With the onset of g-forces, preceding the period of weightlessness, a picture of marked desynchronization of the rhythm was observed in the electrocorticogram (EKoG) which, as a rule, was persistently retained

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[2]The work was performed jointly with A. M. Klochkov.

until the onset of weightlessness. Beginning in the first seconds of weightlessness, the amplitude of the oscillations increased and a noticeable shift in the frequency characteristics of the EKoG began, in the direction of slower oscillations. Instability of the EKoG rhythm and the presence of mixed waves were characteristic. In the period of 25-30 seconds of weightlessness, there was an exchange several times, of the high-amplitude α-like waves by a quick low-amplitude rhythm and vice versa. In this case, the high-amplitude, slower oscillations predominate nevertheless, in the first 5-8 sec of weightlessness. The nature of change in the EKoG under g-forces, following a period of weightlessness, was similar to that, which is observed during the preceding g-forces.

The authors, considering localization of the cortical representation of the vestibular function of the anterior section of the suprasylvian and ectosylvian gyruses, distinguish three separate points, corresponding to projections of individual sections of the vestibular apparatus into the cortex: the utricle, lateral semicircular canal and upper semicircular canal. We located electrodes corresponding to these points. However, we could not notice any differences in the measurements of bioelectric activity under weightlessness and g-forces, in unipolar recording.

Beside the vestibular area of the cortex, the same changes, but less expressed, sometimes were encountered in the visual area of the cortex, especially under g-forces. The effect of g-forces on the EKoG was more intense, and it frequently caused changes in the latter, where no changes were observed under weightlessness. During the transition from weightlessness to subsequent g-forces, which takes place over a period of 1-1.5 sec, bursts of groups of high-amplitude α-like waves, 2-9 sec long, appeared regularly. Such α-like wave bursts appeared several times, during the transition from normal gravity to g-forces. As has already been noted, the onset of weightlessness also is characterized by appearance of high-amplitude α-waves. Thus, all transition states during changes in gravitation were characterized by the appearance of groups of α-like waves, after which a picture develops, which is characteristic of one type of gravitation or another, desynchronization under g-forces and mixed rhythms under weightlessness.

In taking off the biopotentials from the subcortical centers, the relative resistance of their bioelectric activity was noted, to the effect of weightlessness and g-forces. In the same cases, when changes in bioelectric activity of these formations took place, their nature differed from the changes observed in the cerebral cortex. Under g-forces, some increase was noted in the number of slow oscillations with high amplitude, and the picture of mixed /50 waves was not observed, i.e., here, there was no desynchronization of the rhythm which is characteristic of the cortex. Under weightlessness, oscillations with a frequency of 14-16 Hz and high amplitude were predominant, and both the very rapid and slow oscillations were almost absent. In this case, the biopotential frequency was somewhat higher than in horizontal flight and under g-forces.

As a peculiarity of the subcortical center reactions, it should be noted that the changes described above did not arise immediately at the moment of change in gravitation, but that they developed comparatively slowly, and the picture of the preceding period was still preserved in the first 3-4 sec after the change.

All the changes in bioelectric activity of the cortex and subcortical formations described above were observed most distinctly in animals in the waking state. In experiments using light Nembutal narcosis, the nature of the changes remain the same, but the degree of expression was considerably reduced. The comparison of the normal and control samples of weightlessness (after horizontal flight) showed that the directional nature of the changes in EKoG was the same in both cases; however, with g-forces preceding, the changes were more significant under weightlessness.

In this manner, the experiments carried out showed that, during brief weightlessness, the EKoG frequency decreases and amplitude increases in immobilized animals, in the region of the likely vestibular and, to a lesser extent, visual cortical representations. The changes in electrical activity of the subcortical centers under weightlessness were less pronounced than those in the cortex.

Similar data were obtained by R. Grandpierre (1968), in recording EEG of rats, cats and monkeys in aircraft and rocket flights. Under weightlessness, spindles of high-amplitude slow waves appeared in the EEG. In some cases, they were found in the EEG of the reticular formation. The author thinks that "this type of activity is typical of the internal inhibition or of great relaxation, before the transition to sleep."

Data in the literature, on representation of the vestibular functions in the cortex are ambiguous. Some authors consider its localization to be the posterior sections of the suprasylvian gyrus and others, the anterior section of the suprasylvian and ectosylvian gyrus.

Our studies, showing that the most pronounced changes in the EKoG during changes in gravitation are observed in the anterior section of the suprasylvian and ectosylvian gyrus, are evidence in favor of the latter point of view. The presence of similar changes in the visual zone of the cortex apparently is caused by the close interrelationships of the vestibular and visual analyzers.

The regular appearance of α-like wave bursts during transitional modes, most often during the onset of weightlessness, are caused by changes in linear acceleration, rather than angular acceleration, arising during the transitional mode.

In addition to the effect on the vestibular apparatus, the gravitational-inertial factors can have a direct mechanical effect on the brain tissue, and a mediated effect also could take place, as a result of disruption of the hemodynamics. Both could also cause changes in the electrical activity of the brain. However, in this case, the effect of change in gravity should be manifested to the same extent in different regions of the cortex.

Role of the cerebellum in adaptation of animals to weightlessness[3]

The level of bioelectric activity of the cerebellum changes /51 under weightless conditions (Terzuolo, Terzian, 1953). Together with this, there are data on change in frequency of the electrical discharges of the stem neurons of the Deiter's nuclei, during polarization of the anterior lobes of the cerebellum and of the labyrinths (De Vito, et al., 1956; Pompeiano, Cotti, 1956), as well as a series of data on convergence of the labyrinth, visual and proprioceptive discharges to the cerebellum (I. S. Beritov, 1960; Moruzzi, 1959; Gualtierotti, et al., 1961). This indicates participation of the cerebellum in motor coordination and spatial orientation.

To ascertain the role of the cerebellum in formation of postural and motor reactions under weightlessness, experiments were carried out on cats with the cerebellums removed.

The cerebellum was completely removed from one cat 4 months before the experiments. Up to the time of the tests, the principal symptom of the "dynamic period," accompanying cerebellectomy -- extensor rigidity of the extremities -- were completely absent in it (the animal could move for a short time, only along walls, and compensation for the act of standing appeared a month after this operation). The loop-shaped lobes, with the dorsal and ventral paraflocculi adjacent to them were removed from another cat 5 months before the tests. The method of removal of the cerebellum and the nature of certain motor disorders have been described by R. A. Grigor'yan (1963). Two intact cats were used as controls. Each animal was exposed to weightlessness 12 times. To eliminate adjusting movements relative to the nearest surface, the vision of the animals was cut off, by means of masks, in some experiments. Before the start of the experiments under weightlessness and after completion of them, the vestibular status of the animals was examined, including the status with the vision cut off. The head and extremity lifting reflexes, the reflex of readiness to jump, the turnover reaction, as well as the adjusting reflexes, were studied.

The experiments showed that, under weightlessness, the motor activity of <u>intact animals</u> increased sharply. This was noted in the

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[3]The work was performed jointly with O. G. Gazenko, R. A. Grigor'yan and A. M. Klochkov.

initial stage of adaptation to weightlessness, on a background of the characteristic predominance of the extensor tonus of the muscles of the back, neck and extremities. However, this was noted only in the first cycles of weightlessness. Subsequently, in proportion to repetition of weightlessness, the animals gradually adapted to the changed conditions, and their motor activity noticeably decreased. Thus, random swinging of the paws stopped in the 3rd period of weightlessness; the posture with the straight back and straightened extremities was not observed in the 4th-5th period, and rotation of the tail stopped after the 7th period of weightlessness. Cutting off the vision of the intact cats, by means of tying on masks before the 7th period of weightlessness, somewhat increased the motor activity of the animal; beginning with the 8th-9th period, cutting off the vision did not have an effect on the motor behavior of the animals.

In distinction from the normal cats, the sharply expressed state of extensor rigidity of the muscles of the trunk, neck, posterior and, especially, the anterior extremities were characteristic of the cats with the cerebellums removed, which greatly exceeded the similar changes in tonus of the control animals. The animals swung with taut extremities, bending them only at the shoulder and pelvis-femoral joints, and they rotated with nearly straight tails. During the 12 experiments, a decrease in these phenomena was not noted. /52
Rhythmic pendulumlike movements of the extremities (1-2 per sec) were observed, only during the first 4-6 periods of weightlessness. During these sessions, the animals attempted to grasp surrounding objects, but they could not do this, because of the sharp predominance of the extensor tonus in the extremities.

Cutting off the vision of the acerebellar animal had practically no effect on the nature of its motor activity under weightless conditions. The motor activity of the cat with the partially removed cerebellum was strongly increased, an attempt to grasp surrounding objects was noted, in which the muscles of the trunk contracted asymmetrically on the unoperated side, with bending of the longitudinal axis of the body to the right and rotation of the animal to the left: initially, it rotated the head, anterior portion of the trunk followed it and, subsequently, with a jerk, the posterior section performed the same movement. It was noted that the continuous rotating movements of the tail were performed in the direction, opposite to the rotation of the trunk. If the animal succeeded in grasping surrounding objects, the motions described stopped quickly. With the vision cut off, the motor agitation of the animal with the partially removed cerebellum noticeably increased.

In comparing the results of the vestibular status of the experimental animals before conduct of the experiments in weightlessness and after them, no differences were found. The lively vestibular reflexes of the intact animals indicated normal functioning of the vestibular analyzer.

The postural vestibular reflexes of the animal with the cerebellum removed also were preserved; however, the nature of them was changed, because of the presence of dyskinesia: the adjusting reflexes of the body and head and the lifting reflexes of the extremities, in distinction from those of the intact animal, took place on a background of increased extension of the extremities and trunk; the reflex of readiness to jump was well expressed, and the turnover reaction was accomplished even more quickly than that of the intact animal. While a complete turnover ended in 0.5 sec in the control animal, a complete turnover ended in 0.25 sec in the acerebellar animal. In contrast to the intact animal, soft landing on the paws was absent in the acerebellar and, after landing, the animal moved back.

All vestibular reflexes were noticeably increased in the animal with the partially removed cerebellum; the turnover reflex took place more rapidly than those of the intact and acerebellar animals. A complete turn of the trunk for landing ended 0.2 sec after throwing it upside-down with the hand. Turning over was accomplished through the left shoulder; in falling, asymmetry of the trunk (bending to the right) and marked extension of the anterior extremities of the operated side were noted. Conduct of the vestibular tests on the animals with partially removed cerebellums caused a considerable increase in their aggressiveness.

It is known that, under earth conditions, hypertonus of the extensors arises in early periods after cerebellectomy -- "cerebellar release" (Batini, et al., 1956) or after decerebration of the animals -- "decerebration rigidity." In the first case, it is connected with elimination of the tonic inhibitive action of the fascicular nuclei of the cerebellum on the vestibular nuclei of the stem (Sprague, Chambers, 1954; De Vito, et al., 1950). The cerebellar nature of the extensor alleviation also is demonstrated in tests with application of strychnine to the cortex of the paleocerebellum (Terzulclo, Terzian, 1953). In the second case, the hypertonus is connected with elimination of the cortical mesencephalic inhibiting /53 influences. Impulses from the labyrinths (Ye. M. Yuganov, et al., 1953; Moruzzi, 1950) and the musculocutaneous receptors (Batini, et al., 1956), have an important role in regulation of postural tonus.

According to electromyography data (Ye. M. Yuganov, et al., 1963), the tonus of the extensors of decerebralized animals is decreased under weightlessness and by contrast, it is increased in the acerebellar animals, as is evident from this study.

Compensation for the cerebellar release symptom is bound mainly to the inhibiting influence of the brain stem and spinal column (Batini, et al., 1956), as well as, to a certain extent, of the cerebral cortex (Moruzzi, 1959). However, this compensation apparently is incapable of completely replacing the cerebellar inhibition and, therefore, the adaptation to weightlessness, which is observed in the normal cats, could not be found in the acerebellar cats in our experiments.

Adjusting reflexes of animals during weightlessness

This series of experiments had to answer the question as to how long the orienting effect of the force of gravity continues to show up in the adjusting reactions of an animal after disappearance of gravity, which serves as a reference point for the adjusting reactions in weightlessness. By "adjusting reactions," we understand the Stellungsreflex of Magnus (1925). We recall that some Russian authors translate this term as "straightening reactions" (A. V. Samoylov, 1927).

Tests under weightless conditions were carried out on intact animals (3 cats, 6 rabbits) and on labyrinthectomized ones (2 cats, 3 rabbits). All animals were adapted to the effect of weightlessness, i.e., their motor activity did not change with disappearance of the effect of gravity. The following series of experiments was performed: 1) before onset of weightlessness, the animals were immobilized by the trunk and head, in the back down position. Under weightless conditions, after various periods of time after its onset, the animal was released. The presence of the "turnover reaction" was determined; 2) in the absence of the effect of gravity, the animal, immobilized by the trunk, was turned over around its longitudinal axis. The position of the head was determined; 3) before onset of weightlessness, the animal was immobilized by the trunk and head, with the head being turned by 90° from the trunk, around the longitudinal axis of the latter. During weightlessness, the animal was released and the nature of straightening out of the animal was determined; 4) in the absence of gravity, the animals were observed, soaring around the floor, walls or ceiling of the aircraft cabin. The presence of visual adjusting reactions was determined; 5) under weightless conditions, reactions to forward motion were studied: a) reaction of the head; b) lifting reactions; c) readiness to jump; 6) 10-15 sec after onset of weightlessness, the animal was immobilized by the trunk and head and rapidly (in 0.3-0.5 sec) rotated by 180° around the longitudinal axis and was immediately released. The subsequent reaction of the animal was determined. Before and after flight experiments, the vestibular status of all animals was determined under natural gravity. A total of 240 experiments under weightless conditions and 170 experiments under natural gravity were performed. In all tests with the cats, with the exception of study of the visual adjustment under weightlessness, light-impermeable bandages were placed over the eyes of the animals. The experiments with the rabbits were performed, both with and without cutting off the vision.

It was shown in the first series of tests that the "turnover reaction" arose in released animals with intact labyrinths, not more than 4-5 sec after the onset of weightlessness. This reaction was absent in labyrinthectomized animals. In series 2, upon turning the animal with intact labyrinths over under weightlessness, its free head lagged behind the trunk in turning. By 1-3 sec after completion of the turning of the trunk, the head also completed the /54 turn, proving to be straight relative to the trunk. After labyrinthectomy, the lagging of the head in turning the animal was not observed. In series 3, upon releasing the animal with the previously turned head under weightlessness, the head of the animal with intact labyrinths remained fixed, and the trunk turned to a straight position relative to the head.

By contrast, the head of the labyrinthectomized animal turned, with the trunk not moving. Series 4 displayed a visual adjusting reaction under weightlessness in all animals, in the form of turning, after which the legs of the animal proved to be directed towards the nearest surface, regardless of whether it was the floor, wall or ceiling. This reaction was more pronounced in cats; it was displayed in rabbits, in cases, when they soared at a distance of not over 15-20 cm from some surface.

No reactions were found to forward movements (series 5) in our experiments under weightlessness.

Finally, in the last series of experiments, when the animal with the intact labyrinths was released in weightlessness, after rapid (in 0.3-0.5 sec) turning by 180°, a motion, rotating it in the opposite direction arose in it, and it continued to the end of the cycle (15-20 sec). Cutting off the vision strengthened the intensity of these motions. Upon releasing labyrinthectomized animals after rapid turning, random motions were displayed, not leading to rotation of the animal. Turns of the animals in the "turnover reaction" and in experiments of this series 6, were accomplished, by means of "screw" motions of the entire trunk, which began with motions of the posterior part of the trunk and the posterior extremities, the anterior part of the trunk was then involved in this motion and the head turned last.

In examination of the vestibular status of the animals after the experimental flights, no deviations from their preflight state were found. Indications of some fatigue and an increase in protective reactions was noticed in the cats after the flights.

In this manner, both under ground conditions and in the first seconds of a parabolic flight, the "turnover reaction" of the animals was accomplished during the time, when the effect of acceleration does not show up in their gravireceptors, since, in free fall and under weightlessness, the support reaction is absent and the force of gravity cannot act on the body. Consequently, it might be supposed that the starting signal to begin the "turnover reaction" is an aftereffect of the stimulation of the otoliths by the forces of gravity, existing before the onset of weightlessness.

The data of the experiments described above show that the "turnover" reaction arose in the animals, only in the first 4-5 sec of the weightlessness created during a flight along the parabola, i.e., that this aftereffect appears only during this time. The absence of this reaction in laybrinthectomized animals indicates its vestibular origin. Thus, the "turnover reaction" can be evaluated as a following vestibular adjusting reaction. The fact that changes in the bioelectric activity of the subcortical centers do not arise immediately, but 3-4 sec after the change in gravitation, indicates participation of the subcortical nuclei in accomplishment of this reaction. If the stimulus causing this reaction, i.e., the action of the force of gravity, is absent for a period of 4-5 sec, the turnover reaction does not arise. Moreover, in forced turning of the trunk /55 of the animal, its head retained the former position for a certain time, i.e., there was an influence preventing turning of the head, retaining it in the initial position; the head turned together with the trunk in labyrinthectomized animals. This means that, besides the following adjusting reaction noted, accomplishing the "turnover reaction," a ves ibular reaction, stabilizing the head in space, and a neck reaction, calling for maintenance of the straight position of the head and trunk relative to each other, appear during prolonged weightlessness. Both of the latter reactions should prevent the "turnover reaction." The effect of them begins to show up in the 4-5th second of weightlessness, in all likelihood, in proportion to extinction of the aftereffect of the force of gravity. If the head and trunk of an animal are located in the same sagittal plane under weightlessness, both reactions act unidirectionally, stabilizing the posture. In the case, when the head is turned relative to the trunk, they contradict one another. If the animal is soaring in the air in this case, the vestibular reaction proved to be the leading one: the trunk turns over and the head remains stationary. With the trunk immobilized, the head turns to the straight position relative to the trunk after 1-3 sec. Thus, with prolonged stimulation of the proprioceptors of the neck muscles, the neck adjusting (straightening) reaction predominates.

The discrepancy obtained in this study and in the work of Gerathewohl and Stallings (1958), in data on the time, during which the "turnover reaction" is retained in the animals under weightlessness, attracts attention. In connection with this, let us examine the method of the experiment of the American authors. As they reported, during weightlessness, the experimenter took the animal by the skin of the back, turned it by 180° around the longitudinal axis and, then, released it. The animal immediately turned independently in the air, taking the previous position. The experimenter caught the animal by the back and repeated the manipulation, after which repetition of the reaction of the animal followed. The actions of the experimenter and the animal were repeated 8-12 times in a period of 20-22 sec, after which the animal began to turn over independently in the air. It was pointed out that strong excitation of the animal was observed during the experiment. Disappearance of the "turnover reaction" in the tests of the authors cited, in our opinion, is connected least of all with adaptation of the animals to weightless conditions. The return of the animal to the initial position took place for a number of reasons. Gerathewohl and Stallings noted that the head of the animal lagged behind the trunk, which the experimenter rotated, during the turn. Consequently, the reverse turnover, beginning the 5th or 6th second of the weightlessness cycle apparently was accomplished, because of the adjusting vestibular and neck reactions described in this work. Moreover, an abrupt turn of the animal could cause the counterturn reaction, also described in this report. Finally, the vision of the animal was not cut off in the series of tests by the American authors. Thus, the "turnover reaction" could take place, as a consequence of a visual adjusting reaction, retained and well expressed by cats under weightlessness.

The question arises, as to why the animals stop turning to the initial position after forced turning in 20-22 sec of weightlessness. One, the cats' reactions to vestibular stimuli disappear after several repetitions of it, in distinction, for example, from rodents, in which this reaction is very persistent (E. Tutman, G. Vrbova, 1960). /56
Second, the unusual nature of the state of weightlessness, frequent touching of the animal and repeated turning over of it (which was specially tested during parabolic flights in our experiments) caused a strong excitation and, then, rapid fatigue of the animal. Even after free soaring in 3-4 cycles of weightlessness during one flight, the existing initial attempt to hide disappeared from the animal, in which he lay indifferently on the floor, breathed heavily and squeaked from time to time. Indisputably, motor reactions, including the "turnover reaction," of animals in this state could turn out to be suppressed. Thus, the "turnover reaction" in the experiments of Gerathewohl and Stallings apparently disappeared, not as a result of adaptation to weightlessness generated in the animals, but because of overfatigue and development of internal inhibition.

A report of Schock (1961) was mentioned above, on the absence of reaction to forward motions during brief weightlessness. We also did not find these reactions during weightlessness, but they evidently cannot be expected, in the absence of the effects of gravity in their usual manifestations, since, under ground conditions, upon dropping the animal legs downward (in the ventral direction), the pressure of the otoliths on the sensitive hairs of the utricle decreases and, under weightlessness, movement of the animal in the ventral direction causes, not a decrease in pressure on the sensitive hairs, but a prolonging of them. The absence of noticeable motor reactions to forward motions can indicate a reduction in muscular reactivity under weightless conditions, in animals adapted to these conditions. This corresponds to the data of Ye. M. Yuganov and colleagues (1963), on a reduction in electromuscular activity during weightlessness.

Emergence of the counterturning reaction in the absence of gravity confirms preservation of the cupular function under these conditions. Preservation under weightlessness of the central integrating functions of the nervous systems of the animals adapted to weightlessness is confirmed by their active behavior, with the emergence of visual adjusting and grasping reactions under these conditions.

Our data demonstrate that stabilization of the animals (cats) during free fall under ground conditions is accomplished in two ways: initially, by means of a rotating motion, which the caudal part of the trunk begins to execute, the "turnover reaction" is performed; as a result of this, the animal turns out to be oriented in the "legs down" position; during the subsequent fall, this position is preserved, by means of rotary motions of the tail, stabilizing the animal in the counterflow of air.

Thus, during brief weightlessness, motor excitation arises in different species of animals. The following can be distinguished in them: motions similar to those, which are noted in falling of the animals, as well as elements of running. With development of adaptation to weightlessness, the motor excitation of the animals disappears. The duration of adaptation to repeated weightlessness depends, not so much on the evolutionary level of development of the animal, as on its ecological pecularities. Tests with the vision and vestibular apparatus of the animals cut off indicate that the leading factors in forming the motor excitation in them under weightlessness are the vestibular and musculocutaneous afferent signals of the disappearance of gravity, and that the necessary conditions for reduction of this excitation during adaptation to weightlessness /57
is to obtain visual information on stability of the surroundings, and tactile signals of immobilization of the animal, with the vision cut off. Cerebellar influences favor the reduction in motor excitation during adaptation of the animal to weightlessness. Changes in the EEG of animals adapted to weightlessness indicate the development of internal inhibition to a greater extent in the regions of the vestibular and visual representations in the cerebral cortex. The "turnover" reaction is possible for adapted animals in the first 4-5 sec of weightlessness; it then is suppressed, apparently by adjusting reactions: vestibular, stabilizing the head in space, and neck, straightening out.

Reactions of People in Brief Weightlessness

Space biology has now accumulated extensive information, characterizing the functional changes in human and animal bodies during weightlessness. The great diversity of reactions arising under these conditions attract attention. The most significant ones in the initial period of weightlessness are sensory and emotional-psychic reactions (spatial and visual illusions, feeling of fear, euphoria, reduction in the critical relationship to the surroundings), vegetative disorders (nausea, vomiting, dyshidrosis, etc.), disruption of movement coordination and spatial orientation (N. M. Sisakyan, et al., 1961; Ye. M. Yuganov, et al., 1963; I. I. Kas'yan, 1963; L. A. Kitayev-Smyk, 1963a, 1964a; Gerathewohl, Ward, 1960, and others). Numerous authors correctly consider the principal pathogenetic factor of these reactions to be the change in evolution-determined interactions of various functional systems of the organism (V. V. Parin, V. I. Yazdovskiy, 1959; B. M. Yemel'yanov, Ye. M. Yuganov, 1962; G. L. Komendantov, V. I. Kopanev, 1962; I. I. Kas'yan, V. I. Kopanev, 1963; A. V. Lebedinskiy, et al., 1964; L. A. Kitayev-Smyk, 1967a).

Our task was to observe people aboard an aircraft during parabolic flight, for the purpose of revealing the characteristic reactions to brief weightlessness. After a flight, interrogations were carried out by a special scheme, and motion picture photography, with subsequent interpretation of the material, was used extensively. Individual participants in the experiments experienced weightlessness several hundred times. Reaction to weightlessness of 270 persons were studied, of whom 120 had flight experience (more than 100 hours of flight or more than 20 parachute jumps).

Sensory reactions. Spatial illusions

Spatial disorientation arose in nearly all subjects, at the start of their first 1-3 parabolic flights, in the 1st or 2nd second of weightlessness. Many experienced spatial illusions from the very onset of weightlessness, by the nature of which, the subjects could be distributed into the following groups.

31 people were included in the first group. All the subjects felt as though falling downward. The illusion was accompanied by a feeling of fear and disorientation, expressed to one degree or another, in some, right up to loss of a real perception of the surroundings. /58 In the majority of cases, these phenomena disappeared in 3-5 sec, being replaced by a sense of pleasant lightness, "soaring" and, frequently, by a feeling of gladness or hilarity, i.e., by feelings with a pronounced positive coloring.

The second group was composed of 102 persons, who felt neither absence or a decrease in gravity, in the first seconds of weightlessness, but a change in its direction, i.e., they felt as though they were lying on their chest, back or side, hanging head downward (we arbitrarily call these illusions, illusions of turning over); it seemed to some as though they were rising up. These illusory feelings, in distinction from the sense of falling, were retained longer, i.e., from 7 sec to the end of the weightless cycle (26-30 sec); they had a slightly expressed negative emotional coloring. The same illusion was repeated in each subject during weightless cycles, regardless of his position in the cabin.

The third group (123 persons) included people not experiencing spatial illusions.

The fourth group included 14 subjects with mixed illusions. With the onset of weightlessness, they experienced the illusion of falling, lasting 5-10 sec and accompanied by a strong feeling of fear. Immediately after its disappearance, the illusion of turning over or rising arose. These sensations had a marked negative emotional coloring.

A definite phased nature could be noted in formation of the spatial conceptions of people, during development of adaptation to weightlessness.

I. Spatial disorientation, in all likelihood, as a result of the "collision" of contradictory flows of information, was observed in nearly all subjects, at the beginning of their first parabolic flight, for a period of 1-1.5 sec.

II. It might be supposed that, depending on the nature of the subsequent interaction of these flows, four types of spatial perception were distinguished:

a) Signals of falling are not perceived. A conception of the surroundings is created, by means of predominant visual information on stability of the surrounding situation. No spatial disruptions were noted (third group);

b) In all likelihood, as a consequence of the extreme predominance of information on stability of the surroundings, weightlessness does not cause a sensation of falling in a man: on the other hand, it seems to him that the positive acceleration occurring has not disappeared, but has become negative. Subjectively, this is perceived as hanging head downward or rising upward (second group). Under these conditions, it is not excluded that sensory signals, which are subthreshold under normal conditions, participate in formation of the conception of the surroundings under weightlessness, causing an illusion in a number of subjects, of lying on the side, the back, etc.;

c) Gravireceptor information predominates; weightlessness is perceived as falling, accompanied by a feeling of fear. Motor, "lifting" and "grasping" reactions can arise in this case. Instability of the visual functions was noted in a number of cases, in persons with this type of perception (first group) (see below);

d) Predominance of signals of falling are replaced by extreme predominance of information as to stability of the surrounding situation; in this case, the feeling of falling changes to a sensation of hanging head downward (fourth group).

III. The period of discrepancy of the flows of information from /60
the receptor systems of various analyzers ended with formation of a conception of stability of the surrounding situation, in accordance with familiar visual (and, with immobilization of the person, tactile) reference points.

Disruptions of visual perception. 25 men reported changes in visual perception during the effect of weightlessness (Table 17). The visual disruptions found in the flights were similar in a number of cases, which makes it possible to give a combined description of them.

At the beginning of the first stay under weightlessness, three men "saw nothing." Two of them were observed in the flights; there were mimetic reactions characteristic of fright in both of them, at the start of weightlessness. Five men noted "clouding," "diffusion" of visible objects, in the first seconds of their first stay under weightlessness. The field of view of two appeared to be constricted.

One man reported everything he saw during weightlessness; subsequently, he did not remember the visual images, but he remembered the content of the conversation.

The disruption of vision described above is combined with the fact that the ability to see the surroundings was disrupted in all subjects under weightlessness. All 11 men, in whom disruption of this type arose, were representatives of nonflight professions and were in weightlessness for the first time. The visual reactions arose in these people under weightlessness, on a background of spatial illusion, in the form of falling downward and a feeling of fright.

The following type of visual disruption was characterized by the onset of visual illusions of motion in the subjects. Four men described an apparent downward motion of the visible objects with the onset of weightless and upward, after its termination, in the postflight reports. Four others reported, that, during the transition to weightlessness, they saw repeated vertical "jerking" of objects. In observations of them, vertical nystagmoid movements of the eyes were found in three men, during the transition from g-forces to weightlessness and during the first seconds of weightlessness. The instrument panel, from which one subject had to read the indications, appeared to move cyclically ("Slowly downward, then more rapidly upward, etc. I could not read the data in this case") during his first stay in weightlessness. Illusory movements of the entire field of view appeared, according to the reports of subjects; cases of apparent movement of individual objects, on a background of stationary objects, were not noted. In all cases, the illusory motion took place vertically. Of nine men reporting apparent movements of the visual surroundings, three men had considerable flight experience.

The next group of disruptions of vision involved change in depth perception. During the weightless cycle, two men noted an apparent moving away of visible objects and elongation of the cabin. An illusory approach of an observed object arose in one subject during the weightless cycle. The subjective reactions of two other men were of a more complicated nature, and they can be evaluated as a

TABLE 17

DESCRIPTION OF VISUAL PERCEPTION IN WEIGHTLESSNESS

		Frequency of Visual Disruption in Weightlessness				Persistence of Visual Reaction in Weightlessness			
		Persons Without Flight Experience		With Flight Experience		Persons Without Flight Experience		With Flight Experience	
Visual Disruption Observed		Total No.	% of No. Examined (153)	Total No.	% of No. Examined (122)	Duration of Disruption in First Weightlessness Cycle	No. of Weightless Cycles in which Disruption was Observed	Duration of Disruption in First Weightlessness Cycle	No. of Weightless Cycles in which Disruption was Observed
Disruption of Vision	Disappearance of vision	3	1.96	--	--	1-2 sec	1	--	--
	"Clouding" "diffusion"	5	3.27	--	--	3-5 "	1-2	--	--
	Constriction of field of view	2	1.31	--	--	Entire cycle	2	--	--
	Forgetting what is seen	1	0.65	--	--	same	2	--	--
Illusory Motion	Downward movement	2	1.31	2	1.64	"	2-3	Entire cycle	10-20
	Vertical shaking	3	1.96	1	0.82	"	1-3	1-2 sec	12
	Upward-downward movement	1	0.65	--	--	10-15 sec	1	--	--
Change in Depth Perception	Illusion of moving away	1	0.65	1	C.82	Entire cycle	2	Entire cycle	1
	Illusions of approach	1	0.65	--	--	same	1	--	--
Mixed Reaction	"Constriction" of field of view with downward motion	1	0.65	--	--	"	1	--	--
	"Clouding" of field of view with downward "motion"	1	0.65	--	--	2-3 sec	1	--	--
	TOTAL	21	13.71	4	3.28				

combination of different visual illusions.

Thus, only 25 men of the number examined (9%) noted one disruption or arother of visual perception under weightless conditions. In all cases, these phenomena were evaluated by the subjects as "apparent." In the majority of cases, the visual reactions appeared in persons not having flight experience.

Motor reactions

With the onset of weightlessness, spontaneous movements arose /61 in persons under these conditions for the first time, as a rule, in the structure of which a tonic component (raising of the extended arms, drawing up of the leg, backward bending of the trunk), in all likelihood, manifestation of a lifting reaction under weightlessness, as well as a motor component (swinging of the arms and legs), which can be considered to be a "support seeking reaction," could be distinguished. Upon immobilization of the subjects in a chair, these reactions were less pronounced, and they arose in a smaller number of subjects than in free soaring. In a number of cases of persons not having flight experience under weightlessness, in cases when they held a fixed object by the hands before the disappearance of gravity, flexing of the extremities, a "grasping" reaction, arose under weightlessness. Bending of the arm by which the subject was holding on was frequently observed; the other, free arm was raised in this case. Motor reaction sometimes arose when soaring in weightlessness the first time, after repeated stays under these conditions in the immobilized state.

The dynamics of the motor reactions during adaptation to weightlessness were followed in 33 men, who were repeatedly in the free soaring state. In the first cycle, tonic reactions were noted with 28 of them and, in addition, a motor reaction was noted in 12 men, which was followed for no more than three weightlessness cycles. The tonic reactions stopped in 8-15 cycles. They were replaced by soaring, with considerable flexing of the extremities and trunk, with subjects in a relaxed posture.

Spontaneous mimetic reactions were noted in eight men, among those under weightlessness for the first time, together with mimicry adequate to their emotional state, in the 1st-3rd cycle of weightlessness. Five of them dropped the corners of the mouth and screwed up the eyes (offended expression); three other men, according to motion picture data, initially raised their brows and closed their eyes, then, opened the mouth, which was accompanied by a sigh, and they opened the eyes. This reaction arose in the first seconds of weightlessness, and it was repeated 1-8 times, with a frequency of 1-3 cycles of movement per second.

Vegetative reactions

Variously expressed vestibular-vegetative reactions (nausea, vomiting, etc.) arose in a considerable number of subjects, during flights under brief weightlessness. The nature of the spatial perception and development of the vestibular-vegetative reactions were in a definite relation. Thus, these reactions arose in 97 of 102 representatives of the second group, and in each of the 14 men making up the fourth group, whereas, in those experiencing a feeling of falling and fear during weightlessness (first group), there were no vestibular-vegetative disturbances. Of the 123 subjects of the third group, these disruptions were noted in 20 men. Thus, when signals of falling were predominant in the spatial conceptions of people under weightlessness, vestibular-vegetative stability was observed and, with illusions of the upside-down position and lifting, vestibular-vegetative instability occurred, as a rule. Two types of reactions are exceptions: 1) mixed emotional-psychic (feeling of /62
falling and fear) and vestibular-vegetative (nausea, vomiting, etc.) in all 14 men of the fourth group; 2) illusions of the upside-down position, without subsequent appearance of vestibular-vegetative disruptions, in 5 men of the second group. In all likelihood, signals of the vestibular analyzer were predominant in subjects in the first case, at the start of the cycles, and the vestibular-vegetative stability under weightlessness was low. In the second case, on the other hand, visual information with high vestibular stability was predominant.

It has been noted that the tolerance of the state of weightlessness by man is determined by the expression of two types of reactions arising during weightlessness: emotional-psychic (fear, disorientation) and vestibular-vegetative (nausea, vomiting, etc.). Depending on these reactions, all persons observed could be divided into four groups: with good, satisfactory and poor tolerance and not tolerating weightlessness. There were no psychic or vegetative reactions in persons with good tolerance (a weakly expressed disorientation was observed in some, in the first 2-3 sec of the stay under weightlessness). Either weakly expressed psychic (slight fear, disorientation) or small vegetative reactions (increase in salivation, perspiration, nausea) were noted in persons with satisfactory tolerance. The efficiency of the subjects with satisfactory tolerance was practically not reduced.

Persons with a strong feeling of fear and considerable disorientation, accompanied by the illusion of falling, or with marked vegetative reactions (repeated vomiting and the like), were placed in the group with poor tolerance of weightlessness. Persons, in whom, together with vegetative, there were psychic reactions also were added to this group. With the onset of weightlessness, they experienced a feeling of falling and of fear, alternating with the illusion of turning over; subsequently, they vomited and the like. The efficiency of persons in this group decreased significantly in the weightless state.

Psychic or vegetative reactions developed in persons, for whom this state was intolerable, to a strongly expressed degree in some, and these reactions increased with repetition of the weightless cycles. The illusion of falling was accompanied by a feeling of strong fear, leading to complete disorientation, loss of contact with surrounding people and, frequently, to increased motor activity, involuntary cries and temporary cutoff of vision. Such disruptions were noted during all weightless cycles. In vegetative reactions of representatives of this group, they vomited in the first weightless cycle, sometimes in the first seconds, and it was repeated in all weightless cycles and, sometimes, between them. Bubbly bile was found in the vomit. Involuntary urination was observed, and perspiration and salivation increased. The pulse rate decreased. Respiration became shallow. Sharp weakness and adynamia set in, and an effort to lie still with eyes closed appeared. Any movement of the head or eyes increased the vomiting. In the intervals between weightless cycles, the subjects felt somewhat better.

A progressive deterioration of the general state in repetition of the weightless state forced us to terminate a flight earlier than the time planned, in a number of cases. People not tolerating weightlessness in more than two flights (20 cycles) could not be observed.

The dynamics of change in the reactions during repeated stays /63 in the state of brief weightlessness was followed in a large group of people with satisfactory and poor tolerance. Motor reactions did not arise in more than 5 weightless cycles (in flights with eyes open). Psychic reactions (fear and disorientation) decreased after 1-3 weightless cycles and, in the majority of cases, disappeared after 5-20 cycles. Vegetative reactions (nausea, vomiting and the like) began to weaken after 20-30 weightless cycles and disappeared after 40-50 cycles. If psychic and vegetative changes were observed simultaneously in subjects, the psychic took place earlier than the vegetative.

There were women among the persons observed under weightless conditions. Their adaptation processes were the same as those of men. One of the women, enduring 6 periods of weightlessness, revealed that she was in the fourth month of pregnancy. She began to be nauseated with the 4th period of weightlessness and vomited once in the 5th period. The state of health was satisfactory after the flight. The pregnancy of this woman ended at the time of normal births.

How can the phenomena observed be evaluated? The presence of spatial illusions during weightlessness apparently arises, in the majority of subjects, during formation of the new functional spatial analyzer system (G. L. Komendantov, V. N. Kopanev, 1962), and is the result of predominance of information from the gravireceptor or visual analyzers during this process (L. A. Kitayev-Smyk, 1967a, 1970). Tests of people and animals with the vision cut off and in the absence of vestibular functions in the animals confirm this hypothesis. Beside the vestibular impulses, afferent signals from the redistribution of blood in the vascular system and tactile sensations play a definite part in formation of spatial illusions in weightlessness (Dzendolet, 1971). Visual disturbances arising in individual persons under weightlessness are evidently the result of gravireceptor influences on the visual centers. Their action may be both direct and caused by mismatch of the retinal signals and reverse afferentation of the muscular system of the eyes (L. A. Kitayev-Smyk, 1964b; L. A. Kitayev-Smyk, N. I. Pinegin, 1966; Guedri, 1968).

In motor excitation of people and animals under weightlessness, tonic and motor components can be distinguished. They are based on the vestibular-spinal reflexes (Bruggencate, 1971). Experiments on animals have shown that cortical (Schock, 1958) and cerebellar (O. G. Gazenko, et al., 1965) effects participate in formation of the motor reactions under weightlessness. In repeated stays under weightless conditions, the motor excitation is replaced by peaceful soaring, in a posture with predominant flexing of the extremities and trunk. According to our data (L. A. Kitayev-Smyk, 1969), persons with a high degree of adaptation to weightlessness bend the joints of the extremities more during relaxation in free soaring, which was pointed out by Kovit (1964). This is confirmed by reports of the astronauts (A. A. Leonov, V. I. Lebedev, 1971). The genesis of this phenomenon may be, not only predominance of bending of the joints of the extremities and trunk under equitonometric conditions (V. A. Bogdanov, et al., 1970), but a more pronounced reduction in muscle tonus in the extensors under weightlessness (L. A. Kitayev-Smyk, 1963b).

Vegetative reactions characteristic of seasickness syndrome, arising under the repeated influence of weightlessness, is determined by a complicated set of factors, connected with disruption of the interaction of the afferent systems and the integrated functions of the higher vegetative centers (M. D. Yemel'yanov, A. N. Razumeyev, 1972; Greybiel, 1969, and others). Expression of seasickness symptoms in parabolic flights depends on the degree of instability of the subjects toward the cumulative effect of the vestibular stimuli. /64

Centrifugal mechanisms, regulating the sensory flow, by means of the corticofugal "valve" effect, apparently participate in development of adaptation to the repeated effect of weightlessness and g-forces (Ernandez-Peon, et al., 1956).

Interaction of analyzers in forming the reactions of man in weightlessness

To test the assumption stated above experimentally, on the interaction of afferent fluxes in forming spatial conceptions by people under weightlessness, research was conducted on 33 healthy persons, selected in preliminary experiments. A sensation of falling downward, dropping (first group) arose in 10 of them under weightlessness; it seemed to 13 subjects (second group) that the aircraft was flying upside-down with the onset of weightlessness and they, being in it, turned out to be in the "legs up" position; there never were spatial illusions under weightless conditions in 10 persons (third group). Moreover, three men took part in the flights, in whom there was no labyrinth function (fourth group).

The experiments were carried out in the following order; the subjects sat immobilized in a seat, with eyes open, in the first weightless cycle, they sat in the chair, with light-impermeable bandages over the eyes in the 2nd cycle, they floated in the air with eyes open in the 3rd cycle and they floated in the air with bandages on the eyes in the 4th cycle. The subjects were requested to relax the body and extremity muscles and not to perform arbitrary movements during the experimental cycles. In a number of experiments, in which the subjects floated weightless with bandaged eyes, they were given the task of indicating the "down" direction with special pointers, in conformance with their subjective conceptions. Each subject participated in 6-8 experimental cycles. In a special series of experiments, the nature of the spatial sensations of people was determined, while walking over a "sticky" surface, located on the ceiling of the aircraft cabin. The experiments of this series were carried out with five subjects, with and without vision cut off, in 6 weightless cycles each.

After each experiment, the subjects gave an oral report, compiled according to a special scheme, and a written report after each flight, on his sensations and acts during weightlessness. To record postural and motor reactions of the subjects, motion picture photography was used in the flights.

As the experiments showed, in all 10 persons in the first group, cutting off of the vision increased the sensation of fear and of falling, arising in them in the initial weightless cycles, to a greater extent in free fall than when immobilized in the seat. In- /65 voluntary straightening and raising forward of the arms - "upward" was observed in six persons, while floating with closed eyes. This posture was retained 3-4 sec. A more pronounced motor excitation was observed in two men, while floating under weightless conditions: frequent swinging of the arms and movement of the legs, in the form of drawing them up alternating with incomplete straightening of them. The frequency of movement of the arms and legs was 2-3 times per second. Floating weightless by these persons, as a rule, terminated with them tearing off the bandage, opening the eyes and grasping some fixed object with eyes open.

Of 13 representatives of the second group, upon putting the light-impermeable bandages on their eyes, a feeling of turning over upon disappearance of gravity stopped arising in four persons. This illusion did not stop appearing in five men, only in free floating in the air with bandaged eyes. When immobilized in the seat, with both open and closed eyes, they felt turning over, in their words, "they hung head down in the binding system." Each time, three subjects, with onset of weightlessness, both while floating and while immobilized, felt turning over, in their opinion, "since blood rushed to the head." Together with the feeling of hanging head down, always arising in one subject under weightlessness, upon immobilization in the seat with eyes open, while floating in the air with a bandage on the eyes, a feeling of falling and fear appeared, and a motor reaction was noted, in the form of swinging the arms. Thus, 9 men of 13, feeling as though turned upside-down under weightless conditions with intact vision, were deprived of this illusion, upon cutting off the visual and tactile information on the position in space; it was replaced in one man, by a feeling of falling downward.

Of 10 subjects of the third group, 4 men did not notice the onset of new feelings in weightlessness, either with open eyes or with vision cut off. Two men, only while floating with eyes bandaged at the start of the weightless cycles, had a feeling of falling "downward" without a feeling of fear in this case, for 1-2 sec. A feeling of dropping down and of fear arose in 4 subjects, during free floating after disappearance of gravity; in this case, the movements of the arms and legs described above were noted in them. One of these 4 subjects was an experienced test pilot, who had previously performed several hundred cycles of weightlessness.

The sensation of falling or of the upside-down position disappeared in the majority of subjects in 2-6 sec in the weightless cycles, being replaced by a conception of the vertical directions, in accordance with familiar visual or tactile reference points and, in floating with the bandage on the eyes, in accordance with the vertical axis of their own bodies.

According to the reports of three subjects with a defect in the labyrinth function, they did not sense spatial or visual illusions during weightlessness. When immobilized in the seats, both with open and closed eyes, they did not find significant differences between the sensations during horizontal flight and during weightlessness, setting in after the g-forces preceding it. While floating weightless with open eyes, emotional reactions and motor activity, adequate to the unusual situation, developed in them. While floating with closed eyes, a subjectively unpleasant sensation of disorientation arose in two of them; in this case, one subject swung his arms several times. Postural reactions characteristic of healthy people were not noted during weightlessness, in the subjects of the fourth group.

In experiments with walking along a "sticky" surface, a sensation, that the "aircraft cabin was upside-down and, therefore, I am walking along the ceiling like along the floor," arose in all subjects, at the moment of contact of the feet with the "sticky" ceiling of the cabin. /66

Conclusion

In this manner, it has been shown by this investigation that, under brief weightlessness, sensory reactions arise in a number of people, mainly those under these conditions for the first time, in the form of spatial and visual illusions, motor excitation, in which tonic and motor components can be distinguished, and vestibular-vegetative disturbances (nausea, vomiting, etc.). In repeated flights with creation of weightlessness, a decrease in the extent of expression and, then, disappearance of these reactions occurred in a significant majority of those studied. Experiments in weightlessness with the vision cut off and with the absence of vestibular functions in the subjects confirm the hypothesis that spatial conceptions of people in weightlessness depend on predominance of gravireceptor or visual afferent signals under these conditions.

2. Perception of Time Under Conditions of Brief Weightlessness

N75 23111

In solving problems of control of a spacecraft and performing the most diverse working operations, an astronaut must precisely calculate his actions in time. Precise perception of time can be developed (and this is done continually) on earth, during training sessions in the spacecraft trainer. However, this perception of time can change in a space flight, under the influence of unusual flight factors.

We studied the perception of time intervals by astronauts and subjects under conditions of brief weightlessness, created in jet aircraft. Two series of tests were performed, under conditions of brief weightlessness. 16 persons participated in series I. Their task included estimation of a time of stay under weightless conditions, while carrying out some work or another (writing test, work on the coordinograph, determination of a given muscular effort, revolving in the Barany chair, movement in unsupported space, etc.). The physician-tester or pilot-instructor recorded the objective time with a stopwatch. The accuracy of the estimates of time intervals under conditions of brief weightlessness, while performing various tasks, was compared with the accuracy of estimates of time, while carrying out similar tasks under conditions of horizontal flight.

Task execution required various degrees of activity and emotional-volitional stress; it was accompanied by both positive and negative emotions, which depended to a great extent on tolerance of the effects of parabolic flight factors. The nature of the emotional sensations was determined, on the basis of subjective impressions and estimates of tolerance of flight in weightlessness; the latter was estimated by a complex analysis of the reactions of the central nervous, cardiovascular and respiratory systems and vestibular apparatus. Performance of the task did not allow the subject to think of himself. Astronauts, in distinction from test subjects, have had experience in estimating time intervals by counting mentally, while executing the training parachute jumps, which preceded flights in /67 weightlessness. A total of 58 tests were carried out under weightless conditions in this series.

Estimates of time intervals by the test subjects and the astronauts, while performing various tasks under weightless conditions, depended on their emotional sensations. As a rule, in the first flights, the subjects who tolerated weightlessness well underestimated the time of action of this unusual factor. They perceived an interval of 35-40 sec as an interval of 15-20 sec (we call this a quickened flow of time perception). In repeated flights, while performing the same task under weightless conditions, the underestimates of the time interval decreased. In our opinion, this is explained by greater adaptation of the body to the state of weightlessness and to a sharp decrease in emotional stress. Subjects who endured unpleasant sensations in weightlessness estimated an interval of 24-26 sec as a minute or more in duration (we called this a retarded flow of time perception). Thus, to one of the autors (V. I. Lebedev) in the very first flight, a 24-second interval in the first "hump" (when euphoria developed) seemed to pass in an instant, but the second "hump" (when spatial illusions and a negative emotional state arose), it stretched out infinitely long. The time was estimated more precisely under weightless conditions by subjects immobilized by a binding system to the seat, than by those executing an assignment in unsupported space. This is explained by the fact that, in unsupported space, the emotional experiences were expressed more strongly (in connection with the absence of a support and sharper change in the afferent impulses).

The astronauts and test subjects who had much flight experience under weightlessness and tolerated its effects well, more accurately perceived the passage of time, even when moving in unsupported space. Completing flights in weightlessness on 30 November 1965, Yu. A. Gagarin wrote in the log: "Normal feelings in flight. No disorders or peculiarities were observed. Figures were executed easily, coordination normal." He estimated the 24-sec interval in three "humps" as 22, 23 and 21 seconds. Yurii Alekseyevich tolerated rotation in the Barany chair under weightless conditions well, on 1 December 1965, and he described his emotional state thus: "State of health good, feelings normal. Everything as usual in rotation in the chair." Yu. A. Gagarin estimated a 26-second interval of weightlessness as 24 seconds.

Spatial illusions and negative emotional experiences, accompanied by change in perception of time in the direction of overestimating its length, appeared in some subjects, while revolving in the Barany chair under weightless conditions. Thus, for example, unpleasant sensations, which previously had never been noticed during normal activity under weightless conditions, arose in one of the authors (I. F. Chekidra, while rotating in the chair. This cycle of weightlessness appeared unusually long to him. At the same time, during active activities, accompanied by positive emotions, this interval of time under weightlessness was underestimated by 2-[illegible] sec.

And here is how subject P evaluated his feelings during this test. "While revolving in the chair in the weightless state and dropping the head down (with closed eyes), the sensation arose that I was suspended head downward in a bent position." Rotation in the chair lasting 10 sec was estimated as a 25-second interval. Before rotation in the chair, the time under weightlessness was estimated quite accurately (24-26 sec intervals were estimated as 26-28 seconds). /68

14 persons participated in the second series of experiments. 87 tests were carried out with them under weightless conditions. The task consisted of reproducing a 20-second interval under conditions of brief weightlessness. As a result of training sessions, the subjects performed this task in horizontal flight, with an accuracy of ±0.5 sec. They voluntarily chose the method of counting time mentally. The subject turned on and turned off the stopwatch independently, without looking at it.

All the subjects can be divided into three groups, from the test results (Table 18): with adequate, retarded and quickened perception of time flow. 8 subjects had normal, adequate perception of time under weightless conditions. Among them are those whose time interval estimates in weightlessness differed from the estimates of this same interval in horizontal flight by no more than ±0.5 sec. In two of the men, the emotional feelings were negative and in the remaining, positive. In the group with retarded time flow in weightlessness, consisting of three men, there were premature actions, which were connected with overestimating the elasped time interval. All three men had negative emotional feelings, with satisfactory or poor tolerance of the effects of the parabolic flight factors.

A quickened time flow in the mind was noted in three subjects under weightless conditions. This was expressed by delayed action, since the elapsed time interval in the minds of these subjects was underestimated. They all tolerated flights in weightlessness well, experiencing positive emotions in the course of these flights. /69

The results of statistical processing of the data are presented in Table 19. As should have been expected, in the group of subjects with normal perceived time flow under weightless conditions, the deviations from the initial data were not statistically significant (less than 10% confidence).

In the group of subjects with retarded perception of time flow in weightlessness, the deviations in the direction of overestimation of the time intervals were significant: their significance was over 99%. The significance of deviations obtained in the group with quickened perceived time flow also proved to be over 99%.

The underestimates of the time interval (quickened perception of time flow) in a positive emotional state of the subjects and the overestimate of the time interval with negative emotions during weightlessness, which we disclosed in the observations described, are connected with processes originating in the cerebral cortex. According to the data of S. G. Gellershteyn (1958), M. F. Ponomarev (1958)

TABLE 18

REPRODUCTION OF FIXED INTREVAL OF TIME IN HORIZONTAL FLIGHT UNDER NORMAL GRAVITY AND IN BRIEF WEIGHTLESSNESS

Subject	Weightlessness Tolerance	Emotional Feelings in Weightlessness	20-Sec Interval Reproduction Time,		Perceived Time Flow
			In Horizontal Flight	In Weightlessness	
L	Poor	Negative	20.5	17(9)	Retarded
Sv	Satisfactory	"	20	16(2)	"
V	same	"	18.5	19(3)	Normal
B	"	"	20	20.5(4)	"
G	"	"	23	21(4)	Retarded
So	Good	Positive	20	23(8)	Quickened
Ya	"	"	20	21.5(3)	"
K	"	"	20.5	20(6)	Normal
R	"	"	20	20(8)	"
Sh	"	"	21	20.5(8)	"
Ch	"	"	20	22(14)	Quickened
Sh	"	"	20	19.5(7)	Normal
S	"	"	20	20(5)	"
Kh	Outstanding	Normal	20	20(6)	"

NOTE: The 20-sec interval reproduction time is given in arithmetical average values. The number of experiments in weightlessness is indicated in parentheses.

TABLE 19

RESULTS OF STATISTICAL PROCESSING OF DATA ON WEIGHTLESSNESS TIME PERCEPTION

Perceived Time Flow in State of Weightlessness	No. of Subjects	No. of Experiments in Weightlessness	x	σ	m_p	t	Confidence (P) %
Normal	8	47	0.02	0.35	0.5	0.04	10
Quickened	3	25	2.3	1.04	0.2	11.06	99
Retarded	3	15	3.4	1.30	0.3	11.33	99

D. G. Elkin (1962) and others, excitation processes predominate in the cortex with positive emotions, which causes quickening of the perception of time flow. An inhibiting process arises with negative emotions.

The fact that predominance of excitation processes in the cerebral cortex can cause delay in actions and inhibition, premature reactions, as M. F. Ponomarev points out, appears to be unusual at first glance. However, taking the nature of the basic neural processes into consideration, this can be understood. Inhibition (in contrast to excitation) always is manifested in stopping, limiting or decreasing activity. The connection of a premature reaction with inhibition and of a delayed reaction with excitation is accomplished through the subjective slowness or quickness of time flow in the mind. Thus, for example, if some interval of time seems to a man experiencing positive emotions to be shorter, in the task of reproducing this segment of time, he actually recreates a longer time interval (the assigned interval appears to him to be not long enough). We have distinctly observed similar relationships of perception (and this means, reproduction) of time, under conditions of brief weightlessness.

The perception of time is interrelated with the perception of space. This is confirmed by the data of V. I. Lebedev and I. F. Chekidra. The accuracy of perception of change in the angle of rotation of a Barany chair during slow rotation of it in horizontal flight and in weightlessness was studied on subjects, who tolerated flights in weightlessness well. It turned out that, with accelera- /70 tion of the flow of time in the mind, in performing a task in a state of weightlessness, errors in determination of the angle of rotation of the chair were underestimates of the size of the turn, and they increased with increase in time of slow rotation to 15-20 sec. This can be explained as follows. By internal analysis, the subject considered that, let us say, not 20 sec, but 18 sec had elapsed. Consequently, in this interval of time, the chair could have turned to a smaller angle than it was actually turned by the physician-experimenter.

In this manner, the results of experiments under conditions of brief weightlessness confirmed the theoretical concepts of the dependence of time perception on the emotional state of a man. The time test, together with other methods, can be used to precisely define the emotional state of subjects in stress situations.

3. Static-Kinetic Reactions of Man Under Conditions of Brief Weightlessness

N75 23112

There is no experimental work, directly on study of static-kinetic disorders overall, under conditions of brief weightlessness. There are only works, in which either sensory or motor reactions have been studied (see this chapter).

Our task was study of the nature and degree of expression of static-kinetic reactions of a man under conditions of brief weightlessness (during parabolic flights in aircraft) and their dependence on past flight experience, development of criteria for evaluation of the static-kinetic resistance of a man to the effect of brief weightlessness and study of the adaptation capacity of the body. 30 fighter pilots, who had flown 300-2,000 hours in jet aircraft, and 11 men not in the flying profession (physicians, engineers), participated in the study. Such a study has a definite expert and prognostic value, especially in selection and training of space crews. The latter, before the start of a flight cycle in weightlessness, performed an additional 6-10 flights in the zone, in jet aircraft of the same type, for the purpose of removing the emotional background circumstances. The investigations were carried out in two- and multiplace jet aircraft, specially equipped for reproduction of the conditions of brief weightlessness (Fig. 1).

During the flights, the subjects underwent multiple physiological examinations, including study of sensory, vegetative, motor and vestibular-somatic reactions before, during and after a flight. The sensory component of the static-kinetic reactions was studied, by means of analysis of subjective reports and records of the subjects and special questionnaires. The vegetative reactions were studied, by means of visual medical observation, as well as recording of pulse and respiration rates and the cutaneogalvanic resistance at all stages of parabolic flight. The motor reactions under weightless conditions were investigated by visual medical observation and motion picture recording, while performing everyday professional operations and while working on a special electrocoordinograph. The vestibular-somatic reactions were studied while performing modified Boyachek and Barany rotary tests, under conditions of brief weightlessness, as well as before and after a flight. In all, 950 flights, with 3,010 cycles of weightlessness, were accomplished.

It was determined, as a result of analysis of the study material, sensory, vegetative, motor and vestibular-somatic disturbances were observed in a majority of those examined, during the first familiarization flights. /71

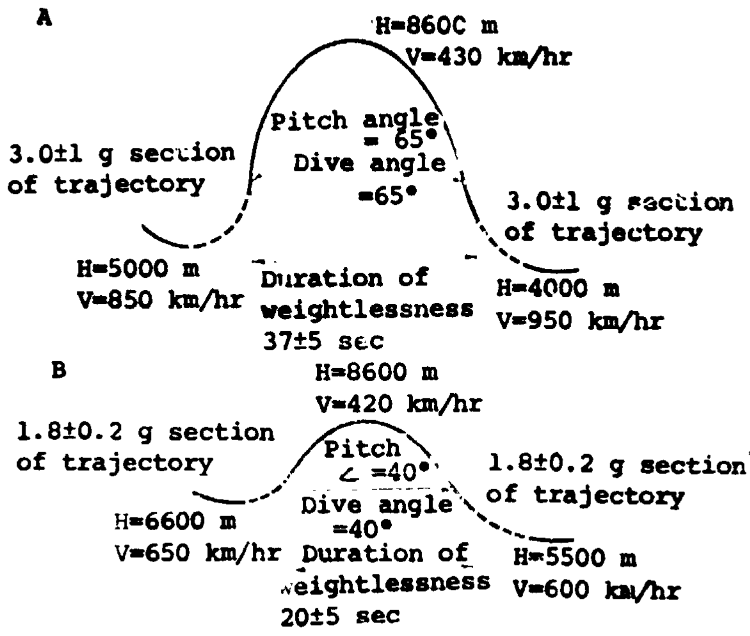

Fig. 1. Physical characteristics of parabolic flight profile in two-place (A) and multiplace (B) jet aircraft

Sensory disturbances under weightless conditions were manifested by various illusory sensations -- lifting the body upward, falling downward, turning to the right, to the left, ahead and back. In some subjects, these sensations occurred on a background of sthenic type reactions (pleasant lightness, feeling of happiness, etc.) and, in others, on a background of the asthenic type (feelings of helplessness, fear, disorientation in space, etc.). The sensory disturbances decreased under the repeated effects of weightlessness, both as to /72 degree of expression and as to number of persons, in whom they were observed (Table 20). The directional nature of these changes was approximately the same in all groups, but the degree of expression of them differed. Thus, in the first group (pilots) unstable illusory sensations and psychosensory reactions of a sthenic nature arose in the majority of subjects at the very start. In those of the non-flight professions examined, the degree of expression of psychosensory disorders was more significant.

In a special series of studies, the importance of immobilization of the bodies of the subjects at the workplace and of visual orientation in the frequency of sensory disturbances was determined. In the event immobilization was better, the subjects more rarely lost orientation in space and experienced unfavorable sensory reactions and vice versa. In the absence of visual control, the frequency of disorientation phenomena approximately doubled in all subjects.

TABLE 20

FREQUENCY OF APPEARANCE OF ILLUSORY SENSATIONS AND VEGETATIVE REACTIONS OF SUBJECTS OF THE FIRST AND SECOND GROUPS (number of persons) UNDER CONDITIONS OF BRIEF WEIGHTLESSNESS

Subject Group	Nature of Reaction	Weightlessness Cycle Number															
		[illegible]	2	4	6	8	10	12	14	16	18	20	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1st	Illusory sensations	25	21	10	4	3	2	1									
	Vegetative reactions	7	6	4	6	4	3	1									
2nd	Illusory sensations	11	8	6	6	5	3	2	2	2	1	1	1	1	1	1	1
	Vegetative reactions	10	8	7	5	4	4	2	2	2	2	1	1	1	1	1	1

Beside sensory disturbances, shifts toward vegetative reactions were observed in a number of subjects during parabolic flight, manifested by subjective feelings of discomfort (general weakness, poor health, unpleasant feelings in the substernal region, dizziness, etc.), as well as by objectively recorded reactions and changes in the cardiovascular and respiratory systems of the body. In analysis of the vegetative disturbances, their direct dependence on flight experience and level of general physical readiness of the subjects was revealed (see Table 20).

As a rule, the shifts were insignificant in the pilot, and they were manifested by moderate changes in pulse and respiration, as well as by reddening of the face (I degree vegetative reactions). In representatives of the second group, very often, in the first seconds of weightlessness, the face became pale and increased perspiration and nausea set in, with considerable changes in pulse rate (II and III degree vegetative reactions).

The differences between these groups of subjects also was revealed by analysis of the increase in rate of adaptation. Vegetative disorders were absent: after the 12th weightless cycle in the first group and only after the 30th in the second group. Adaptation of the body to weightlessness was retained 3-4 months by the pilots and somewhat less in the remaining subjects, 2-3 months.

Anal[illegible] of the motion pict[illegible] material showed that motions during th[illegible] irst flights frequently were inaccurate, disproportionate, sweeping and abrupt or excessively slow, etc. In work on the coordinograph, where the fine coordination of motion was studied, motor disorders were qualitatively approximately the same, but they were more significant in magnitude and were observed more frequently.

In special experiments, L. V. Chkaidze and I. F. Chekidra jointly carried out a biomechanical study of the motor activity under weightless conditions, by cyclogramometry. Analysis of the resulting material showed that disturbances in coordination of motion was caused by a decrease approximately in half of the major dy mic components of motion, rearrangement of the terrestrial stereotype and a still greater "corticalization" of execution of movements.

In performing the rotating test, it was determined that, under weightless conditions, in comparison with the horizontal section of a flight, in which terrestrial gravity was retained, static-kinetic disorders were observed almost 1-1/2 times more often.

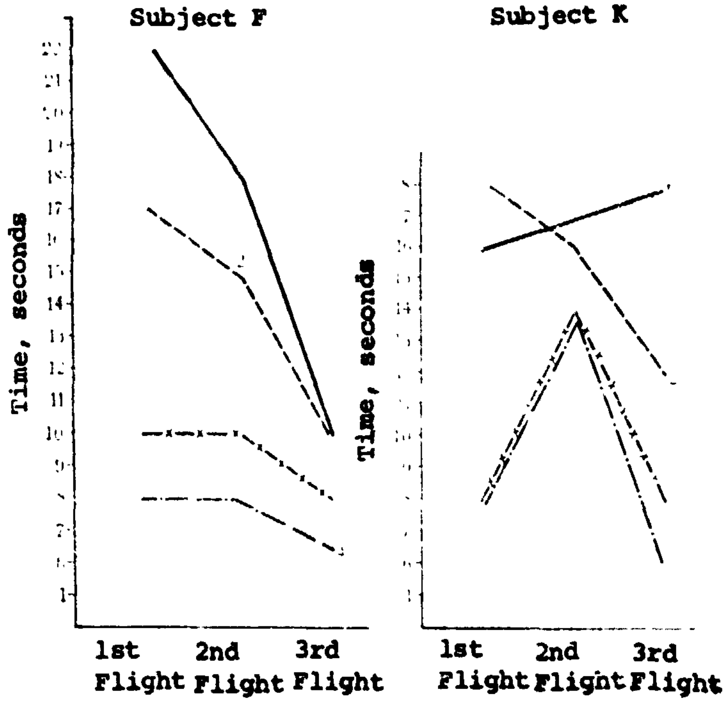

Fig. 2. Duration of postrotation nystagmus and illusions of counterrotation (in seconds) of subject F, resistant to weightlessness, and K, with decreased resistance after the first, second and third parabolic flights: 1) preflight nystagmus; 2) postflight nystagmus; 3) preflight illusions; 4) postflight illusions.

Beside this, the dependence of changes in the nature of protective motions and duration of postrotation nystagmus on level of resistance of subject to parabolic flight factors was developed. In persons who were resistant, as a rule, under weightless conditions and on earth after a flight, the postrotation nystagmus was shortened, compared with the data base and protective motions decreased; in nonresistant persons, the changes were in the opposite direction (Fig. 2). /73

The degree of expression of static-kinetic disorders were inversely proportional to the level of flight readiness of the subjects. Thus, disorders were noted in 16.7% of the pilot group in the first familiarization flights and in 81.9% of the group of persons with non-flight professions. At the same time, there were no static-kinetic disorders, beginning with the first cycle of weightlessness, in five pilots, who had flown more than 1500 hours in jet fighter aircraft.

Repeated brief weightlessness favored a gradual decrease in expression of static-kinetic disorders.

Analysis of the data presented above permits flight along a parabolic curve to be considered a functional test, for evaluation of the static-kinetic stability of a man. It can be evaluated as high, good, satisfactory and unsatisfactory. The criterion of high static-kinetic stability of the body is the absence of sensory, vegetative and motor disorders; the criterion of good stability, moderately /74 expressed, quickly-passing disturbances in the first 3-5 cycles of weightlessness; the criterion of satisfactory stability, marked, long-retained sensory, vegetative, motor and vestibular-somatic reactions during 6-10 cycles of weightlessness; finally, the criterion of unsatisfactory static-kinetic stability was sharply expressed disorders preserved during the first 10-15 cycles of weightlessness, with considerable reduction in efficiency.

The mechanism of origin of static-kinetic disorders apparently is disturbance of the functional, systematic nature of the analyzers reflecting space (G. L. Komendantov, V. I. Kopanev, 1962; M. D. Yemel'yanov, Ye. M. Yuganov, 1962; V. N. Barnatskiy, 1962, and others). The accustomed terrestrial afferentation from the majority of mechanoreceptors changes under weightless conditions, as a consequence of which, illusory and motor disturbances are observed initially in the subjects and, then, vestibular-vegetative disturbances.

Our studies also have demonstrated that a man becomes accustomed to the unusual conditions of weightlessness relatively quickly. With repetition, the disorders were expressed to a lesser extent and were observed in a smaller number of persons. These data coincide with the opinions of the majority of investigators (G. Beck, 1959; Gerathewohl, 1952, 1956; Ye. M. Yuganov, et al., 1961, 1962, 1963; L. A. Kitayev-Smyk, 1963, 1964; K. L. Khilov, 1964). Acclimatization apparently is caused by the formation of a new functional system of the analyzers, which is adequate to the unusual conditions and to the changed afferent background. Tests indicate that the expression of disturbances, rate of adaptation and length of retention of it are dependent to a great extent by preceding flight experience of the subjects, the degree of immobilization at the workplace, and the presence of visual stimuli (Table 21). Static-kinetic disorders /75 were observed most rarely of all among the flight personnel with a high level of readiness, with firm immobilization at the workplace and preserved visual reference points. They were expressed to a greater extent in failure to maintain one or more of the conditions indicated above. The adaptation rate changed in a similar manner.

TABLE 21

NUMBER OF ACTIONS OF BRIEF WEIGHTLESSNESS NECESSARY FOR ONSET OF ADAPTATION OF THE BODY AND ITS RETENTION TIMES

Nature of Reaction	% of Subjects	First Group			Second Group		
		No. of Cycles Necessary for Onset of Adaptation	Adaptation Retention Time, mos.	No. of Cycles Necessary for Recovery of Adaptation	No. of Cycles Necessary for Onset of Adaptation	Adaptation Retention Time, mos.	No. of Cycles Necessary for Recovery of Adaptation
Sensory	50	3	4	--	10	2-3	--
	75	5		--	15		--
	100	15		1-5	35		3-6
Vegetative	50	--	4	--	6	2-3	--
	75	1		--	15		--
	100	15		1-5	35		4-6
Motor	50	3	3	--	10	2	--
	75	6		--	15		--
	100	20	3	1-6	35		5-10
Vestibular-Somatic	50	3		--	12	2-3	--
	75	12		--	27		--
	100	18		1-6	36		6-9
Average Data Considering All Indications	50	3	3-4	--	12	2-3	--
	75	12	--	1-6	27		6-10
	100	20	--	--	36		--

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4. Space Form of Motionsickness

In connection with the intensive development of all types of transport, including spacecraft, the problem of seasickness (motionsickness) is becoming more and more important.

Interest in it is still increasing, because it is closely meshed with the problem of weightlessness, of which is a significant obstacle to the mastery of space. Weightlessness undoubtedly is one of the causes of seasickness.

As a result of study of the effect on man of partial weightlessness, lasting 1-2 sec, created in ground units, approximate information has been obtained, since the exposure time was short (Bergeret, 1952; V. S. Gurfinkel', et al., 1959; Clark, Clamann, et al., 1960).

According to the data of Ogle (1957) and other investigators (Ye. M. Yuganov, 1965; I. I. Kas'yan, et al., 1966; I. A. Kolosov, 1969; Ward, et al., 1959, and others), people have reacted differently to weightlessness lasting up to one min: the adjustment of some, in a flight along a Kepler trajectory, was good, raised a little; a feeling of discomfort arose in others and, in repeated weightlessness, vestibular-vegetative shifts were observed (dizziness, nausea, disorientation, etc.); in still others, vomiting began immediately.

It would seem that, in launching a rocket, when weightlessness was more prolonged (up to 8 min), the vestibular-vegetative disruptions should be expressed more strongly. However, in work carried out on animals, both here (A. M. Galkin, O. G. Gorlov, et al., 1958; B. G. Bugrov, et al., 1958) and abroad (Henry, et al., 1952), this was not confirmed. It apparently was difficult to discover vestibular-vegetative reactions of animals by the methods used.

A large amount of biomedical information on the motionsickness problem has been obtained during flights of Soviet and American astronauts. As is well known, motionsickness is characterized by sensory, motor and vegetative symptoms. It turned out that, under conditions of weightlessness, they occurred in some astronauts. Thus, sensory disruptions of various lengths were observed in a portion of the Soviet astronauts (N. M. Sisakyan, V. I. Yazdovskiy, 1962, 1964; Ye. I. Vorob'yev, et al., 1969, 1970). In particular, astronaut A. G. Nikolayev felt the illusion of motion on "entry into weightlessness." A brief feeling of forward inclination of the trunk arose in him. P. R. Popovich and G. S. Titov had clearer illusory sensations during this period. They indicated an illusion of flight in the upside-down position. B. E. Yegorov and K. P. Feoktistov experienced similar sensations, only their illusions were more prolonged; they arose with the eyes both closed and open during the entire flight (Ye. M. Yuganov, et al., 1965). During the flight in the Salyut 9 spacecraft, V. I. Sevast'yanov noted still /76
still another type of illusory sensation, which he called "continuous

motion," arising at the moment of cutting off the engine unit in the middle of the flight.

Beside illusory sensations, the astronauts noted some somatic reactions. Thus, in the 38th to 45th orbit, brief nystagmoid movements of the eyes of V. V. Tereshkova were recorded. I. T. Akulinichev, M. D. Yemel'yanov, et al., 1965 , analyzing them, found that a similarity with normal nystagmus was expressed, in the frequency of movements (2-3 per sec), their duration (8-15 sec) and the presence of slow and rapid components. The difference consisted of the frequency dynamics (gradual increase with subsequent slowing down) and obliteration of differences between the rapid and slow phases with acceleration of the nystagmoid movements. In the opinion of the authors, these movements are connected with change in the functional state of the vestibular analyzer, on a background of weakening of corrective actions on the part of the central nervous system.

A slightly expressed asymmetry of the oculomotor reactions was revealed in astronaut P. R. Popovich, owing to changes in the function of the vestibular analyzer and redistribution of the tonus of the eye muscles.

Vegetative reactions, caused by development of seasickness or the action of static-kinetic stimuli, also were noted when the astronauts were under weightless conditions. With rapid movements of the head or turns of the trunk, some of the astronauts became dizzy (G. S. Titov, P. R. Popovich, B. B. Yegorov, K. P. Feoktistov) and had signs of discomfort (G. T. Beregovoy, A. G. Nikolayev, V. I. Sevast'yanov).

Physician-astronaut B. B. Yegorov reported that the feeling of dizziness was similar to the feeling arising in a man, from the effects of galvanic stimuli on the vestibular apparatus (B. B. Yegerov, 1964, 1967). According to the testimony of A. G. Nikolayev and V. I. Sevast'yanov, the discomfort under "vestibular load" was not similar to any of the effects on the ground (I. I. Bryanov, et al., 1970). All of this confirmed the first statements of K. E. Tsiolkovskiy (1911) that, in the state of weightlessness, disruptions of orientation in space, dizziness, etc., must be expected.

Marked seasickness developed in some of the astronauts during prolonged weightlessness. G. S. Titov first described this state. Definite shifts in the cardiovascular system and respiration, as well as vestibular-vegetative disturbances, reduction in appetite, dizziness, nausea and other symptoms, were recorded in him. The disorders decreased, when the astronaut took a convenient posture and did not make abrupt movements (G. S. Titov, 1961); they decreased considerably after sleep and disappeared completely after switching on the braking system of the spacecraft. The astronaut compares these phenomena with the state of seasickness, which is observed when using aerial transport (the aerial form of motion sickness).

Astronauts B. B. Yegorov and K. P. Feoktistov also displayed seasickness symptoms. During the flight in the Voskhod spacecraft, after 1-1/2 - 2 hours of the flight, the first unpleasant sensations arose in the substernal region of B. B. Yegorov. They increased, and they reached a maximum expression in the 7th hour of the flight. The seasickness symptoms disappeared after sleep. Similar phenomena, but less expressed, occurred in K. P. Feoktistov (Ye. M. Yuganov, et al., 1965).

Interesting data were obtained during the space flight of V. V. /77 Tereshkova. Although she evaluated her state as good, after 5-6 hours of the flight, her face appeared objectively in the television frames to be concentrated, there were few facial expressions, and motion of the head was noticeably limited. Observations of the instruments were carried out mainly by eye movements; slowness of speech was noted. The responses were primarily single words, speech was somewhat monotonic and somnolence and reduction in appetite were noted (N. M. Sisakyan, 1965). Specialists, analyzing radio transmission and television data, as well as the nystagmoid eye movements and slow waves on the EEG, concluded that all this was connected to some extent with the specific effect of weightlessness on the vestibular apparatus.

Seasickness symptoms also were observed in the American astronauts. During the first space flights in the Mercury and Gemini programs, feelings of "discomfort" arose in the astronauts in the state of weightlessness, because of the absence of the pressure of the backs and seats of the chairs, as well as of the weight of objects and clothing. Marked seasickness developed in several American astronauts. Thus, during the flight of Apollo 8, F. Borman felt nausea and pain in the stomach. Some poor health was experienced by other crew members. However, in the opinions of specialists, their seasickness was caused by the effect of medicinals (soporific) and abrupt motions of the head and trunk in the first hours under weightlessness. According to the data of Berry (1971), of 27 astronauts flying in Apollo spacecraft, 6 had unpleasant sensations in the stomach and 2 had nausea and vomiting.

Thus, we have a basis at present for speaking of the space form of seasickness (G. L. Komendantov, V. I. Kopanev, 1962).

The clinical picture of the space form of seasickness has much in common with ordinary "sea" or "air" sickness in the latent course of them (V. I. Kopanev, 1970). A reduction in appetite, dizziness, nausea, change in sense of taste, fluctuation in heart and respiration rate and other vegetative indicators, reduction in amplitude of the T-spike on the EKG and appearance of low-frequency oscillations in the EEG are noted. However, there are some singularities: a simple course, retention of efficiency, comparatively long period of development of seasickness from the start of weightlessness; a more pronounced connection between disruptions of orientation in space (illusory sensations) and vegetative reactions, than in the ground forms of seasickness (V. I. Kopanev, Ye. M. Yuganov, 1972). In fact, all astronauts who had some symptoms of seasickness noted that efficiency did not decrease significantly, in this case. Considerable length of the latent period of development of seasickness from the start of weightlessness also was quite characteristic: it required at least 4 hours.

Under ground conditions, seasickness develops, as a rule, considerably more rapidly. These singularities (the simple course and delay in development) apparently are explained by high individual resistance of the astronauts to the set of effects of space flight factors (result of selection and training).

Three singularities are more interesting. A close connection between expression of illusory sensations (flight in the upside- /78
down position, etc.) and vegetative reactions is quite characteristic of the space form of seasickness. It turned out that quite long and persistent illusions of position in space were observed in the majority of persons with seasickness symptoms. In essence, they can be considered as the first signs of the beginning of seasickness. For ground types of motionsickness ("sea," "air," etc.), this pattern appears considerably less often.

The necessity has arisen for study of the physiological mechanisms of space sickness. The basis for explanation of the genesis of motion-sickness is the generally accepted theory of V. I. Boyachek (1909, 1934, 1946), the correctness of which was subsequently confirmed by his students and successors (K. L. Khilov, 1933, 1934, 1936, 1939; G. G. Kulikovskiy, 1935, 1939; I. Ya. Borshchevskiy, 1937, 1939; A. I. Vozhzhova, 1946, and others). According to this theory, vertical movement is of significant value in development of seasickness. Inclined, circular and other motions, although they cause the state of seasickness, they do so to a lesser extent. Mechanical movements are perceived by the receptors of the vestibular analyzer, interoreceptors, proprioreceptors and cutaneomechanical sensitive elements, in which the specific organ of this perception is the otolith apparatus, with a very low stimulation threshold. Light stimuli, caused by movements in space, are perceived by the visual analyzer.

It has been taken for granted that the basic causes of development of the state of seasickness are unusual mechanical conditions, which man can experience: g-forces, weightlessness, changes in barometric pressure, etc. (G. V. Altukhov, et al., 1962, 1965; V. I. Kopanev, 1963, 1964, 1970; V. S. Kompanets, 1968, and others). Optokinetic stimuli are among the supplementary causes. Other external environmental conditions have a significant effect on seasickness: oxygen starvation, changed temperature conditions, chemical stimuli, etc. (V. I. Kopanev, 1965; N. A. Razsolov, 1965; V. I. Kopanev, et al., 1966; S. S. Markaryan, et al., 1973).

The anthropometric singularities of man affect development of seasickness to a definite extent: sex, weight, age (P. N. Pynin, 1888; V. I. Kopanev, 1970, and others).

The basic mechanism of development of seasickness is the summation of small, initially normal, adjusting reactions of the body to static-kinetic stimuli (mechanical, optical, etc.). The stimuli causing seasickness act on the receptors of the analyzers in the functional system perceiving space and participating in carrying out the balancing function. The vestibular analyzer (labyrinth mechanism) and, to a lesser extent, the visual, proprioceptive, cutaneomechanical and interoceptive extralabyrinth mechanisms of seasickness have a large part in the genesis of seasickness (A. I. Onufrash, 1970; K. K. Andronik, 1973, and others).

At the start of action of stimuli causing seasickness, the excitation propagates through specific reflex pathways (normal reactions) and, then, the summation of the reactions leads to a pathological state of the nervous system and of the entire body. Excitation by these receptors propagates, not only through specific pathways, and the reaction then is accompanied by vegetative disruptions -- vomiting, dizziness, etc. (G. L. Komendantov, et al., 1972). According to our data (G. L. Komendantov, V. I. Kopanev, 1963), /79
seasickness has four phases. The first phase is increased excitability (irradiation of weak excitation in the nervous system); the second phase is retardation (simultaneous negative induction); the third phase is the onset of sharp excitation (periodic irradiation of strong excitation); and the fourth phase is suppression (maximum inhibition).

Fluctuations of various functions (one of the indicators of the state of their regulatory mechanisms) and static-kinetic sensitivity change, according to these phases (N. A. Razsolov, 1965; A. I. Onufrash, 1970; L. A. Pomogaylo, 1970, and others).

The sympathetic nervous system plays a significant role in the development of motionsickness. Removal of the upper and lower sympathetic nodes in experimental animals leads to almost immediate transition of the seasickness process in them to the second phase (predominance of the parasympathetic nature of the regulation of the function). The results of preliminary training (adaptation to rocking) could not be detected in the operative animals. The role of the reticular formations in the seasickness process in intact animals and in animals with the upper and lower sympathetic nodes removed has been established. The sympathetic nervous system, as the efferent link in the self-regulation mechanism of the nervous system, is of significant value in adaptation of the organism to new, unusual mechanical conditions (L. I. Chernikova, 1971, 1972, 1972).

Slightly expressed erythrocytosis, leukocytosis, neutrophilesis and lymphopenia have been found in experimental seasickness of animals (data of K. A. Pimenova). The number of reticulocytes changed most significantly (two- fourfold), reaching 26%, with an initial 4-13%. The number of reticulocytes was high (up to 35%) in animals, with the upper sympathetic nodes removed before rocking.

After seasickness, fluctuations in the indicators were very much greater (amplitude from 20 to 46%), which indicates disruption of one of the regulatory mechanisms of this system.

It follows from the work of I. I. Bryanov and F. D. Gorbov (1952), V. V. Boriskin (1954), A. I. Vozhzhova (1947), R. A. Okunev (1958), V. I. Kopanev (1961), N. A. Razsolov (1966) and others that the state of the higher nervous activity is of great importance in the genesis of seasickness: persons of the strong type become seasick less often and it proceeds easier; the opposite is noted in persons with a weak type of nervous system.

Conditioned reflex mechanisms play a specific part in development of seasickness. Thus, such stimuli as type of aircraft, ship rigging, etc. facilitate development of seasickness in persons, who have experienced seasickness in the past (Ya. I. Trusevich, 1887; P. N. Pynin, 1888; M. O. Perfil'yev, 1891; L. R. Brodovskiy, 1900; A. I. Vozhzhova, 1946; V. V. Rassvetayev, 1958; Bard, 1948, and others). It turned out that the conditioned reflex component of seasickness cannot only start, but end it, since it is known that emergency signals, great dizziness, responsibility for the life of the crew, etc., quickly terminate the state of seasickness, as a rule (Ya. I. Trusevich, 1887; McMullen, 1955, and others). This apparently explains the increased resistance of some pilots to "bumpiness," while controlling an aircraft (effect of the working dominant) and reduction of this stability in a flight as a passenger (K. K. Platonov, 1957). In all likelihood, the mechanism of external slowing down and dominants are the basis of these phenomena.

Disturbances in the interactions of a number of analyzers apparently has some part in development of seasickness (I. M. Sechenov, 1906; I. P. Pavlov, 1926; L. A. Orbeli, 1938). The question is of disruption of the dynamic functional system in work of the analyzers participating in perception of movement in space: vestibular, propriocentive, visual, interoceptive and cutaneomechanical (G. L. Komendantov, 1959, 1965, 1966; G. L. Komendantov, K. A. Pimenova, 1973). In prolonged rolling, owing to reflex effects, a considerable number of changed signals reach the analyzers from the mechanoreceptors, as a result of which, the combined activity of the analyzers is disrupted and seasickness develops. /80

It is possible that the origin of the vestibular-vegetative shifts in weightlessness are caused by the following. As is well known, mechanical actions connected with gravitation stop in weightlessness (V. V. Parin, V. I. Yazdovskiy, 1959). As a consequence of this, the activity of the analyzer systems perceiving movement of the body in space is disrupted, and seasickness phenomena develop. The reduction in seasickness of astronauts in the sleeping period also becomes understandable, since, according to the data of P. N. Pynin (1888) and other authors, vestibular-vegetative disturbances caused by the action of rolling and rotation during a time when a man is asleep are manifested to a less marked extent. However, this proposed mechanism of reduction in seasickness requires additional investigations on subsequent space flights.

A considerable reduction in seasickness after switching on the braking units can be explained by termination of the state of weightlessness and, to a certain extent, by inhibition of the vestibular-vegetative reactions, under the influence of the working dominants, in connection with the onset of the most critical moment, entry into the dense layers of the atmosphere and landing.

In analysis of the vestibular-vegetative disorders observed in astronauts, still another mechanism should evidently also be kept in mind -- the effect of Coriolis acceleration, arising in movement of the head relative to the center of rotation of the spacecraft cabin. This is confirmed by the data on increase in the vestibular-vegetative phenomenon in movements of the head. There are indirect data, confirming the correctness of this assumption, in the works of Graybiel and colleagues (1960) and Clark and colleagues (1961). In some subjects, slowly rotated while moving the head under ground conditions, these authors observed dizziness, nausea, vomiting and other vestibular disorders, similar to the state of seasickness.

However, the clinical picture of spacesickness cannot be explained by Coriolis accelerations alone, since the vestibular-vegetative disorders do not disappear when an astronaut is in a peaceful situation.

Beside the physiological substantiation of the vestibular-vegetative reactions indicated, still another mechanism is possible under weightless conditions. As is well known, the property of inertia is preserved under decreased gravitational effects; therefore, the otoliths, having a certain mass, will be a source of unusual afferentation (change, decreased). This kind of impulse from the otoliths apparently has a less inhibiting effect on excitability of the semicircular canal receptors, as a consequence of which their excitability is increased, by virtue of the reciprocal relationships (V. I. Boyachek, 1927, 1946; K. L. Khilov, 1939, 1952; V. I. Kopanev, 1960; I. A. Kolosov, et al., 1967). In this case, normal movements of the head become superthreshold and cause vegetative shifts.

It follows from the material reported above that, under ground /81 conditions, reflex mechanisms (and, possibly, neurohumoral ones, but they have not yet been studied sufficiently) play the principal role in the genesis of seasickness. Disruptions of the functional system will be rare. Thus, they will occur during the action of rolling on a man in a closed space or in darkness (cabin, hold of a ship, etc.), when all the mechanoreceptors indicate mechanical actions. Visual stimulation at this time signals relative rest of the body of the man. This disagreement in analyzer activity favors intensification of seasickness. The activity of the functional system perceiving space and participating in carrying out the balancing function of the human and animal bodies, is disrupted during "bumping" of an aircraft, as a consequence of unusual load acting on this system -- repeated small, brief g-forces and weightlessness for a long period. According to our hypothesis, the main mechanism of seasickness under weightless conditions is disruption of the interaction of the analyzers (disruption of the functional system), owing to weakening and distortion of the afferentation, originating from the mechanoreceptors, etc.

Coriolis accelerations, as well as increased excitability of the semicircular canal receptors, as a consequence of weakening of the inhibiting effect of the otolith portion of the vestibular analyzer, apparently has an important role in the genesis of seasickness, as was pointed out above. Concerning the conditioned reflex mechanism, it acquires different values, both under ground transport and space flight conditions, depending on many circumstances.

Adaptation of the body to these unusual living conditions is very important. An evaluation of the adaptation process can be carried out, both from the recovery of coordination of voluntary motor acts, and from the degree of expression of vegetative reactions. If the adaptation process is evaluated on recovery of motor coordination, it sets in quite quickly, in the opinion of the majority of authors.

Tests of the effect of weightlessness in flights along a Kepler trajectory have shown that, in a number of cases, upon repetition, vegetative disorders also gradually disappear (L. A. Kitayev-Smyk, 1963, 1967; I. I. Kas'yan, 1966; V. A. Kolosov, 1969, and others).

Adaptation to weightless conditions can be explained by formation of a new functional system in the activities of many analyzers. In this case, together with unusual afferentation from the mechanical receptors, visual perception takes on the main part in analysis of spatial relationships (V. V. Parin, V. I. Yazdovskiy, 1959; N. M. Sisakyan, V. V. Parin, V. N. Chernigovskiy, V. I. Yazdovskiy, 1962; Strughold, 1955, 1957, and others). It follows from this that the rate of adaptation to weightless conditions is determined by the speed of formation of new functional systems in analyzer interactions. The reticular formations of the brain stem play a significant role here. According to the data of Word (1962), new functional systems are created and consolidated more rapidly in pilots, with high reticular formation activity. This allows them to fly well, under complicated meteorological conditions and to tolerate weightlessness better. Beside this, typological singularities of the nervous system, primarily mobility of the nerve processes, are of great importance in creating functional systems (I. P. Pavlov). Since a new system most often will be fragile, unstable, the possibility is not excluded of disruption of it by the action of unfavorable factors. This is of /82
great importance for prophylaxis of seasickness in a space flight.

Taking the physiological mechanisms into account, the following pathways of prophylaxis of seasickness of astronauts can be planned:

1. Special selection of persons, suitable for space flight, by state of health. Special attention should be given here to evaluation of the static-kinetic stability, development of more nearly

perfect methods of investigation of it, etc.;

2. Extensive use of training exercises (various physical exercises, special apparatus, flights along the weightlessness parabola), which increase the static-kinetic stability of the plastic properties of the nervous system. All this creates conditions for forming new functional systems in analysis of spatial relationships. Some examples of training exercises are flights under complicated meteorological conditions, flights under a hood, with partial replacement of the visual reference points and instrument readings, aircraft flight along the Kepler parabola, with reproduction of brief weightlessness. In this case, conditions of rapid transition in activity of the central nervous system from one functional system to another is generated;

3. Creation of optimum physiological-hygienic conditions in the spacecraft cabin, since deterioration in them may entail slowing of formation of a new functional system;

4. Use of pharmacological agents, increasing efficiency of man and resistance of the body to unusual mechanical conditions, especially weightlessness, when a new functional system of analyzer interactions still has not consolidated. In the future, there apparently will be extensive use of various nervous system stimulators, increasing the nonspecific resistance of the body (N. V. Lazarev, et al., 1959; V. I. Kopanev, 1961, and others).

5. Continual improvement of spacecraft (flight stabilization, etc.). It is quite possible that, for purposes of creating favorable conditions for forming a new functional system, the so-called up and down in the cabin will have to be strengthened, by means of various artificial reference points, for example, by means of various light and sound stimuli and, possibly, odors (K. E. Tsiolkovskiy, 1911; K. K. Platonov, 1959).

Organization of optimum working and rest conditions for the astronauts during flights is very important in prophylaxis of spacesickness. Reasonable compression of work operations, constant occupation and other measures favor an increase in resistance to weightlessness.

Of course, the problem of spacesickness will be solved to a certain extent if artificial weight is reproduced under space flight conditions (K. E. Tsiolkovskiy, 1910). However, seasickness is possible in this case, because of Coriolis acceleration information (Ye. M. Yuganov, 1962; M. D. Yemel'yanov, 1968; B. B. Bokhov, M. D. Yemel'yanov, 1970; M. D. Yemel'yanov, A. N. Razumeyev, 1972; Graybiel, 1971).

It can be concluded from everything which has been said, that spacesickness under weightless conditions is explained mainly by disruption of the activity of the functional system perceiving space and participating in carrying out the balancing function, consisting, in particular, of the vestibular, proprioceptive, interoceptive, visual and cutaneomechanical analyzers. It can be assumed that, under specific conditions, Coriolis acceleration also is a cause of spacesickness.

The conditioned reflex component, which can cause, intensify, weaken or remove seasickness, has a certain role in development of spacesickness. /83

Adaptation is possible in spacesickness, by virtue of formation of a new functional system, which is adequate to the new mechanical conditions of weightlessness.

Selection, training, creation of optimum conditions in the spacecraft cabin, medicinal, and technical improvement of spacecraft play an important role in prophylaxis of the space form of seasickness.

The necessity for further study of the spacesickness (motion-sickness) problem should be emphasized again in conclusion, since it is a well-known obstacle to mastery and use of new, improved types of transport.

5. Vestibular Reactions of Astronauts During Flight in Voskhod Spacecraft

N75 23114

As is well known, sensory and vegetative disturbances arose in some Soviet and American astronauts during orbital flight. The cause of these disorders is still not completely clear; however, the importance of the vestibular analyzer in their genesis is completely obvious. The latter has been confirmed experimentally. Thus, immediately after cutting out the vestibular apparatus of animals under ground conditions, vestibular-somatic, vestibular-vegetative disturbances are observed (disruption of the statics, rotating movements, change in pulse rate, etc.). Approximately the same phenomena arise in intact animals, in the first minutes of the weightless conditions (Ye. M. Yuganov, et al., 1962; L. A. Kitayev-Smyk, 1963 -- see section 1 of this chapter; and others). Such shifts turn out to be considerably less pronounced in labyrinthectomized animals, under these conditions (Ye. M. Yuganov, D. V. Afanas'yev, 1964; Beck, 1954; Schock, 1961, and others).

In the light of this, the importance of study of vestibular reaction of astronauts during long orbital flights becomes understandable (G. L. Komendantov, V. I. Kopanev, 1962; V. V. Baranovskiy, et al., 1962; N. M. Sisakyan, et al., 1962, and others). In this respect, there is definite interest in the results of the flights of the multiplace Voskhod spacecraft, which, besides solution of the basic problem (study of the effect of prolonged weightlessness on the basic physiological functions and efficiency of astronauts, etc.), permitted evaluation of the simultaneous effects of weightlessness on several men, with different levels of vestibular stability. The latter was a partial, but nevertheless, important purpose of this flight.

Preparation for the flight and performance of it was characterized by a number of similarities, significantly differentiating it from all preceding spacecraft flights. First, persons with various degrees of conditioning of the vestibular analyzer were permitted on the flight: V. M. Komarov had more stable reactions, and he underwent vestibular training for a longer time than K. P. Feoktistov and B. B. Yegorov. In one case or another, elements of active and passive exercises were used, with the latter being carried out several times per week /84 and always alternating with active special exercises in the general physical training system. Before the start, during and after training exercises, the functional state of the vestibular analyzer was studied, using the following methods and means:

a) Rotating a chair with transfer to an unstable support. For a period of 10 sec, the person being examined was rotated in one direction and, then, in the other. After stopping rotation, the chair was transferred to an unstable support and the person being examined had to maintain equilibrium. The time for restoration of equilibrium and the subjective feelings were recorded;

b) A rotating chair, in which Coriolis accelerations were created. The chair was rotated at a rate of 180°/sec; in this case, the person being examined periodically tilts the head and trunk forward by almost 90°. Tilting was carried out for a period of 3 sec, after which a 5-second rest followed and, then, straightening up. Rotation continued for a period of 1 minute, there was then a minute break, during which the pulse rate, subjective feelings and expression of vegetative reactions were recorded. After 1 min, the action was repeated, but with rotation in the opposite direction. With a similar action of the Coriolis acceleration, the time of onset of adverse reactions was determined;

c) Khilov swing. The subject was swung with eyes closed for a period of 15 min. The vegetative reactions and subjective feelings were noted.

After training, the recovery time of all astronauts decreased considerably, after rotation and transfer to the unstable support. For V. M. Komarov, it decreased from 5 to 3 sec, for K. P. Feoktistov, from 10.8 to 4 sec and, for B. B. Yegorov, from 7.5 to 5.3 sec (the average time is given). The resistance of the vestibular analyzer to the Coriolis acceleration effects also changed. Thus, for V. M. Komarov, paleness and light perspiration set in in the second minute of Coriolis acceleration before training and, after training, in the 12th minute. For K. P. Feoktistov, the 1st and 5th minutes, respectively, and, for B. B. Yegorov, the 2nd and 11th minutes. After training, no vestibular-vegetative reactions while swinging in the /85 Khilov swing was observed in the astronauts. Their resistance to the effects of optokinetic stimuli also increased; the illusion of rotation arose before training during this action and, after training, it did not appear.

Despite the fact that vestibular stability of all astronauts increased as a result of training, it was not identical in them at the start of the flight. This also was confirmed during certain other tests and examinations, in particular, in special parabolic flights, which were carried out in the process of the final examination for determination of individual tolerance of the brief effect of weightlessness by the astronauts (Table 22). Under conditions of brief weightlessness, some lability of the pulse rate, compared with the initial values, was noted in B. B. Yegorov and K. P. Feoktistov. The pulse of V. M. Komarov was practically unchanged. Movements of the first two astronauts in flight were somewhat constrained, but those of V. M. Komarov were quite adequate and coordinated.

TABLE 22

DYNAMICS OF PULSE RATE AND RESPIRATION OF ASTRONAUTS DURING FAMILIARIZATION-TRAINING FLIGHTS (data of 3 weightless cycles on 1st flight)

Astronaut	Indication	Preflight	Flight Duration							Postflight
			Horizontal	g-force	Weightlessness			Horizontal	g-force	
					10	20	30			
V. M. Komarov	Pulse, beat/min	66	70	78	66	60	60	—	68	60
			68	76	60	60	60	76	68	
			68	—	54	54	54	76	60	
	Respiration, cycle/min	14	14	15	16	14	16	18	14	
			14	—	14	14	14	18	16	14
			16	17	14	16	16	18	16	
K. P. Feoktistov	Pulse, beat/min	74	—	110	90	90	84	96	90	68
			90	100	-	--	—	105	84	
			84	102	90	86	76	98	78	
	Respiration, cycle/min	14		20	21	18	18	18	18	16
				--	18	16	18	24	18	
			18	21	20	18	16	18	16	
B. B. Yegorov	Pulse, beat/min	72	108	126	98	98	102	—	100	
			100	110	96	84	90	—	90	
			90	114	84	84	84	—	—	
	Respiration, cycle/min	16	—	20	24	24	24	—	20	18
			22	20	—	—	—	—	22	
			22	30	—	—	—	—	—	

After performing parabolic flights, no vestibular-vegetative reactions were observed in V. M. Komarov, and his behavior was adequate. Degree I vegetative reactions (becoming pale) were noted in K. P. Feoktistov; accentuated mobility, caution and degree II vegetative reactions (paleness, hyperhidrosis, lability of the pulse) were observed in B. B. Yegorov.

It is clear from the report of the astronauts on their feelings during the familiarization-training flights, that V. M. Komarov experienced a feeling of pleasant lightness. There was no deterioration in state of health or efficiency. The state of health, frame of mind and efficiency of K. P. Feoktistov were excellent during and after the flight. B. B. Yegorov felt more poorly. The first flight did not leave a favorable impression on him. Partial removal of the g-forces left the impression of heavy physical work. The sensations were more interesting in the second flight. He performed work easily and quickly and noted no illusions. Some euphoria. State of well-being and efficiency were good in the third flight.

Thus, with a high level of vestibular stability, there were no vestibular-vegetative disorders under weightless conditions.

The relatively low threshold value of excitability of the vestibular analyzer to a galvanic current, the presence of vegetative reactions under the cumulative effect of Coriolis acceleration and the lower tolerance of brief weightlessness in the flights were indicators, which permitted evaluation of the vestibular stability of K. P. Feoktistov and B. B. Yegorov as satisfactory.

Investigations during the flight of the Voskhod spacecraft contemplated study of the vestibular-sensory, motor and vegetative reactions.

The following were used for this:

a) Self-analysis data (written and oral report);

b) Graphic test. In performing it, the subject assumed a posture convenient for writing and, under visual control, drew 10 small circles in the journal initially, along a horizontal line, then 10 small circles along a vertical line and, finally, 10 small circles along the diagonal, forming two sides of a square and its diagonal, as it were. The sizes of the small circles were not larger than the sizes of the letter o in ordinary writing. The test was then repeated, but with the eyes closed. In this case, the initial point of the writing also was determined with the eyes closed. The results of the study were evaluated, by the size of the angles formed by the horizontal, vertical and by diagonal lines;

c) Indicating test. In performing it, the subject, with eyes /86
open and closed, reaches one of the control panel instruments, located at a distance of the extended arm from the face. The results of the test were written down in the journal: the direction was noted with

arrows and the size of deviation in centimeters, by numbers;

d) Investigation of the excitability thresholds of the vestibular analyzer to galvanic current. A special apparatus was used for this purpose. The excitability threshold was estimated from sensory reaction data -- the illusion of banking. While working, the person being examined attached electrodes in front of the tragus of each ear then set the control panel mechanism in the position, which would insure reproduction of the required current, started the current pulse delay mechanism, occupied the initial position with eyes closed and noted the presence of illusions. In the absence of the banking illusion, the current strength was increased, until the time when it arose. The minimum current strength, at which the sensation of banking appeared, was adopted as the threshold. After this, reaction of the threshold current was repeated twice, immediately after which, the writing test was carried out in the first case and the indicating test in the second. Performance of the writing and indicating tests before application of the threshold galvanic current was the control.

The results of the investigation showed that reaction of g-forces in the powered section of the flight and at the moment of transition to weightlessness did not cause any adverse reactions. During orbital flight, illusory sensations of the upside-down position of the body in space arose in astronauts B. B. Yegorov and K. P. Feoktistov. It seemed to one of them that he was face down, in a half-bent position, and it seemed to the other that he was turned head downward. B. B. Yegorov and K. P. Feoktistov noted that the illusions arose in them, with both closed and open eyes. According to the reports of the astronauts, these sensations were not distressing, and they did not seriously interfere with execution of the planned work, but they increased when concentrating attention on their feelings.

In distinction from the preceding space flights, in which rapidly passing illusory sensations arose only at the moment of transition from the effect of g-forces to weightlessness, a fundamentally new phenomenon was discovered on this flight, the illusion of the upside-down position was observed by the astronaut during the entire period of weightlessness, i.e., it was of a constant nature. The illusions disappeared only with the beginning of reaction of g-forces during descent of the craft. Together with the illusions, K. P. Feoktistov and B. B. Yegorov also manifested dizziness in orbital flight, with moderate or abrupt movements of the head. The dizziness was similar to the feeling, which usually appeared with the action of the galvanic current on the vestibular analyzer. In connection with these phenomena, astronauts B. B. Yegorov and K. P. Feoktistov attempted to move less and, in performing work, they moved smoothly. The dizziness was not accompanied by the onset of involuntary movements of the eyes, as occurs with the effect of angular and Coriolis accelerations.

It is extremely important that the nature and degree of expression of illusory sensations and dizziness during free flight of the craft were the same as in the stabilized position of the craft. This fact is additional confirmation of the fact that the cause of onset of illusory effects, in all likelihood, is not only the action of Coriolis acceleration, but the direct effect of weightlessness.

We would only have the right to speak of the etiological and pathogenetic importance of Coriolis acceleration in genesis of the reactions observed, on condition that the nature and degree of vestibular reactions observed during the free flight period in the stabilized position changed significantly.

After 1-1/2 - 2 hours of flight (2nd orbit) symptoms of vestibular-vegetative disorders appeared in B. B. Yegorov; decrease in appetite and unpleasant sensation in the substernal region. These symptoms gradually increased, and they reached the maximum expression in the 7th hour (5th orbit). The vestibular-vegetative disorders almost completely stopped after sleep. Similar symptoms also were noted in K. P. Feoktistov, but they were less pronounced. /87

As a result of the vestibulometric investigations carried out directly in flight, it was found that the numerical values of the excitability threshold of the vestibular analyzer to the galvanic current were the same under weightless conditions, as in the ground situation; they were 3.2 mA for V. M. Komarov, 1.9 mA for K. P. Feoktistov and 1.4 mA for B. B. Yegorov. However, in view of the extremely small number of measurements, this observation cannot be a basis for any conclusions, as to changes in sensitivity of the vestibular analyzer in orbital flight. There is no doubt that a similar type of investigation must be continued, so as to obtain quantitatively adequate data.

In analysis of the results of the indicating and writing tests, only a negligible reduction in accuracy of performance of fine, coordinated movements was revealed, which can be evaluated as a consequence of change in functional state of the vestibular and motor analyzers (Table 23). Changes in accuracy of movements in the indicating test did not exceed 1.5 cm, compared with the control test. /88

The results of the flight showed that existing methods of ground examination permits forecasting, to a certain extent, the possibility of emergence of vestibular disorders in flight. V. M. Komarov turned out to have excellent vestibular stability before the flight, and no adverse vestibular reactions were observed in him during the flight. The vestibular reactions of K. P. Feoktistov and B. B. Yegorov were rated as satisfactory; vestibular-vegetative reactions, of the space-sickness type, developed in them.

It must be noted that use of the vestibular examination method is still insufficient for determination of the nature and degree of manifestation of possible vestibular disorders. The fact is that, under space flight conditions, the onset of adverse reactions is not only determined by changed vestibular afferentation, but it depends

TABLE 23

RESULTS OF PERFORMANCE OF WRITING TESTS BY ASTRONAUTS UNDER GROUND CONDITIONS AND DURING FLIGHT OF VOSKHOD SPACECRAFT (in degrees)

Astronaut	Stage of Investigation	Eyes Open			Eyes Closed		
		Angles					
		AB	A	B	AB	A	B
V. M. Komarov	Ground conditions	88	42	46	81	41	40
	during flight 1st investigation	86	49	37	75	48	27
	2nd investigation	87	51	36	87	52	35
	After stimulation with galvanic current	89	52	37	82	61	[illegible]
K. P. Feoktistov	Ground conditions	88	38	50	82	40	42
	during flight 1st investigation	89	50	39	39	—	37
	after stimulation with galvanic current	90	44	46	80	26	54
B. B. Yegorov	Ground conditions	95	32	63	76	45	[illegible]
	during flight 1st investigation	90	49	41	80	25	[illegible]
	after stimulation with galvanic current	90	42	48	91	47	[illegible]
	2nd investigation	89	43	46	99	39	[illegible]
	after stimulation with galvanic current	89	48	41	84	35	49

Note: Angle AB is formed by the vertical and horizontal lines of small circles; angle A, by the horizontal and diagonal lines; angle B, by the vertical and diagonal lines of small circles.

on disruption of the interaction of other analyzer systems. In connection with this, in improving existing methods of vestibular selection, the development of such procedures is required, as would take account of the fine mechanisms of interaction of the vestibular analyzers with other afferent systems. In particular, it is necessary that procedures, permitting evaluation of all features, on which vestibular stability depends, be represented uniformly: the excitability thresholds of the vestibular and otolith apparatus in the pure form (cupulometry, otolithometry), the singularities of inhibiting processes and resistance to cumulative actions.

Thus, the observations have shown that the differing vestibular resistances of the Voskhod spacecraft crew members to a one-day stay under weightless conditions (high in V. M. Komarov and satisfactory in B. B. Yegorov and K. P. Feoktistov) is connected with nonuniform initial sensitivity of the vestibular apparatus, as well as with different lengths of vestibular training.

It should [illegible] emphasized at the same time that intensive vestibular training of persons with a moderate degree of sensitivity of the vestibular analyzer does not ensure vestibular stability under weightless conditions.

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CHAPTER 3

VEGETATIVE REACTIONS IN WEIGHTLESSNESS

1. Blood Circulation Under Weightless Conditions

In study of the action of weightless conditions on man, their effect on blood circulation has always attracted the attention of investigators, since life and efficiency of the body depend greatly on the functional state of the cardiovascular system and the blood-producing organs. /89

In recent years, domestic and foreign investigators have obtained quite a large amount of material on the effect of weightlessness on the blood circulation system of animals and man (B. G. Bugrov, et al., 1958; A. M. Galkin, et al., 1958; Yu. M. Volynkin, et al., 1962; R. M. Babayevskiy, O. G. Gazenko, 1962; V. V. Parin, et al., 1962; N. M. Sisakyan, V. I. Yazdovskiy, 1962, 1964; V. I. Yakovlev, 1962; I. T. Akulinichev, et al., 1963; I. I. Kas'yan, 1963; I. I. Kas'yan, et al., 1965; P. V. Vasil'yev, et al., 1965; Yu. Ye. Moskalenko, et al., 1971; Augerson, et al., 1961; Laughlin, et al., 1961; Berry, 1963). Nevertheless, up to the present time, there have been no generalized works on these questions, although the necessity for this is completely obvious. We have attempted to fill this gap. Both materials from our research and data in the literature have been used here.

The basic stages of mastery of circumterrestrial space, with participation of animals, in the Soviet Union, are characterized in Table 24. Data on the flights of the Soviet astronauts were presented in Table 1.

Tables 25 and 26 contain information on the changes of certain indicators of the work of the cardiovascular system of dogs, during suborbital flights, up to altitudes of 100-473 km.

In the experimental animals under weightless conditions, as a rule, the pulse slowed down and the blood pressure decreased. This /90 state was preserved regularly to the end of the state of weightlessness. In the first half of the period of weightlessness, the pulse was accelerated in 6 cases, slowed in 12 and remained unchanged in 4 cases, with respect to the data of examination at the end of injection of the craft into orbit. In the second half of the weightless period the pulse rate was the initial one in the majority of measurements (see Table 25). All the animals can be divided into three groups, by direction of the physiological reactions: 1) with distinct

TABLE 24

BASIC STAGES OF MASTERY OF CIRCUMTERRESTRIAL SPACE WITH PARTICIPATION OF ANIMALS

Nature of Flight	Launch Date	Investi-gation	Stay Time in Weight-lessness	Indicators of Functional State of Cardiovascular Systems
Suborbital flights				
Up to altitude of 110 km	1949-1956	26 dogs	3.7 min	Pulse rate, blood pressure
Up to altitude of 210-212 km	1956-1960	20 "	6 "	Pulse rate, blood pressure, bioelectric activity of heart (EKG in two leads)
Up to altitude of 450-473 km	1958-1959	6 "	9 "	same
Orbital flight	3 Nov 1957	Layka	During entire orbital flight 25 hrs	Pulse rate, blood pressure, bioelectric activity of heart (EKG chest lead)
same	19 Aug 1960	Belka and Strelka		Pulse rate, bioelectric activity of heart (EKG in chest leads), phonocardiogram, blood pressure
"	1 Dec 1960	Pchelka and Mushka	25 hrs	Pulse rate, bioelectric activity of heart (EKG), phonocardiogram, seismocardiogram
"	9 Mar 1961	Chernushka	65 min	Pulse rate, heart muscle biopotentials (EKG in two leads), sphygmogram
"	22 Mar	Zvezdochka	65 "	same
Orbital flight	22 Feb 1966	Veterok and Ugolek	528 hrs	Pulse rate, respiration rate, bioelectric activity of heart (EKG), seismocardiogram, blood pressure, hematological study

TABLE 25

CHANGE IN PULSE RATE AND BLOOD PRESSURE OF DOGS DURING THEIR STAY UNDER WEIGHTLESS CONDITIONS (not over 690 sec), COMPARED WITH DATA RECORDED AT END OF POWERED SECTION

Flight Altitude, km	No. of Dogs	Physiological Indicators	Initial Data, Moment of Injection of Craft into Orbit	Weightlessness					
				First Period			Second Period		
				Increase	Decrease	Unchanged	Increase	Decrease	Unchanged
100—110	8	Pulse rate, beat/min	60—170	2 / 15—37	4 / 15—32	2 / 0	1 / 78	—	6 / 0
		Maximum level of blood pressure, mm Hg	130—170	—	2 / 15—24	2 / 0	—	—	—
		Minimum level of blood pressure, mm Hg	60—75	—	3 / 12—15	1 / 0	—	—	—
200—212	10	Pulse rate, beat/min	115—265	4 / 12—22	4 / 15—127	2 / 0	2 / 60—80	—	6 / 0
		Maximum level of blood pressure, mm Hg	200—240	—	4 / 25—40	—		2 / 15—30	2 / 0
		Minimum level of blood pressure, mm Hg	55—70	—	1 / 0	—		3 / 15—20	2 / 0
450—473	6	Pulse rate, beat/min	160—210	—	4 / 20—65	—	1 / 40	—	5 / 0
		Maximum level of blood pressure, mm Hg	188—265	—	3 / 15—35	—		2 / 20—30	—
		Minimum level of blood pressure, mm Hg	105—138	—	1 / 20	2 / 0	—	—	2 / 0

Note: In the numerator, number of measurements; in the denominator, range of change in indices studied.

TABLE 26

CHANGE IN BLOOD PRESSURE AND PULSE RATE IN NARCOTIZED ANIMALS DURING SUBORBITAL FLIGHTS UP TO ALTITUDES OF 210-212 km

Name of Dog	Indicator	30 sec before Launch	Weightlessness, sec		
			83—170	170—260	260—440
Belka	Pulse rate, beat/min	90	84—90	90—96	84—90
	Arterial pressure (maximum) mm Hg	—	85—90	90	80—90
Modnitsa	Pulse rate, beat/min	210	216	200—192	188—180
Pal'ma	Pulse rate, beat/min	120	140—145	145	145
	Arterial pressure (maximum) mm Hg	172—220	200—180	180—170	—
	Arterial pressure (minimum) mm Hg	—	110—135	100—110	100—110

slowing down of the pulse and reduction in blood pressure; 2) without noticeable changes in these indices; 3) with increase in pulse rate and increase in blood pressure. The first group was the most numerous. /91

V. I. Yakovlev (1962), in a study of the state of the peripheral blood circulation in animals, before flights in geophysical ballistic rockets in the upper layers of the atmosphere, during flight and after it, determined that the maximum arterial and venous pressure and blood flow rate were unchanged. There are no significant disturbances of the peripheral vessels, with the exception of some reduction in vascular tonus. G. I. Pavlov (1963), studying the arterial and venous pressure of intact and labyrinthectomized dogs, in an acute experiment under weightless conditions (during flight along a Kepler parabola), found that the maximum and minimum arterial pressure of intact dogs decreased by 20-40 mm Hg, at the beginning of weightlessness; the blood pressure in the right auricle dropped by 15-25 mm Hg. By the end of the period of weightlessness (in 25-30 sec), the arterial pressure had returned to the initial values and the venous pressure increased somewhat, but remained below the initial values. The changes were negligible in the labyrinthectomized dogs. The author connects these reactions with the vestibular analyzer function. /92

In a number of experiments to reveal certain physiological mechanisms, studies were carried out on narcotized animals. No expressed changes were observed, on the part of the pulse rate and arterial pressure, in the animals under narcosis. This fact indicates a large role of the exteroceptive and interoceptive reflexes and the functional state of the higher sections of the central nervous system in forming physiological reactions. Similar results were obtained in the work of Henry and colleagues (1952), in experiments carried out on narcotized monkeys in rocket flights to altitudes of 60-120 km. Significant disruptions of the vegetative functions were not noted, but a tendency towards reduction in arterial and venous pressure was observed in the weightless state.

Morphological examinations of the blood were carried out before and after suborbital flights. Regularly, with the exception of one case, an increase in number of leukocytes and stabnuclear forms (from 2 to 30%) and a decrease in number of lymphocytes were noted. It is difficult at present to establish the cause of this phenomenon. It apparently is caused by development of stress reactions in the animals to the entire set of factors and, first and foremost, to the effect of g-forces during entry into the dense layers of the atmosphere and the impact g-forces in landing. A definite part also is played by redistribution of the blood and, primarily, entry into it of white elements from depositing organs (I. I. Kas'yan, et al., /93
1962). Preflight and postflight examination of the red blood of 12 dogs demonstrated the absence of deviations from normal.

Quite a number of studies have now been carried out, on the effect of brief weightlessness on man, carried out during flights of aircraft along a Kepler parabola (I. I. Kas'yan, 1962, 1963; Diringshofen, 1951, 1959; Beck, 1953, 1954, 1956, 1958, 1959, and others) and during rocket launches (Augerson, Laughlin, 1961; Laughlin, Augerson, 1961, and others).

Data on the pulse rate and arterial pressure dynamics of persons examined during weightlessness parabola flight are presented in Table 27. All those examined can be divided into three groups, by direction of change in these indicators: The indicators decreased in representatives of the first group; they increased in persons in the second group; and the indicators were unchanged in representatives of the third group. During horizontal flight, a quickening of the pulse was observed in the majority of those examined, which apparently is evidence of nervous-emotional stress. Weightlessness, as an unusual factor, initially favored an increase in stress; however, this stress decreased subsequently, in proportion to the effect of weightlessness, as a result of which a tendency towards slowing down of the pulse and a decrease in arterial pressure was noted. In this case, the rate of return of the cardiovascular system functions to normal depended mainly on individual singularities of the body (I. I. Kas'yan, 1963, and others).

Data from study of the brain and peripheral blood circulation are of definite interest. Test results have shown that, despite large individual differences, some general regularities are observed /94
in the reactions of the intracranial and peripheral blood circulation during brief weightlessness. While an increase in pulse wave amplitudes by 35-50% over the initial level was noted in the lower extremity rheograms, during the time of action of g-forces before and after the weightless stage, during weightlessness, the pulse wave became equal to the initial ones or less than them. In distinction from this, the rheoencephalogram pulse waves (recorded with temporal electrodes) changed little during the action of g-forces.

TABLE 27

CHANGE IN PULSE RATE AND BLOOD PRESSURE OF 83 SUBJECTS DURING HORIZONTAL FLIGHT AND AFTER WEIGHTLESSNESS PARABOLA FLIGHT, COMPARED WITH BASELINE DATA, AND IN PERIOD OF WEIGHTLESSNESS WITH RESPECT TO RESULTS OF EXAMINATION DURING HORIZONTAL FLIGHT

Initial Preflight Data	Horizontal Flight			Weightlessness						Postflight		
				In 1st Half			In 2nd Half					
	Increase	Decrease	Unchanged	Increase	Decrease	Unchanged	Increase	Decrease	Unchanged	Increase	Decrease	Unchanged
Pulse, beat/min												
50–82	224 / 5–60	68 / 5–12	56 / 0	105 / 5–54	134 / 5–36	64 / 0	63 / 5–39	90 / 5–36	38 / 0	29 / 5–15	105 / 5–26	41 / 0
Arterial Pressure (maximum), mm Hg												
110–165	58 / 5–40	28 / 5–20	6 / 0	15 / 5–20	36 / 5–35	7 / 0	—	2 / 5–20	1 / 0	36 / 5–15	84 / 5–15	51 / 0
Arterial Pressure (minimum), mm Hg												
53–87	31 / 5–15	22 / 5–22	12 / 0	12 / 5–15	43 / 5–20	10 / 0	1 / 15	2 / 5–10	—	62 / 5–30	39 / 5–10	70 / 0

Note: Number of measurements in numerator; range of indicators studied in denominator.

However, in the first few seconds of weightlessness, their amplitude decreased from the initial by 15-25%, but it then recovered. The fact itself that the intracranial pulsation under conditions of brief weightlessness changes negligibly is evidence of the possibility of stabilization of the blood circulation in the brain, by means of special regional mechanisms (Lassen, 1959; Yu. Ye. Moskalenko, 1967).

Characteristic changes were found in analysis of the bioelectric phenomena taking place in the cardiac muscle. I. I. Kas'yan (1962), in tests on 55 subjects, found that the EKG elements began to return to normal, together with a slowing down of the pulse, under conditions of brief weightlessness. The P_2, R_2 and T_2 spike voltages approach the values recorded in horizontal flight, and the P-Q, QRS, O-T, as well as the electrical axis of the heart, were within permissible limits of physiological fluctuations.

It can be concluded from the materials on the effect of brief weightlessness (up to 45 sec) that there are no significant disturbances of the cardiovascular system during weightlessness of this

length. Data also were obtained in these studies, on the reduction in arterial pressure, decrease in pulse rate and instability of certain vegetative indicators under weightless conditions. However, these data are insufficient for final conclusions on the state of blood circulation under conditions of prolonged weightlessness. Moreover, during the parabolic flights in aircraft, before and after the state of weightlessness, g-forces acted (up to 3.5 g), which made data analysis extremely difficult. Special studies were necessary, on animals under prolonged weightlessness. This became possible with the launches of artificial earth satellites. In the /95
first experiment, in the prelaunch period, the cardiovascular system indicators were within normal limits: pulse rate was 78-120 beats per minute, length of P-Q and Q-T intervals were 0.12-0.2 and 0.18-0.26 sec, respectively. After injection of the satellite into orbit, the pulse rate initially increased somewhat, compared with data obtained during injection of the craft into orbit, and it then began to gradually approach the initial data. However, it was reached approximately three times slower than under ground conditions, when the animals were subjected to g-forces of the same magnitude. The length of the P-Q and Q-T intervals in the weightless state were within 0.09-0.12 and 0.21-0.25 sec, respectively. The shape and size of the T-spike underwent quite considerable changes: It was negative in the prelaunch period and positive, during orbital flight. These changes in T-spike amplitude apparently depended on change in position of the electrical axis of the heart.

TABLE 28

CHANGE IN PULSE RATE (beats per minute) OF DOGS DURING LONG STAY UNDER WEIGHTLESS CONDITIONS

Name of Dog	Statistical Indicator	Initial Prelaunch Data		Weightlessness (Orbits)									
		4 hrs	5 min	2	3	4	[illegible]	6	7	12	16	1[illegible]	1[illegible]
Strelka	M	85	72	69	70	75	79	88	113	121	101	117	88
	σ	—	7.0	1.8	11.5	7.9	17.8	24.8	18.1	11.5	14.5	17.4	21.1
Belka	M	70	62	70	69	74	61	180	136	85	71	93	74
	σ		14.0	6.7	8.4	8.2	3.1	27.4	45.9	4.4	6.3	13.3	8.5
Pchelka	M	86	119	88	86	74	71	80	77	80	66	60	67
	σ	19.7	11.1	12.9	10.3	13.4	7.7	8.1	8.9	—	—	—	—
Mushka	M	83	120	168	117	104	100	93	94	106	80	95	87
	σ	21.6	8.7	23.6	8.0	7.1	5.3	13.1	14.2	—	—	—	—

Note: M, arithmetic mean; σ, root mean deviation.

TABLE 29

CHANGE IN CERTAIN ELECTROCARDIOGRAM INDICATORS OF DOGS DURING LONG STAY UNDER WEIGHTLESS CONDITIONS (average data)

Name of Dog	EKG Parameter	Initial Prelaunch Data		Weightlessness (Orbits)									
		4 hrs	5 min	2	3	4	5	6	7	1[illegible]	1[illegible]	1[illegible]	16
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Strelka	P—Q, c	0.11	0.15	0.11	0.11	0.11	0.10	0 10	0.09	0.09	0.08	0.10	0.10
	Q—T »	0 25	0.43	0.25	0.24	0.23	0.24	0.23	0.25	0.25	0.25	0.22	0 2[illegible]
	P_1, **rel units**	—	—	0,19	0.18	0.20	0.21	0.18	0.20	0.21	0.19	0.18	0.1[illegible]
	R_1 » »	—	—	1,02	1.01	0.83	0,99	0.99	0.85	0.98	0.91	0.89	0.[illegible]
	T_1 » »	—	—	0.11	0 14	0 13	0.17	0.13	0.13	0.23	0.17	0.18	0.12
	Sys Ind, %	34	43	28.5	28.5	28.9	30.9	33.9	48.1	50.9	4[illegible].1	43.0	3[illegible].0
Belka	P—Q, c	0.10	—	0.10	0.11	0.11	0.09	0.07	0.09	0.07	0.08	0.09	0.09
	Q—T »	0.31	0.26	0.27	0.30	0.29	0.25	0.22	0.25	0.28	0.27	0.23	0.24
	P_1, **rel units**	—	—	0 13	0.15	0.17	0.14	0.10	0.13	0.15	0.12	0.15	0.14
	R_1 » »	—	—	0.49	0.48	0.50	0.41	0.24	0.51	0.48	0.41	0 49	0 47
	T_1 » »	—	—	0.33	0.29	0 25	0.23	0.10	0.25	0.23	0.15	0.22	0 22
	Sys Ind, %	36	51	31,7	35.7	37.4	25.8	62.3	30 9	39 0	32.6	36.0	29 0
Pchelka	P—Q, c	0.13	0 12	0.13	0.10	0.14	0.13	0.10	0 11	0.09	0 13	0.14	0.12
	Q—T »	0.20	0.18	0 21	0.20	0.21	0.20	0.21	0.22	0 20	0.22	0.22	0 22
	P_1, **rel units**	—	0.15	0 16	0 36	0.22	0 17	0.40	0.24	0 1	0.1	0.1	0.2
	R_1 » »	—	0.35	1,23	2 67	1.6	1.23	3.1	1.79	1.0	1 2	1.5	1.[illegible]
	T_1 » »	—	0.33	0 18	0 44	0 27	0.33	0.7	0.34	—	—	—	—
	Sys Ind, %	27.7	36.5	31.0	29.0	26.0	23 5	27.6	27.0	27.6	24.0	22.0	25.[illegible]
Mushka	P—Q, c	0 11	0.10	0.08	0.10	0.10	0.11	0.10	0.10	0.10	0,10	0.10	0 10
	Q—T »	0.25	0.24	0.20	0.23	0.23	0.23	0 24	0.24	0.23	0.24	0.26	0.24
	P_1,	—	0 13	0.10	0.10	0.11	0.12	0.10	0.10	0.10	0,10	0.10	0.10
	R_1 » »	—	0.70	0.75	0.68	0.56	0.56	0.72	0.68	0.5	0.68	0.5	0 [illegible]
	T_1 » »	—	0.35	0.47	0.33	0.28	0.27	0.34	0.38	—	—	—	—
		33.8	47.6	56.9	44,9	40 2	39.0	35.6	37.8	38.0	34 0	40.5	[illegible]

In subsequent launches of space satellites with animals aboard, a great amount of biomedical information was obtained. Some data on the physiological reactions of the experimental animals are presented in Tables 29 and 30. Analysis of the material shows that changes in the time parameters of the EKG and pulse rate are mutually correlated. In those cases when there is a quickening of the pulse, shortening of the P-Q and Q-T intervals is observed, and vice versa. In nearly all the animals, during the stay under weightless conditions, the pulse and electrocardiogram, initially changed, then approached the initial values: quite rapidly in some, slowly in others (by the 2nd orbit around the earth for Strelka and Pchelka, in the 1st by Belka and in the 14th by Mushka). /96

The instability of the pulse rate should be noted in all experimental animals; it was retained to the end of the stay under weightless conditions. Considerable quickening of the pulse was observed in Belka and Strelka, during the 7th and 13th orbits around the earth. V. V. Parin and colleagues (1962) explain this by periodic, wavelike shifts in the sympathetic and parasympathetic

TABLE 30

CHANGE IN CERTAIN PHYSIOLOGICAL INDICATORS OF DOGS DURING THEIR STAY UNDER WEIGHTLESS CONDITIONS FOR ABOUT AN HOUR (average data)

Name of Dog	Physiological Indicator	Initial Prelaunch Data		Periods of Weightlessness		
		4 hrs	5 min	H-1	H-2	H-K
Chernushka	Pulse rate, beat/min	127	147	135	136	101
	$P-Q$, c	0.06	0.10	0.10	0.08	0.11
	$Q-T$ "	0.24	0.18	0.18	0.21	0.21
	P_1, rel units	—	0.23	0.30	0.25	0.27
	R_1 " "	—	0.90	1.33	[illegible]	1.61
	T_1 " "	-	-0.37	−0.26	[illegible]	−0.32
	Sys. Ind., %	—	44.0	42.0	[illegible]	35.0
Zvezdochka	Pulse rate, beat/min	—	93.0	138	102	—
	$P-Q$, c	0.06	0.10	0.09	0	—
	$Q-T$, c	0.26	0.22	0.19	0.23	—
	P_1, rel units	—	0.40	0.36	0.43	—
	R_1 " "	—	1.96	1.78	1.83	—
	T_1 " "	-	0.38	0.42	0.38	
	Sys. Ind., %	--	[illegible]	[illegible]	[illegible]	-

Note: H-1, first 5 min; H-2, second 5 min; H-K, final 5 min of flight under weightless conditions.

effects, caused by change in afferentation. In this case, the increase in pulse rate also may be connected with the diurnal rhythm. As is known, the 6th and 7th orbits corresponded to the end of one day and the 13th and 14th orbits to the start of another. Analysis of the EKG amplitude parameters was the most difficult. In six dogs, the P_1-spike amplitude in the weightless state increased in one (Zvezdochka), increased in four and was practically unchanged in one (Strelka). The R_1-spike voltage increased in Chernushka and Pchelka, decreased in Zvezdochka, Strelka and Mushka and was unchanged in Belka. The direction of the change in T_1-spike amplitude was still more indeterminate. It increased in two dogs (Zvezdochka, Strelka), decreased in Chernushka and Belka and was unchanged in Pchelka and Mushka. These differences are explained to a certain extent, by the individual singularities of the higher regulating mechanisms of the vegetative functions of the animals and the singularities of the telemetry. As is well-known, discrete recording of the EKG increases the error in determination of the amplitudes, especially of the P- and R-spikes, the more so that the recording quality frequently decreases, because of imposition of muscle biocurrents, generated by movements of the animals. During the orbital flights of Belka and Strelka, arterial pressure and phonocardiograms were recorded. Analysis of the data obtained shows that the arterial pressure decreased under weightless conditions, as a rule; however, there were periods when it increased. Thus, the arterial pressure of Strelka directly before the flight was 140/51 /97 mm Hg, 96/34 mm Hg during the 4th orbit around the earth and 112/31 mm Hg on the 14th orbit. A weakening of tones I and II of the heart was noted in this dog under weightless conditions although, in the prelaunch examinations, the phonocardiogram was normal for this species of animal (V. V. Antipov, et al., 1962).

It could be concluded from the materials obtained during the /98
long stay of the animals under weightless conditions, that research with human participation was possible. As is well known, 25 men in the USSR have completed orbital space flights at the present time; three of them have flown twice, and V. A. Shatalov and A. S. Yeliseyev, three times.

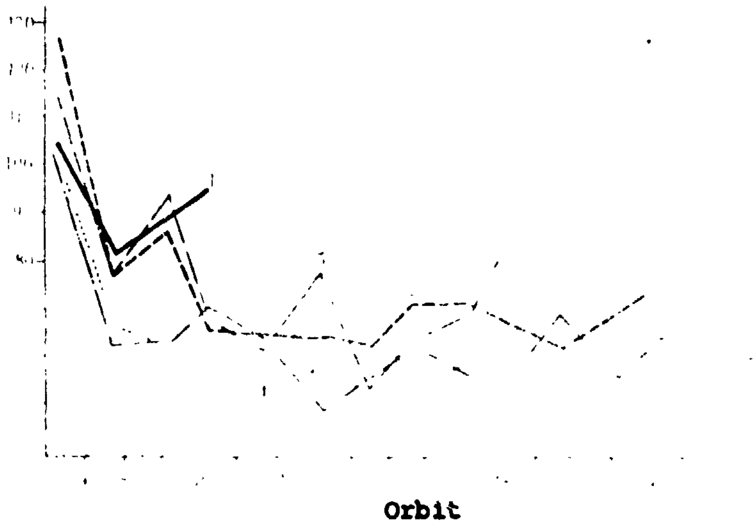

Fig. 3. Pulse rate at individual stages of flight under weightless conditions, of astronauts G. S. Titov (1), A. G. Nikolayev (2), V. F. Bykovskiy (3), P. R. Popovich (4) and V. V. Tereshkova (5).

Some indicators of the functional state of the cardiovascular systems of the astronauts during space flights are presented in Figs. 3-7. In a previously published work, we described the dynamics of change in these indicators (V. I. Yazdovskiy, et al., 1964). Here, we only note the direction of these changes. Thus, the pulse rate gradually decreased under weightless conditions (see Fig. 3), and it became equal to the initial (examination day several days before launch) and, frequently, even below it. In almost all cases, /99
a definite instability of this indicator was noted. In short intervals of time (without any evident cause), the pulse rate fluctuated by 10-15 beat/min and more. This was especially pronounced in G. S. Titov, P. R. Popovich and V. V. Tereshkova. It might be thought that the effect of tonus of the vagus nerve, which becomes predominant, increases under orbital flight conditions. In an analysis of the

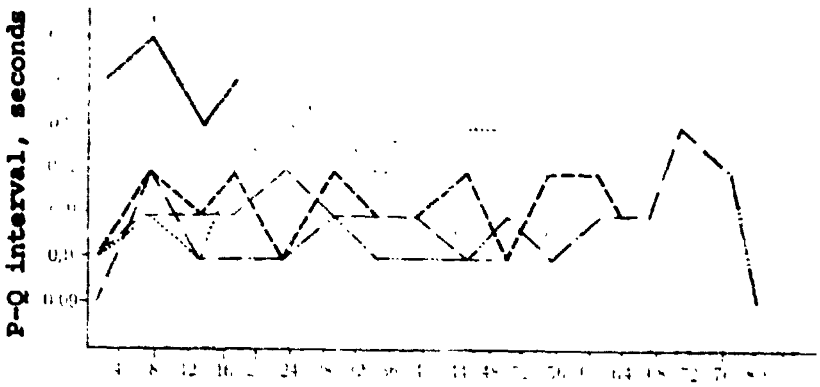

Fig.4. Change in P-Q interval of EKG of astronauts: de:.gnation same as in Fig. 3

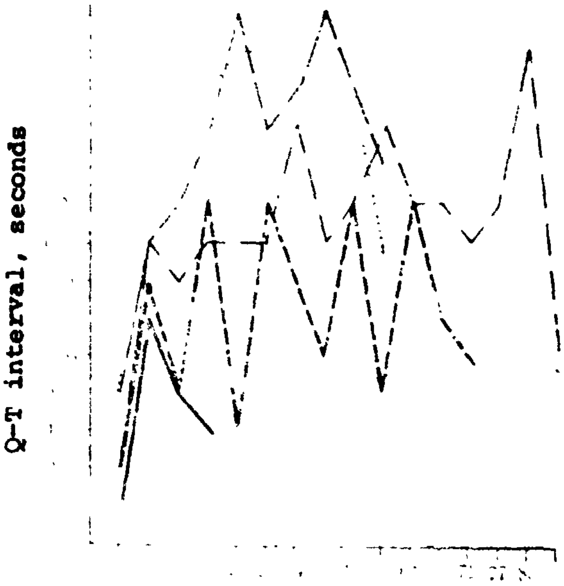

Fig. 5. Change in Q-T interval of EKG of astronauts: designation same as in Fig. 3

variability of the R-R interval, it was shown that the difference of the maximum and minimum R-R interval (in 100 cardiac sets) approached the values, characteristic of the sleep period on earth when the vagus effect is most pronounced (R. M. Bayevskiy, K. I. Zhukov, 1964; P. V. Vasil'ev, et al., 1965). We also noticed a tendency of the heartbeat toward an appreciable reduction (analyzed by orbit of each flight) in A. G. Nikolayev and V. N. Volkov, during the second flight (Fig. 8), as well as in V. A. Shatalov and A. S. Yeliseyev in the last two flights. This indicates adaptation of the body to the state of weightlessness.

Judging from the general nature of the changes, the regulatory fluctuations of the cardiovascular system will smooth out, in all likelihood, in proportion to adaptation of the man to weightless conditions. Two types of reactions were revealed in study of the blood pressure. The first type is characterized by some increase in systolic and diastolic pressure, both in the state of rest and after completion of a measured physical workload, and a noticeable decrease in systolic and diastolic pressure was inherent in the second type of reaction. Thus, with astronauts V. A. Shatalov, V. V. Gorbatko, A. S. Yeliseyev and V. N. Kubasov, in 18 measurements after complet-

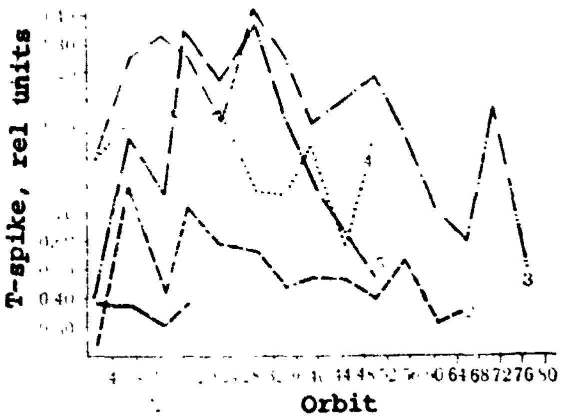

Fig. 6. Change in T-spike amplitude on EKG of astronauts: designations same as in Fig. 3

ing various flight program operations and in 13 measurements in the state of rest, the systolic pressure was increased by 12-28 mm Hg and, in 9 measurements, the diastolic pressure turned out to be increased by 10-20 mm Hg over the average data in the preflight period (Fig. 9). For astronauts A. V. Filipchenko, G. S. Shonin and V. N. Volkov, both in the state of rest and after completion of measured physical /101
workloads, an appreciable decrease was noted in the systolic and diastolic pressure, especially on the 4th and 5th days of the flight (Fig. 10).

Studies carried out during the 18-day flight of the Soyuz 9 spacecraft showed that the blood pressure level of V. I. Sevast'yanov in the state of rest was close to the preflight level. Some increase in systolic pressure, beginning with the 47th orbit of the flight, was observed in A. G. Nikolayev. It increased especially noticeably after performing a measured workload and physical exercises, compared with similar workloads under ground conditions. The arterial pressure of the American astronauts F. Borman and D. Lovell also increased somewhat, after normal physical exercises under weightless conditions, remaining at the 130/70 mm Hg level on the average (Berry, 1966).

Studies performed during the 24-day flight of the Salyut orbital station disclosed that the blood pressure level (measured with the Krasnogvardeyets plant tonometer by the astronauts themselves) of G. T. Dobrovol'skiy and V. N. Volkov in the state of rest was

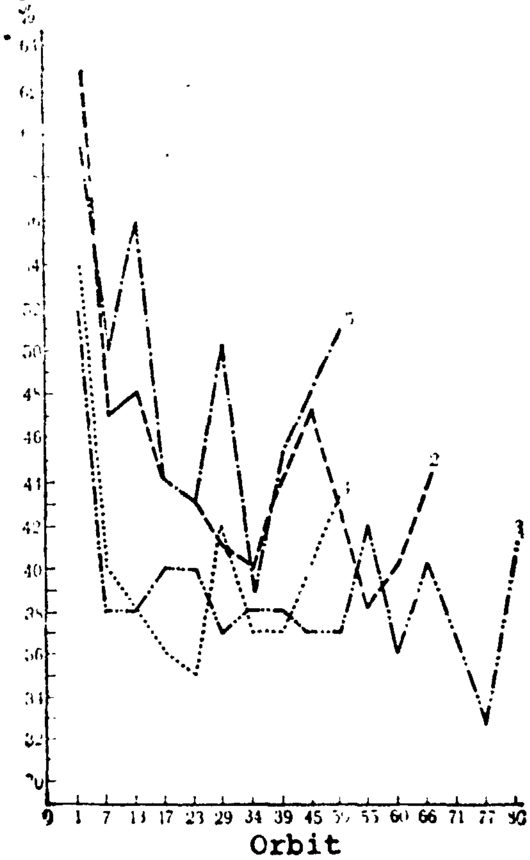

Fig. 7. Change (in percent) of systolic index of astronauts: designations same as in Fig. 3

close to the preflight level (Fig. 11), and some increase in systolic pressure was observed in V. I. Patsayev on the 16th day of the flight. Some increase in pulse pressure, an increase in systolic and a small decrease in diastolic pressure, compared with the preflight level, was characteristic of the Soyuz 9 and Salyut crews in the 18- and 24-day flights. Individual elements of the electrocardiogram changed in various ways: The Q-T interval was shortened /102 at the beginning and end of the weightless period and somewhat lengthened in the middle of it (see Fig. 5), the P-Q interval changed approximately the same way, but less distinctly (see Fig. 4); the T-spike amplitude increased in proportion to the stay under

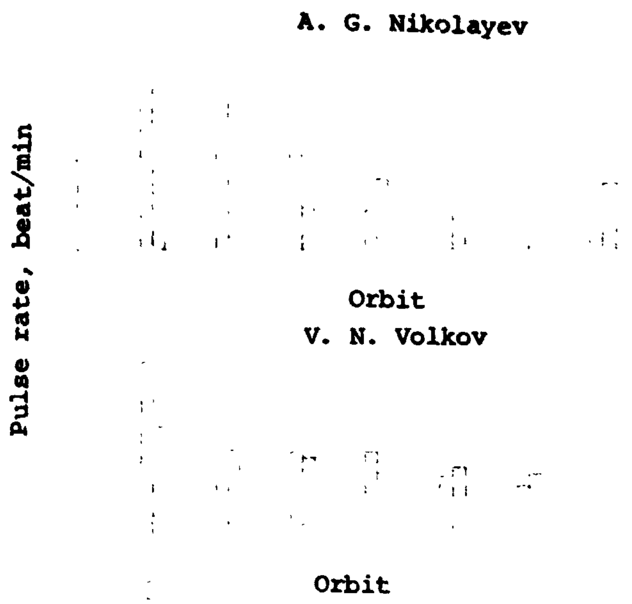

Fig. 8. Pulse rate of astronauts A. G. Nikolayev and V. N. Volkov during 1st (1) and 2nd (2) orbital flights

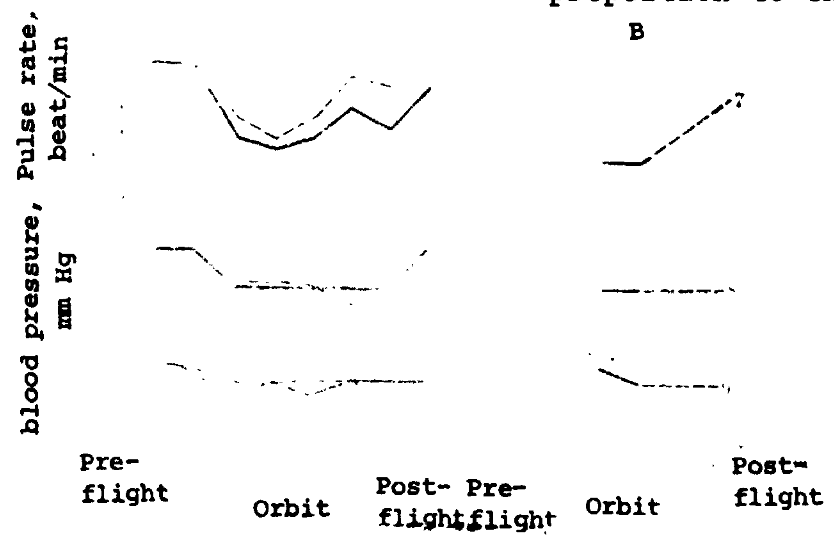

Fig. 9. Pulse rate and blood pressure of V. A. Shatalov before, during and after orbital flight: A, before and during physical loading; B, 2 min after completion of measured physical workload; 1) pulse rate before physical load; 2) pulse rate 15 sec after completion of measured workload; 3-4) blood pressure before workload; 5-6) blood pressure 15-20 sec after load; 7) pulse rate 2 min after completion of functional test; 8-9) blood pressure 2 min after load

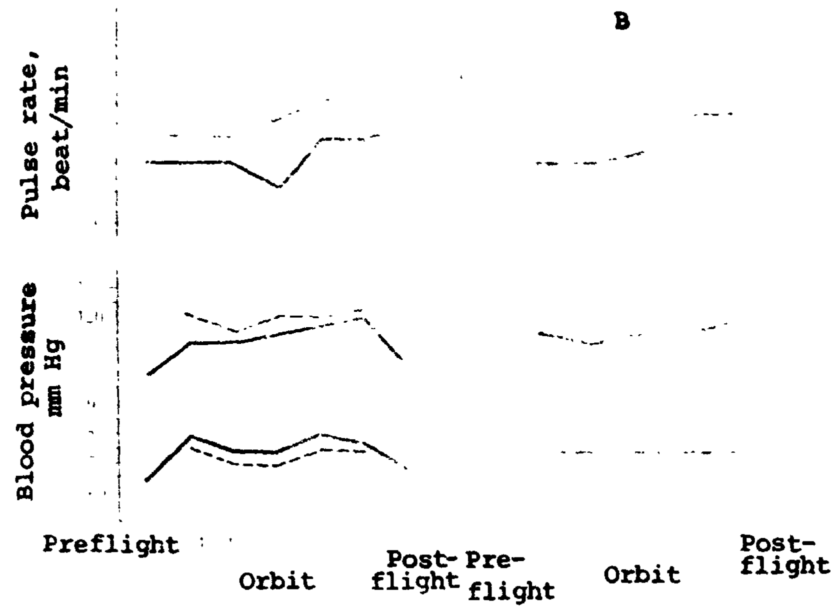

Fig. 10. Pulse rate and blood pressure of G. S. Shonin before, during and after orbital flight: A, before and during physical loading; B, 2 min after completion of workload; 1) pulse rate in state of rest; 2) pulse rate 15 sec after completion of physical workload; 3-4) blood pressure in state of rest; 5-6) blood pressure 15-20 sec after completion of workload; 7) pulse rate 2 min after functional test; 8-9) blood pressure 2 min after workload

weightless conditions, being reduced at the beginning and end of it (see Fig. 6). The systolic index gradually decreased (see Fig. 7). The data presented in these figures indicate large fluctuations in the indices studied.

The mechanical function of the heart (kinetocardiogram and seismocardiogram) was studied in astronauts G. S. Titov, V. F. Bykovskiy and V. V. Tereshkova in flight. It was found that it did not change significantly (N. M. Sisakyan, V. I. Yazdovskiy, 1962), although there were some deviations: a negligible increase in mechanical systole, reduction in amplitude indices, etc.

Data on the state of the blood circulation under conditions of prolonged weightlessness, obtained after the flights of Soyez 9 and Salyut (for more detail, see following sections of this chapter), /103 coincide to a great extent, with the results of studies carried out on animals and on people under brief weightlessness, during aircraft flights along the Kepler parabola. It can be concluded from the material obtained that the blood circulation of man, when staying

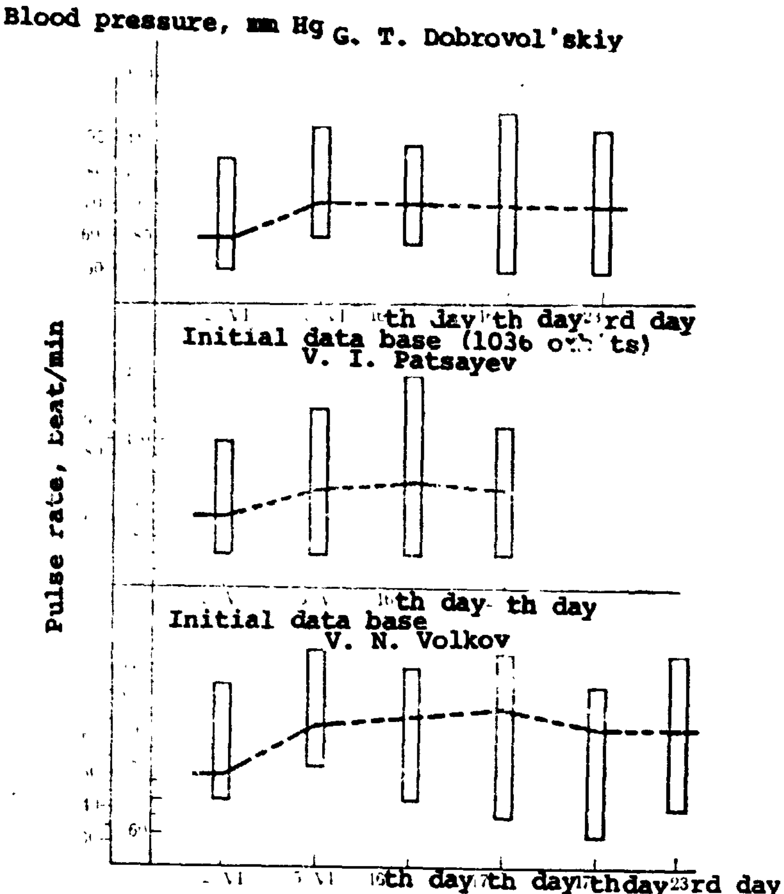

Fig. 11. Pulse rate (curve) and blood pressure (columns) of astronauts G. T. Dobrovol'skiy, V. I. Patsayev and V. N. Volkov before and during orbital flight in Salyut space station

under weightless conditions for a period of 18-24 days of flight, is not significantly disturbed; however, there are some peculiarities in the functioning of the cardiovascular system under these conditions: a reduction in the heart rate, change in the blood pressure level a slow recovery of some indicators (pulse rate, respiration, etc.) to the initial level under weightless conditions, after the powered phase of the flight.

Up to the present time, the physiological mechanisms of the effect of weightlessness on animal and human bodies still has not been completely studied. Thus, Stutman and Olson (1960) found that, during brief weightlessness in parabolic flights, the blood pressure decreases and the return of venous blood decreases. Burch and Gerathewohl (1960) evaluate this phenomenon as a functional adaptation of the heart to decreased mechanical load. Graybiel and colleagues (1959) attempt to explain the reduction in pulse of monkeys under weightless conditions by fright of the animals, in which slowing down of the cardiac contractions and dilation of the vessels can take place. One can scarcely completely agree with this, since this reaction is retained for a long time (hours, days) under weightless conditions and, mainly, it is observed in both animals and man.

Experimental data and data in the literature permit the thought of direct and mediated effects of weightlessness on the blood circulation (see Chapter 1, section 3). We understand the direct action to be the entire set of reactions, caused by the considerable decrease in hydrostatic pressure of the blood. As a result, the blood pressure (arterial and venous) decreases, accumulation of blood takes place in the veins, venous outflow from the upper parts of the body apparently is hindered, etc. The latter may entail a relative increase in intracranial pressure and, consequently, an increase in tonus of the parasympathetic nervous system, with all the consequences flowing from it: a decrease in pulse rate, decrease in blood pressure, etc. Accumulation of blood in the veins, in turn, also is a powerful stimulus of the vascular receptors, which slow down the heart activity and increase the tonus of the vagus nerve by reflex.

We understand the mediated effect of weightlessness on blood circulation to be the entire set of cardiovascular reactions, arising as a result of disturbances of the functional system of the analyzers (proprioceptive, cutaneomechanical, interoceptive, visual, vestibular), participating in analysis of the spatial relationship and in placing the body in space (G. L. Komendantov, 1959, and others). It is known that balancing of the body is accomplished, by means of adjusting reflexes, the most ancient reflex reactions, counteracting the force of gravity (G. L. Komendantov, 1963, and others). The adjusting reflexes change under weightless conditions (V. I. Yazdovskiy, et al., 1960), since the afferentation from all mechanoreceptors changes significantly. The change in adjusting reflexes unavoidably affects the vegetative component, primarily, the blood circulation function. The considerable fluctuations of some vegetative indices (pulse, etc.) becomes understandable. The question arises, as to the importance of the mechanisms of the effect of weightlessness on the body, both /104
direct and mediated. Apparently, with immobilization of a man under these conditions, the first mechanism is determinative. In the unfixed situation, in the state of free "floating," the second mechanism will be predominant, in all likelihood, since changes in the motor component of the adjusting reflexes are more pronounced in this case, and the vegetative component changes accordingly.

The unusual afferentation from the vestibular analyzer apparently is of great importance in the genesis of vegetative disturbances. According to some data (Ye. M. Yuganov, 1963; G. I. Pavlov, 1963; Beckh,et al., 1953, 1954; Schock, 1961, and others), the vegetative reactions are expressed to a lesser extent by labyrinthectomized animals under weightless conditions. G. L. Komendantov and V. I. Kopannev (1962) consider that the visual and vestibular analyzers have the main role in spatial orientation under ground conditions and only the visual, in weightlessness.

Analysis of experimental material, obtained during the stays of the astronauts under weightless conditions, shows that the pulse becomes slower and the blood pressure decreases, sometimes below the level recorded on earth. However, a definite dependence of decrease in the cardiovascular system function on stay time under weightless conditions could not be established. This apparently is because the body always attempts to maintain the vegetative functions at a level sufficient for normal activity of the major organs. As have been established by a number of authors, the blood pressure decreases by not more than 10-15 percent, for this reason, and, moreover, the nervous-emotional excitation, which causes an increase in blood pressure and speeding up of the pulse is extremely important.

As has already been pointed out, some adaptation to the unusual conditions develops, in proportion to the stay in the state of weightlessness. The physiological basis of this adaptation apparently is formation of a new functional system in the work of the analyzers, participating in analysis of the spatial relationships and in placing the body in space. In this case, consolidation of the vegetative component takes place after its formation, at a level, which is adequate for the new conditions. Nevertheless, it should be kept in mind that the new system is unstable, and that the possibility is not excluded of disturbance of it by the action of unfavorable factors: fatigue, temperature effects, etc. This must be taken into consideration in organization of the work and rest of people, during a long stay under weightless conditions.

It can hardly be expected that these disturbances will develop, under conditions of prolonged weightlessness. However, they can arise in people, who are already adapted to weightlessness, when they return to earth.

There already are some experimental data (Beckh, 1958, 1959; I. I. Kas'yan, V. I. Kopanev, 1963, and others), indicating that adaptation may not set in under the prolonged effect of weightlessness, but, on the contrary, the vestibular-vegetative effects will increase in the fourth period, especially in persons who are not resistant to the effect of weightlessness. The necessity arises from this of continual improvement in the methods of selection of astronauts, training of them, and also development of prophylactic agents, directed towards increasing the resistance of the body to the harmful effect of prolonged weightlessness (Chapter 6 of this book is devoted to /105
this problem). In connection with this, the proposal of Gerathewohl and Ward (1960), on prophylaxis of venous congestion, is interesting. In the opinion of these authors, a unit is required, in which moderate squeezing of the foot muscles is accomplished. We also consider a suit, with a vibrating device, encompassing the upper and lower extremities, to be useful. As a result of periodically turning it on, the overall tonus of the muscles would be increased and movement of the blood toward the heart would be facilitated. Biostimulation of the muscles would apparently be effective.

Investigators have attempted to explain the unusual slowness of recovery of the pulse rate to the initial values, of men and animals, during their stay under weightless conditions, by the contrast effect, after the body enters another state from one state (V. N. Chernov, V. I. Yakovlev, 1958; Gerathewohl, Ward, 1960, and others). We think that, moreover, slowing down of adaptation of the cardiovascular system is caused by the time for formation of the new functional system of the analyzers, participating in placing the body in space, as well as by hormonal shifts. As is well-known, the launch of a spacecraft, g-forces and weightlessness are strong biological stimuli. In this case, a large quantity of humoral substances is discharged into the blood, which apparently has a considerable effect, preventing rapid recovery of some indicators to the initial values.

2. Some Results of Medical Studies of Voskhod 2 Spacecraft Crew Members

N75 23116

The first exit of a man from a spacecraft into space was accomplished at 11 hours 37 min 18 March 1965. The flight was performed in the Voskhod 2 spacecraft. The spacecraft commander was pilot-astronaut P. I. Belyayev and the second pilot, pilot-astronaut A. A. Leonov. The basic tasks of the flight were to test the designs of provision for exit of man from the craft, to determine the possibilities of movement and work of an astronaut in unsupported space, to carry out medical monitoring of the state of the astronauts in performing extravehicular activity and the subsequent day-long flight and to monitor the radiation situation.

In distinction from previous designs, Voskhod 2 had an airlock chamber and a system, providing for movement from the sealed cabin into open space. The air regeneration and conditioning system was fundamentally the same as that installed in Voskhod (A. M. Genin, G. I. Voronin, A. G. Fomin, 1965).

Training of the astronauts, with the exception of training exercises in movement and work in unsupported space, was the same as before the preceding flight (Ye. A. Karpov, 1966). The medical monitoring system and procedures under flight conditions were described earlier in a number of publications (O. G. Gazenko, A. A. Gyurdzhian, 1965). An addition to the medical monitoring system was the control panel of the spacecraft commander, to which data was furnished on heart and respiration rate of the astronaut outside. This permitted more careful control of the actions and work of the pilot outside. An important feature also was that both pilot-astronauts were trained in the conduct of medical tests and successfully accomplished them in flight.

Clinical-physiological examination of the astronauts before and after the flight were carried out by the same scheme as in the preceding flights. Research has shown that the radiation dose during /106 the flight and the extravehicular activity, taking the RBE into account, was not over 0.3 rem. This dose could not have a harmful effect on the health of the astronaut (Yu. M. Volynkin, et al., 1966). The results of study of biological subjects aboard the spacecraft and in the spacesuit of A. A. Leonov during the extravehicular activity confirmed this (V. N. Zhukov-Verezhnikov, et al., 1966).

The correct schedule for taking food and water was of great importance, for a positive emotional state of mind, feeling well and high efficiency of the astronauts in flight, the more so, that the extravehicular activity of A. A. Leonov required additional energy expenditures. In connection with this, the daily food ration was set at 3250 kcal, vs. 2530-2770 kcal in the flights of the Vostok and Voskhod craft. On the day before launch, both astronauts received food similar to that onboard. The eating schedule was the same as recommended in flight: 4 times a day, with 4-5 hour intervals in the daytime and 7-8 hours at night. Since the interval between breakfast on earth and the first meal in flight could be 8 hours, breakfast on the launch day was increased to 1000 kcal. Moreover, after putting on the spacesuits, 1-1/2 hours before launch, the astronauts ate a chocolate bar and drank juice from a tube (about 250 kcal).

During the flight, the astronauts had to receive about 140 g of protein, 115 g of fat and 388 g of carbohydrates with the food. The daily ration contained 4 mg each of vitamins B_1, B_2 and B_6 and 100 μg of vitamin B_{12}, 4 mg of folic acid, 20 mg of pantothenic acid, 200 mg of vitamin C, 30 mg of vitamin PP, 100 mg of vitamin P, 2 mg of vitamin A and 50 mg of vitamin E. The selection of foodstuffs included natural, cooked foodstuffs, packed in film packages or tubes. The daily water standard was increased to 2 l, vs. 1.25 l of the Voskhod crew. Moreover, the astronauts could obtain about 878 g of water with juices and foodstuffs.

In selecting the time for eating, the astronauts were governed to a considerable extent by the situation and appetite. They drank little water, although P. I. Belyayev noted increased thirst, which he connected with the specific food ration. The astronauts had no feelings of discomfort in the gastrointestinal tract during the flight. Upon completion of the flight, the onboard food ration was evaluated as adequate by the astronauts.

Analysis of the nitrogen metabolism indices can give an additional idea of the effectiveness of the food ration and of the metabolism in the bodies of the astronauts during the flight. On the 2nd-3rd day for the flight, a total nitrogen content in the daily urine was 11.5-13.6 g for P. I. Belyayev, and 12.4-13.8 g for A. A. Leonov. Two days after the flight, a somewhat larger amount of total nitrogen was found in the daily urine of the astronauts: 16.9 g for P. I. Belyayev and 14.7 g for A. A. Leonov. Recalculated to protein, this total nitrogen level corresponded after the flight to 105.6 g for P. I. Belyayev and 91.2 g for A. A. Leonov. If the values presented are compared with the protein content in the food ration of the astronaut (around 140 g), it can be concluded that the food had an adequate protein content. Some increase in nitrogen excretion with the urine after the flight may be explained by the active activity of the astronauts and the nervous-emotional stress, which is in accordance with the increase in activity of the adrenals and with an increase of adrenalin, noradrenalin, 17-oxy- and 17-ketosteroid, as well as creatinine content in the urine. The creatinine coefficient of P. I. Belyayev increased after the flight from 29 to 36 and from /107
24 to 32, for A. A. Leonov. (The results of the biochemical studies

TABLE 31

BLOOD PRESSURE, PULSE AND RESPIRATION RATE OF ASTRONAUTS BEFORE AND AFTER ORBITAL FLIGHT IN VOSKHOD 2 SPACECRAFT

Astronaut	Indicator	Preflight				Postflight		
		6 Mar	14 Mar	17 Mar	18 Mar	21 Mar	[illegible] Mar	17 Apr
P. I. Belyayev	Pulse, beat/min	64	64	60	60	80	56	64
	Respiration, cycle/min	8	—	10	10	10	—	—
	Blood pressure, mm Hg	100/65	100/70	100/65	100/70	115/80	105/70	105/70
A. A. Leonov	Pulse, beat/min	56	56	52	60	72	56	60
	Respiration, cycle/min	12	—	10	10	12	—	—
	Blood pressure, mm Hg	115/65	110/65	115/70	115/70	120/50	115/65	110/65

Note: Materials of V. G. Terent'yev, A. V. Nikitin, and others were used in compiling the table.

TABLE 32

CHANGE IN CERTAIN EKG INDICATORS OF P. I. BELYAYEV AND A. A. LEONOV AT 5 MIN READINESS AND AT START OF WEIGHTLESSNESS

Astronaut	Indicator	Statistical Index	Prelaunch min		Start of Weightlessness, min				
			−5	−1	1	2	3	4	5
P. I. Belyayev	Pulse rate, beat/min	M	83	78	92.3	88.2	103.4	122.4	111 1
		σ	6.89	6 93	8,95	8.03	9.82	14 08	17.33
		C	8.3	9 0	9,7	9.1	9.5	11 5	15.6
A. A. Leonov	Same	M	82	80	103 4	88.2	90.9	90 9	109 1
		σ	7,7	8.3	8.55	8.49	6.27	7.27	8.73
		C	8.7	9.2	8,27	10.2	6 9	8,0	8.00
P. I. Belyayev	Duration of ventricular complex, Q-T	M	0.33	0,34	0.32	0.32	0.31	0 29	0.29
		σ	0.011	0 012	0 010	0.013	0.012	0.027	0.018
		C	3 3	3.6	3.13	4.04	3 86	9,34	6.09
A. A. Leonov	Same	M	0.34	0 34	0.32	0.34	0 34	0.34	0.32
		σ	0,012	0.012	0 016	0 016	0 010	0 009	0.017
		C	3 4	3.5	4 8	4.6	2 9	2.7	5.3

Note: In this table and in Table 33, M is the mean value, σ is the root mean deviation and C is the coefficient of variation.

are presented, from the data of I. S. Balakhovskiy, T. A. Orlova, et al.)

The body weight of the astronauts did not change significantly after the flight. In an examination of P. I. Belyayev on the 2nd day, it was reduced by 1 kg from the preflight and by 0.9 kg for A. A. Leonov. The astronauts had approximately the same weight loss, during ground development of the extravehicular activity program, under conditions of a rarefied atmosphere: by 0.6 kg for P. I. Belyayev and by 0.9 kg for A. A. Leonov. In the preceding flight in the Voskhod craft, the body weight of the astronauts decreased by 2.5-3 kg in the first days, compared with the initial weights.

The specific gravity of the urine of P. I. Belyayev and A. A. /108
Leonov was much increased, in an analysis two days after the flight. A small increase in the amount of sodium and chlorine eliminated with the urine of A. A. Leonov, as well as an increase in the amount of mucus and the appearance of casts, was noted.

In a hematological examination during the prelaunch period, an /109
increase in number of lymphocytes was found in both astronauts: from 30 to 36.5% in P. I. Belyayev and from 21.5 to 37.5% in A. A. Leonov. The total number of leukocytes increased to 8400-8800 cells per mm^3. A similar change in white cells was observed in other /110
astronauts, in an examination at the launch. These changes can be explained by general stress reactions of the body.

As a result of postflight examination of P. I. Belyayev and A. A. Leonov, a moderate increase in number of leukocytes was found (8400-9000 cells per mm^3). The blood composition and other hematological indicators were normal. The content of sugar, chlorine and cholesterol in the blood did not differ from the preflight level.

The astronauts felt well during the prelaunch period, frame of mind was elevated, and both astronauts actively participated in the flight preparations. The pulse rate of P. I. Belyayev was 60-64 beats per minute in the morning hours, and respiration rate was 8-10 cycles per minute. The maximum blood pressure was 100 mm Hg and the minimum, 65-70 mm Hg. During this time, the pulse rate of A. A. Leonov was 52-60 beats per minute, respiration rate 10-12 cycles per minute; maximum blood pressure 110-115 mm Hg, minimum 65-70 mm Hg, and pulse pressure 45-50 mm Hg (Table 31).

In the 5-minute readiness period, the astronauts remained outwardly peaceful, but the heart rate increased: to 83 beats per minute for P. I. Belyayev and to 82 beats per minute for A. A. Leonov, and the respiration rate increased to 18 and 20 cycles per minute, respectively. Compared with preceding astronauts, the changes in pulse and respiration rate of P. I. Belyayev and A. A. Leonov were moderate. The root mean deviation and coefficient of variation of certain EKG indicators also changed comparatively little as the launch approached (Table 32).

TABLE 33

HEART AND RESPIRATION RATES OF ASTRONAUTS IN PREFLIGHT PERIOD AND UNDER ORBITAL FLIGHT CONDITIONS

Astronaut	Statistical Index	Prelaunch Period (5 min readiness)	Orbital Flight (orbits)												
			1	2	3	4	5	6	7	13	14	15	16	17	18
Heart rate, beat/min															
P. I. Belyayev	M	83	105	90	84	76	84	79	73	77	87	97	90	94	111
	σ	6.89	16.2	10.2	8.48	8.51	7.56	7.9	6.57	6.93	6.96	12.6	11 7	11.3	10
	C	8.3	15.4	11.3	10.1	11.2	9.0	10	9.0	9.0	8.0	13.0	13.0	12 0	9.0
A. A. Leonov	M	82	100	118	60	64	70	70	54	70	77	71	73	75	86
	σ	7.7	8.2	5.9	5.8	8.6	6.5	7.0	5.3	9.9	10.8	9.3	9.8	8.4	8.6
	C	8.7	8.2	5.0	9.6	13.4	9.3	10	9.8	14.1	14.0	13.1	13.4	11.2	10.0
Respiration rate, cycle/min															
P. I. Belyayev	M	17.7	21	22	18	18.5	18.6	17.6	14.0	18.8	18.8	18.2	18 5	15.8	76.6
	σ	4.42	7.35	7.48	7.74	6 68	6.51	6.69	5.18	7.52	7.90	8.55	7.40	6.16	6 18
	C	25	35	34	43	36	35	38	37	40	42	47	40	39	35
A. A. Leonov	M	20	24	22	18	17	18	[illegible]	14	18	20	18	19	18	20
	σ	6.70	6.91	8.14	3.76	5.78	6.30	4.75	4.62	4.32	6.60	4.32	5.32	5.94	5.40
	C	33.5	28.8	37	32	34	35	25	33	24	33	24	28	33	27

TABLE 34

CERTAIN EKG INDICATORS OF ASTRONAUT A. A. LEONOV IN PRELAUNCH PERIOD AND DURING EXTRAVEHICULAR ACTIVITY (2nd orbit of flight)

Indicator	Pre-launch Period	Time in Open Space, min																		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Auricular-Ventricular Conductivity (P-Q), sec	0.14	0.15	0.16	0.15	0.16	0.16	0.20	0.20	0.17	0.18	—	0.17	0.18	—	—	0.18	0.18	0.17	0.18	—
Duration of Ventricular Complex (Q-T), sec	0.34	0.38	0.37	0.36	0.34	0.33	0.32	0.32	0.31	0.31	0.32	0.33	0.33	0.32	0.33	0.40	0.4[illegible]	0.41	0.42	0.41
Duration of R-R Interval sec	0.69	0.56	0.45	0.45	0.41	0.39	0.39	0.40	0.39	0.39	0.39	0.39	0.40	0.37	0.38	0.44	0.51	0.56	0.66	0.59
Systolic Index, %	49.3	68.0	82.3	80.0	83.0	84.5	82.0	80.0	79.5	79.5	82.0	84.5	82.5	86.5	86.8	91.0	80.5	73.0	63.5	69.5
EKG-spike Height, mm:																				
R	9.9	10.2	9.8	8.3	9.9	9.8	10.5	10.0	8.6	9.2	—	8.0	8.4	—	—	12.5	12.3	12.0	12.5	—
T	3.4	2.7	4.1	4.7	3.6	3.8	4.7	4.3	3.8	4.4	—	—	4.7	—	—	4.9	4.3	3.3	4.0	—

TABLE 35

SOME INDICES OF CARDIAC ACTIVITY OF ASTRONAUTS IN PRELAUNCH PERIOD AND UNDER ORBITAL FLIGHT CONDITIONS (average data)

Astronaut	Indicator	Pre-launch Period	Weightlessness (orbits)												
			1	2	3	4	5	6	7	13	14	15	16	17	18
P. I. Belyayev	Auricular-Ventricular Conductivity (P-Q), sec	0.15	0.16	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.16	0.16	0.16	0.14
A. A. Leonov		0.14	0.14	0 16	0.17	0.16	0.18	0.18	0.15	0.15	0.15	0.14	0.15	0.14	0.14
P. I. Belyayev	Duration of Ventricular Complex (Q-T)sec	0.33	0.30	0.32	0.34	0.35	0.34	0 34	0.35	0.35	0.33	0.32	0.32	0.32	0.39
A. A. Leonov		0.34	0.34	0.36	0.42	0.40	0.38	0.38	0.42	0.40	0.38	0 39	0.38	0.38	0.36
P. I. Belyayev	R-R Interval Duration, sec	0.72	0.57	0.66	0.71	0 79	0.71	0.76	0.82	0.78	0.69	0.62	0 67	0 64	0.55
A. A. Leonov		0.69	0.60	0.51	1.00	0.94	0.86	0.86	1.12	0.85	0.78	0.84	0 82	0.80	0.70
P. I. Belyayev	Systolic Index, %	46	52.6	49	49	44.3	48	45	43	45.2	48 0	51.6	48	50	54.5
A. A. Leonov		49.3	57	50.5	42	42.5	44	44 3	37.5	47.4	48.8	46 4	46.3	47 5	51.4
P. I. Belyayev	R-spikeHeight, rel units	9.91	9.33	10 2	11.8	10.4	10 0	9.9	10	8.5	10	9.7	11.2	—	—
A. A. Leonov		5.7	4.3	3 9	3.9	4.2	4.0	4.2	4.1	5.1	4.9	4.0	4.4	3.1	2 7
P. I. Belyayev	T-spikeHeight, rel units	1.09	1.0	1.37	1.20	1.40	1.30	1.30	1.30	1.40	1 90	1.20	1.30	0.84	1.40
A. A. Leonov		3.4	3.2	2 8	4.9	4 0	3.6	4.0	4.0	3.2	3.4	3.0	3.6	3.8	3 6

The g-forces during injection into orbit were tolerated well by the astronauts, and the shifts in the physiological functions were less than in the majority of other astronauts in preceding flights (P. V. Vasil'ev, A. R. Kotovskaya, 1965). After injection into orbit, P. I. Belyayev and A. A. Leonov did not note any unpleasant feelings or illusions. The pulse rate during the period of transi- /111
tion from g-force to weightlessness fluctuated between 88 and 122 beats per minute. Changes in duration of the electrical systole and certain other EKG indicators in this period corresponded to the heart rate, and they were expressed slightly (see Table 32).

In the first orbit of the flight, the heart and respiration rates of both astronauts remained elevated: 105 for P. I. Belyayev and 100 beats per minute for A. A. Leonov. The respiration rates were 21 and 24 cycles per minute, respectively. A sharp increase in variability of these indices, compared with the prelaunch period was characteristic of P. I. Belyayev (Table 33), which apparently is connected with nervous-emotional stress, caused by preparations for the first extravehicular activity, accomplished by A. A. Leonov.

The stage of direct exit from the craft into space was more tense for A. A. Leonov. His heart rate increased here to 152 per minute and, upon return to the airlock chamber from space, briefly, to 162 per minute. The respiration rate reached maximum values at this time, 25-36 cycles per minute. Data on changes of certain EKG indicators during the extravehicular activity period are presented in Table 34 (3-14 min).

The materials in the table indicate that the changes in the EKG were somewhat unusual. Thus, for example, despite quickening of the heart rate (decrease in the R-R interval), the auricular-ventricular conductivity slowed down. The length of the electrical systole (Q-T interval) increased relatively, in which a particularly marked increase in it was observed after the return of A. A. Leonov to the airlock chamber, on a background of slowing of the heart contractions. The R- and T-spike amplitudes, during the extravehicular activity of A. A. Leonov, also increased relatively, in which an especially noticeable increase in value of the R-spike was observed after return to the airlock chamber, on a background of slowing of the heart rhythm. These changes apparently are connected with the preceding physical and nervous-emotional stress; however, they lasted a short /112
time and, just like the pulse rate, they returned to the initial values after the return of A. A. Leonov to the craft.

In the succeeding period (3rd-7th orbits), the heart and respiration rate of both astronauts had a tendency to decrease (see Table 33); in this case, it was expressed more in the 7th orbit, when the astronauts rested or performed simple operations. The heart rate of P. I. Belyayev decreased to 73 in this period and, of A. A. Leonov, to 54 beats per minute. A similar direction of the cardiovascular system reaction has been noted in astronauts by other authors (V. I.

Yazdovskiy, et al., 1964; R. . Bayevskiy, O. G. Gazenko. 1964; I. I. Kas'yan, et al., 1964; P. V. Vasil'ev, 1965; I. I. Kas'yan, et al., 1965; I. S. Balakhovskiy, et al., 1966). The respiration rate during this period was 14 cycles per minute for each astronaut, on the average. The fluctuations in the heart rate of P. I. Belyayev decreased and, of A. A. Leonov, remained as before. The fluctuation in respiration rate of both astronauts was not significantly changed from that of the initial period of the flight.

In the second half of the flight (orbits 13-18), the heart rate increased noticeably, especially before descent of the craft. For P. I. Belyayev, it reached 94-111 in orbits 17-18 and, for A. A. Leonov, 75-86 beats per minute. The respiration rate in the second half of the flight changed considerably less than in the first.

The electrocardiogram indicators basically corresponded to changes in pulse rate during the entire flight. In the first half, in parallel with the tendency towards reduction in pulse rate, the length of the electrical systole of the ventricles increased from 0.30-0.34 to 0.35-0.42 sec, and the systolic index decreased from 57-53 to 43-43.8%. The auricular-ventricular conductivity increased from 0.14-0.16 to 0.17-0.18 sec in the initial period. In the second half of the flight, together with a quickening of the pulse, the duration of the electrical systole of the ventricles decreased from 0.35-0.40 to 0.30-0.36 sec, and the systolic index increased from 38-43 to 52-55% (Table 35). Changes in the EKG, with the exception of the somewhat unusual time indicators of A. A. Leonov during the extravehicular activity and single nodal extrasystoles of P. I. Belyayev in this period, as well as in the preparation and descent of the craft to earth, was within the limit of physiological fluctuations, and did not differ from those observed in preceding flights.

In the first days after landing, both astronauts had rhythmic and well-filled pulses: 58 in P. I. Belyayev and 52-54 beats per minute in A. A. Leonov. Respiration was peaceful, and its rate was 12-14 cycles per minute. The decrease in pulse and respiration was accompanied by symptoms of moderate general fatigue.

A clinical examination on the third day after landing disclosed an increase in pulse rate from 60-64 to 74-80 beats per minute. The quickening was still larger in a test, which included standing up. While the pulses of both astronauts quickened to 76 beats per minute before the flight, it increased to 102 in P. I. Belyayev and to 96 beats per minute in A. A. Leonov after the flight. The systolic and diastolic pressure, under conditions of relative rest, increased by 15 mm Hg for P. I. Belyayev and the diastolic pressure of A. A. Leonov decreased by 15 mm Hg.

A postflight electrocardiographic study showed an increase in intraventricular conductivity time, in shortening the cardiac cycle. /113

The QRS interval of P. I. Belyayev increased from 0.08 tc 0.09 sec, and that of A. A. Leonov, from 0.09-0.10 to 0.11-0.12 sec. The sum of the P-spike amplitudes in three standard leads increased in the astronauts, by 55 and 69%, respectively; the sum of the T-spike amplitudes decreased by approximately 10%, and the sum of the R-spike amplitudes was unchanged. The systolic index exceeded the proper values by 7-11%. In a vectorimetric analysis of the electrocardiogram, no noticeable dynamics were revealed in the values and direction of the QRS vectors, T and intraventricular gradient G. As a result of the ballistocardiographic study, no peculiarities were found either.

The hemodynamics indicators of A. A. Leonov were normal. In comparison with the baseline data, together with a quickening of the pulse (+15%), a decrease was noted in cardiac output, from 100 to 84 ml. The minute circulation, modulus of elasticity ratio and other indicators did not change significantly.

A single investigation of certain external respiration indicators was carried out by the astronauts under flight conditions. The vital capacity of the lungs of the astronauts decreased a little: from 4600 to 3500 ml for P. I. Belyayev and from 5200 to 4200 ml for A. A. Leonov. On the third day after landing, the vital capacity of the lungs was within normal limits, although somewhat less than the initial: 4400 for P. I. Belyayev and 4900 ml for A. A. Leonov. The respiratory volume and pulmonary ventilation of both astronauts approximately doubled in flight. After the flight, the pulmonary ventilation of P. I. Belyayev increased by 51% and, of A. A. Leonov, by 18%, over the prelaunch values. The daily energy use, according to gas exchange data, exceeded the initial data on the third day after landing: P. I. Belyayev by 28% and A. A. Leonov by 20%.

TABLE 36

BODY TEMPERATURE OF A. A. LEONOV IN VARIOUS ORBITS OF ORBITAL FLIGHT

Orbit	Body Temperature, °C			Orbit	Body Temperature, °C		
	Avg.	Min.	Max.		Avg.	Min.	Max.
1	36.00	35.5	36.8	13	36.00	36.0	36.1
2	37.35	36.6	37.6	14	36.30	36.3	36.4
4	35.20	35.[illegible]	35.4	15	35.50	35.0	35.8
5	36.50	36.5	36.6	16	36.00	35.4	37.4
6	36.30	36.0	36.6	17	36.20	35.0	37.6
7	35.45	35.4	35.5				

The study of the body temperature in flight was carried out only on A. A. Leonov. The limits of variation of it and the average values are presented in Table 36. During the extravehicular activity of A. A. Leonov, the body temperature was increased by 1.35° on the average, compared with that in the first orbit; the minimum and maximum indicators increased simultaneously, and they were the greatest, compared with data recorded in other orbits of the flight. A sharp increase in body temperature on the second orbit involved the great physical efforts and nervous-emotional stress endured by A. A. Leonov, in executing the extravehicular activity program. In a simulation of the flight program in a heat and barometric chamber, the body temperature of A. A. Leonov also increased, but less (by 0.8° on the average). In the fourth orbit, the body temperature of A. A. Leonov was lower than in the first orbit (35.2°, instead of 36°). The reduction in temperature apparently reflected, not an /114
increase in ventilation of the body surface but, to a considerable extent, the general condition of the astronaut. A similar reduction in temperature can be seen in orbits 7 and 15, when the astronaut was in a state of relative rest and ventilation was normal. At the end of the flight, the range of change in body temperature of A. A. Leonov sharply increased, which probably was due to preparations for the first landing of the spacecraft on earth performed with manual control systems.

The body temperature of both astronauts was normal after landing, and it differed from that recorded in the prelaunch period.

In-flight studies of pain and tactile sensitivity, two-dimensional three-dimensional and stereognostic senses showed that they were not significantly changed under weightless conditions in either astronaut. Only recognition of certain numbers, pricked into paper, was hindered. Thus, P. I. Belyayev could not correctly identify the number 5, and A. A. Leonov, the number 3 (number size 2 × 1.5 cm).

Analysis of the dynamics of oculomotor activity of the astronauts in flight showed that, in the first two orbits, the number of waves on the elecrooculogram (EOG) reached 105-110 per minute for both astronauts. The number of oculomotor reactions decreased by orbits 3-4, and they subsequently fluctuated within comparatively small limits: 10-40 movements per minute. At the end of the flight, the number of eye movements increased somewhat. Such EOG dynamics correspond to the heart and respiration rates and, evidently, reflect the general state of the astronauts. Similar EOG changes were observed in preceding flights (I. T. Akulinichev, et al., 1965).

In analysis of the EOG curve amplitudes and shapes, it can be /115
noted that eye movements of the astronauts were quite symmetrical all during the flight. Pathological asymmetry, characteristic of disturbances of eye muscle tonus, were not recorded. Slow and

large-amplitude oculomotor reactions, characteristic of a period of falling asleep or of sharp fatigue, were not found. Small and medium amplitude motions predominated on EOG, with increase in oculomotor activity in flight. Group oculomotor activity, connected with observation of rapidly occurring phenomena, lasted 3-7 sec, in the majority of cases. On a background of increased oculomotor activity, or at times after it, small-amplitude optokinetic nystagmus was observed, with a frequency of 3-4 movements per second, for a period of 1-1.5 sec.

In an electroencephalographic examination of the astronauts, on the third day after the flight, predominance of the β-rhythm, with a frequency of 18-20 Hz and amplitudes up to 35 μV, was noted in P. I. Belyayev, which was expressed in the right central-occipital lead; single, sharp waves, with a frequency of 30 Hz and amplitudes up to 30 μV. On the EEG of A. A. Leonov, on the third day of the flight, a regular α rhythm, with a frequency of 10-11 Hz and amplitudes up to 30-50 μV, a β-rhythm, with a frequency of 18-20 Hz and amplitude of 10-15 μV and single slow, low-amplitude waves, with a frequency of 5-7 Hz were recorded in the left frontal-central lead. Compared with the baseline examinations of both astronauts, the slow electrical rhythms increased. This evidently indicated an increase in the inhibiting processes in the cerebral cortex, in connection with general fatigue.

The working memory of both astronauts decreased somewhat in /116 flight, according to the test of reproduction of curves, but it was less than that of astronaut B. B. Yegorov in the preceding flight which apparently was due to the higher state of training of P. I. Belyayev and A. A. Leonov, in particular, the greater preparation for the effects of various stress factors.

The results of study of efficiency, by a test of tracking the nature of a curve, is of special interest. The test included 50 sinusoidal and 22 square pulses, set up in a changing sequence. An examination, conducted immediately after the return of A. A. Leonov to the craft, showed that the number of errors and the latent reaction period increased in both astronauts, especially at signals, with frequencies above 0.5 Hz.

The changes in A. A. Leonov, despite the extravehicular activity, were less pronounced than those of P. I. Belyayev. (A detailed analysis of astronaut efficiency is given in section 3 of Chapter 6.)

The time characteristics of work with a telegraph key increased for both astronauts in flight, and it was particularly sharp in the first hour of the flight. Thus, the break between transmission elements doubled and the duration of the dash increased. In the 4th hour of the flight, these working characteristics approached those recorded on earth, in the training craft. A similar direction of change in occupational efficiency was observed in V. M. Komarov and B. B. Yegorov, in the flight of Voskhod (Ye. A. Ivanov, V. A. Popov, L. S. Khachatur'yants, 1965).

An experimental psychological examination after the flight revealed comparatively small fluctuations of the average values of the latent periods of simple and complex motor reactions, a negligible number of erroneous responses and stable reproduction of the time intervals. All this indicates a quite high level of the basic psychological functions and good efficiency of the astronauts.

In a detailed clinical-physiological and laboratory examination a month after the flight, no significant differences from the conditions in the preflight period were found in P. I. Belyayev or A. A. Leonov.

3. Basic Results of Medical Examinations of Soyuz Spacecraft Crew Members

Successful completion of the series of manned flights of the Vostok and Voskhod spacecraft inthe USSR created the necessary prerequisites for putting into practice the research programs in the Soyuz spacecraft. Flights in this program were completed between 1968 and 1971. Eight satellites were injected into orbit, and 13 astronauts stayed awhile in space, two of them two times. The astronauts flew about 2,042 man hours in all in the Soyuz program. Information on the Soyuz type craft is presented in Table 37.

The primary biomedical research tasks during the flights of the Soyuz craft were:

--Study of phenomenology of change in various systems of the human body under conditions of prolonged weightlessness (up to 18 days);

--Study of the state of reserve capabilities of the human body upon return to normal conditions of life on earth after a prolonged stay in flight;

--Study of the dynamics of astronaut efficiency in performing /117
certain working operations, as well as on the basis of evaluation of performance of special tests.

General Characteristics of Flight Conditions

The flights of the Soyuz spacecraft took place in a quiet radiation situation. As should have been expected, the highest value of the integral radiation dose was recorded during the 18-day flight of Soyuz 9. However, in this case, up to the time of completion of the flight, it did not exceed 0.4 rad (V. I. Vorob'ev, 1970). Indisputably, this amount did not present a danger for A. G. Nikolayev or V. I. Sevast'yanov.

TABLE 37

GENERAL INFORMATION ON FLIGHTS OF SOYUZ 3–SOYUZ 9 MANNED SPACECRAFT

Spacecraft	Astronaut		Date and Time of Launch	Number Orbits Around Earth	Date and Time of Landing	Flight Duration	Microclimate Characteristics			
	Name	Year of Birth					Pressure, mm, Hg	Tempera-ture, °C	Oxygen Partial Pressure, mm Hg	Carbon Dioxide Partial Pressure mm Hg
Soyuz 3	G. T. Beregovoi	1921	26 Oct 1968 11 hr 34 min	64	30 Oct 1968 10 hr 25 min	94 hr 51 min	767—836	18.3—22.6	184.4—248	1.0—2.9
Soyuz 4	V. A. Shatalov:*	1927	14 Jan 1969 10 hr 39 min	48	17 Jan 1969 9 hr 53 min	71 " 14 "	750 -800	18.0—22	157—186	0.1—8.4
		1934 1933			47 hr 39 min					
Soyuz 5	B. V. Volynov A. S. Yeliseyev Ye. V. Khrunov	1934 1934	15 Jan 1969 10 hr 14 min	49	18 Jan 1969 10 hr 56 min	72 " 46 "	767—840	16.0—21.6	168—238	0—12.3
Soyuz 6	G. S. Shonin V. N. Kubasov	1935 1935	11 Oct 1969 14 hr 10 min	80	16 Oct 1969 12 hr 52 min	118 " 42 "	720—848	16.5—23.5	168—252	6.5—15.1
Soyuz 7	A. V. Filipchenko V. N. Volkov V. V. Gorbatko	1928 1935 1927	12 Oct 1969 13 hr 45 min	80	17 Oct 1969 12 hr 26 min	118 " 41 "	750—809	18.0—23.6	160—202	0.8—12
Soyuz 8	V. A. Shatalov A. S. Yeliseyev	1934 1929	13 Oct 1969 13 hr 29 min	80	18 Oct 1969 12 hr 10 min	118 " 41 "	735—825	18.3—23.6	186—240	1.1—15
Soyuz 9	A. G. Nikolayev V. I. Sevast'yanov	1935	1 June 1970 22 hr	286	19 June 1970 14 hr 59 min	425 "	732—890	17—28	157—285	1.3—10.7

*A. S. Yeliseyev and Ye. V. Khrunov transferred to the craft from Soyuz 5 orbit 36

The life support systems maintained the microclimate parameters of the inhabited sections within the assigned limits. The greatest range of fluctuation was noted during the flight of Soyuz 9. During the transfer of A. S. Yeliseyev and Ye. V. Khrunov from Soyuz 5 to Soyuz 4, the autonomous life support systems maintained an absolute pressure of 241-268 mm Hg in the spacesuits, with a carbon dioxide partial pressure of 0.1-0.4 mm Hg and a heat exchanger outlet air temperature of 19.4-19.8°.

The food ration of the crews of the Soyuz 3-Soyuz 5 spacecraft was made up of dehydrated and preserved foodstuffs, in ready-to-serve form. It contained 143 g of protein, 106 g of fat and 254 g of carbohydrates. The total calorie value was 2635 kcal. The ration was made up of a three-day menu, with four meals a day. The food ration of the crews of Soyuz 6-Soyuz 8, with the same food value as the preceding, contained fewer dehydrated foodstuffs; a portion of them was replaced by foodstuffs preserved by other methods, which had received a higher rating by the astronauts in preceding flights. Taking flight duration and the motor behavior of the astronauts into consideration, the average daily calorie value of the ration for the Soyuz 9 crew was increased to 2800 kcal. In this case, the selection of foodstuffs was expanded considerably. Heating of the main dishes and drinks (coffee, cocoa) also was provided for. The ration contained 139 g of protein, 88 g of fat and 345 g of carbohydrates. The ration was balanced with essential amino acids, and it contained the normal amount of the basic mineral elements and polyunsaturated fatty acids (V. N. Bychkov, et al., 1970). The food ration of the Soyuz 9 crew was supplemented with Undevid type polyvitamin lozenges. The astronauts took them two times a day. The selection of foodstuffs was chosen, considering the individual tastes of the astronauts. The average daily water consumption was 1.95-2.15 l per man (including water contained in the foodstuffs and drinks, as well as 0.35 l of metabolic water).

The personal hygiene sets of the Soyuz crews included cloths and towels, both dry and wetted with a special lotion, intended for care of the skin of the face and hands, rubbing the gums, etc. The flight program of Soyuz 9 provided for special "bath" days (days 7 and 14 of the flight), when the astronauts changed underwear and initially rubbed the body with a towel wetted with lotion and, then, with a dry towel. The personal hygiene sets of the crews also included mechanical and safety razors and combs.

The work and rest schedule of the astronauts in the first flights of the Soyuz spacecraft was compiled, on the basis of the principle of preserving the 24-hour daily cycle, with a single 8-hour sleep each day. A certain change in the work and rest schedule from flight to flight was in the direction of increasing the free time, number and duration of physical training exercises and a reduction of the total number of working hours. /118

During the flights of Soyuz 3-Soyuz 8, the motor activity of the astronauts was not regulated, in connection with the short duration of these flights. In the 18-day flight of Soyuz 9, the astronauts performed a set of physical exercises, lasting up to 60 min, twice a day. The morning set of physical exercises began approximately 2-1/2 hours after sleeping and the evening, 2 hours before going to sleep. The special organization of the motor behavior of the astronauts during the flight of Soyuz 9 was connected with the greater length of this flight and the necessity for preventive treatment of possible disturbances, caused by the flight factors.

The physical exercise set was made up of repeating three-day cycles. A cycle included exercises of a speed-strength nature (1st day), sustained strength (2nd day) and general endurance (3rd day); the 4th day of the training cycle was devoted to active recreation. The load was not planned on this day, and the astronauts could select the type and number of exercises, at their discretion. During each training exercise, the load was distributed uniformly over all the groups of muscles, with the accent on exercises simulating walking, running and inertial-impact actions (Ye. I. Vorob'ev, et al., 1970). Rubber shock absorbers and a special suit, permitting the astronauts to confine themselves to a platform installed on the manhole and equipped with loops for fastening the shock absorbers, were used as the loads. According to the report of astronauts, they enjoyed the training, noting an effect "muscular joy" from the physical exercises and an "energy charge" for the entire working day (see section 3, Chapter 5).

During the 18-day flight of Soyuz 9, "days off" were provided on days 9 and 17 of the flight, during which the astronauts were freed as much as possible from programmed work. These days were used for active recreation.

Medical Monitoring System

To make it possible to carry out physiological examinations and medical monitoring of the condition of the Soyuz crew members, a special method of obtaining medical information was developed (Yu. G. Nefedov, et al., 1970). The following types and sources of information were used here, for operational medical monitoring of the condition of the astronauts:

--Materials of the radiotraffic of the crew with the ground command-measurement complex, including reports from onboard of the state of health of the astronauts, according to self- and mutual monitoring data;

--Materials from television observation of the crew members;

--Telemetry data, characterizing the functional state of the cardiovascular and respiratory systems, microclimate parameters of the inhabited sections of the craft and the spacesuits (pressure, temperature, relative humidity, oxygen partial pressure, carbon dioxide partial pressure).

The onboard medical monitoring equipment provided for measurement and transmission to ground measurement points of electrocardiograms (EKG), seismocardiograms (SKG), pneumograms (PG) and heart rate (PR) of each astronaut, as well as measurement and display on the medical monitoring panel of the heart rate and body temperature of astronauts in spacesuits, performing extravehicular activity. These indices were measured at the stage of preparation for transfer and in the process of the transfer itself. /119

Production of the information was ensured by a unified system of sensors -- seismocardiographic and pneumographic sensors (the first, of the induction, the second, of the tensometric type), two sets of silver electrocardiographic electrodes, as well as a strap system of fastening with cable leads. The seismocardiographic (SKG) and pneumographic (PG) sensors were fastened, by means of a special system: SKG, in the region of the top impulse, the PG, on the anterior abdominal wall, in the upper sections of it. One of the EKG electrode sets is installed on thoracic cage, in the DS lead (active electrodes to the right and left of the middle axillary lines, at the level of ribs VI, VII). The electrodes of the second set were attached to the skin of the thoracic cage, by means of a cement composition developed for this purpose, in a section close to the A lead, according to Nebu (active electrodes were located: one along the ribline, in the upper third of the sternum, the other along the left mid-clavicular line, at the level of ribs VI, VII), and they were used for recording the EKG, during preparation for and accomplishment of the transfer operation. Gluing the electrodes in the leads indicated ensured production of electrocardiograms with minimum signal distortion, while the astronauts were performing work in the spacesuit. Since individual stages of the transfer program were executed during flight outside the zone of radio visibility of the ground measurement points, the spacecraft commander followed the heart rate and body temperature.

An indicating instrument, installed on the medical monitoring panel in the descent vehicle of the Soyuz spacecraft, was used as a heart rate indicator. During work in the spacesuit, a rectal body temperature sensor was used to obtain the information.

Signal lamps, with two lighting modes, corresponding to the two threshold values of the measured quantity (38.3 and 39°), on the medical monitoring panel of the Soyuz spacecraft, were the body temperature indicators.

During the flight of Soyuz 9, to carry out medical monitoring of the astronauts, a functional test was carried out once every other day during a communications session (Ye. I. Vorob'ev, et al., 1970). This test consisted of three series of stretching the rubber shock absorbers in a position on the back. Ten stretches were carried out in each series (once per second), at 5 sec intervals. The physiological indicators were recorded, with the astronaut at rest, for a period of 1 minute before the test, while performing it and 2 min after finishing it. According to the program, each astronaut performed this test once every other day.

In the medical provisions of comparatively short (up to 5 days) flights of the Soyuz 3-Soyuz 8 spacecraft the physiological parameters were taken and transmitted by telemetry, during practically the entire time the craft was in the radio visibility zone in the territory of the USSR. During the 18-day flight of Soyuz 9, it was decided that it was possible to reject this scheme: the astronauts were permitted to independently remove and put on the physiological sensor and electrode system belt. In this case, recording of the physiological parameters of each astronaut was carried out at least twice a day (morning and evening, according to the onboard order of the day). Besides, the flight program provided for days, when, for the purpose of monitoring the dynamics of the diurnal periodicity of the physiological parameters, they were recorded continuously during all telemetry communications sessions.

Results of In-Flight Studies

During the entire time of the flight, the astronauts evaluated their state of health as excellent or good. A detailed analysis of the medical history data revealed some interesting facts. Thus, G. T. Beregovoy reported that, at the start of the flight, he noted some increase in the interval between the intention to perform a motor act and the act itself, as well as a slightly expressed feeling of discomfort with abrupt turns of the head. At the moment of pressing the head against the headrest with eyes open, it seemed to him that the craft was rotating and, with eyes closed, that his body was rotating. All these sensations disappeared upon raising the head, when there was no contact with the headrest. In the first 20 min of weightlessness, A. G. Nikolayev had a sensation of a 30° upward movement of the instrument panel. Moreover, upon abruptly inclining the trunk or head and with simultaneous immobilization of the legs, both A. G. Nikolayev and V. I. Sevast'yanov experienced a sensation, similar to that which took place on earth, at the moment of action of Coriolis acceleration. /120

Upon entering the state of weightlessness, all the astronauts had a subjective sensation of blood rushing to the head. In their words, this sensation was approximately the same as that of a man with the head downward, under the conditions of earth. Some puffiness and reddening of the face emerged here, as well as reddening of the sclera of the eyes. The intensity of the sensation of blood rushing to the head usually decreased after the first days of the flight and, in a number of cases, it was subsequently obliterated. However, by fixing the attention on this sensation, it again became somewhat aggravated. The impression is created by the data reported by the astronauts, that the acuteness of the sensation of blood rushing to the head decreased noticeably, when, during the so-called twisting of the craft, the astronauts took a position along the centripetal force vector (head toward the center of rotation). This sensation apparently is connected with a specific redistribution of the blood in the body for weightlessness.

Astronauts A. G. Nikolayev and V. I. Sevast'yanov, analyzing the peculiarities of executing motions in the state of weightlessness, noted that, at the start of the flight, they had some difficulties in estimating the muscular efforts necessary to execute the corresponding motions. However, these phenomena disappeared by days 3 or 4 of the flight, which apparently is evidence of working out a new motor stereotype. Pushing away with the legs, the astronaut could correct the body position without difficulty and move in the required direction, practically without conscious control of these actions. V. I. Sevast'yanov pointed out that he could easily grasp and move individual objects with his legs.

Analysis of radioconversation data, the reports of the astronauts on their state of health and television observations has permitted determination of the behavior of the astronauts over the entire extent of the flight as correct and adequate to the specific situations. The speech of the astronauts was distinct and precise. According to television observation data, full-size movements were performed; no disturbances of movement coordination were revealed. Television and radio reporting were carried out, with active participation by all crew members. In this case, answers to questions followed immediately and were adequate. The efficiency of all astronauts was high for the entire duration of the flight. Execution of complicated maneuvers, including approach and docking, conduct of numerous experiments, as well as successful performance of work outside the craft, are primary evidence of this. However, after performing complicated experiments and completing a work-saturated /123 day, the astronauts noted some fatigue, which completely disappeared after sleeping. The feeling of thirst usually was somewhat reduced in flight. Natural functions were not disrupted, although the stool was not always regular. Thus, the first defecation of the Soyuz 9 crew members was on the fourth day of the flight and the next, as a rule, two days later. Urination was regular, 2-5 times per day.

Sleep was deep during the 18-day flight, after a few days of adaptation; its duration was 7-9 hours. In the words of the astronaut, sleep "always brought freshness and cheerfulness." They fell asleep quickly, approximately as on earth. V. I. Sevast'yanov preferred to sleep in an unsecured sleeping bag. On the first day of the flight, he sometimes fell asleep for 10-15 min in his free time.

As a result of processing the medical information, general patterns obtained in the physiological indicators under the influence of flight factors and conditions, first and foremost, such an integral indicator as heart rate, were revealed.

A quantitative estimate of the change in heart rate, respiration rate and basic EKG indicators did not disclose differences in the dynamics of these indicators in different astronauts, during the powered section of the flight and during the descent. In an examination during the 5-minute readiness period, the heart rates of all astronauts increased sharply and the time indices of the EKG decreased. These changes were still more pronounced in the first or second minute of the flight in the powered section, and they subsequently had a tendency to decrease. The most pronounced changes in physiological indicators were noted in the descent portion.

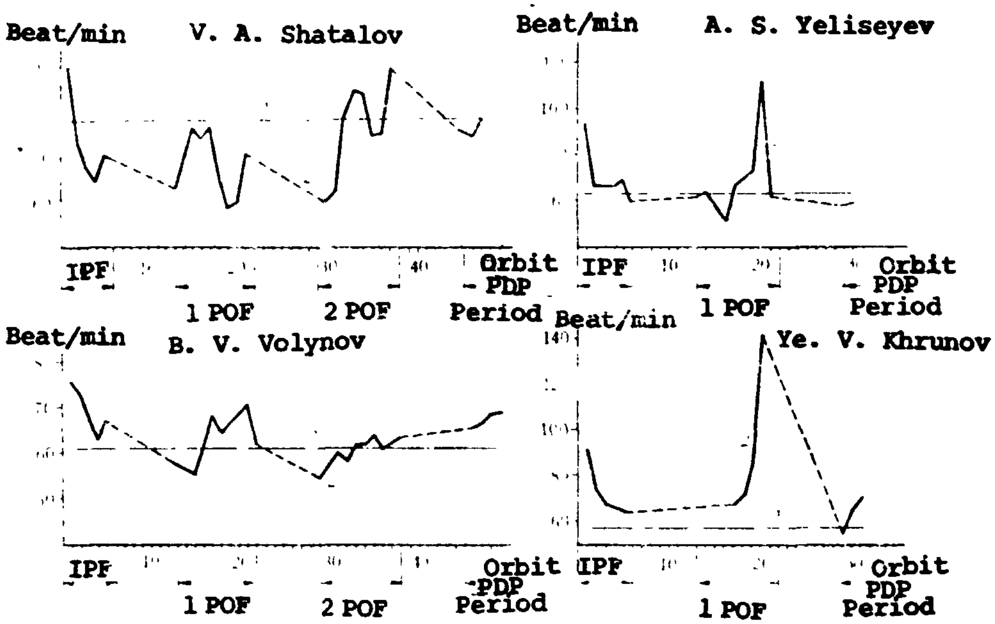

Fig. 12. Heart rate dynamics of Soyuz 4 and Soyuz 5 spacecraft crew members during orbital flight: 1) average indices in preflight period; 2) average indices in flight; IPF initial period of orbital flight (orbits 1-7); 1 POF first (orbits 13-23) period of orbital flight; 2 POF second period (orbits 29-39); PDP predescent period of flight (last 3-4 orbits).

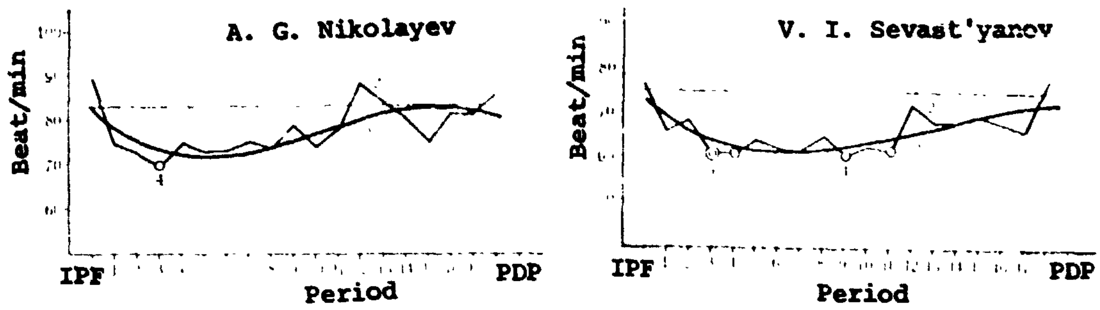

Fig. 13. Dynamics of average heart rates of Soyuz 9 spacecraft crew members in orbital flight: 1) average preflight period values in waking state; 2) average values of physiological indices in different periods of orbital flight; 3) smoothed curve, characterizing direction of change of physiological indices in orbital flight; IPF initial period of orbital flight; PDP predescent period; 4) average values of indices in a given period; statistically significant ($P < 0.05$) difference from average values of preflight period; 5) average values of indices in a given period; statistically significant differences from average preflight period values ($0.05 < P \leq 0.10$).

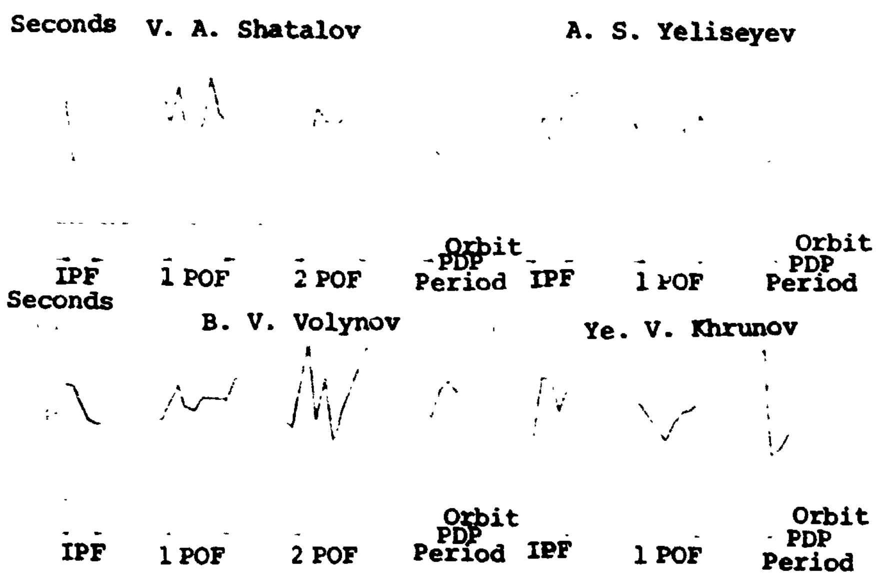

Fig. 14. Dynamics of average length of asynchronous heart contraction period of Soyuz 4 and Soyuz 5 spacecraft crew members in orbital flight: designations same as in Fig. 12.

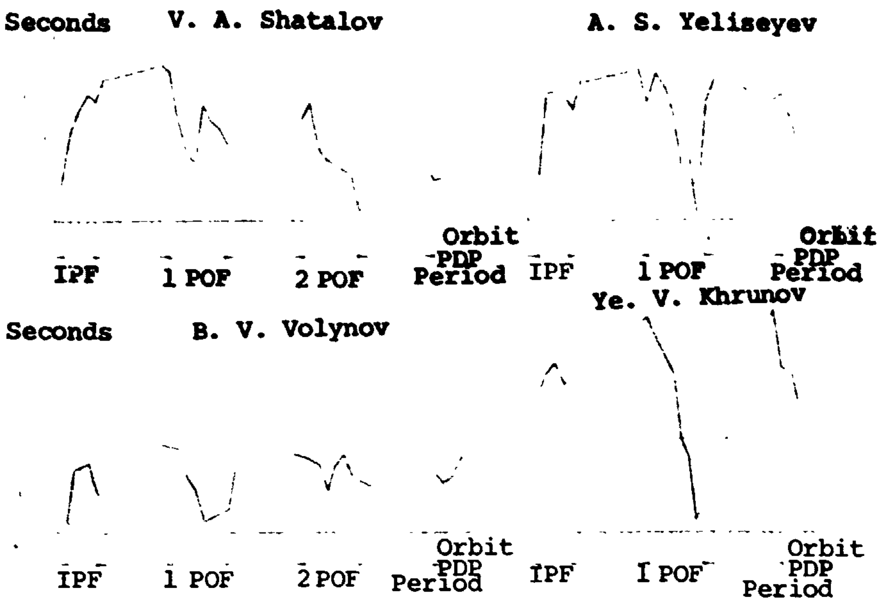

Fig. 15. Dynamics of difference between actual and proper value of electromechanical systole of Soyuz 4 and Soyuz 5 spacecraft crew members in orbital flight: designations same as in Fig. 12.

After injection of the craft into orbit, the heart rate and other physiological indices had a tendency to return to normal. The heart rates of the Soyuz 4, Soyuz 5 and Soyuz 9 spacecraft crew members reached the preflight values after 5-6 orbits and, subsequently (outside the period of work in the unsealed sections of the craft and in open space), stayed at a lower average level than in the preflight period or did not differ from it (Fig. 12).

The heart rates of A. G. Nikolayev and V. I. Sevast'yanov had a tendency to increase in the last third of the flight, and they practically reached the preflight values (Fig. 13).

Reactions of the heart contractions to the standard physical load of both astronauts were not subject to significant changes for the duration of the flight. The dynamics of the electric systole and systolic index, although they determined the heart rate, the values of these indicators and the deviation from their proper values usually either did not differ from the preflight or were less than that. The duration of intraventricular conductivity and the period of asynchronous contraction of the Soyuz 4 and Soyuz 5 crew members somewhat exceeded the initial values in all cases (Fig. 14).

The length of the electromechanical and mechanical systole changed in direct proportion to heart rate. In this case, the average systole values, as well as the differences between them and the correct values of nearly all Soyuz 4 and Soyuz 5 astronauts exceeded the preflight data by statistically significant amounts (Fig. 15). In connection with this, the electromechanical coefficient also was very much higher than the values in the preflight period.

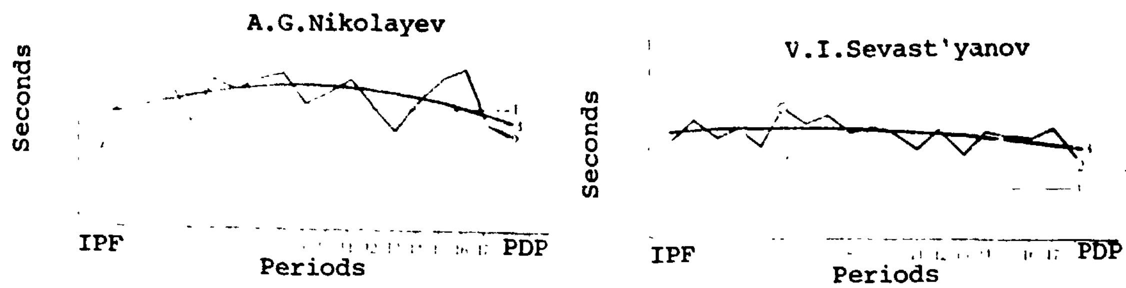

Fig. 16. Dynamics of average length of asynchronous heart contraction period of Soyuz 9 spacecraft crew members in orbital flight: designations same as in Fig. 13.

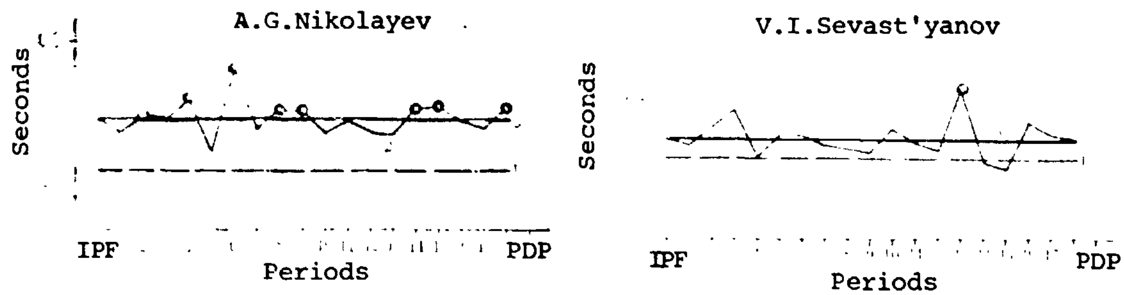

Fig. 17. Dynamics of difference between actual and proper values of mechanical systole of Soyuz 9 spacecraft crew members in orbital flight: designations same as in Fig. 13.

The duration of intraventricular conductivity, the asynchronous contraction phase and the differences between the actual and proper mechanical systole values of A. G. Nikolayev and V. I. Sevast'yanov also exceeded the baseline data, although these differences were not statistically significant in all periods of the flight (Figs. 16 and 17). During preparation for and performing extravehicular activity, there was a statistically significant and sharp increase in heart rate, respiration rate and systolic index, and decrease in the time indices of the electrocardiograms and seismocardiograms, electromechanical coefficient and duration of the first and second oscillatory cycles. /124

It should be noted that the changes in physiological indices, during the period of preparation for and accomplishing the transfer were not unexpected, and that they did not differ significantly from the data recorded on other astronauts. /125

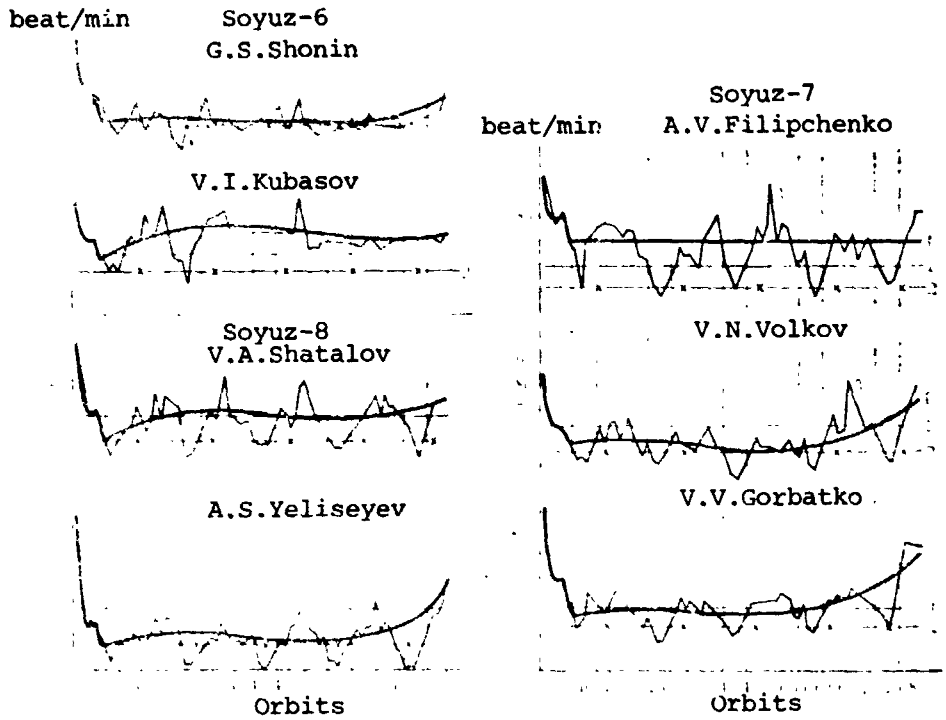

Fig. 18. Dynamics of heart rates of Soyuz 6-Soyuz 8 spacecraft crew members in flight: 1) average preflight period values during waking hours; 2) same during sleep; 3) indices during flight; 4) smoothed curve characterizing direction of change in physiological indices during orbital flight; orbits 7-12, 23-28, 39-44, 56-60, divided by vertical lines, correspond to astronaut sleeping periods.

Data on changes in the physiological indices of the crew members of Soyuz 3, Soyuz 6, Soyuz 7 and Soyuz 8 were somewhat different than those of the astronauts flying in Soyuz 4, Soyuz 5 and Soyuz 9. In the first case, the heart rates of the astronauts, although there was a tendency towards a slow recovery to the preflight values, they were somewhat higher than the initial for G. T. Beregovoy, V. N. Kubasov and A. V. Filipchenko during practically the entire flight (Fig. 18). The in-flight heart rates of the remaining crew members, except A. S. Yeliseyev, did not differ significantly from the preflight values. The length of the asynchronous contraction period

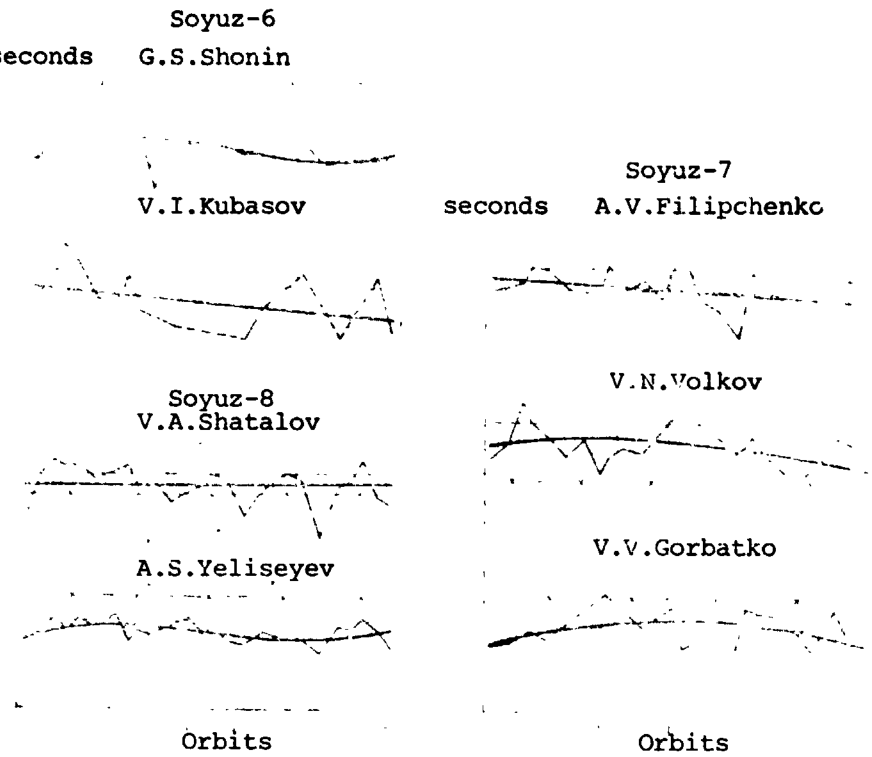

Fig. 19. Dynamics of length of asynchronous heart contraction period of Soyuz 6-Soyuz 8 spacecraft crew members in orbital flight: designations same as in Fig. 18.

during flight also was the same as in the preflight period or even somewhat less (for G. T. Beregovoy and A. V. Filipchenko; Fig. 19). No increase was revealed in the difference between the actual and proper electromechanical and mechanical systole values in flight, during waking periods, compared with preflight period data (Fig. 20). All of these features of the change in physiological indices in flight, of the Soyuz 3, Soyuz 6 and Soyuz 8 crew members, apparently were connected with nervous-emotional stress, caused by execution of numerous spacecraft maneuvers and other complicated operations. The orientation in space of the astronauts was hindered with eyes closed, during practically the entire extent of the flight. Thus, during free floating in the cabin with eyes closed, the astronauts quickly lost the idea of their body positions with respect to the cabin coordinates. A. G. Nikolayev and V. I. Sevast'yanov, determining the vertical direction with open and closed eyes, using the Vertical' apparatus, committed more significant errors in each test than preflight (O. G. Gazenko, B. S. Alyakrinskiy, 1970).

Analysis of the daily urine of the Soyuz 9 crew members, collected on the 1st, 2nd and 18th days of the flight, showed an

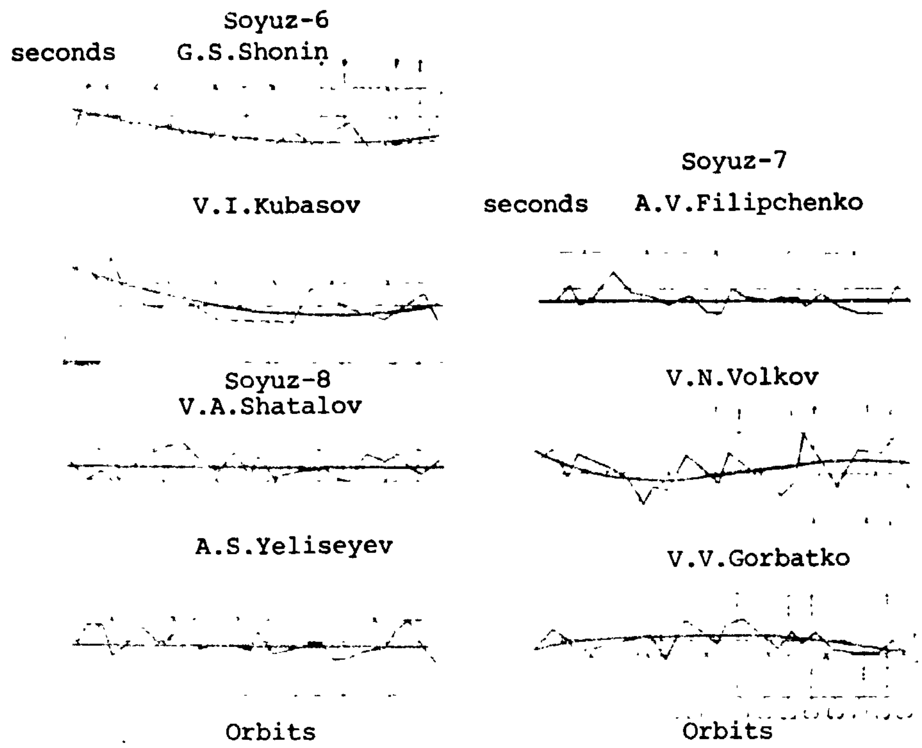

Fig. 20. Dynamics of difference between actual and proper electromechanical systole values of Soyuz 6-Soyuz 8 spacecraft crew members in orbital flight: designations same as in Fig. 18.

increase in excretion of potassium, calcium, sulfur, phosphorus and nitrogen. In this case, the amount of oxycorticosteroids in the first two portions of urine was decreased, but it hardly differed from the baseline data in the third portion (O. G. Gazenko, B. S. Alyakrinskiy, 1970).

Results of Postflight Examinations

The crew members of Soyuz 3-Soyuz 8 spacecraft did not make any complaints of painful feelings or poor state of health after the flight. They felt only fatigue, connected with performance of the comprehensive flight program. However, five of the seven crew members of the Soyuz 6, Soyuz 7 and Soyuz 8 noted an apparent increase (approximately double) in weight of objects immediately after landing. This feeling was manifested by a disproportion (decrease) of the effort in performing certain motor acts (Ye. I. Vorob'yev et al., 1970).

After the flight of Soyuz 9, A. G. Nikolayev and V. I. Sevast'yanov reported that their heads, arms, legs and even internal organs became unusually heavy (O. G. Gazenko, B. S. Alyakrinskiy, 1970; Ye. I. Vorob'yev 1970); they felt their weight. It was difficult for the astronauts to preserve the vertical posture in the first hours after the flight, and they preferred to lie down. /128 A change to the vertical position was accompanied by a deterioration in sense of well-being (dizziness and weakness appeared). These sensations disturbed the astronauts for a period of 2-3 days, but the degree of expression of them gradually decreased. It was characteristic that, even in the prone position, they experienced a feeling of being "pressed" into the bed. A day after landing, the gait of the astronauts remained unsure. Considerable effort was required to preserve the vertical posture. Thus, coming down the aircraft ladder, they moved slowly, holding onto the handrails and spreading their legs wide. However, despite this, they could independently climb to the third floor by the stairway. The faces of the astronauts were pinched, they were pale, they looked fatigued and they complained of general weakness and pains in the leg and back muscles. The muscle pains increased in the 2nd to 5th days after the flight. This apparently was connected with expansion of the motor behavior. In a clinical-physiological examination, the greatest changes in the postflight period were in the motor sphere and cardiovascular system of the Soyuz 9 crew members.

In examination of the neuromuscular apparatus, in flights lasting up to 5 days, marked changes in the motor functions were not disclosed. Moreover, some decrease was found in the tonus of the muscles of the lower extremities (the examination was carried out by the methods of Sirman and Uflyanda) and central force (L. I. Kakurin, et al., 1970, 1971). The tonus and strength of the muscles of the upper extremities, as well as the perimeters of the extremities, were practically unchanged. With increase in flight duration to 18 days, more pronounced changes were observed in the neuromuscular system. They were manifested by large reductions in the tonus and strength of the antigravity muscles, a considerable increase in the reflex excitability of the neuromuscular apparatus (bioelectric activity of the muscles participating in accomplishing the knee reflex increases), a decrease in the strength of the back extensors (central force) on the 3rd day after the flight was reduced by 40 kg for A. G. Nikolayev and by 65 kg for V. I. Sevast'yanov) and a moderately expressed atrophy of the leg muscles; the perimeters of the calves and thighs of both astronauts decreased (M. A. Cherepakhin, V. I. Pervushin, 1970). At the same time, in an examination of the muscles of the shoulder girdle, the data obtained was practically unchanged from the preflight.

From the stabilographic examination data after the flight, regulation of the vertical posture deteriorated; the amplitude of oscillations of the common center of gravity increased and their frequency decreased in almost all the astronauts, with eyes open and closed (B. N. Petukhov, et al., 1970; Ye. I. Vorob'yev, et al., 1970). These changes were marked in the Soyuz 9 crew members, and, in distinction from the astronauts participating in the preceding flights their regulation of the vertical posture became normal, only on the 10th day after the flight.

In an examination, using the seismotremography method, an increase in frequency and amplitude of physiological tremor was disclosed. Thus, the stabilographic and seismotremographic examination data in the postflight period indicates some imbalance in the mechanisms regulating muscle efforts directed toward compensation of the force of gravity.

As a result of study of the reactions of the cardiovascular and respiratory systems, by measured, submaximum physical loads (1400 kgm), in work on the bicycle ergometer, a more pronounced increase in heart rate and reduction in the oxygen pulse, without /129 significant changes in the oxygen consumption, than in the preflight period, was established in the crew members of Soyuz 6, Soyuz 7 and Soyuz 8 (Ye. I. Vorob'yev, et al., 1970). Exhalation of carbon dioxide and the respiratory coefficient increased. Four astronauts of the seven subjectively tolerated the physical load with greater difficulty. In a hemodynamic examination in the postflight period, a more significant increase in maximum and average arterial pressure and a more marked reduction in minimum pressure was found in a number of cases, after performing the physical loading, as well as a change in the nature of their recovery, in particular, a lag in recovery of the minimum arterial pressure. The nature of the changes described apparently indicates some deterioration in the functional condition of the oxygen transport system and the regulatory capacity of the cardiovascular system.

The greatest changes in conduct of the passive orthostatic tests were noted after the 18-day flight. Thus, two or three days after the flight, the reactions of the Soyuz 9 crew members to the test were considerably more pronounced than before the flight, and they were greater than those of astronauts after the 4- and 5-day flights of the remaining Soyuz spacecraft (Ye. I. Vorob'yev, et al., 1970; V. V. Kalinichenko, et al,1970). For example, V. I. Sevast'yanov tolerated the 10-minute passive vertical position with difficulty. In this case, his maximum heart rate reached 128 beats per minute (96 beats per minute before the flight), with a tendency to decrease at the end of the test, which is an unfavorable sign, indicating the possibility of development of collapse. Some decrease in orthostatic tolerance was observed in A. G. Nikolayev, three days after the flight. His pulse rate in this test increased to 102 beats per minute (to 98 beats per minute before the flight). It is interesting to note that, five days after landing, the extent of reduction in orthostatic tolerance of A. G. Nikolayev was more marked than after three days. In this period, the change in physiological indices of

V. I. Sevast'yanov were less than on the 2nd day of examination. Finally, on the 11th day after landing, practically all of the indices recorded returned towards the preflight level, although some of them, nevertheless, had not reached them.

A reduction in orthostatic tolerance after a flight has repeatedly been noted before. The flight of Soyuz 9 is not an exception, in this respect. Moreover, such a significant reduction in orthostatic tolerance after this flight, when the astronauts could not be in the vertical position, although it was not unexpected, deserves the most fixed attention.

Study of the density of specific sections of the skeletons of A. G. Nikolayev and V. I. Sevast'yanov, conducted by means of X-ray photometry and ultrasound methods, revealed a small reduction in density, with these changes being more pronounced in the lower extremities. Thus, the optical density of the calcaneus was decreased (in an examination on the 2nd day) by 8.5-9.6%, and that of the primary phalanges of the fingers, by 4.26-5.56% on the average. On the 22nd day after landing, the optical density of the bones still had not reached the initial level.

The body weight of the astronauts after the flights was reduced in all cases (Table 38). However, after flights lasting 3-5 days, the weight was quickly recovered (in the course of 3-5 days). This rapid recovery of weight, as well as the increase in hematocrit, noted in a number of cases, and the absence of muscular atrophy apparently is evidence that the reduction in body weight in flights lasting 3-5 days, involve dehydration of the body. In connection /130 with the slow weight recovery after the 18-day flight, an increase in tissue catabolism processes and their predominance over synthetic processes must be thought of.

The hydrophilic nature of the blood was decreased, as a rule, in a study for one or two days after a flight. It usually was restored by the third day after a flight (Ye. I. Vorob'yev, et al., 1969, 1970). During the first day after landing, the astronauts experienced a strong thirst, with a simultaneous reduction in diuresis. In a water loading test, carried out the first or second day after flight, water retention in the body was revealed in nearly all astronauts. V. A. Shatalov and A. S. Yeliseyev (Soyuz 8), as well as A. G. Nikolayev and V. I. Sevast'yanov (Soyuz 9), were exceptions, in this respect. Signs of readjustment of the hydrostatic status were found in the astronauts during the flight. The majority of them had a reduced feeling of thirst. Regular changes in urination frequency at various stages of the flights were not noted. However, the portions of urine eliminated in the first days of the flight were greater than on earth, in a number of cases.

The main result of the biomedical research, carried out during the manned flights of the Soyuz spacecraft, is the reasoned proof of

TABLE 38

DATA ON BODY WEIGHT LOSS AFTER SPACE FLIGHTS

Astronaut	Length of Flight	Decrease in Body Weight, kg
G. T. Beregovoy	2 da 22 hr 51 min	2.4
V. A. Shatalov	2 » 23 » 14 »	4.0
B. V. Volynov	3 » 46 »	2.4
A. S. Yeliseyev	1 » 23 » 39 »	2.0
Ye. V. Khrunov	1 » 23 » 39 »	2.0
G. S. Shonin	4 » 22 » 42 »	2.4
V. N. Kubasov	4 » 22 » 42 »	2.1
A. V. Filipchenko	4 » 22 » 41 »	3.9
V. V. Gorbatko	4 » 22 » 41 »	2.0
V. N. Volkov	4 » 22 » 41 »	2.4
V. A. Shatalov	4 » 22 » 41 »	2.2
A. S. Yeliseyev	4 » 22 » 41 »	3.6
A. G. Nikolayev	17 » 17 »	2.7
V. I. Sevast'yanov	17 » 17 »	4.0

the possibility of not only long (up to 18 days) stays of man under space flight conditions, but of the variety of his activities.

As a result of completion of the Soyuz program, a vast amount of information has been accumulated, indicating the appearance of shifts in a number of systems of the human body.

It has been established that, in distinction from unidirectional changes during orbiting and descent of spacecraft, the heart rate and other cardiac activity indicators during orbital flight, even under conditions of a joint flight in one craft, there were statistically significant differences in the direction of the changes in different astronauts.

During the orbital flights of Soyuz 4 through Soyuz 9, a reduction in pulse rate was noted after a few hours of flight, as well as /131 an increase in the asynchronous contraction phase and difference between the actual and proper electromechanical and mechanical systole values, compared with the preflight data. It is possible that the shifts revealed indicate an unloading nature in the reaction of the cardiovascular system.

In distinction from the changes described, there was not a clearly expressed "unloading" reaction syndrome, on the part of the cardiovascular system, in Soyuz 3 crew members. During waking hours, the regular increase in duration of the intraventricular conductivity and electrical systole, and an increase in the asynchronous contraction period did not occur, and there were no differences between the actual and proper electromechanical systole values or decrease in the Hegglin indicator. The singularities of change in the cardiac activity indicators noted could be connected with the fact that, during these flights, the astronauts executed complex maneuvers.

Thus, the neuropsychic load caused by performance of complex dynamic operations, although it did not show up noticeably in the general condition and efficiency of the astronauts, nevertheless, caused distinct changes in the heart activity indices.

The EKG and electromechanical relation changes discussed, as well as the change in activity of the first and second vibrational cycles of the SKG, apparently indicate a functional adjustment of the blood circulation apparatus. They are caused both by the singularities of regulation connected with the effect of weightlessness, nervous-emotional stress and change in the hemodynamic relationships (in particular, with redistribution of the blood) and, in all likelihood, with changes in the water-salt metabolism.

Thus, the observed changes in the physiological reactions of the cardiovascular system indicate an adequate, full functional value of the blood circulation apparatus under rest conditions.

In the postflight period, changes in the basic functions of the bodies of all astronauts (with some individual variations in expression) were manifested by development of signs of asthenization and fatigue; a subjective feeling of increase in the weight of objects and of one's own body; deterioration in regulation of the vertical posture, decrease in orthostatic tolerance, tonus and strength of the antigravitation muscles, progressing with increase in flight duration; a decrease in mineral saturation of bone tissues; and a decrease in body weight. Overall, the set of changes observed in the basic physiological systems in the postflight period indicate that the process of adaptation to normal conditions of life on earth, after a prolonged stay under weightless conditions, takes place with certain difficulties and is accompanied by marked stress on the physiological systems.

The specific weight of different factors of space flight, with respect to effect on the body, is far from unambiguous.

Fluctuations of the microclimate parameters, as the results of statistical processing by covariance analysis showed, were not definitive. The total radiation doses received by the astronauts during the entire flight period were not over 0.4 rad and, consequently, could not cause a response reaction of the organism; nervous-emotional stress also did not have a great importance in the changes in physiological functions of the Soyuz 9 crew members during the 18-day flight, since the content of oxycorticosteroids in the urine, which is an indicator of this state, to a certain extent, was even somewhat lower than in the baseline examinations. This /132
circumstance possibly is connected with the fact that the flight took place in complete accordance with the program. Moreover, some decrease in oxycorticosteroid content in the urine permits the hypothesis to be made that there was no activation of the hypothalamo-

hypophyseal-adrenal system under the entire set of orbital flight factors. In other words, in an orbital flight lasting 18 days, no pronounced state of stress was observed. This phenomenon may be connected with the reduction in activity of the dorsal section of the hypothalamus, which plays the leading part in regulation of ACTH secretion by the hypophysis, as a consequence of decrease in the effective impulses from the proprioceptors and other mechanoreceptors, which has been demonstrated in laboratory experiments on animals, by E. Gellhorn and G. Loofbourrow (1966).

Thus, the microclimate, radiation and nervous-emotional stress were not of significant value in emergence of the response reactions of the human body in space flight. Weightlessness, hypokinesia and the intense activity of the crew members apparently were definitive. O. G. Gazenko and B. S. Alyakrinskiy (1970) considered that one of the important causes of change in physiological functions during the 18-day flight is the unusual diurnal rhythm of the crew members (at the beginning of the flight, sleep began at 7:00 a.m. Moscow time, and, at the end of the flight, the beginning of sleep had shifted to midnight).

In the light of what has been reported, prophylaxis of the negative effect of flight factors on the body can be achieved, only by carrying out an extensive set of measures, including rational arrangement of the work-and-rest schedule, specially arranged physical exercises and motor-activity schedule, the use of onboard training exercises and the correct use of pharmacological agents.

4. Condition of Cardiovascular Systems of Astronauts During Flight of Soyuz Orbital Station

After the flights of some American astronauts, a decrease in their orthostatic tolerance was observed, accompanied by a deterioration in condition, during a change of the body from the horizontal position to the vertical (Berry, 1966, 1969; Dietlein, Judy, 1966).

The reaction of the blood circulation of A. G. Nikolayev and V. I. Sevast'yanov to orthostatic effects turned out to be significant, after the 18-day flight in Soyuz 9. As has already been stated in the preceding section, during the first days, the astronauts had difficulty in tolerating a 10-minute orthostatic test, in the process of which they developed paleness of the face, quickening of the pulse and a decrease in stroke volume of the blood. These phenomena were especially pronounced in V. I. Sevast'yanov (V. V. Kolinichenko, V. A. Gornato, et al., 1970). Thus, the effects of prolonged space flight factors results in changes arising in the cardiovascular systems of the astronauts, which limit the duration of the flight and require the conduct of special research under actual flight conditions. In this connection, in the Soviet Union, in preparing for the flight of the Salyut orbital station, a system of periodic medical examinations in a special Polinom apparatus was developed, permitting extensive studies of the blood circulation functions to be performed in flight.

The studies were carried out, for the purpose of study of an overall direction and mechanisms of change in the basic indices of the blood circulation system, under the influence of flight factors, /133 determination of the possibility of predicting orthostatic tolerance of astronauts right during a flight, study of the adequacy of hemodynamic models of weightlessness to actual flight conditions, evaluating the possibilities of a new medical monitoring system, based on a considerable increase in diversity of examination methods, using removable sensors and special functional tests.

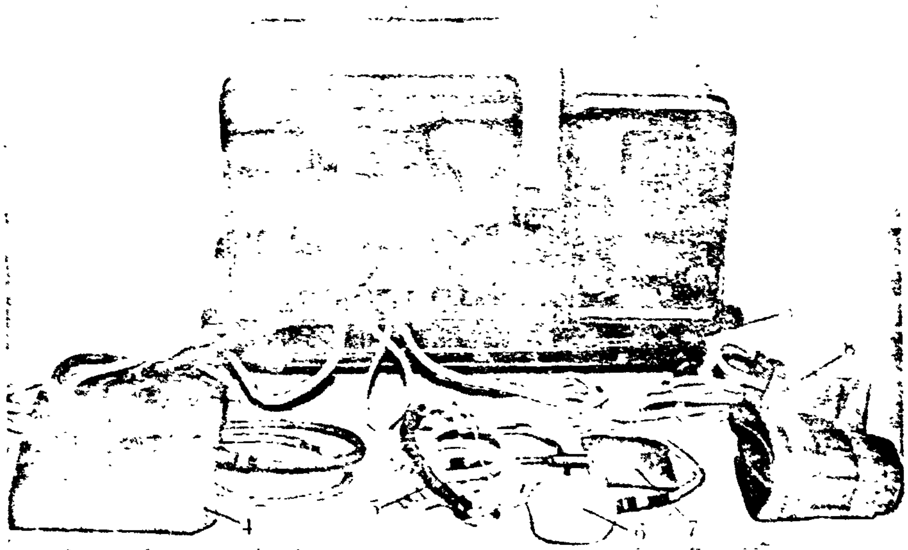

Fig. 21. Outward appearance of Polinom apparatus with second program sensors: 1) measurement channel unit; 2) indicator unit; 3) pneumatic unit; 4) tachyoscillographic cuff with sensor; 5) distal-perimetric oscillogram sensor; 6) kinetocardiographic sensor; 7) kinetocardiogram receiver; 8) thigh pulse cuff with sensor.

Basically, studies of the blood circulation of the Salyut space station crew was the mechanocardiography of V. N. Savitskiy (1963), modified by us, with tachyoscillogram and distal-perimetric oscillograms of the brachial artery, kinetocardiograms in the region of the top impulse of the heart, sphygmograms of the brachial artery and pressure signs in the brachial cuff being recorded by the Polinom apparatus (Fig. 21).

The heart rate, diastolic, mean dynamic, lateral and final systolic arterial pressure, rate of propagation of the pulse wave, in the section from the beginning of the aorta to the middle of the brachial and upper third of the femoral artery and duration of the cardiac cycle phases were determined from the curves recorded.

The stroke and minute volume of the blood were calculated by the Bremser-Rank formula (1930), and the interphase index K, from the ratio $t_{isovol.} \times 100/t_{expel}$, where $t_{isovol.}$ is the duration of the isovolumetric contraction phase of the left ventricle (in seconds), t_{expel} is the duration of the blood expulsion phase of the left ventricle (in seconds), and 100 is a factor to convert the results to percent.

Examinations were carried out twice in the preflight period: 2-1/2 months and 10 days before the flight. In flight, they were started on the 4th day and repeated every 3-4 days through day 21. Just as on earth, the recordings were carried out under rest conditions, during a functional test, with creation of negative pressure on the lower half of the body, and after a proportioned physical workload. The Polinom apparatus functioned normally in flight.

Physiological information was transmitted to earth by continuous radiotelemetry or were recorded by an onboard, multichannel magnetic storage device. /134

Examination at Rest

The volume study of blood circulation, carried out directly during the orbital flight of Salyut, can be decided from tne data of Table 39.

TABLE 39

NUMBER OF EXAMINATIONS CARRIED OUT IN POLINOM-2M APPARATUS DURING FLIGHT OF SALYUT CREW

Examination Conditions	G. T. Dobrovol'skiy	V. N. Volkov	V. I. Patsayev
At rest	5 (3)	6 (4)	4 (3)
After physical workload	4 (1)	5 (3)	—
With creation of negative pressure	1 (1)	—	1 (1)
Total number of examinations of each astronaut	10 (5)	11 (7)	5 (4)

Note: Number of examinations, from which minute volume of blood was calculated is in parentheses.

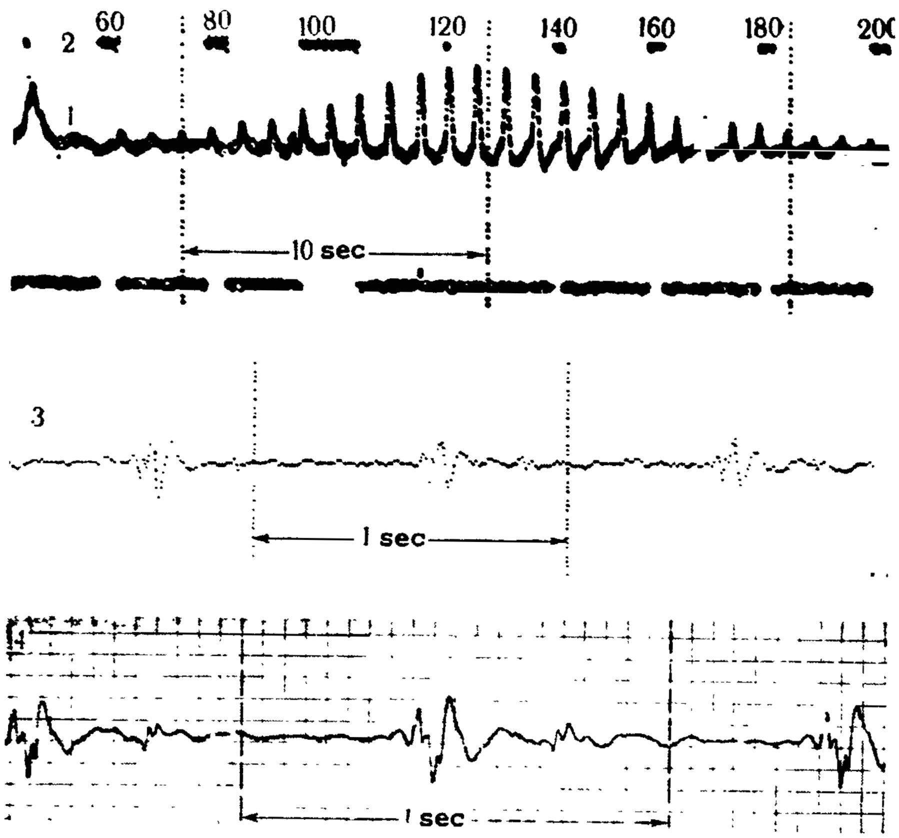

Fig. 22. Samples of flight recordings of tachyoscillogram (1), pressure in brachial cuff (2) of G. T. Dobrovol'skiy 22 June 1971, kinetocardiogram transmitted by telemetry (3) and recorded in magnetic storage device (4) of V. I. Patsayev.

The crew handled the entire conduct of the examinations. The recordings obtained, carried out while observing the conditions specified by the instructions, were of high quality and could be interpreted completely (Fig. 22). However, significant difficulties arose during the flight, with recording the pulse of the femoral artery. In connection with this, the stroke volume of blood was calculated, in the majority of cases, by incorporation of the propagation rate of the pulse wave in the sections of the vessels from the aorta to the middle of the brachial artery in the Bremser-Rank formula.

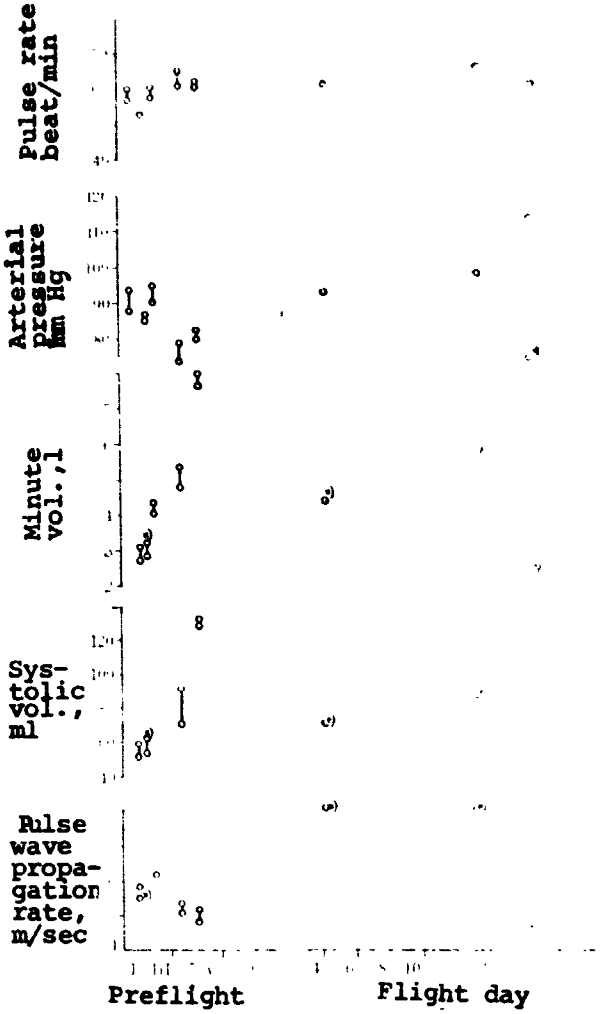

Fig. 23. Blood circulation index dynamics of G. T. Dobrovol'skiy during preflight examination and during flight of Salyut: the symbol × indicates that the measurements were carried out with a specific time of propagation of the pulse wave to the brachial artery.

The dynamics of the basic blood circulation indices, recorded for the astronauts during the preflight examination and on various days of the flight, at rest and directly before per- /136 formance of functional workloads, are shown in Figs. 23, 24 and 25. It is evident from the data presented that the changes in blood circulation during the flight are characterized by some stress of this function. If the hemodynamic indicators are compared with the initial ones, recorded for spacecraft commander G. T. Dobrovol'skiy and engineer-researcher V. I. Patsayev on earth, their values turn out to be closer to the results of the last examination, which was performed directly before going out to the spaceport. The last preparations for launch, final medical examinations, etc., took place at this time. Thus, the saturated nature of the working day of the astronauts was much more intensive than 2-1/2 months preflight, when the crew of the space station was first examined under the flight program. The heart rate of G. T. Dobrovol'skiy in flight, just like on 27 May 1971, was 60-66 beats per minute. The mean arterial pressure ~ the 4th and 13th days of the f t were 3.5 and 9% /137 above 90 mm Hg, respectively, and 31.5% on day 16. In an absolute majority of cases, it was 5-10% below this value in the preflight examination and 3-4.5% higher only two times.

The minute volume of the blood exceeded 5.5 l in flight, in two out of three cases (by 3.5% in one case and 54.5% in the other), and it was 20% less in one case. During the preflight examination, the minute volume of blood proved to be greater than

5.5 1 in only two cases of six: by 4.5% and 40-45%, respectively. It was 44-51% less in one case and 23-25% in three cases. The systolic blood volume duplicated the minute volume dynamics to a considerable extent. The pulse wave propagation rate from the aorta to the middle of the brachial artery of the station commander was above the initial rate on days 4 and 13.

Single extrasystoles were recorded throughout the flight for G. T. Dobrovol'skiy; they were determined from changes in the tachyoscillogram and kinetocardiogram complexes.

The heart rate of V. I. Patsayev, during conduct of the periodic in-flight examinations, was 72-77 beats per minute. During the preflight examinations, it was 60 beats or less and, only on 18 March 1971, just before performing a functional test with a physical workload, it reached 73 beats per minute.

The mean arterial pressure was 33.5 and 31.5% above 90 mm Hg on days 5 and 12 of the flight and 90% above on day 13. The maximum increase in mean pressure on earth, compared with the control value, was 25-27%, and this was observed only once, 27 May 1971. During the remaining examinations, it usually was 7-13% higher than 90 mm Hg.

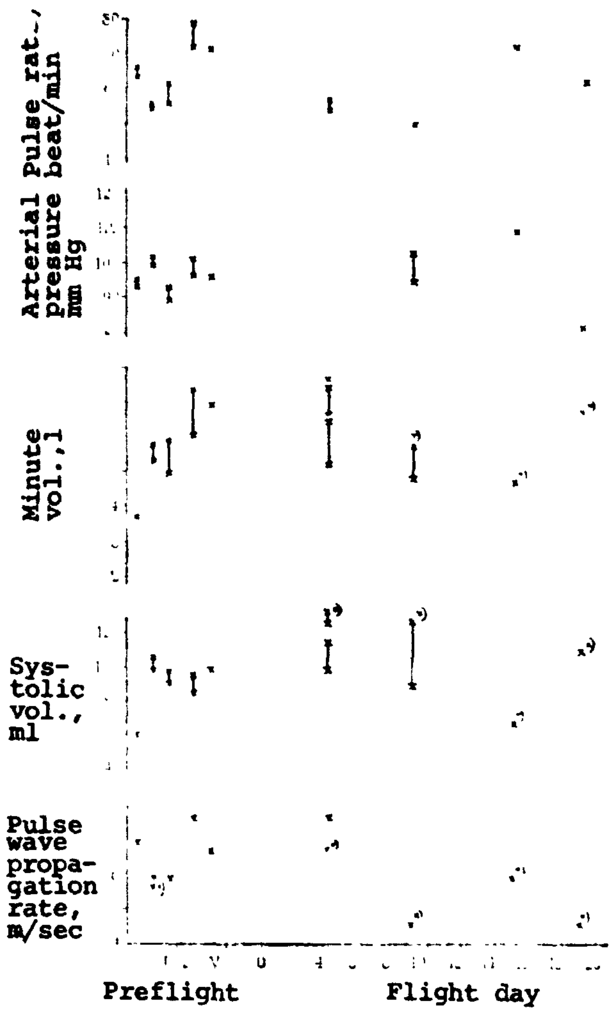

Fig. 24. Blood circulation index dynamics of V. N. Volkov in preflight examination and during flight of Salyut: designations same as in Fig. 23.

The minute volume of blood in all three examinations inflight under rest conditions held at the 5.5-6.5 l level. It was below 5.5 1 8 of 10 times in the preflight examination.

The systolic blood volume remained stable in flight, which correlated with the pulse rate to a greater extent than for G. T. Dobrovol'skiy, and it was lower than in a majority of measurements on ear . The pulse wave propagation rate along the arteries of V. I. Patsayev held at its lowest level on days 5 and 13 of the

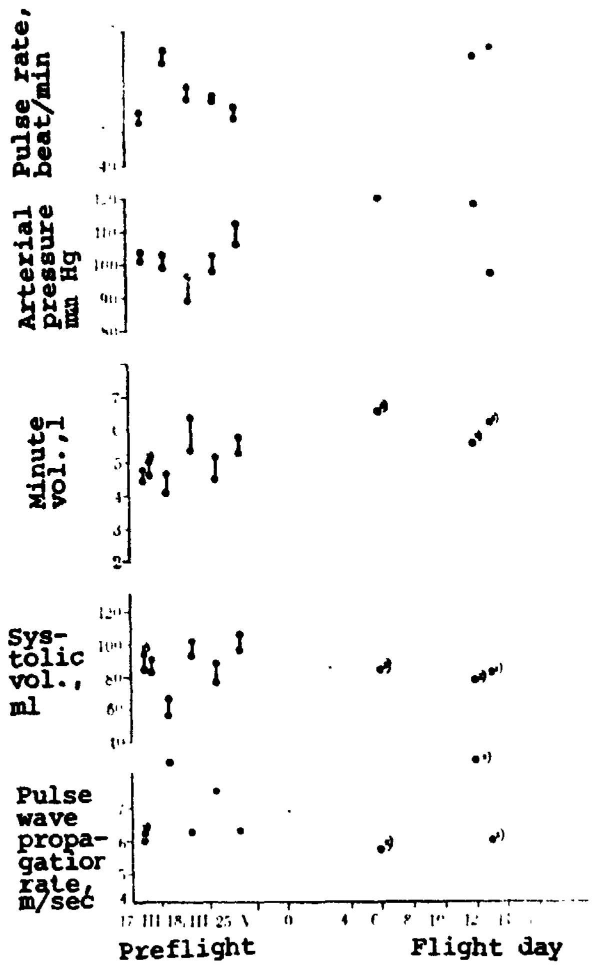

Fig. 25. Blood circulation index dynamics of V. I. Patsayev in preflight examination and during flight of Salyut: designations same as in Fig. 23.

flight; it somewhat exceeded the highest value recorded on earth on day 12.

In distinction from G. T. Dobrovol'skiy and V. I. Patsayev, the hemodynamic indices of V. N. Volkov during the in-flight examinations usually was at the level of the average values recorded on earth or below his minima. Thus, his heart rate was 50 beats per minute on day 9. In the preflight examination, its lowest value was 56 beats per minute. The average arterial pressure decreased to 82 mm Hg on day 19. In a flight program examination on earth, it was not once below 90 mm Hg. The pulse wave propagation rate along the arteries had still more pronounced deviations. It turned out to be 20% lower than the lowest initial value on days 9 and 19. However, there were days during the flight, when the blood circulation indices of V. N. Volkov reached the maximum values noted on earth or exceeded them. It was the same with the minute and systolic blood volume and pulse wave propagation rate on the 4th day of the flight and with arterial pressure on day 15. Such an important blood circulation index as the minute volume of blood corresponded to /138 the initial values to a greater extent for V. N. Volkov in flight than for G. T. Dobrovol'skiy and V. I. Patsayev, but his did not once decrease to the minimum level (3.7 l) observed during preflight examinations.

The results of study of the phase structure of the cardiac cycle performed on the top kinetocardiogram, recorded on different days of the flight, confirms the conclusion, drawn in analysis of the overall hemodynamics, that the state of the blood circulation studied in flight under rest conditions has singularities, indicating a certain stress on the function. The duration of the isovolumetric contraction phase, during all studies, without exception, was at the lowest level recorded on earth, or 0.005-0.010 sec shorter (Fig. 26). Subsequent shortening of this phase was noted in G. T. Dobrovol'skiy and V. N. Volkov on days 16 and 21 of the flight and, in V. I. Patsayev, on day 13.

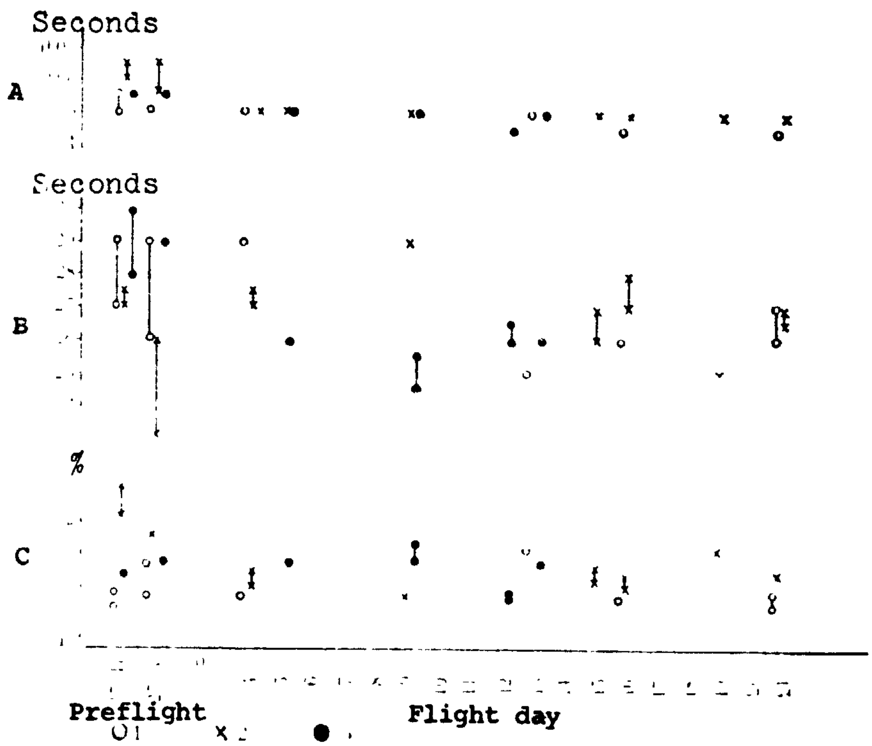

Fig. 26. Duration of left ventricle phases of G. T. Dobrovol'skiy (1), V. N. Volkov (2), and V. I. Patsayev (3) in preflight examination and during Salyut space station flight: A, isovolumetric contraction phase; B, blood expulsion phase; C, interphase index.

The left ventricle blood expulsion period changed within broader limits and had a tendency to shorten in G. T. Dobrovol'skiy and V. I. Patsayev; for V. N. Volkov, it equaled the preflight or exceeded it. The interphase index was lower than the initial, and it turned out to be slightly higher than recorded on earth only one time, in G. T. Dobrovol'skiy.

Fundamental conclusions can be drawn from a general analysis of the data presented.

1. Oscillations in the blood circulation indices of all crew members, on various days of flight, did not go beyond the limits of change in them during preflight examination on earth, in a majority of cases.

2. No changes in blood circulation were found in examination of the astronauts under rest conditions, which could have any clear connection with increase in length of the orbital station flight.

3. The effect of the flight factors does not completely smooth out the individual singularities of reactions of the blood circulation system, characteristic of the body of each astronaut.

In working out the system of periodic examinations for the Salyut space station, together with fabrication of the new Polinom-2M medical monitoring apparatus, much attention was given to finding a functional test, which would make it possible to objectively evaluate changes in orthostatic tolerance of the astronauts in flight. Extensive experimental research has shown that the functional test, with creation of a negative pressure on the lower half of the body, corresponds to the task to the greatest extent. The changes in the cardiovascular system arising in this test turned out to be very close to those, which are observed in changing the body from the horizontal position to the passive vertical.

A vacuum of -60 mm Hg practically coincided with the effect of the orthostatic tolerance test. However, the reduction in orthostatic tolerance of those examined can be decided, with considerably lower negative pressures, -27-36 mm Hg. After verification in clinostatic hypodynamia and water immersion tests, they were recommended for conduct of tests of the astronauts, under orbital flight conditions.

The functional test was carried out with the person being examined immersed in the vacuum container, to the upper level of the ridge of the ilium, in the horizontal preflight examination and in the vertical position in flight. A vacuum of 27 mm Hg was created inside the container in the first two minutes of the preflight examination and 36 mm Hg in the next three minutes. After this, the pressure in it was equalized with the atmosphere. The functional test was performed in flight by G. T. Dobrovol'skiy and V. I. Patsayev on 19 June 1971, in day 13 of the flight (Figs. 27 and 28). V. I. Patsayev strictly maintained the assigned vacuum conditions, and G. T. Dobrovol'skiy created a negative pressure of 30 mm Hg in the first two minutes of the test and 40 mm Hg in the next three min, which was 3-4 mm Hg higher than the assigned values. /139

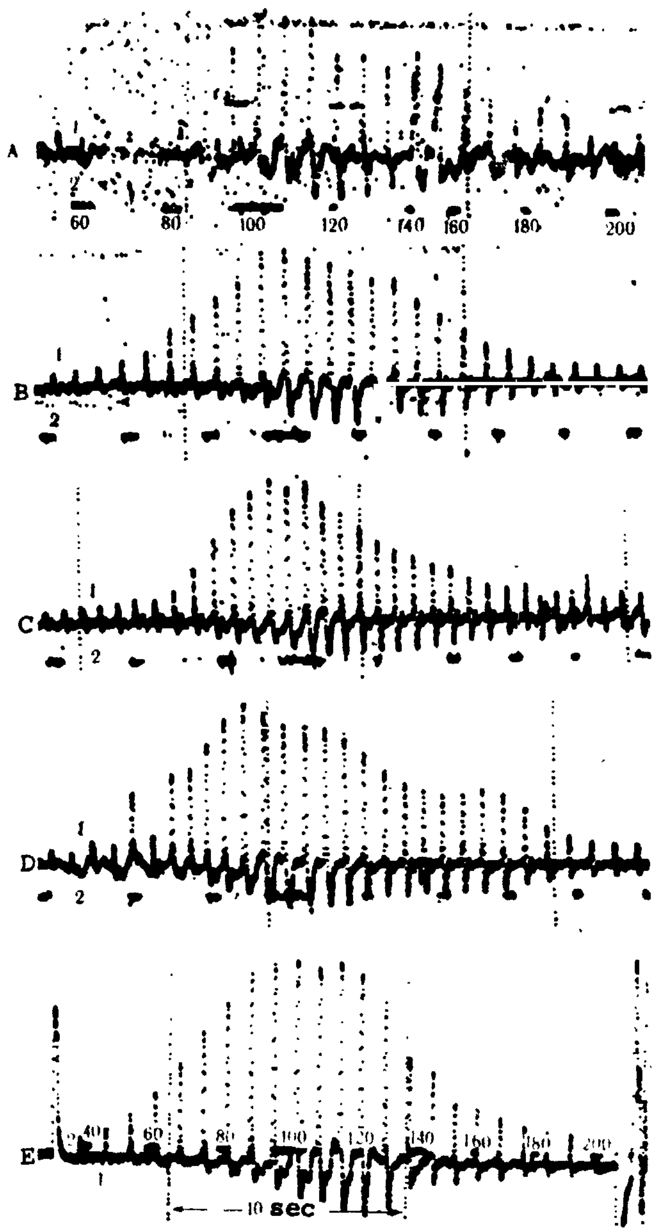

Fig. 27. Tachyoscillogram (1) of G. T. Dobrovol'skiy and pressure signs in cuff (2), recorded on day 13 of flight, at rest (A), at 35 sec (B), at 2 min 40 sec (C), and 4 min (D) of functional test , with negative pressure on lower half of body and at 2 min 30 sec (E) of recovery period.

In neither radioconversations conducted during the functional test, nor on subsequent days, nor in entries in the station log, did the astronauts note a complaint of deterioration in the state of health during the process of creating negative pressure. Nevertheless, compared with the hemodynamics indices recorded in performing the test on earth and in flight, a more pronounced reaction of the cardiovascular system to this test was found in flight.

As is evident from the data presented in Figs. 29 and 30, in creating negative pressure in flight, the direction of change in the hemodynamics indicator remains the /140 same as on earth; however, the absolute values of their deviations from the initial value are more pronounced.

The heart rate of G. T. Dobrovol'skiy, in performing the test with negative pressure in the preflight period, was practically unchanged or increased by 4-5 beats per minute. In flight, it was higher than the initial by 9 beats in 30 sec of the test, and at 2 min, by 24-17 beats per minute. In this case, directly before creating negative pressure, his heart rate also was higher than on earth.

Changes in other blood circulation indices of the spacecraft commander were more pronounced, during creation of negative pressure on the 13th day of the flight. The mean arterial pressure decreased from 98 to 86 mm Hg. In the preflight examination, it

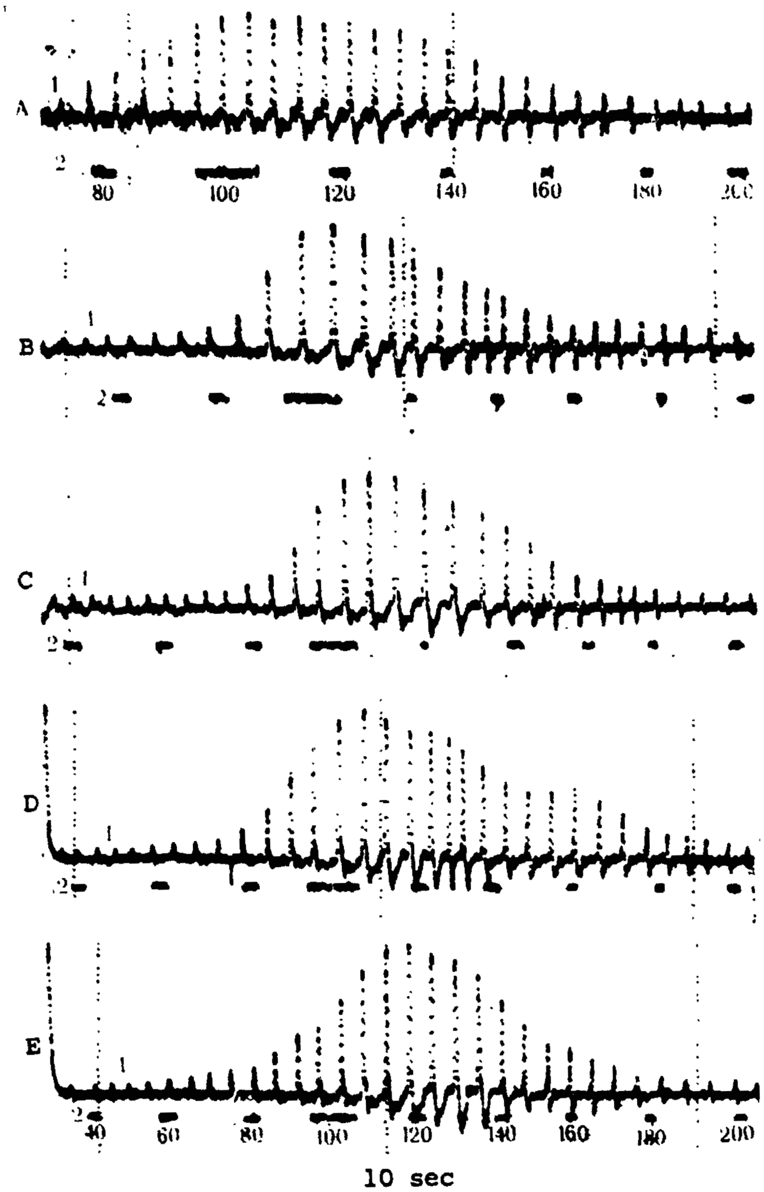

Fig. 28. Tachyoscillogram (1) of V. I. Patsayev and pressure signs in cuff (2), recorded on day 13 of flight, at rest (A), at 20 sec (B), at 1 min 40 sec (C), at 3 min 40 sec (D) and at 4 min 20 sec (E) of functional test with negative pressure on lower half of body.

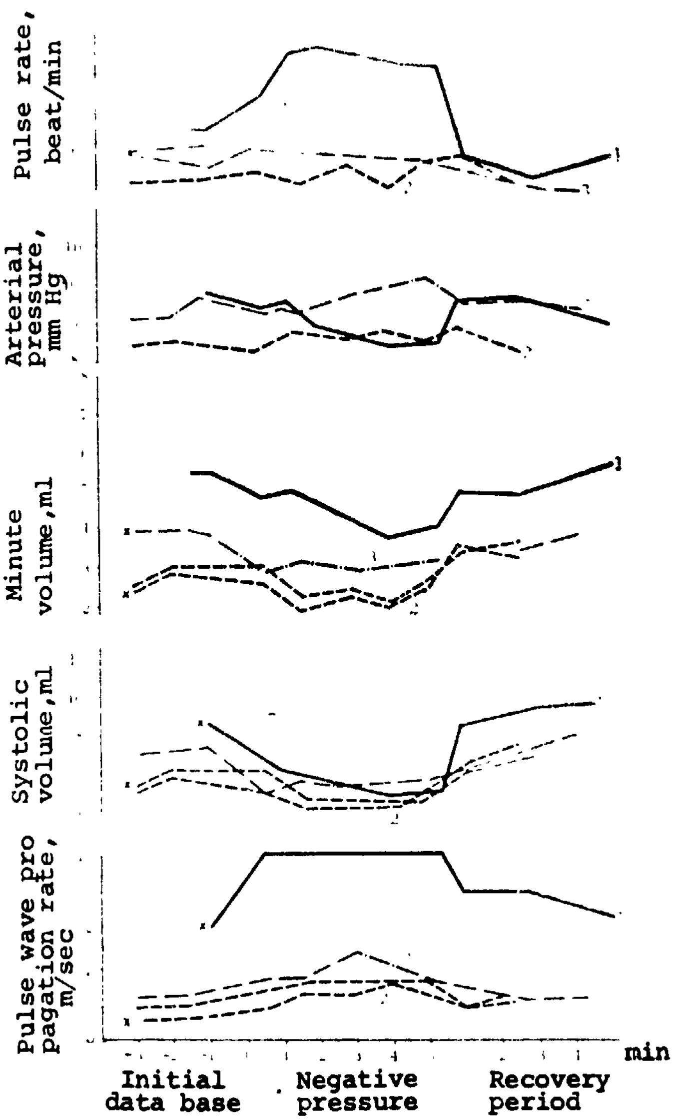

Fig. 29. Blood circulation index dynamics of G. T. Dobrovol'skiy in functional test, with negative pressure on lower half of body: 1) on day 13 of Salyut flight; 2) in preflight examination at 10:00 a.m. 17 March 1971; 3) in preflight examination at 2:00 p.m. 17 March 1971; the ×-symbols here and in Fig. 30 show that the data were calculated from pulse wave propagation time to brachial artery.

equaled the initial or increased by 8-10 mm Hg. The minute volume of blood decreased by 1.7 l and the systolic, by 37 ml. Their maximum decreases on earth were 1.1 l and 22 ml. The pulse wave propagation rate along the ascending aorta, subclavian and upper half of the brachial artery increased sharply over the preflight data.

The heart rate of V. I. Patsayev increased by 14 beats per minute under negative pressure on the 13th day of the flight, although his initial pulse rate before the test was 15-20 beats per minute higher than on earth. In two tests during the preflight period, the heart rate of V. I. Patsayev increased by 7-10 beats and, in one test (27 May 1971), just as in flight, by 14 beats per minute. The arterial pressure reaction was more marked in flight, but it differed by change in direction from the reaction of G. T. Dobrovol'skiy. As is seen in Fig. 30, the mean pressure of V. I. Patsayev gradually increased during decompression and, during subsequent measurements, directly before equalizing the pressure in the vacuum chamber, it was 18 mm Hg higher than the initial. His mean pressure also increased under negative pressure on earth, but the absolute figures of increase in it were not over 8-10 mm Hg. The changes in heart rate and arterial pressure of the engineer-investigator, noted during flight, took place on a background of reduction of minute and systolic blood volume in the first 1-1/2 min, approximately the same as on earth. In the next 2-1/2 min of the test in flight, the minute volume of

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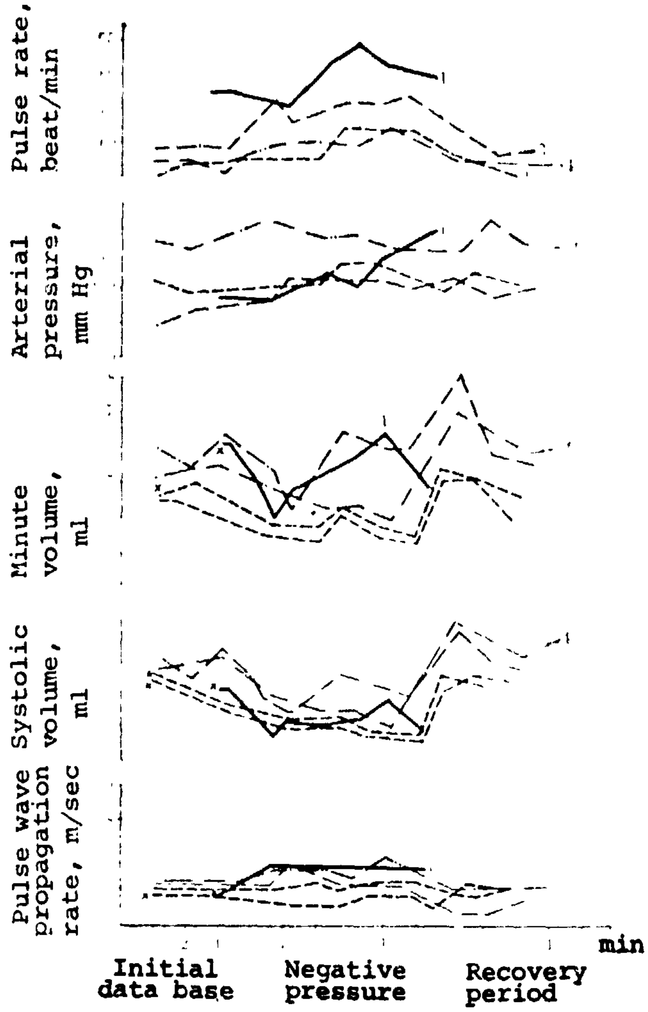

Fig. 30. Blood circulation index dynamics of V. I. Patsayev in functional test with negative pressure on lower half of body: 1) on 13th day of Salyut flight; in preflight examination at 10:00 a.m. 17 March 1971; 3) same at 2:00 p.m. 17 March 1971; 4) in preflight examination 27 May 1971.

the blood became equal to the initial value and again decreased considerably. A somewhat larger increase in pulse wave propagation rate along the vessels was /146 observed in V. I. Patsayev in flight than during decompression on earth.

With negative pressure in the lower half of the body, the amplitudes of kinetocardiogram elements connected with expulsion of blood from and entry of it into the ventricle decreased (Fig. 31).

More pronounced changes of the cardiac cycle phases developed in the astronauts than on earth. This is easily seen in Fig. 32, in which the dynamics of the /148 lengths of the isovolumetric contraction phase and left ventricle blood expulsion period and change in the interphase index K, during pressure reduction on the 13th day of the flight and in the preflight period, are presented.

The blood expulsion phase duration of G. T. Dobrovol'skiy under flight conditions decreased by 28% over the initial and by 6-14% on earth. Coefficient K increased by 53% and by 33% on earth.

The in-flight changes of V. I. Patsayev were very close to the changes of G. T. Dobrovol'skiy. The blood expulsion phase during the functional test with negative pressure decreased by 23% in flight, and coefficient K increased by 54%. During the preflight examination, his expulsion period length decreased by 7-15%, and the value of coefficient K increased by only 16-29%. The increase in length of the isometric contraction phase of the left ventricle of V. I. Patsayev, during in-flight decompression was more pronounced than that of G. T. Dovrovol'skiy, but, just as with him, it remained within the limits noted in conduct of the test with decompression on earth.

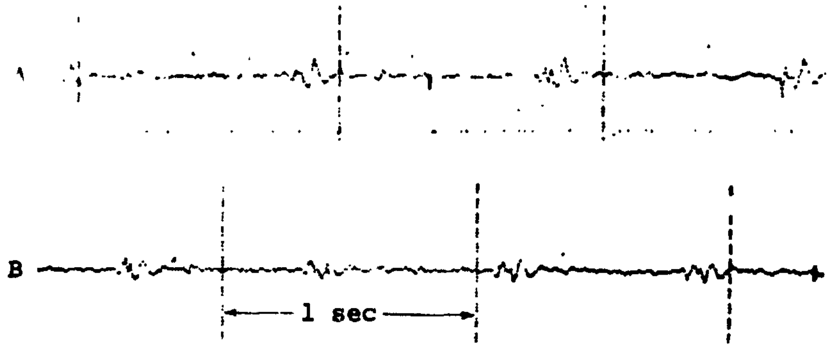

Fig. 31. Change in kinetocardiograms during test with negative pressure of lower half of body of G. T. Dobrovol'skiy in flight: A, before test; B, last minute of test.

A functional test with physical workload also was conducted. In this test on earth, the astronauts, depending on their weight, performed 17-21 squats per minute. V. N. Volkov performed 17 squats in 35 sec on 25 May 1971. Aboard the spacecraft, he performed 30 or 40 squats in 1 min-1 min 20 sec, holding a rubber shock absorber with 25 kg resistance in each hand. Assuming that the squat amplitude was 0.5 m, by approximate calculations, the work performed must have fluctuated from 1100 to 1500 kgm. As is shown by analysis of the oscillogram, during a physical workload in flight, V. N. Volkov performed 30 squats in 40-44 sec on days 4 and 9, 40 squats in 1 min 17 sec on day 15, 30 squats in 51 sec on day 16 and 30 squats in 1 min on day 21. G. T. Dobrovol'skiy, approximately on the 4th day, performed 30 squats in 1 min, 40 squats in 1 min on day 16 and 35 squats in 54 sec on day 21.

The squat test in flight was accompanied by more pronounced deviations of the hemodynamic indices (Figs. 33-38). The heart rate recovered more slowly. However, in all cases, when the dynamics of pulse rate was successfully followed, under the recording conditions, for a period of 2-3 min in a row, it successfully returned to normal during this time.

The differences can most often be explained by the magnitude of the load or performance rate. The extent of loading of the crew with current work and their fatigue apparently played a significant role. In any case, the pulse recovery of V. N. Volkov on 15 June 1971 took place considerably faster than on 10 June 1971, and that of 27 June 1971, faster than those of 21 and 22 June 1971.

The heart rate dynamics of G. T. Dobrovol'skiy after loading also were practically identical on 10 June 1971 and 27 June 1971.

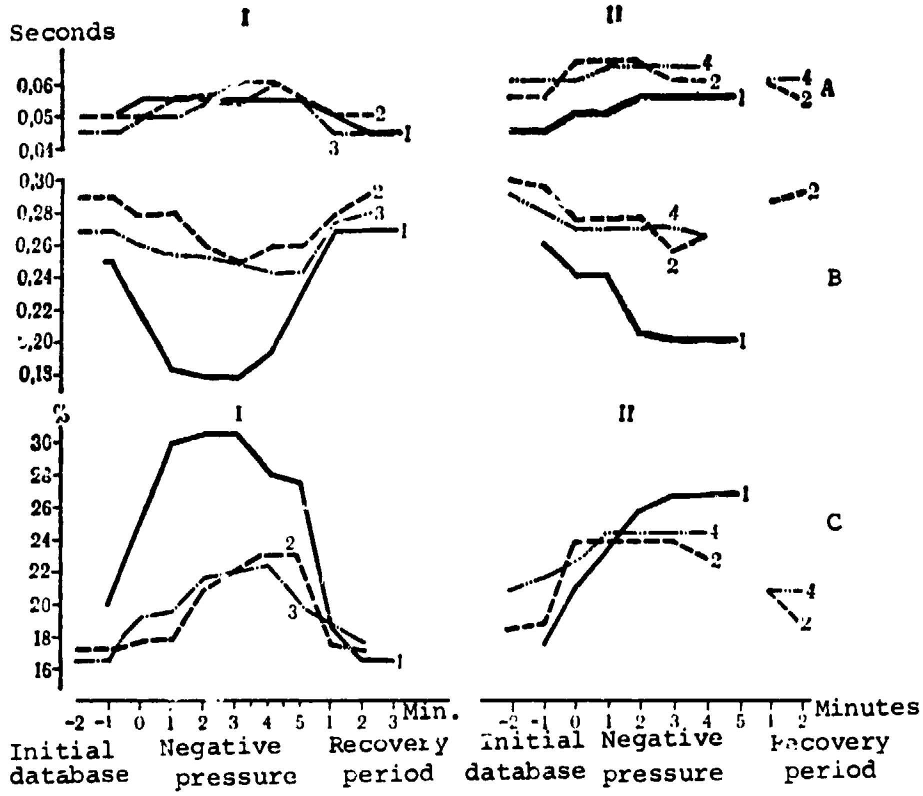

Fig. 32. Dynamics of left ventricle phases of G. T. Dobrovol'skiy (I) and V. I. Patsayev (II) during functional test with negative pressure on lower half of body: A, isovolumetric contraction phase; B, blood expulsion phase; C, interphase index; 1) on 13th day of Salyut flight; 2) in preflight examination at 10:00 a.m. 17 March 1971; 3) same at 2:00 p.m. 17 March 1971; 4) same 25 May 1971.

A reduction in diastolic arterial pressure and an increase in lateral and final systolic pressure were observed in V. N. Volkov, after physical workload in flight, just as on earth. The average pressure was unchanged or decreased. The minute blood volume stayed at the initial level or increased. The most significant increase in it was observed on the 9th and 15th days of the flight. A maximum quickening of the pulse also was recorded on days 15 and 16, in response to the workload (by 93-120%). On one of these days, V. N. Volkov performed 40 squats and on the other, 30, not, however, in 60, but in 51 sec. Slower return to normal of the minute blood volume took place in flight. The reduction in diastolic and increase in systolic arterial pressure also turned out to be prolonged. The amplitude of the respiratory pressure waves increased. /149

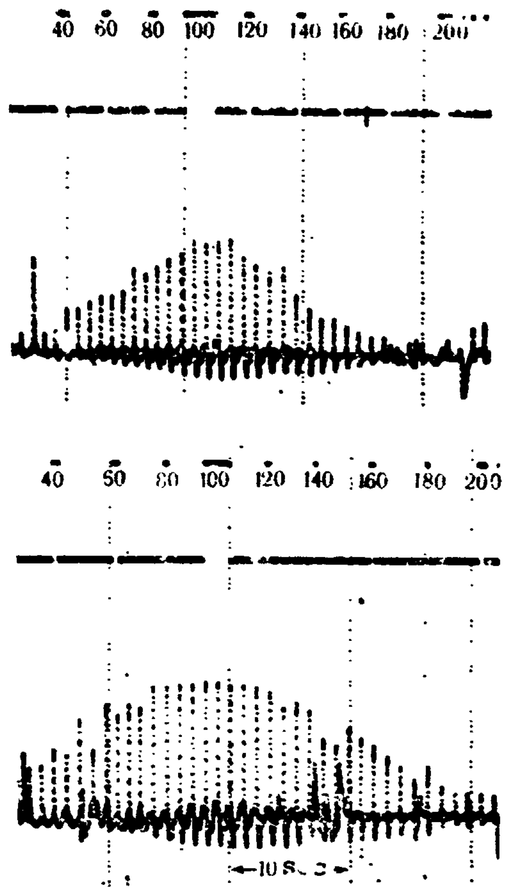

Fig. 33. Tachyoscillogram of V. N. Volkov, recorded in flight 10 June 1971, in functional test with physical workload: I) before physical workload; II) in first minute of recovery period; numbers are upper arm cuff pressure indicators.

In interpreting the tape, a brief increase in heart rate and increase in pressure could be seen, in response to movement of the person being examined, particularly with adjustment of the equipment and pulling up the thigh cuff, which could be judged from the "jerks" on the oscillograms. This increase in arterial pressure apparently took place in V. N. Volkov, in recording the initial data, before the physical workload on the 15th day. Judging from the changes in the tachyoscillogram during its recording, all the pressure indices increased by a minimum of 20-25 mm Hg and, then, decreased most quickly. As a result, a false impression was created of a large (45-50 mm Hg) pressure drop immediately after the physical workload. G. T. Dobrovol'skiy had an unusually high arterial pressure and minute volume of blood on 22 June 197̄ , on da .6 of the flight (see Figs. 22 and 36). 30-40 sec after performing the test, his minimum pressure decreased by 16 mm Hg, the minute blood volume increased by 1.6 l and the pulse wave propagation rate on the artery increased by 1.4 m/sec. By the 6th minute of the recovery period, the minimum arterial pressure remained 8 mm Hg below the initial, and the minute blood volume increased by 4.9 l, in comparison with it.

The results of mechanocardiographic study of the blood circulation under a physical workload fully confirms the research data of the cardiac cycle phases in these tests.

As is evident from Fig. :7, the amplitudes of kinetocardiogram elements immediately after the workload in flight increased approximately 1-1/. - 2 times and returned to the initial level in 3 min of

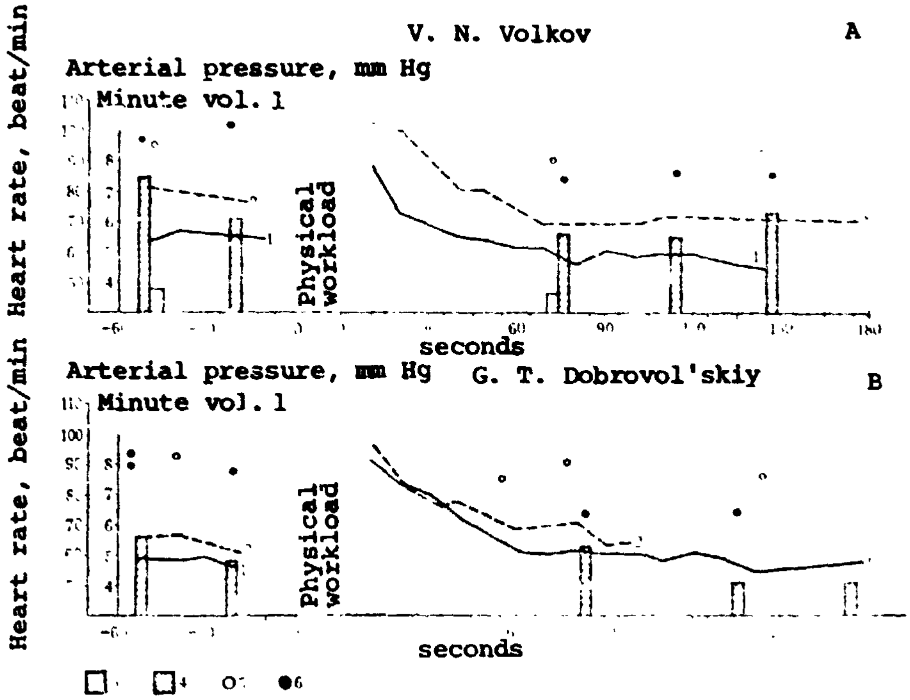

Fig. 34. Blood circulation index dynamics of V. N. Volkov (A) and G. T. Dobrovol'skiy (B) in functional tests with physical workload during preflight examination: 1), 2), heartrate; 3), 4) blood circulation minute volume; 5), 6), mean dynamic arterial pressure on 17 March and 27 May 1971, respectively.

the recovery period. In preflight examination, changes in kinetocardiogram amplitudes with this workload were more moderate and became normal more rapidly. In a comparison of the cardiac cycle phase dynamics after a physical workload, the more significant shortening of the isovolumetric contraction phase of the left ventricle, especially the period of expulsion of blood by it, than in the preflight examination, attracts attention (Fig. 38). /150

In one test with a physical workload, conducted with G. T. Dobrovol'skiy before the flight, the isovolumetric contraction phase was unchanged at the end of the first minute of the recovery period and, in another test, it decreased by 10%. On days 4, 9, 16 and 21 of the flight, it increased by 11% each time and by 20% one time. The blood expulsion period in the preflight examination decreased or increased by 3-4%. The change in it inflight was the same as that of the isovolumetric control action phase, but it was not of a progressive nature, connected with increase in flight duration; rather it was very much larger (13-20%). The change in cardiac cycle phase structure of V. N. Volkov after physical workload in flight was of a similar nature; the isovolumetric contraction phase of the left ventricle decreased on days 4 and 15, by 20%, by 10% /151 on days 16 and 21; it did not change on day 9. In the preflight

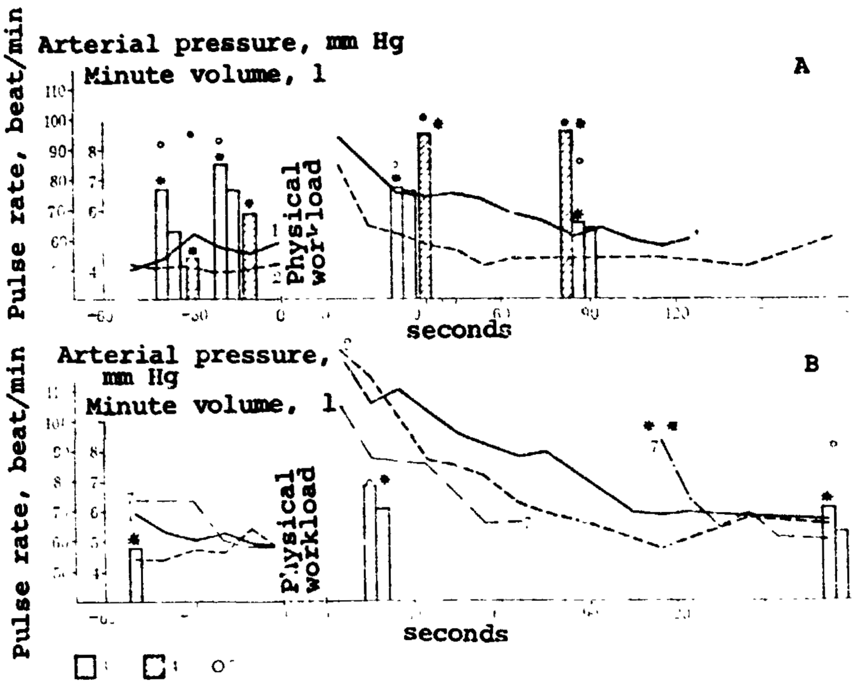

Fig. 35. Blood circulation index dynamics of V. N. Volkov in functional test with physical workload during flight of Salyut space station: A, 1), 2) heart rate; 3), 4) blood circulation minute volume; 5), 6) mean dynamic arterial pressure on days 4 and 9 of flight, respectively; B, 1) heart rate; 3) blood circulation minute volume; 5) mean dynamic arterial pressure on day 15 of flight; 2),7) heart rate on days 16 and 21 of flight; asterisks here and in Fig. 36 show the minute volume, determined by incorporation of the pulse wave velocity to the brachial artery into the Bremser-Rank formula; two asterisks indicate quickening of heart beat, connected with adjustment of equipment.

examination, it remained at the initial level one time, but it decreased by 16% another time. The blood expulsion period in flight decreased by 11-19%, by the end of the first minute of the recovery period; during examination on earth, it decreased or increased by 4%.

In analyzing the results of periodic studies of the blood circulation with the Polinom-2M apparatus, we consider it necessary to stress their preliminary nature. This is explained by both the relatively small amount of data obtained and by the errors committed, for example, in determination of the blood flow rate. The physical workload magnitude was not strictly regulated in flight; a test with

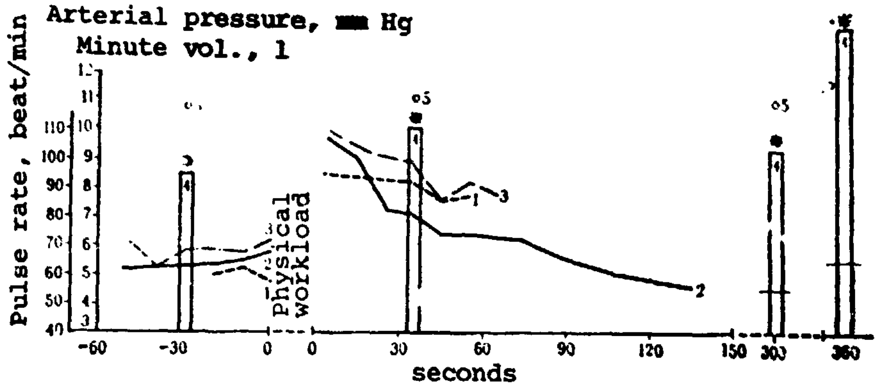

Fig. 36. Blood circulation index dynamics of G. T. Dobrovol'skiy in performing functional test with physical workload in flight of Salyut space station: 1), 2), 3) heart rate on 4th, 16th and 21st day of flight; 4) blood circulation minute volume; 5) mean dynamic arterial pressure on 16th day of flight.

negative pressure on the lower half of the body was only performed once. These studies will be continued and, only upon accumulation of considerably more material, can a more complete conclusion be made.

Three questions deserve the greatest attention:

1. To what extent are the changes in blood circulation recorded in flight specific for the effect of weightlessness and to what extent do they coincide with or differ from data obtained in simulated weightlessness on earth?

2. Is further change in the condition of the astronauts observed, in proportion to increase in flight time? of what do they consist, and can objective criteria of orthostatic tolerance in flight be found? /152

3. Are the methods and functional tests used in flight adequate to answer these questions, and what proposals can be made for improvement of methods of examining the crew in subsequent flights?

It is right to ask these questions for two reasons. First, the flight of the Salyut space station crew was longer than all the preceding ones. Second, equipment, permitting the crew to carry out the most extensive studies of the blood circulation system, compared with those performed earlier, was installed aboard the station. /153

Fig. 37. Kinetocardiogram of V. N. Volkov, recorded in flight 22 June 1971 during functional test with physical workload: A, before workload; B, at 5 sec; C, at 1 minute; D, at 3rd minute of recovery period.

Analysis of the data of the periodic medical examinations leads to concluding that, under rest conditions in flight, the changes in a number of blood circulation indices are similar, in some ways, to their dynamics in prolonged clinostatic hypodynamia.

For comparison, the results of study of blood circulation with the Polinom-2M apparatus, on various days of an experiment, with a 30-day stay of the subjects under strict bed rest conditions, with the head end of the bed inclined 4° below the horizontal line, are presented in Fig. 39.

According to data in the literature, as a rule, in clinostatic hypodynamia experiments, the pulse quickens, the arterial pressure and tonus of the vessels increases and the systolic and minute volumes of the blood decrease.

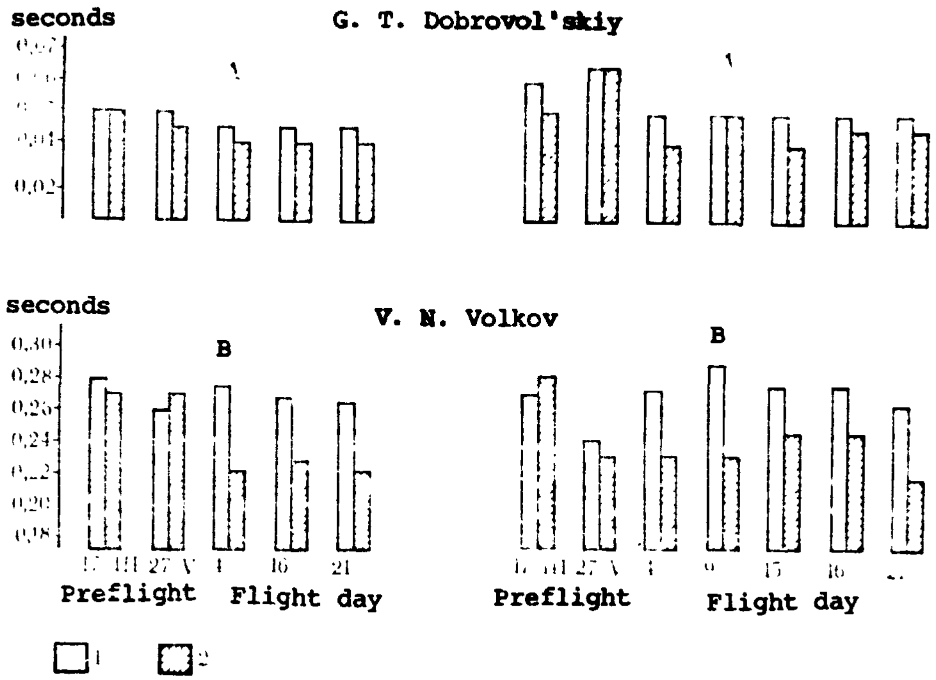

Fig. 38. Duration of left ventricle phases of G. T. Dobrovol'skiy and V. N. Volkov during functional test with physical workload: A, isovolumetric contraction phase B, blood expulsion phase; 1) before physical workload; 2) 10-20 sec of recovery period.

In simulating weightlessness on earth, in cases of two subjects (S and N) presented, a quickening of the pulse was observed on the 9th-10th day, and the pulse of one (K) did not change noticeably. The arterial pressure and pulse wave propagation rate along the arteries of all three subjects increased. The minute and systolic blood volume had wave-like dynamics, with a noticeable tendency to increase, on days, when the examination preceded conduct of a functional test with negative pressure (days 9, 16, 21 and 2? of hypodynamia).

In flight, as has already been noted, the minute blood volume was greater than in the preflight period. By contrast, the pulse wave propagation rate was more often at the level of its minimum values on earth or below them. Only two records were exceptions: those of G. T. Dobrovol'skiy on days 4 and 13 and of V. I. Patsayev on day 12. It must be kept in mind here that, in the preflight examination, the pulse wave propagation rate was recorded more often, in the section from the origin of the aorta to the upper one-third of the femoral artery, but, in flight, from the origin of the

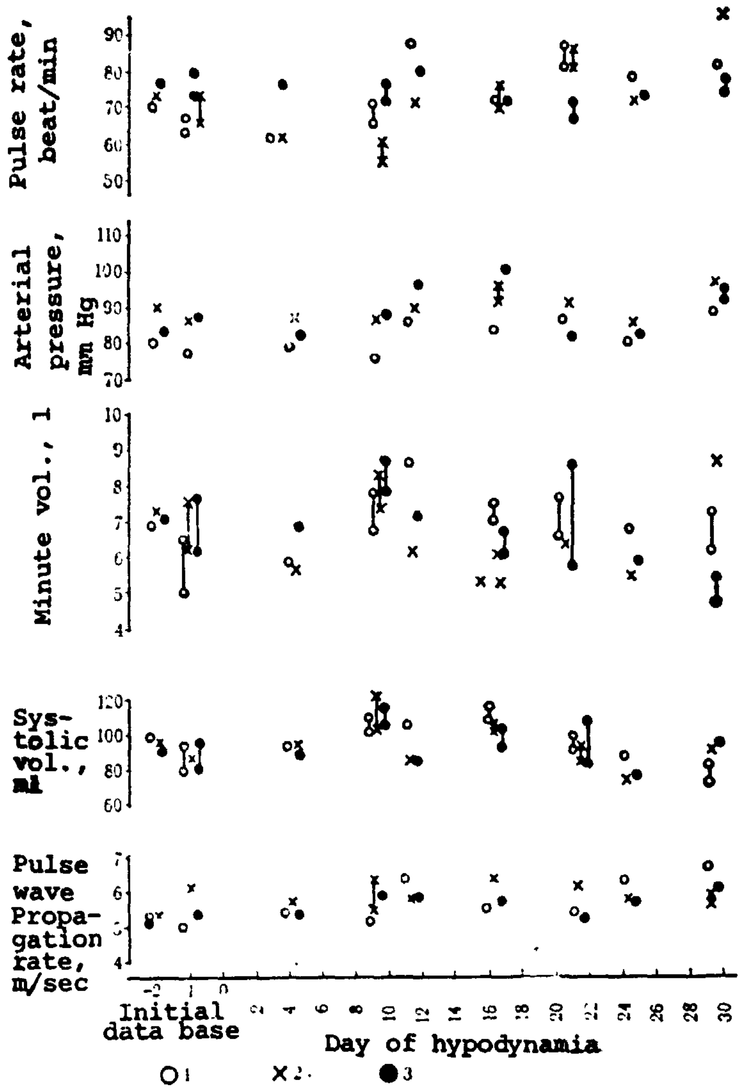

Fig. 39. Blood circulation index dynamics in 30-day clinostatic hypodynamia of subjects S(1), N(2) and K(3).

aorta to the middle of the brachial artery, i.e., in vessels containing more muscle elements. Thus, it would be more logical to expect the reverse relationship: an increase in pulse wave propagation rate along the arteries in flight. Finally, the broader amplitude of fluctuations of some blood circulation indices in flight, than in the simulated experiments, cannot fail to be noticed. Thus, the pulse wave propagation rate of G. T. Dobrovol'skiy on days 4 and 13 of the flight were 35% higher than the initial and 25% lower on day 16.

The difference between days 4 and 13 and day 16 was 44.5%. Comparing days 13 and 16, the average pressure was 21% higher. The average pressure of V. I. Patsayev on day 13 was lower than on days 12 and 5, by 20.5 and 22.5%, respectively. In turn, the pulse wave propagation rate on day 12 proved to be 42.5 and 49% higher than on days 13 and 5. The pulse wave propagation rate along the arteries of V. N. Volkov was 49% higher on day 4 than on day 9. The average pressure was 34% higher on day 15 than on day 19.

In model experiments, the difference in pulse wave propagation rate along the arteries usually was 6-8% and 27%, in individual cases. The divergence between the values of the average pressure recorded on different days was 6-14% and, on only one day, it was 20%. However, in our opinion, it would be incorrect to attribute /154 the changes in blood circulation state in flight to the effect of prolonged weightlessness alone. The crew performed a saturated program of scientific experiments. This, like the quite high background of emotional stress characteristic of space flights, could not fail to be reflected in the functioning of the cardiovascular system and to affect the dynamics of its indices.

Data are presented in Fig. 40, on changes in the isovolumetric contraction phase of the left ventricle and the blood expulsion phase of it, in subjects under clinostatic hypodynamia. If Fig. 40 is compared with Fig. 26, the difference becomes obvious.

In the flight of the Salyut space station, the isovolumetric contraction phase of V. N. Volkov shortened by 16.5-25%, that of V. I. Patsayev by 9-18.5%, and that of G. T. Dobrovol'skiy was unchanged on days 4 and 9; it was 10% less than the initial on the 13th, 16th and 22nd days. The blood expulsion phase of V. N. Volkov at rest either equaled the preflight or was 3.5-9.5% less than it, that of G. T. Dobrovol'skiy was 8.5-13.5% less and that of V. I. Patsayev, 10-13.5%. As a result, the interphase index K of V. N. Volkov decreased by 9-25.5%. That of G. T. Dobrovol'skiy was equal to the preflight or exceeded it by 4.5-11.5% and that of V. I. Patsayev exceeded it by 3.5-5.5%.

In similar recordings during model experiments, the isovolumetric contraction phase was lengthened by 10-20% and, sometimes, by 20-30% /155 the blood expulsion phase remained equal to the initial or decreased by 7-10% and even by 14-17%. As a consequence of this, the interphase index K [illegible]eased by 10-20 and even by 40-50%.

In model experiments, the change in cardiac cycle phases was extremely stable, and it does not disappear during use of such prophylactic means for hypodynamia as physical training, occlusion cuffs and pharmacological preparations. It seemed as though this change should develop in flight and would be a most reliable indicator of the effect of weightlessness. However, this hypothesis was not validated. Thus, this question requires further study.

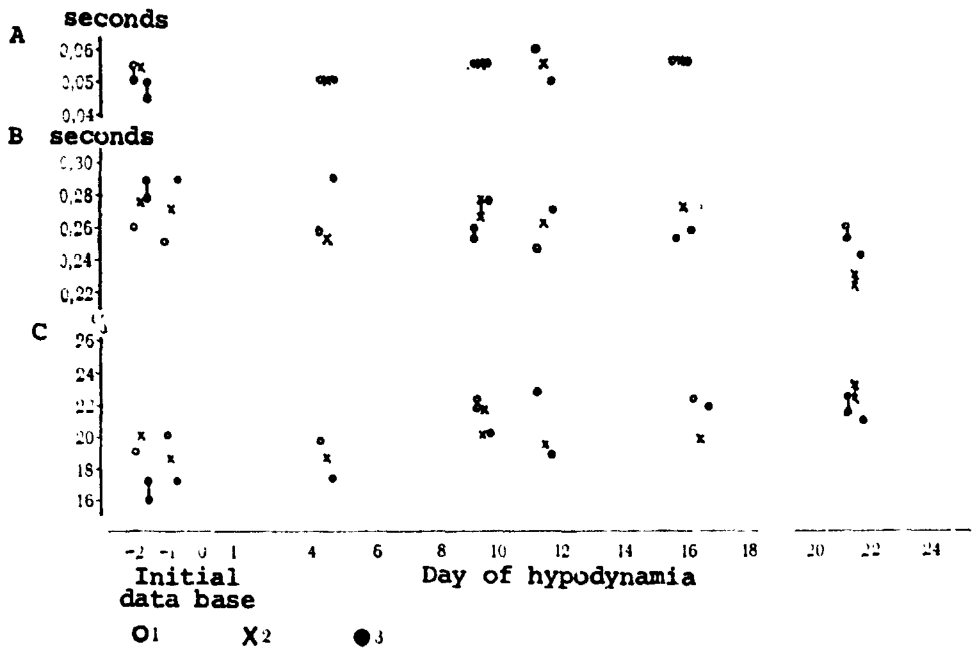

Fig. 40. Left ventricle phase duration in 30-day clinostatic hypodynamia of subjects S(1), N(2) and K(3): A, isovolumetric contraction phase; B, blood expulsion phase; C, interphase index.

Together with materials indicating incomplete coincidence of the dynamics of the individual blood circulation indices in flight and in the simulated effect of weightlessness on earth, the crew of the Salyut space station also obtained data, demonstra ing the presence of a great similarity between them. This mainly concerns the reduction in orthostatic tolerance, which is manifested in poorer tolerance of the functional test with negative pressure on the lower half of the body. The dynamics of the basic blood circulation indicators of station commander G. T. Dobrovol'skiy and engineer-investigator V. I. Patsayev had the same direction in this test on the 13th day of flight, as in the preflight examination and execution of decompression in the model experiments. However, the absolute value of the change in blood circulation in flight was more pronounced. It must be thought that these changes are connected with the direct effect of weightlessness. At the same time, the superimposition of the weakening effect of fatigue on the examination day is possible. /156

The dynamics of arterial pressure and minute volume of blood deserve particular attention. It is known that, in conducting an orthostatic test and limiting the return of blood, by means of evacuation of a vacuum chamber, the minute volume of blood can decrease considerably (P. V. Buyanov, N. V. Pisarenko, 1968; Wolthuis, et al., 1970). The arterial pressure either increases somewhat or remains unchanged from the initial level in these tests. Preservation of the arterial pressure level or an increase of it favors constriction of the total lumen of resistant vessels and quickening of the pulse, which always accompanies this action.

A gradual reduction of the average arterial pressure of G. T. Dobrovol'skiy began during conduct of the test, at the end of the second week of the flight. It occurred on a background of quickening of the pulse, in a period when the minute volume of blood stabilized after a preliminary decrease and even increased relatively. This direction of change can be connected with insufficiency of the reactions of the arterioles to the sympathetic nervous system (V. A. Degtyarev, V. M. Khayutin, 1971).

According to hemodynamics research data, V. I. Patsayev tolerated the functional tests with negative pressure in flight better than G. T. Dobrovol'skiy. However, a more significant increase in arterial pressure was recorded in him during decompression than on earth, and more pronounced oscillations of the minute volume of blood were noted, which cannot be evaluated favorably. The change in cardiac cycle phase under negative pressure in flight was expressed more strongly than on earth, and it was almost identical in both astronauts. A comparison of these data with the results of model experiments indicates that just as great changes in the basic cardiac cycle phases and interphase index K are observed in persons with reduced tolerance of orthostatic effects (Figs. 41 and 42). /157

Thus, the studies of blood circulation performed by the crew of the Salyut space station considerably extended existing concepts of the effect of prolonged space flight on the human body. They demonstrated that, in distinction from the clinostatic hypodynamia, a more pronounced tendency is observed in flight, under rest conditions, towards an increase in minute volume of the blood and a decrease in pulse wave propagation rate. The individual blood circulation indices had large amplitude fluctuations on various examination days; practically no increase in isovolumetric contraction period was noted.

After physical workloads, a slow recovery of the heart rate, arterial pressure and minute volume of the blood were revealed. In this case, there was an increased reaction to the functional test with negative pressure on the lower half of the body.

Transient factors, such as emotional stress of the astronauts, insufficient rest, etc., may play a significant role in the genesis of the changes noted in state of the cardiovascular system.

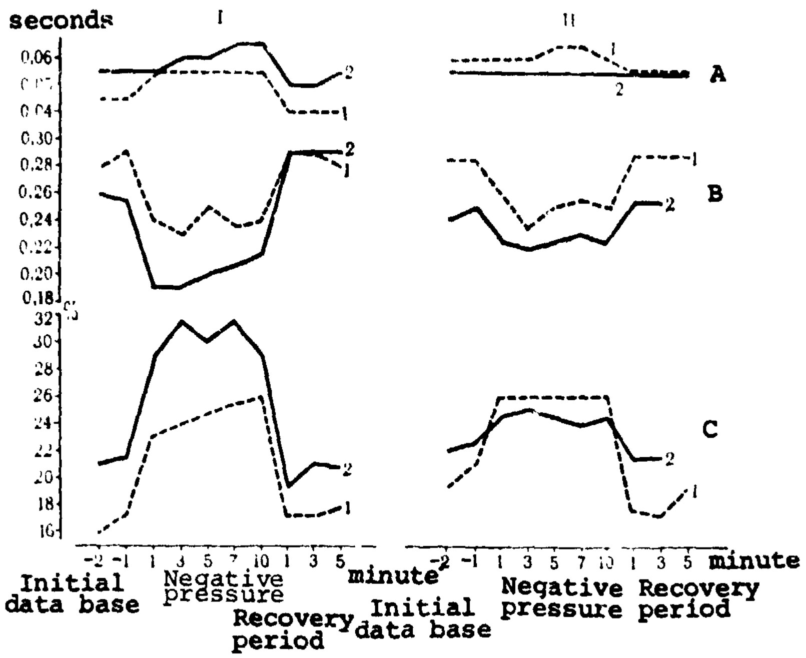

Fig. 41. Duration of left ventricle phases of subject S with low orthostatic tolerance (I) and K with high orthostatic tolerance (II) in functional test with negative pressure before hypodynamia (1) and at end of 2nd week of clinostatic hypodynamia (2): A, isovolumetric contraction phase; B, blood expulsion phase; C, interphase index.

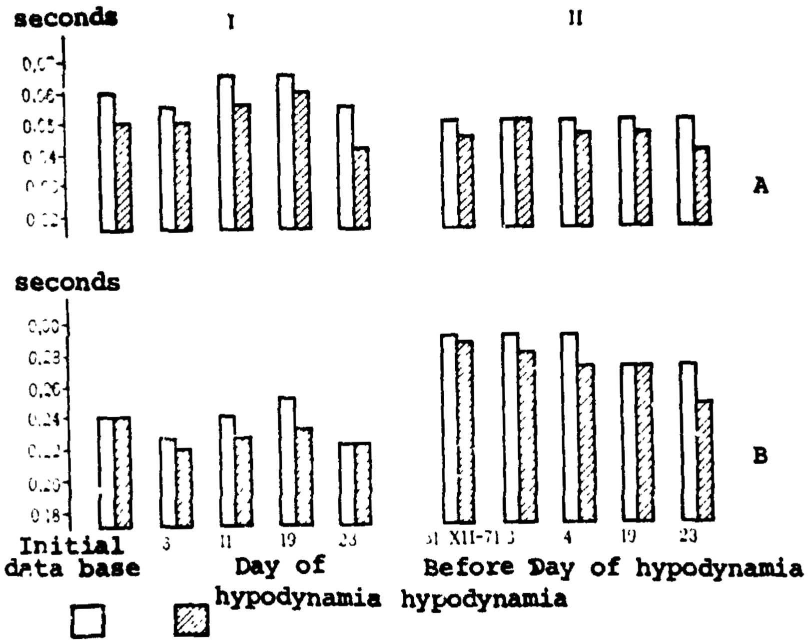

Fig. 42. Duration of left ventricle phases of subject Sh (I), and Ni (II) during physical workload in 30-day clinostatic hypodynamia tests: A, isovolumetric contraction phase; B, blood expulsion phase; 1) before physical workload; 2) 20-30 sec of recovery period.

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5. Respiration, Respiratory Metabolism and Energy Consumption Under Weightless Conditions

The prospects of further growth of long space flights are being determined to a great extent by the permissible duration of the effect of weightlessness on the human body.

Study of the effect of prolonged weightlessness on the human body, questions of adaptation to these conditions, as well as the course of readaptation upon return of an astronaut to earth are inseparably bound to the necessity for study of the dynamics of metabolic processes. In this area, the most general scientific and practical data on the functional state of the body and the shifts taking place in it under weightless conditions can be given by study of the respiratory metabolism, as an integral index of the changes taking place in the body. Knowledge of the average oxygen consumption and carbon dioxide discharge and calculation of the energy consumption in performing one job or another makes it possible to solve problems, connected with life support of long flights in spacecraft and orbital stations. Among these problems are:

--Creation of the optimum gaseous environment, both in the cabins of flight vehicles, where man will be a part of a closed matter cycle (O. G. Gazenko, 1962; V. I. Yazdovskiy, N. M. Sisakyan, 1962) and in spacesuits, during work of astronauts in space (I. I. Kas'yan, et al., 1969, 1971);

--Development of efficient eating schedules and provision of the necessary foodstores, based on energy consumption; /158

--Preservation of the heat balance of the human body at the optimum level, ensuring long-term retention of efficiency, especially during work in a spacesuit, etc.

The state of efficiency and of readiness of an astronaut to return to increased gravity conditions (i.e., after prolonged weightlessness to earth conditions) can be decided, from the respiratory metabolism dynamics in a proportioned physical workload (G. F. Makarov, 1967). Consequently, study of the functional condition of external respiration, respiratory metabolism and energy consumption of a man, during a long stay under weightlessness, has exceptionally inportant theoretical, practical and prognostic value for space medicine.

The respiration indices of a man under weightless conditions have been studied by both Soviet and foreign investigators, beginning with the first flight of man in space. While there already are some ideas of the change in respiratory rate, its rhythm and the structure of the respiratory cycle under prolonged weightlessness, we have available very limited information on the indicators characterizing respiratory metabolism rates and the energy consumption level in various types of activity under weightlessness.

Research conducted by G. F. Makarov (P. K. Isakov, et al., 1964), during flights of man in an aircraft along a Kepler parabola, have shown that pulmonary ventilation increases noticeably and the oxygen consumption and energy consumption increase in brief weightlessness. In subsequent work (I. I. Kas'yan, et al., 1967, 1969, 1971), an increase in metabolic process rates under conditions of brief weightlessness was noted, not only in a state of relative rest, but in performing proportioned physical workloads and various working tasks.

Correlated data on the functional state of respiration, respiratory metabolism and energy consumption of a man under weightless conditions (brief, reproduced in an aircraft), in orbital flights lasting from 3 to 18 days, as well as in simulation of certain conditions of weightlessness (water immersion, weightlessness test stand), are presented in this section. Studies of respiration, respiratory metabolism and energy consumption have been carried out, depending on conditions, using methods permitting comparable results to be obtained (I. I. Kas'yan, et al., 1969). The studies were carried out, both at rest and while performing various proportioned physical workloads.

In parabolic aircraft flights, as well as in all experiments with simulated weightless conditions on earth, study of respiratory metabolism was carried out by the Douglas-Holden method. In orbital flights and in studies under conditions of brief weightlessness (comparatively) small-size instruments were used -- spiroanemometers, having adapters for collecting exhaled air into special sealed burettes (for subsequent analysis in the Holden apparatus).

The respiratory metabolism indicators (minute volume of respiration, oxygen consumption, carbon dioxide discharge) were converted into the STPD system,[4] and the respiration volumes (pulmonary ventilation, vital capacity of the lungs, inhalation and exhalation volumes), to the BTPS system.

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[4]STPD, BTPS are the international standard conditions for calculation of energy consumption and volumes.

TABLE 40

RESPIRATORY METABOLISM AND ENERGY CONSUMPTION INDICES OF SUBJECTS AT REST IN BRIEF WEIGHTLESSNESS, OBTAINED BY USE OF DOUGLAS-HOLDEN AND SPIROANEMOMETRIC METHODS

Subject	Oxygen consumption, ml/min			Carbon dioxide discharge, ml/min			Energy consumption, kcal/hour		
	Initial	Weightlessness	Deviation from Initial DataBase	Initial	Weightlessness	Deviation from Initial DataBase	Initial	Weightlessness	Deviation from Initial DataBase
Studies by Douglas-Holden Method									
N	320	533	+213	260	412	+152	92.4	152.2	+60.0
N	300	383	+ 83	232	304	+ 72	85.7	110.3	+24.6
Shch	337	428	+ 91	240	344	+104	94.8	120.5	+88.1
Shch	292	391	+ 99	237	312	+ 75	83.9	112.2	+28.2
Shch	277	352	+ 75	244	309	+ 65	80.3	102.0	+21.6
D	280	393	+113	230	333	+103	80.9	114.7	+33.6
B	279	395	+116	215	290	+ 75	79.7	111 7	+31.6
Arithmetic mean			+113			+ 92			+41.1
Study with Spiroanemometer									
V	274	306	+ 32	228	254	+ 26	79.1	88.7	+ 9.6
Gn	254	432	+178	194	403	+209	72.6	128.3	+55.7
Gv	330	549	+219	228	430	+202	92.3	157.2	+64.8
T	327	465	+238	204	343	+139	67.2	132.0	+64 8
K	214	325	+111	208	295	+ 87	64.2	96.5	+32.4
K	233	434	+201	211	354	+143	69.0	125.4	+56.4
K	230	252	+ 22	174	184	+ 10	65.4	71.4	+ 6.0
K	256	283	+ 27	191	197	+ 6	73.2	79.8	+ 6.6
K	366	546	+180	304	463	+159	106.2	159.0	+52.8
Arithmetic mean			+134			+109			+39.0

Effect of Brief Weightlessness

Research results obtained in parabolic aircraft flights show /159 that, during brief weightlessness, a significant (by all methods used) increase in rate of respiratory metabolism processes was observed in all subjects, both compared with data obtained on earth before the flight and with respect to respiratory metabolism indices in the horizontal portion of the flight. Thus, the minute consumption of oxygen in the brief weightlessness period exceeded the initial data by 22-238 ml/min, and the energy consumption of the subjects in a state of relative rest was 6-88 kcal/hour greater (Table 40).

The respiration indices under brief weightlessness (respiration rate, vital capacity of the lungs, pulmonary ventilation) were also above the initial ones (Table 41). Thus, the respiration rate in brief weightlessness increased by 18% on the average, pulmonary ventilation by 44% and vital capacity of the lungs by 10%. It /160 also was revealed that the structure of the respiratory cycle changes in brief weightlessness; the ratio of the inhalation and exhalation phases changes.

TABLE 41

CHANGE IN RESPIRATION INDICES OF SUBJECTS AT REST IN DIFFERENT SECTIONS OF PARABOLIC FLIGHT

Flight Section	Pulmonary Ventilation, l/min	Respiration rate cycle/min	Vital capacity of lungs, ml
Horizontal (M±m)	9.0±2.2	11±2.8	3800±436
In weightlessness (M±m)	13.0±2.7	13±3.8	4200±700

A similar regularity was disclosed (V. I. Sokolkov, et al., 1971) in subjects at rest, under water immersion conditions lasting up to 18 hours (Table 42). Thus, pulmonary ventilation in a two-hour water immersion of the subjects increased by 9.8% on the average, and by 13.4% after 18 hours, compared with the initial data base (in the horizontal position before immersion); the oxygen consumption increased during the same times by 18.4 and 16.9%, and the energy consumption increased by 19 and 17.5%, respectively. Similar changes in respiratory metabolism of immersed subjects are noted by other authors (N. Ye. Panferova, et al., 1968; Ye. Ye. Bulenkov, et al., 1968; Wessler, et al., 1959; Howard, et al., 1967).

The program of conquest of space and the nearest planets contemplates, together with extensive introduction of automation, the use of manual labor of an astronaut, for example, in assembly-disassembly work. In this respect, the question arises as to the energy consumption

TABLE 42

RESPIRATORY METABOLISM AND ENERGY CONSUMPTION DYNAMICS OF WATER IMMERSION SUBJECTS (data of V. I. Sokolkov, et al., 1971)

Condition	Respiration rate cycle/min	Pulmonary ventilation, l/min	Oxygen consumption, ml/min	Energy consumption, kcal/hr
Before immersion ($M \pm m$)	12.7 ± 0.48	6.17 ± 0.20	274.4 ± 8.3	78.0 ± 2.4
2-hr " ($M \pm m$)	13.9 ± 0.64	6.78 ± 0.17	324.5 ± 6.6	93.0 ± 1.7
8-hr " ($M \pm m$)	14.6 ± 0.67	6.63 ± 0.20	321 ± 9.6	91.8 ± 2.7
18-hr " ($M \pm m$)	14.5 ± 0.66	6.99 ± 0.23	320 ± 7.4	91.8 ± 2.1

in performing one work task or another, planned by the flight program.

Many investigators think that considerably longer time and larger energy consumption is required to perform any work under weightless conditions, than under earth conditions. This is confirmed by the experimental simulation of weightlessness under ground conditions and during performance of work by astronauts in orbital flights (P. K. Isakov, Stasevich, 1962; P. K. Isakov, et al., 1964; I. I. Kas'yan, et al., 1967, 1969, 1971; Armstrong, 1953; Beckh, 1958). Together with this, in the opinions of a number of authors, energy consumption by man under weightless conditions will be less than under earth conditions (V. N. Chernov, V. I. Yakovlev, 1958; A. M. Genin, et al., 1965; Henry, et al., 1952). /161

As research on respiratory metabolism in Kepler parabola aircraft flights which we have conducted have shown, performance of proportioned physical workloads and individual working tasks by subjects under brief weightlessness requires higher energy consumption than the same work, performed in the horizontal section of a flight or on earth (Fig. 43). Thus, in performing a proportioned physical workload (work with an expander of 100.8 kgm), the oxygen consumption, while working under weightless conditions, increased by 185 ml/min on the average (compared with the indices obtained during work in the horizontal section of the flight), and the energy consumption in this period increased by 55 kcal/hour; in performing individual working tasks, the oxygen consumption and energy consumption in weightlessness increased by 291 ml/min and 83.4 kcal/hour, respectively.

In the work of subjects in special equipment, the changes in indices of respiration, respiratory metabolism and energy consumption in brief weightlessness were still more pronounced. In this case, the respiration rate increased especially sharply. In this period, it varied from 29.2±1.55 to 31.2±1.50 cycles per minute (Table 43).

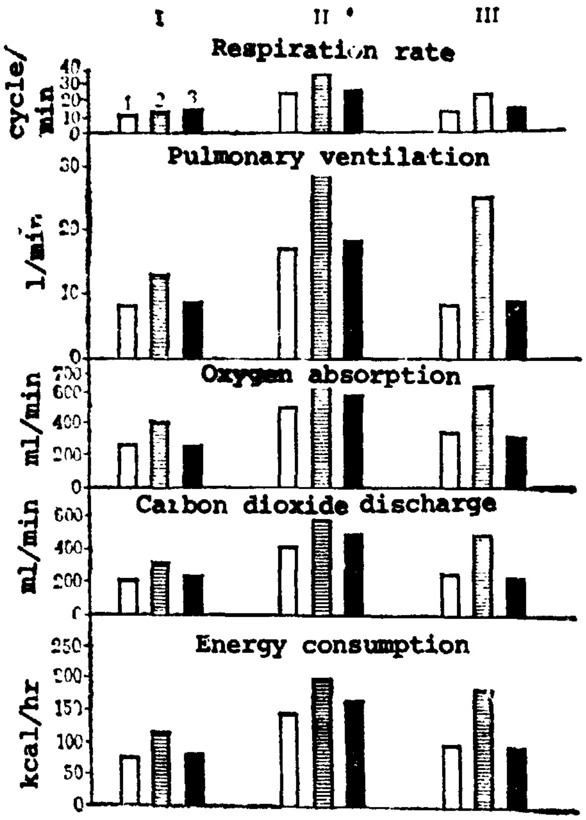

Fig. 43. Respiratory metabolism indices of subjects in state of rest and while working during parabolic flight in aircraft: I, at rest; II, while performing measured physical workload; III, in performing working tasks; 1) horizontal section of flight; 2) weightlessness; 3) after flight.

Considerable individual fluctuations in the respiratory metabolism indices must be noted, in performance of the identical physical workload in brief weightlessness. Even in the same subject, the energy consumption changed from one "hump" to another and from one flight to another. Thus, for example, the oxygen consumption of subject S, in working in normal clothing under weightless conditions, was higher than in the horizontal section /162 by 227 ml/min and, in performing the same work in special equipment, by 533 ml/min, i.e., it almost doubled. The energy consumption increased here by 83 and 153 kcal/hour, respectively.

On the average, the respiration rate of subjects, in work under brief weightlessness in special equipment, was 63-85% higher, than in performing the same work in the horizontal section of the flight, the pulmonary ventilation increased by 20-39% and the energy consumption by 22-26%. The energy consumption during the same activity varied appreciably, depending on age, weight, state of training of the subject and the rate of performance of the working operations by them.

Experiments, conducted in a weightlessness simulator test stand (unsupported stand), for the purpose of study of the bioenergetic singularities of human activity under weightless conditions, demonstrated that, as in brief weightlessness, the energy consumption in simulation of the absence of weight in an unsupported position, was higher than in performing the same work, under conditions of simulation of normal (terrestrial) body weight of the subjects, in this same test stand (Table 44). It was determined that the increase in energy consumption in performing one working operation or another in the unsupported position in the test stand involves the way in which the subject is secured to the object of work, in particular, with the number of points of attachment.

TABLE 43

CHANGE IN RESPIRATION AND ENERGY CONSUMPTION INDICES OF SUBJECTS WHILE PERFORMING VARIOUS WORKING TASKS IN KEPLER PARABOLA FLIGHTS

Clothing	Type of Work	Statistical Index	Horizontal Flight: Respiration rate, cycle/min	Horizontal Flight: Pulmonary ventilation, l/min	Horizontal Flight: Energy consumption, kcal/min	Weightlessness: Respiration rate, cycle/min	Weightlessness: Pulmonary ventilation, l/min	Weightlessness: Energy consumption, kcal/min
Normal clothing	Proportioned physical load(100.8 kg/m)	M±m	26.44 0.9	20.22 0.8	3.94 0.14	29.5 1.5	25.42 0.8	4.82 0.16
Special equipment	Special work	M±m	19.49 1.49	17.46 1.46	3.54 0.25	27.64 1.36	26.43 1.31	5.032 0.246
	Purposeful activity	M ±m	17.9 0.71	27.3 2.22	5.22 0.39	29.2 1.55	32.7 2.14	6.34 0.45
	Various working tasks	M ±m	16.9 0.89	13.7 1.59	2.84 0.27	31.2 1.60	19.0 2.74	3.59 0.37

Notes: 1. Proportioned physical workload, work with expander. 2. Special work, pumping out condensate. 3. Purposeful activity, transfer from one craft to another in pressurized spacesuit. 4. Working task, performance of separate elements of assembly work.

As is evident from Table 44, with the subject secured to the work object at three supporting points (two hands, considering the working hand to be a point of attachment also, and joining the legs /163 together), the oxygen consumption in simulated weightlessness in the unsupported test stand was increased by 14% over the baseline data. With the subject secured to the work object by two points (only two hands), the oxygen consumption increased by 27%. The energy consumption of the subjects increased by 13 and 25%, respectively. Thus, with increase in number of points by which the subject is secured to the object of work from two to three, the energy consumption in performing the same operation, under simulated weightlessness conditions (unsupported conditions) decreased almost to half.

It must be noted that, if "working" energy consumption is taken into consideration, i.e., energy consumption only in performing the operation (excluding energy consumption in preserving the standing posture for the corresponding interval of time), the difference in values of the "working" energy consumption in performing the same operation, under simulated weightless conditions (unsupported conditions) and ground conditions will be considerably higher. The total

TABLE 44

RESPIRATORY METABOLISM AND ENERGY CONSUMPTION VS. NUMBER OF ATTACHMENT POINTS IN PERFORMING SPECIAL WORK IN UNSUPPORTED TEST STAND (simulating weightless conditions)

Method of securing to object	Test stand normal conditions			Test Stand Simulation of weightlessness (unsupported position)		
	Pulmonary ventilation, l/min	Oxygen consumption, ml/min	Energy consumption, kcal/min	Pulmonary ventilation, l/min	Oxygen consumption, ml/min	Energy consumption kcal/min
At 2 points (M±m)	9.2±0.38	356±9.4	1.75±0.05	11.4±0.33	462±11.4	2.28±0.06
At 3 points (M±m)	9.8±0.96	411±3.3	2.02±0.02	11.4±0.97	468±5.2	2.29±0.02

energy consumption in performing a "bolt tightening" operation, under unsupported conditions simulated in the test stand, was almost double (21 kcal vs. 12 kcal) that under earth conditions, and the "purely working" energy consumption under the simulated conditions was 2.27 times greater (9.08 kcal vs. 4 kcal) than the "working" energy consumption under ground conditions; in this case, the subjects used 1.64 times more time than on earth, in performing the operation (19.68 min vs. 12 min).

Thus, judging from the results of the study, the effect of brief weightlessness reproduced in parabolic aircraft flights and the effect of certain conditions of weightlessness simulated in ground experiments (on the unsupported test stand and immersion medium tests), lead to a significant increase in rate of the metabolic processes, both with the subjects in a state of relative rest and in performing various kinds of work.

The dynamics of the metabolic processes in prolonged hypodynamia experiments were different (Fig. 44). Analysis of the experimental data showed that, with the subjects under prolonged hypodynamia, pulmonary ventilation, oxygen consumption and basal metabolism gradually decrease , and that this reduction was more pronounced in subjects under complete hypodynamia and, to a lesser extent, in persons performing a daily set of physical exercises. In the first case, the metabolism was reduced by 30-40% and, in the second, only /165 by 5-10% from the initial data (I. P. Neumyvakin, 1969). Thus, the pulmonary ventilation of subject V (curve 4), in complete hypodynamia in water, decreased from 7.6 to 6 l/min by the 11th day, the oxygen consumption decreased from 303 to 210 ml/min and the basal metabolism decreased from 2058 to 1470 kcal/day. A similar reduction in metabolism was observed in subject P (curve 5), in the mock-up chair of a laboratory object. The metabolism of subject G (curve 1), who was in water and performed a daily set of physical exercises during the test, after some increase in the first 4 days of immersion

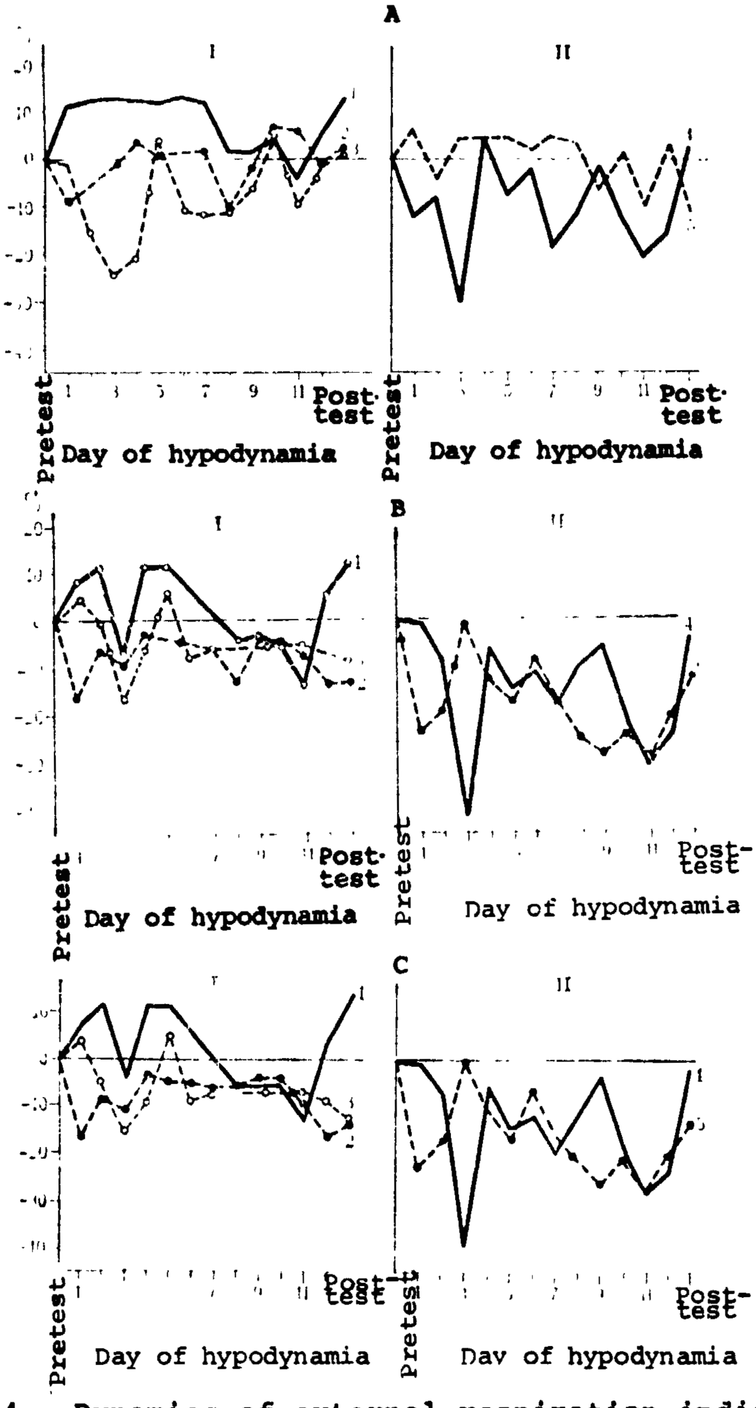

Fig. 44. Dynamics of external respiration indices of subjects in prolonged hypodynamia: I, with daily performance of physical exercise sets; II, without exercise; A, pulmonary ventilation; B, oxygen consumption; C, basal metabolism; 1) subject G and 4) subject V immersed; 2) subject P; 3) subject G and 5) subject P in mockup chair of laboratory object.

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(by 11-12% of the initial data), began to decrease gradually. By the 11th day of the test, the oxygen consumption decreased from 260 to 226 ml/min, and the basal metabolism decreased from 1756 to 1539 kcal/day. The minute respiration volume decreased only to the initial value. Similar data were obtained with the subject in the mockup chair of the laboratory object and in daily performance of a set of physical exercises.

Effect of Prolonged Weightlessness on Respiration and Respiratory and Energy Metabolism

A study of the effect of prolonged weightlessness on metabolism was first carried out during the flight of Voskhod 2.

Analysis of the external respiration indices, obtained during orbital flights, has shown that, in the transition period from g-forces to the state of weightlessness, some tendency was observed toward increase of the respiration rate over that of the 5-minute readiness examination. The changes in respiration rate were the same in the first orbits of the flight. This apparently was due to neuroemotional stress of the astronauts in the initial period of the space flight. In the subsequent period in orbital flight, the respiration rate gradually decreased, reaching the prelaunch level at times. Thus, the respiration rate of Yu. A. Gagarin, at the beginning of the period of weightlessness, 10-15 minutes into the flight in the Vostok spacecraft, increased to 37 cycles per minute, with an initial (prelaunch) value of 25 cycles per minute. Subsequently, the respiration rate stayed at the level of 25-27 cycles per minute, on the average. The respiration amplitude increased /166
a little in this period (Fig. 45). The respiration rate of G. S. Titov, in the flight of Vostok 2, was higher than the prelaunch level in only the first five orbits of the flight; subsequently, it turned out to be lower than the prelaunch level. The changes in respiration rates of other astronauts in orbital flights, lasting from 70 to 95 hours, were similar (Table 45). Thus, the average respiration rates of V. V. Tereshkova, P. R. Popovich, V. A. Shatalov and Ye. V. Khrunov (Soyuz 5) exceeded the initial rate at all stages of the orbital flight. After the transfer of Ye. V. Khrunov through open space, his respiration rate decreased to the initial values. The respiration rate of A. G. Nikolayev (Vostok 3) was more stable in flight, with negligible deviations from the baseline level.

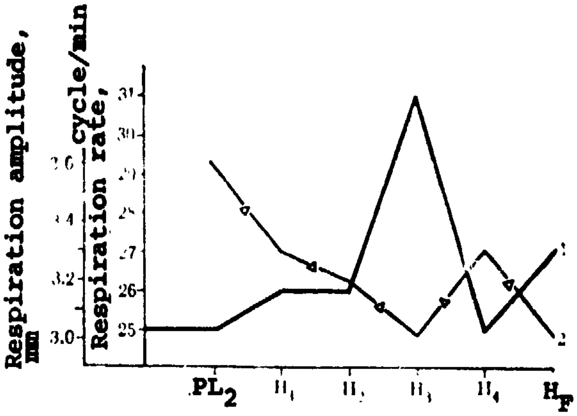

Fig. 45. Respiration rate and amplitude of Yu. A. Gagarin in orbital flight: 1) respiration amplitude; 2) respiration rate; PL_2 5-min readiness examination; H_1, H_F initial and final periods of weightlessness.

In orbital flights lasting up 119 hours, the respiration rates of the astronauts also stabilized after the first days of the flight, mainly at the level of the 4-hour prelaunch readiness, and they increased, depending on the type of work performed. The pulse rate decreased below the initial level at times in the state of rest, not reaching, however, the values observed at rest on the earth (Table 46).

The data on change and respiration rate of astronauts during extravehicular activity are of particular interest. As the data obtained in the orbital flight of Voskhod 2 showed, the respiration rate of P. I. Belyayev

TABLE 45

RESPIRATION RATE (cycles per minute) OF ASTRONAUTS AT SEPARATE STAGES OF ORBITAL FLIGHT, LASTING FROM 70 TO 95 HOURS (average data)

Astronaut	Earth Conditions	4 hrs before launch	Flight Day 1: Number of Orbits of Flight 1	7	13	Flight Day 2: 17	23	29	Flight Day 3: 33	39	43—45	Flight Day 4: 49—53	55	60—61
A. G. Nikolayev	10—11	10	13.7	11.4	11.0	11.3	11.0	10.0	11.1	12.4	11.0	13.0	11.7	9.8
P. R. Popovich	11—13	20	19.1	18.6	18.2	17.4	16.4	15.0	15.3	14.9	16.3	—	—	—
V. V. Tereshkova	13—16	12	20.5	21.3	22.5	21.9	21.0	21.8	21.8	21.5	19.7	—	—	—
V. A. Shatalov	8—12	18	20.0	18.0	18.0	18.0	18.0	18.0	21.0	20.0	20.0	—	—	—
Ye. V. Khrunov	11—14	12—15	20.0	21.0	24.0	22.0	24.0	—	36.0	13.7	14.0	24—12	—	—

and A. A. Leonov increased over that of the prelaunch period, from 18 to 22 cycles per minute and from 20 to 24 cycles per minute, respectively. During the extravehicular activity of A. A. Leonov, his respiration rate reached 26-36 cycles per minute. In the 7th orbit, the respiration rates of both astronauts decreased to 14-15 cycles per minute, i.e., below the level of the prelaunch 5-minute readiness period.

The respiration rate of Ye. V. Khrunov (Soyuz 5) increased, during preparation for transfer to Soyuz 4, to 27 cycles per minute

TABLE 46

RESPIRATION RATE (cycles per minute) OF ASTRONAUTS IN SEPARATE STAGES OF ORBITAL FLIGHT LASTING UP TO 119 HOURS

Astronaut	Earth Conditions	4 hrs before launch	Day of flight														
			1	2		3—4			4		5		6		7		
			Number of Orbit in Flight														
			1	7	13	21	27—29	31—37	39—40	43—45	49—51	55—59	60—63	67—69	70—73	77—79	81
V. F. Bykovskiy	12	19	24.3	16.6	18.0	19.9	21.3	19.0	18.5	18.4	18.3	18.3	17.0	18.9	19.2	18.1	17.5
G. S. Shonin	10	21	24.0	18.0	16	20	22	24—18	22—18	22—17	22—17	24—18	20—19	21—18	20—17	20—16	—
V. N. Kubasov	10	30	36	28—20	34—22	36—23	24—18	24—22	25—21	30—24	24—20	23—20	22—20	30—22	—	26—23	—
A. V. Filipchenko	9	17	24	24—22	24—22	18—16	24—18	21—18	21—18	24—20	23—19	24—18	22—20	22—19	22—19	24—22	—
V. V. Gorbatko	10	18	34	24—20	23—20		20—18	20—16	21—16	21—18	21—19	23—18	23—19	23—21	23—21	24—22	—

on the average and, during the transfer, to 36 cycles per minute. The maximum respiration rate during the transfer was 49 cycles per minute (Ye. I. Vorob'yev, et al., 1969).

Thus, the general direction of change in respiration rate of a man under conditions of prolonged weightlessness (up to 119 hours) is its establishment at a relatively higher level than under normal ground conditions. Individual, more pronounced changes in respiration rate, noted in the astronauts during orbital flights, are connected with motor activity of the astronauts and with stress /167 effects (extravehicular activity, performance of flight program operations, conducting radioconversations, etc.). This regularity in respiration rate dynamics under weightless conditions was followed in longer orbital flights (Soyuz 9 spacecraft, 424 hours and Salyut orbital station, 24 days). Thus the pulse rate of A. G. Nikolayev (Soyuz 9) was 22 cycles per minute during the first orbit and, in the second and succeeding orbits of the first days of the flight, it decreased to 15 cycles per minute. Subsequently, in the 49th-50th, 174th, 190th, 257th and 267th orbits, his respiration rate increased at times to 20 cycles per minute or decreased to 12-13 cycles per minute (61st, 77th, 157th and 212th orbit), remaining at the level of 15-16 cycles per minute during the entire 18-day flight, on the average. V. I. Sevast'yanov's respiration rate during the 18-day orbital flight was more stable, and it was 13-15 cycles per minute, on the average.

There is great interest in analysis of the dynamics of change in individual phases of the respiratory cycles of astronauts P. I. Belyayev and A. A. Leonov. For P. I Belyayev, in the first two orbits of the orbital flight, the duration of individual phases of the respiratory cycle corresponded to quickening of respiration and, in orbits 3-7, while maintaining the respiration at 16 cycles per minute, it increased (Fig. 46). The longest respiratory pause was reached in orbit 7, when respiration was the slowest. At this time, a minimum respiration amplitude was noted. For A. A. Leonov, in the first orbit of the orbital flight, together with quickening of /168 respiration, the duration of respiratory cycle phases decreased. The inhalation time and respiratory pause increased somewhat in orbit 2. The length of all phases of the respiratory cycle increased in orbits 3-7 and, in orbits 13-17, the length of the exhalation phase continued to increase, corresponding to quickening of respiration, and the remaining phases of the respiratory cycle decreased. A similar change was not observed in the exhalation phase of P. I. Belyayev. The respiratory movement amplitude of A. A. Leonov increased at the beginning and end of the flight, but it decreased in the middle of the flight.

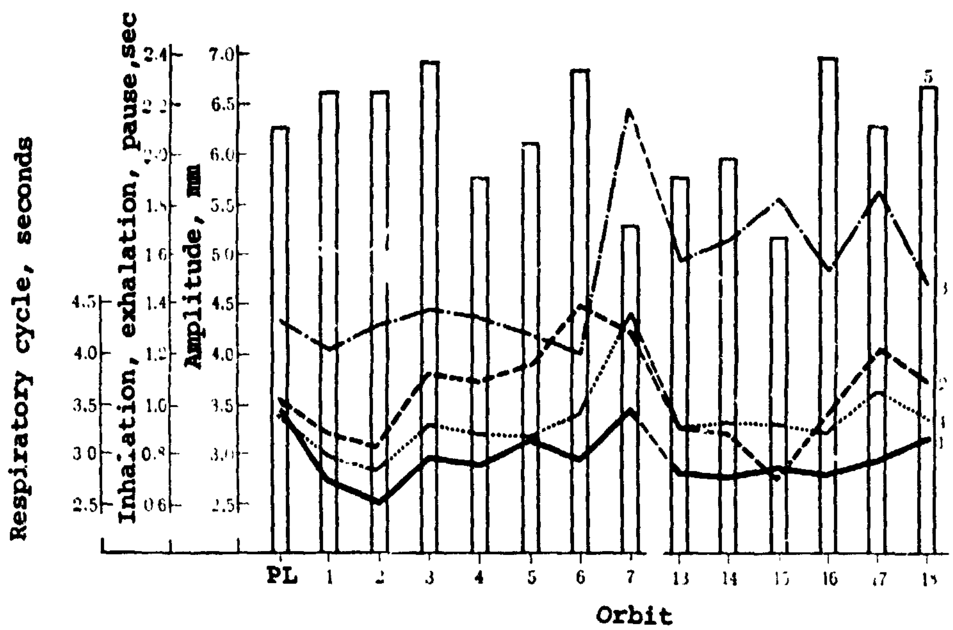

Fig. 46. Change in respiration phase and amplitude of P. I. Belyayev in prelaunch period and in different orbits of orbital flight: 1) inhalation; 2) exhalation; 3) pause; 4) respiratory cycle; 5) respiration amplitude.

The coefficients of variation of the respiratory cycles and respiration amplitude of P. I. Belyayev changed in the opposite direction from respiration rate, namely: at the start and end of flight, when respiration was more rapid, the coefficients of variation were at a minimum and, in the middle and second half of the flight (orbits 7, 13, 15), when respiration was slower, they reached the greatest values (Fig. 47).

The dynamics of change in the coefficient of variation of respiration phase and amplitude of A. A. Leonov were similar to the changes of P. I. Belyayev noted above. However, there were individual singularities. Thus, for example, despite the slowing of respiration in the middle of the flight, the coefficient of variation of the respiratory pauses have a tendency to decrease during the entire period of weightlessness; the coefficient of variation of the inhalation phase and the respiratory cycle in the second half of the flight (orbits 13-16) were less than in the first half (orbits 3-6), on the average, and they fluctuated within narrow limits, although the respiration rate in these sections was approximately the same (17-19 cycles per minute in the first half of flight and 18-20 cycles in the second half). The reason for this change in respiration phase and amplitude remains vague now. On the whole, analysis of the respiratory cycle phases and their coefficients of variation indicate relative stability in the respiration function of both astronauts.

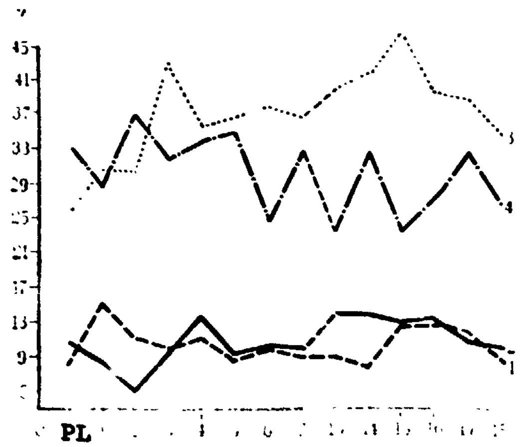

Fig. 47. Change in coefficient of variation of respiration rate and pulse rate of P. I. Belyayev and A. A. Leonov in prelaunch period and in different orbits of orbital flight: 1) pulse rate of P. I. Belyayev; 2) pulse rate of A. A. Leonov; 3) respiration rate of P. I. Belyayev; 4) respiration rate of A. A. Leonov.

The effect of proportioned workloads on the respiration function was studied, beginning with the flight of the Voskhod spacecraft. It was determined that, in the workload period (squeezing a dynamometer with the hand, with a force of 3-5 kg for a minute), the respiration rate increased somewhat and the respiratory cycle phases changed in all crew members. Thus, the respiratory cycle duration of V. M. Komarov decreased, owing to shortening inhalation, exhalation and the pause. The reduction in the respiratory pause of B. B. Yegorov also was the main reason for quickening respiration. It also was determined that the curves, characterizing the change in respiratory cycle phases, had pronounced individual differences and quickly returned to the initial values after ending work with the dynamograph (A. D. Voskresenskiy, I. I. Kas'yan, D. T. Maksimov, 1966).

During inflight performance of various proportioned workloads (pumping out the condensate, work with the expander, etc.) by spacecraft crew members of Soyuz 6 and Soyuz 9, it was revealed that the respiration rate, both in the quiet state and immediately after performing proportioned workloads, changed ambiguously. Depending on the nature of change in respiration rate, three types of reaction can be distinguished. In the first type, the respiration rate noticeably increases over the initial level in weightlessness. This was observed in both the quiet state and 10-15 sec after performing physical workloads (Fig. 48A). In the second type, the respiration rate decreased somewhat immediately after performing proportioned workloads in weightlessness. The third type of reaction is characterized by increase and decrease in respiration rate for the duration /169 of the entire orbital flight (both with the astronaut at rest and in performing proportioned workloads; see Fig. 48B).

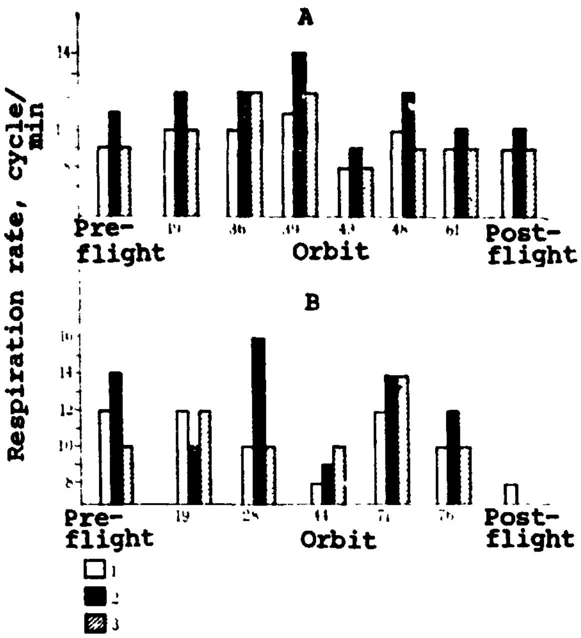

Fig. 48. Respiration rate of astronauts before and after performing proportioned physical workload in orbital flight: 1) before workload; 2) 15-20 sec after workload; 3) 2 min after workload; A, 1st type of reaction; B, 3rd type of reaction.

Together with study of the effect of weightlessness on respiration rate and pulmonary ventilation, beginning with the flight of Voskhod 2, the vital capacity of the lungs (VCL) was studied. Analysis of the data obtained show that changes in the VCL under weightless conditions were ambiguous. In the majority of cases, the VCL, measured in astronauts in the state of relative rest during 1-3 days of orbital flight, was lower than the initial preflight data base. In 3-5 days of flight, the VCL changes both decreased and increased. For example, that of P. I. Belyayev was 1100 ml below the baseline data, that of A. A. Leonov 1000 ml, that of V. N. Kubasov, 200 ml, and that of G. S. Shonin, according to the data of four studies (days 1-4 of the flight), by 180 ml below the baseline data, on the average. The VCL of Ye. V. Khrunov in the first day of orbital flight was found to be 200 ml above the baseline data. The VCL changes of V. V. Gorbatko in days 1-5 of the flight varied, according to the data of four studies, from 200 to 500 ml. The VCL of A. G. Nikolayev (Soyuz 9) on the 8th and 16th days of flight increased by 600 and 800 ml, respectively. In the postflight period, the VCL rapidly returned to the initial level, with negligible fluctuations in one direction or the other (from ±50 to ±300 ml).

In performing proportioned physical workloads in weightlessness, the vital capacity of the lungs varied more than during the same workload performed under earth conditions.

While a proportioned physical workload on earth led to a stable reduction in VCL (by 50-150 ml, compared with rest), both a reduction (by 100-400 ml) and an increase (by 100-900 ml) of the VCL was recorded under weightless conditions. Performance of a proportioned physical workload in the postflight period, like before the flight, caused a 50-100 ml reduction in VCL, in the majority of cases.

Thus, changes in the vital capacity of the lungs under orbital weightlessness conditions also are characterized by great variability both . magnitude of change and in direction of the shifts. In the majority of cases, the vital capacity of the lungs was lower in weightlessness than in the preflight period.

In connection with the fact that study of the respiratory metabolism and energy consumption indices of the astronauts was conducted during flights of different lengths, and that the astronauts were occupied with nonuniform activities before the studies and performed different measured physical workloads, it is advisable to analyze the data obtained separately for each flight.

Execution of the Voskhod 2 flight program required great emotional and physical stress of the astronauts: the first extravehicular activity was accomplished. This was reflected in the respiratory metabolism and energy consumption indices.

As is clear from Table 47, the respiratory metabolism rate increased considerably under weightless conditions in both astronauts. The pulmonary ventilation of P. I. Belyayev increased by 92% from the initial state and, of A. A. Leonov, by 185%. This increase took place mainly, because of change in respiratory volume, which increased by 532 ml for P. I. Belyayev and by 692 ml for A. A. Leonov. The respiration rate of both astronauts changed less. The consumption of oxygen, investigated in A. A. Leonov under orbital weightlessness /170
conditions, was increased by 206.4 ml/min (over data on earth); it was 2-7 ml/min below that on earth for P. I. Belyayev. Carbon dioxide discharge by A. A. Leonov increased by 64 ml/min, and that of P. I. Belyayev decreased a little. The energy consumption at the moment of study of respiratory metabolism under weightlessness was 2.2 kcal/min for A. A. Leonov and 0.81 kcal/min for P. I. Belyayev (I. I. Kas'yan, et al., 1969).

Similar changes were found in study of respiratory metabolism and energy consumption of the crew members of Soyuz 4 and Soyuz 5, /171
accomplishing "docking" and transfer from one craft to the other through open space (Table 48).

Analysis of the results of 14 studies of respiratory metabolism, carried out on V. A. Shatalov and Ye. V. Khrunov in a 72-hour orbital flight, revealed a higher metabolism level than under ground conditions. Thus, the pulmonary ventilation, measured under weightless conditions in a state of relative rest, was higher than before the flight: by 2.36-2.80 l/min for V. A. Shatalov and by 0.52-5.02 l/min for Ye. V. Khrunov. The greatest increase in pulmonary ventilation was noted in V. A. Shatalov, in the 12th orbit (the first day of the flight) and the smallest, in the 27th orbit (2nd day of the flight). The oxygen consumption in weightlessness of Ye. V. Khrunov was 240 ml/min; it was 225 ml/min on earth.

The energy consumption of V. A. Shatalov and Ye. V. Khrunov, measured under orbital weightless conditions, also were greater than before the flight. According to the data of six studies, conducted

TABLE 47

RESPIRATION INDICES OF ASTRONAUTS P. I. BELYAYEV AND A. A. LEONOV DURING ORBITAL FLIGHT IN VOSKHOD 2

Index	P. I. Belyayev			A. A. Leonov		
	Pre-flight	In-flight	Post-flight	Pre-flight	In-flight	Post-flight
Respiration rate, cycle/min	7.0	8.0	9.2	11.4	14.0	9.[illegible]
Respiratory volume, ml	718	1251	830	488	1180	670
Pulmonary ventilation, l/min (corrected to STPD conditions)	4.6	8.92	7.14	5.16	14.70	6.13

on V. A. Shatalov in flight, the energy consumption in a state of relative rest exceeded the initial values by 0.94-1.39 kcal/min; the energy consumption of Ye. V. Khrunov under these conditions was 0.06-1.45 kcal/min higher. The highest energy consumption by V. A. Shatalov was recorded in orbit 7 (first day of the flight) and the lowest, in the 43rd orbit (3rd day).

When the astronauts performed proportioned physical workloads during a space flight, the fluctuations in respiratory metabolism indices under weightless conditions were still more pronounced (see Table 48). Thus, compared with data obtained before performance of a physical workload, the increase in pulmonary ventilation of V. A. Shatalov was from 3.6 to 8.5 l/min, in different orbits of the flight. Of six studies, his maximum increase in pulmonary ventilation in a physical workload was observed in the third day of the flight (orbit 43) and the minimum increase, on the 2nd day of the flight (orbit 27). /172

In experiments performed by the crews of Soyuz 6 and Soyuz 7 (22 studies of 4 astronauts, in weightlessness for about 119 hours), a distinct increase also was noted in pulmonary ventilation, compared with preflight data. This increase was more marked in performing proportioned physical workloads. Thus, from data of 11 studies of pulmonary ventilation of astronauts in a state of relative rest, the minute volume of respiration in different orbits of the flight was 2.07 l/min higher than the baseline (see Table 48). The maximum increase in pulmonary ventilation was noted in G. S. Shonin on the 3rd day of the flight (orbit 34), in V. V. Gorbatko in the 18th and 19th orbit (days 2 and 3 of the flight) and in A. V. Filipchenko, on the 5th day of the flight (orbit 79). /173

The energy consumption of the astronauts, calculated from the pulmonary ventilation (11 observations) under weightless conditions, also was increased over the baseline observations before the flight, by an average of 0.59 kcal/min. The maximum increase in energy consumption of the astronauts in a state of relative rest was:

TABLE 48

MINUTE RESPIRATION VOLUME OF ASTRONAUTS IN ORBITAL FLIGHT, AT REST AND AFTER WORK (liters)

Astronaut	Preflight			Under Weightless Conditions							Postflight		
	Inflight	After physical workload		Dayofflight	Orbit	Activity before Examination	At rest	Physical workload (Pumping out condensate)	After physical workload		At rest	After physical workload	
		15 min	2 hr						15 min	2 hr		15 min	2 hr
V.A. Shatalov	7.24	—	—	1	7	—	11.4	3 min	16.9	—	—	—	—
				1	13		12.4	3 »	16.0	—	—	—	—
				2	21		11.2	3 »	14 9	—	—	—	—
				2	27		9.6	3 »	13.2	—			
				3	40		10.8	3 »	17.5	—			
				3	43		10.9	3 »	19.4	—	9.24	—	—
Ye.V. Khrunov	7.58	—	—	3	40	Radiocom	8 1	—	—	—			
				3	43	Postsleep	12.6		—	—	9.13	—	—
G.S. Shonin	10.2	—	—	1	1	Radiocom	11.4	2 min	20.0	—			
				3	34	Filling burette	16.9	2 »	21.8	—			
				3	37	Radiocom	14 9	2 »	19.2	—			
				4	60	Photography	13.8	2 »	20.2	—	9.4	—	—
V.N. Kubasov	11.13	—	—	3	34	Monitor systems	13.2	2 »	16.7	—	7.85	—	—
A.V.Filipchenko	10.9	15.9	—	5	69	Radiocom	15.0	Expander	18.7	—	7.85	—	—
				»	79	»	15.9	»	20.4	—	9.75	13.2	—
V.V. Gorbatko	6 86	7.47	—	2	18	Breakfast	12.9	Expander	13.5	—			
				3	38	Photography	7.85	»	9.7	—			
				3	49	Same	11.9	»	13.1	—			
				5	70	» »	9.4	»	14.2	—	5.0	8.7	—
A.G. Nikolayev	7.16	12.3	8.3	8	116	Radiocom	11.9	Expander	17.8	10.1			
				16	240	»	11 7	»	16.2	11.7	7.7	10.4	7.7

by G. S. Shonin in day 3 of the flight (+0.96 kcal/min), by A. V. Filipchenko on day 5 of the flight (+1.07 kcal/min) and by V. V. Gorbatko on day 3 of the flight (+0.72 kcal/min).

Study of pulmonary ventilation in flight, immediately after the astronauts performed proportioned physical workloads, showed more pronounced shifts of the minute volume of respiration than the changes observed in performing the same work on earth. The increase in pulmonary ventilation of G. S. Shonin and V. N. Kubasov, while working in weightlessness (pumping out condensate) in various orbits of the flight, varied from 3.5 to 8.6 l/min compared with data obtained before each study in a state of rest). Performance of the same work on earth caused an increase in pulmonary ventilation of only 1.2-1.3 l/min. The increase in pulmonary ventilation of A. V. Filipchenko and V. V. Gorbatko in a proportioned physical workload in weightlessness (work with the expander), from the data of six studies, was an average of 2.8 l/min. The maximum increase in pulmonary ventilation, in work performed in weightlessness, was observed for A. V. Filipchenko (4.5 l/min) and for V. V. Gorbatko (4.8 l/min) on the 5th day of the flight (69th and 79th orbits for the first and 70th orbit for the second astronaut). The energy consumption of the astronauts in performing proportioned physical workloads, calculated from the pulmonary ventilation value, also were higher than the energy consumption in the same work under earth conditions. The greatest increase of energy consumption proved to be that of G. S. Shonin in orbit 34 (3rd day of the flight) and of V. V. Gorbatko in the 70th orbit (5th day of the flight).

A study of respiratory metabolism, carried out on G. S. Shonin in the first days of the flight, showed that oxygen consumption by the astronaut, in performing a proportioned physical workload, increased by 189%, elimination of carbon dioxide increased by 209% and the energy consumption increased by 193%, over the indices obtained before each workload in a state of relative rest.

In an analysis of materials of the 18-day flight of Soyuz 9, the same pattern of change in pulmonary respiration was found, as in the preceding flights of shorter duration. Thus, the minute volume of respiration of A. G. Nikolayev in a state of relative rest, in the 116th and 240th orbits (days 8 and 16 of the flight) were 4.74 and 4.54 l/min higher, respectively, than before the flight.

In performing a proportioned physical workload (work with the expander), the pulmonary ventilation of A. G. Nikolayev in the 116th and 240th orbits increased, in the first case, from 11.9 to 17.8 l/min and, in the second, from 11.7 to 16.2 l/min. The pulmonary /174 ventilation 2 min after the workload recovered to the value recorded in a quiet state before work with the expander (it turned out to be even a little lower than before the workload in the 116th orbit).

It must be noted that, both in a state of rest and in performing a proportioned workload, the pulmonary ventilation decreased somewhat at the end of the flight, to values, which practically coincided with the data obtained for A. G. Nikolayev while performing training flights in the aircraft-laboratory.

Study of the respiratory metabolism of A. G. Nikolayev was carried out simultaneously with determination of pulmonary ventilation, i.e., in the 116th and 240th orbits of the flight. In both cases, oxygen consumption and energy consumption, studied both at rest and in performing a proportioned physical workload, were greater than under earth conditions. However, a reduction in respiratory metabolism indices was noted by the 16th day of the flight, both in the state of relative rest and in performing the proportioned physical workload, although the oxygen consumption at rest on the 16th day remained 80% higher than on earth for A. G. Nikolayev.

Study of the respiratory metabolism in the postflight period showed that the metabolic shift of the astronauts were retained for a long time after the end of the flight.

The oxygen consumption and energy consumption of P. I. Belyayev, A. A. Leonov, V. A. Shatalov and Ye. V. Khrunov, studied a day after the flight in a state of relative rest, was 12-66% higher, than in the preflight period. The oxygen consumption of V. N. Kubasov, A. V. Filipchenko and V. V. Gorbatko a day after the flight, was 5-23% below the baseline data. The metabolism of A. G. Nikolayev after the flight of Soyuz 9 returned to the initial value on the 8th day after the flight.

Thus, the collated results of study of the state of respiration, respiratory metabolism and energy consumption of the crews of Voskhod 2, Soyuz 4 and Soyuz 9 indicates that the effect of prolonged weightlessness on the human body is displayed by an increase in metabolism rates, retained for periods of up to 18 days continuous stay under these conditions.

The changes in respiration rate come down to expression of it by quickening at the start of flight and after descent of the spacecraft. In the middle of the flight, these changes were determined by the nature of the activities of the astronauts: both quickening and slowing down of respiration were observed, depending on the physical and psychic loads. Thus, for example, radioconversations, which were carried out at a very high rate, caused a noticeable quickening of respiration. Respiration quickened especially sharply in the astronauts, in preparing for extravehicular activity and while performing it. In a state of relative rest and during sleep, the respiration rate decreased. However, it must be noted overall that the respiration rate was maintained at a relatively higher level, than under the corresponding conditions on earth.

The pulmonary ventilation volume, oxygen consumption and carbon dioxide elimination, and the level of energy consumption of the astronauts under weightless conditions also were higher than in the initial state (preflight) and, when the astronauts were in a state of rest after performing various operations and while they performed proportioned physical workloads. The greatest increase in metabolism rate was observed on days 1-5 of the flight. With further stay in weightlessness (up to 18 days), the respiratory metabolism decreased /175 somewhat, not reaching however, the initial indices, obtained in conduct of similar studies on earth.

It should be assumed that the marked increase in rate of metabolic processes, especially in the first days a man is in weightlessness, is connected with manifestation of general, nonspecific reactions of the body to the change in environmental conditions. Under new physical conditions, as a consequence of change in the accustomed flow of information and of the progressing disagreement in the functioning of the majority of analyzers (O. G. Gazenko, 1962; P. K. Isakov, 1963, 1964; Ye. M. Yuganov, 1963, 1965; I. I. Kas'yan, et al., 1966, 1969, 1971; P. V. Vasil'ev, 1969), imperfections in the coordination-compensatory mechanisms accomplishing human posture preservation at rest and at work, apparently arises. The more pronounced shift in respiratory metabolism, during the alternating effects of brief weightlessness and g-forces (in parabolic aircraft flights) and in simulation of weightlessness in immersion media, are evidence of this. Subsequently, as studies in long space flights has shown, in proportion to the reduction in neuroemotional and psychic stress, adaptation to weightlessness and working out of new work stereotypes, relative stabilization and reduction in the metabolic processes to a lower level sets in. The reduction in metabolism rate can also be due to the effect of hypokinesia. However, on the basis of data obtained in experiments with subjects secured in various ways during work in the unsupported test stand, it should be thought that, with complete adaptation of the body to weightless conditions, the performance of any physical work in weightlessness with inadequate securing of the man, would always be accompanied by higher energy consumption. This is connected with the fact that additional energy must be expended in unsupported space to maintain the body in the initial position while working. It can also be assumed that one of the causes of the increase in metabolism rate in weightlessness may be change in hemodynamics in the body, with redistribution of the blood, an increase in its central volume. This confirms experimental data, obtained in brief weightlessness in parabolic aircraft flights (I. I. Kas'yan, G. F. Makarov, V. I. Sokolkov, 1971).

In all likelihood, changes in the vital capacity of the lungs under prolonged weightlessness also are due to the hemodynamic shifts indicated above.

Of course, in connection with the conduct of a small number of experiments, the data obtained still do not permit final conclusions to be drawn. Further research on longer flights is necessary for this.

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6. Urea, Sugar, Nonesterified Fatty Acid and Cholesterol Content of the Blood in Prolonged Weightlessness

As a result of study of the urine composition of the astronauts during flights and immediately after ending them, some disturbances of the metabolic processes have been successfully revealed. These disturbances were expressed by dehydration and inability to retain /177 electrolytes in the body (I. S. Balakhovskiy, et al., 1971; Lutwak, et al., 1969; Berry, 1971). To evaluate other aspects of metabolism, there was interest in studying the urea, sugar, nonesterified fatty acid and cholesterol content of the blood of the astronauts, during the flight of Salyut; these are substances, determination of which is extensively done in clinical biochemistry.

We undertook the first effort to carry out such a study in 1964, during the flight of the Voskhod spacecraft (I. S. Balakhovskiy, et al., 1966). Determination of urea was of interest, because there are data on change in kidney condition after flights (I. S. Balakhovskiy, et al., 1971). The sugar and nonesterified fatty acids are the main sources of energy of the body; therefore, investigation of their content permits determination of the degree of conditioning of the person being examined, on the one hand, and, on the other, to indirectly approach an explanation of the functional state of the internal secretion glands. An increase in blood cholesterol is a sign of development of atherosclerosis. Moreover, determination of its content allows evaluation of the food ration. All these considerations served as a basis for development of a complex microchemical blood analysis method, suitable for use aboard spacecraft. This method was investigated during the flight of the Voskhod spacecraft in 1964 and the Salyut station in 1971. Similar studies have been carried out in ground experiments, when flight conditions were simulated by prolonged hypodynamia. This permitted a more nearly valid approach to the results obtained directly in space.

Biochemical studies of whole blood and serum have been carried out, using the method adopted in our laboratory for analysis of blood dried on filter paper (T. A. Orlova, I. S. Balakhovskiy, 1969). In examination of astronauts on earth, as well as during simulated tests, blood or serum samples are applied to filter paper and dried in air. In flight, the astronauts themselves took the blood samples, by pricking the flesh of the finger and squeezing out a drop of about 0.1 ml in volume onto the filter paper. They placed the paper /178 in a special, sealed container, containing a moisture absorbent (Fig. 49); the blood dried out in it. The total weight of the container, containing the paper with blood and absorbent, remained constant, in this case. In dried form, the blood was preserved for the entire traveltime and was returned to earth. The amount of blood sampled was determined in the laboratory, by weighing the container.

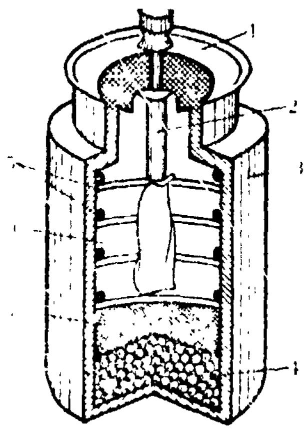

Fig. 49. Blood sampling container: 1) rubber cover; 2) rod for attaching paper; 3) container housing; 4) section with silica gel; 5) spring compressing the silica gel; 6) paper for sampling blood; 7) capron mesh, separating the section with silica gel.

The dry blood residue was determined simultaneously, by weighing the paper itself.

Determination of the nonesterified fatty acid content was also carried out by a micromethod specially developed in our laboratory (T. A. Orlova, I. S. Balakhovskiy, 1969).

To facilitate the blood sampling procedures aboard the craft, everything necessary (needle-scarifier, blood sample container with disinfectant) was placed in a special storage box, an autonomous blood microanalyzer (AMAK-3) (Fig. 50). The astronaut made a record of sampling the blood on the lid of this box. There was transparent tape in the box, on which blood smears were made for morphological examination.

Change in Certain Biochemical Blood Indices in Hypodynamia

The effect of hypodynamia on the urine, sugar, nonesterified fatty acid and cholesterol content of the blood was studied in several tests, which were performed at various times, by various groups of investigators.

As a rule, two or three series were set up simultaneously. One of them was a control, with "pure" hypodynamia and, in the other series, one prophylactic measure or procedure or another was tested. In all cases, those examined, healthy young men, were on a strict bed rest regime during the entire time of the experiment. They could not take a vertical position, but could turn over from side to side in bed. Details of conduct of the tests in series III-VI have been discussed in an article of I. S. Balakhovskiy and colleagues (1972) and, in series VIII and IX, in a book of P. A. Sorokin and colleagues (1969). In test series II, those examined were under reduced /179 barometric pressure, corresponding to altitudes between 2 and 4.5 km above sea level, for a period of 6 hours daily. In test series III, negative pressure on the lower half of the body (NPLB) was used as the prophylactic measure, by applying a vacuum container. Training exercises also were carried out in the vacuum container, but at a lower rate, in series IV. Besides, those examined did physical exercises, increasing their daily energy consumption by approximately 500 kcal. Electrical stimulation of the muscles was done for prophylactic purposes in series VI, and physical training, also equivalent to approximately 500 kcal per day, was used in series IX. In series IV, V, VI, VIII and IX, those examined ate a selection of dry and preserved foodstuffs, with a total calorie value of 2700-2900 kcal, which was similar in composition to the onboard food of the astronauts. There was the usual hospital food in series III and VII.

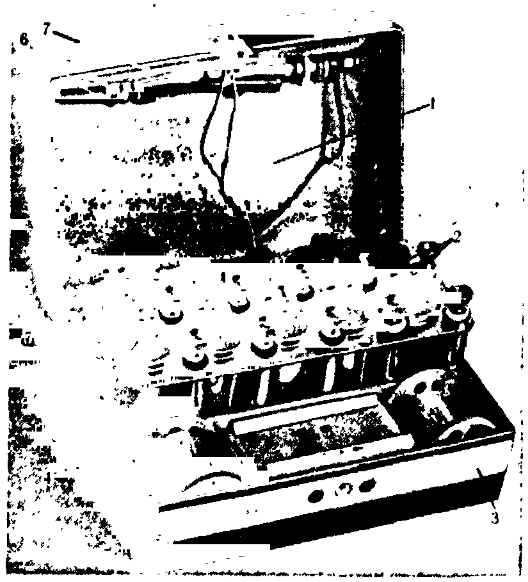

Fig. 50. Autonomous blood micro-analyzer (AMAK): 1) cover; 2) blood sample containers; 3) base of box; 4) object glass; 5) needle-scarifier; 6) small beakers for disinfecting solution; 7) film-winding mechanism.

It is clear from Table 49 that the urea content of the blood increased somewhat during the model test, as a rule, regardless of whether or not prophylactic measures were used. The blood sugar content changed differently (Table 50): during hypodynamia tests, it decreased to one extent or another in the majority of cases, but it increased again at the end of the test. There was a particularly distinct increase in level in the group with "pure" hypodynamia (series V), on the day after the end of the experiment. The physical workload and other prophylactic measures had a negligible effect on the blood sugar content during hypodynamia, but it prevented an increase in it immediately after the end of the test. This is striking, in a comparison of the results obtained in test series IV and V. The nonesterified fatty acid content (Table 51) did not change significantly in the bed rest conditions, but, just like the sugar content, it increased sharply in the control group on the day after the end of the test, when those examined had already assumed the vertical position. Physical training and electrical stimulation of /180
the muscles prevented this increase.

The blood and serum cholesterol concentrations increased during the tests, as a rule (Table 52). In determination of this substance by the method of Il'k (which is accepted as unified at the present time), the direction of change was similar, but the absolute indices were somewhat lower, since all cholesterol in the serum cannot be detected by this method. The cholesterol content did not increase in the groups of subjects with hypoxia (series II) and with electrical stimulation of the muscles (series VI), as well as when eating hospital rations. It must be kept in mind, in analyzing these data, that the cholesterol level increases with age. Since our subjects

TABLE 49

CHANGE IN UREA CONTENT IN SIMULATED EXPERIMENTS WITH BED REST CONDITIONS AND DURING STAY IN SMALL-VOLUME CHAMBERS

Test Duration in Days	Test Series	Test Conditions	Num	Material	Urea Content, mg %										
					Before Test	Days After Start of Test							Days After Test End		
						2—3	8—9	15—17	19—20	25—30	60	100	2	7—8	10—16
up to 25	—	stay in small volume chambers	up to	blood	M 30 m 1.4 n 19	37 2.1 8	—	38 1.6 8	—	38 1.8	—	—	—	—	—
20	— I II	Bed rest Bed rest (control of 2 series) Bed rest Hypoxia	6 2 4	blood »	M 29 m 1.3 28(30,26) M 30(25—34) m 1.9	— — — —	34 2.1 32(31,33) 36(29—44) 2.6	— — — —	36 0.9 33(31,35) 38 2.5	— — — —	— — —	— — —	— — —	27 1.6 25(25;25) 28 2.2(24—36)	— 25 (24;26) —
30	IV, V, VI	Bed rest, physical work load and NPLB In series VI electrical stimulation in series VI		serum	M 33 m 1.6	— —	— —	— —	36 2.3	— —	— —	— —	32 1.7	— —	27 1.3
100	VIII, IX	Bed rest in series VIII, in series IX, same and physical workload		blood	M 32 m 2.2	—	—	35 2.4	—	—	36 1.4	34 2.0			

Note: In this and the following tables of this section, the limits of fluctuation of the indices are given in parentheses.

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TABLE 50

CHANGE IN BLOOD SUGAR CONTENT DURING HYPODYNAMIA

Test Duration in Days	Test Series	Test Conditions	Number of Ob serva tions	Material	Sugar Content, mg %							
					Before Test	Days After Start of Test					Days After Test End	
						5—10	15—20	30	60	100	2	15—20
20	I	bed rest (control)	2	blood	60 (54; 65)	66 (65; 68)	66 (60; 71)	—	—	—	—	73 (71; 75)
		Bed rest and Hypoxia	4	»	68 (56—74)	72 (69—73)	72 (64—79)	—	—	—	—	73 (70—76)
30	IV	Bed rest Physiological workload and NPLB	3	serum	68 (66—72)	—	60 (56—65)	—	—	—	65 (60—67)	64 (61—67)
	V	Bed rest (control)	3	»	71 (59—80)	—	62 (55—68)	—	—	—	77 (70—85)	67 (58—72)
	VI	Bed rest with electrical stimulation	3	»	62 (60—63)	—	60 (58—65)	—	—	—	73 (70—75)	64 (61—70)
	IV—VI	Average values of series IV, V and VI	9	»	67±2.5	—	61±1.3	—	—	—	—	65±1.9
			9	»	69±2.0	66±2.1	62±1.3	45±1.9	—	—	—	—
	VII	Bed rest										
100	VIII	Bed rest (control)	3	blood	91 (83—97)	—	56 (53—60)	—	78 (69—86)	109 (103—119)	—	—
	IX	Bed rest and physical workload	3	»	85 (73—104)	—	66 (52—70)	—	79 (76—84)	89 (67—107)	—	—
	VIII—IX	Average of series VIII and IX	6	»	88±4.9	—	58±2.7	—	78±2.5	—	—	—

TABLE 51

CHANGE IN NONESTERIFIED FATTY ACID CONTENT OF BLOOD SERUM IN HYPODYNAMIA

Test Series	Test Conditions	Number of Observations	Nonesterified Fatty Acid Content, μeq/l					
			Test Day				Day After Test	
			Before Test	10	20	29	2	15—20
IV	Bed rest, physical workload, NELB	3	600 (555—6[illegible])	—	950 (750—1260)	—	730 (650—855)	690 (570—8[illegible])
V	Bed rest (control)	3	610 (575—690	—	700 (650—780)	—	1200 (1100—1[illegible])	600 (560—650)
VI	Bed rest and electrical stimulation of muscles	3	860 (710—1135)	—	640 (580—670)	—	700 (675—755)	700 (540—8[illegible])
II—VI	Avg data of series of similar tests		M 650 m ±50 n 16	—	700 ±60 12	—	—	560 ±40 15
VII	Bed rest	9	M 480 m ±90	440 ±80	450 ±100	630 ±130	—	—

Note: Test duration, 30 days.

were not a uniform group in this respect (their ages varied from 20 to 35 years), the research data in each series must be compared with its initial values.

Changes in Certain Biochemical Indices of the Blood During Flight

During a flight, astronauts sampled blood three times for analysis. The results of these determinations are comparable with the preflight and postflight examination data in 3-5 day flights, as well as with the results of analyses of samples, taken during the flight of Voskhod, presented in Table 53.

For technical reasons, the results of determination of the dry residue were reliable only at the start of a flight. On the 5th day, the dry residue of G. T. Dobrovolskiy was 22.3%, that of V. N. Volkov 20.5% and that of V. I. Patsayev, 22.8%. All the indices were normal, and they indicated the absence of marked hemoconcentration.

The blood urea content of V. I. Patsayev increased most of all. This increase was maintained for the entire flight, and it frequently exceeded 40 mg %. During a 1-day flight of the Voskhod spacecraft crew members, the urea concentration also was elevated.

TABLE 52

CHANCE IN BLOOD CHOLESTEROL CONTENT IN HYPODYNAMIA

Test Duration in Days	Test Series	Test Conditions		Material	Cholesterol Content, mg%							
					Before Test		Days After Start of Test				Days After End of Test	
						8—10	17—20	[illegible]	60	100	2	17—20
20	I	Bed rest (control)	2	Blood	170 (165; 175)	200 (188; 208)	190 (175; 200)	—	—	—		160 (165; 155)
		Bed rest, Hypoxia	4	»	170 (154—184)	170 (152—180)	170 (157—188)	—	—	—		140 (132—154)
30	III	Bed rest, NPLB	3	Plasma	185 (170—200)			—	—	—	260 (240—275)	250 (240—275)
	IV	" " " physical workload	3	Serum	210 (200—215)		230 (212—243)	—	—	—	260 (225—290)	240 (225—255)
	V	Bed rest	3	»	260 (227—305)		300 (260—325)	—	—	—	330 (300—360)	280 (230—355)
		Average values of series III, IV and V	9	Plasma or Serum	M 220 m 14		260 16	—	—	—	280 14	260 13
	VI	Bed rest and electrical stimulation of muscles	3	Serum	270 (230—330)		255 (190—345)				250 (195—300)	230 (190—290)
	VII	Bed rest	9	»	M 280 m 14	260 63	270 34	270 17	— —	— —		
100	VIII	Bed rest	3	Blood	170 (158—182)		217 (202—236)		210 (207—220)	230 (226—235)		
	IX	Bed rest and physical workload	3	»	170 (151—183)		230 (212—249)		240 (208—278)	230 (177—281)		
		Average of series VIII and IX	6	»	M 170 m 5		225 7		225 11	230 13		

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TABLE 53

UREA, SUGAR AND CHOLESTEROL CONTENT OF BLOOD OF CREW MEMBERS OF SALYUT SPACE STATION, COMPARED WITH DATA OBTAINED IN OTHER FLIGHTS

Spacecraft	Astronaut		Preflight		Day of Flight				Post-flight
			Base line	At Launch	1	5	15	22	
Urea, mg %									
Voskhod	K.P.Feoktistov, V.V.Yegorov		25 23	31	47 51; 41	— —	— —	— —	40 40
Salyut	G.T.Dobrovolskiy, V.N.Volkov, V.I.Patsayev		32 34 42	38 32 33	— — —	50 33 53	41 — 53	43 39 50	— — —
Average data of flights of up to 5 days of Voskhod 1, Voskhod 2 and Soyuz 3-8		M σ n	31 6.4 190	33 6.0 13					36 6 0 17
Sugar, mg%									
Voskhod	K.P.Feoktistov, V.V.Yegorov		75 115	100 115	85 76; 112	— —	— —	— —	105 55
Salyut	G.T.Dobrovolskiy, V.N.Volkov, V.I.Patsayev		95 93 92	80 81 84	— — —	83 66 75	80 — 78	140 110 92	— — —
Average data of flights of up to 5 days of Voskhod 1, Voskhod 2 and Soyuz 3-8		M σ n	85 17 185	87 12 13	— — —	— — —	— — —	— — —	90 16 17
Cholesterol, mg%									
Salyut	G.T.Dobrovolskiy, V.N.Volkov, V.I.Patsayev		190 260 220	210 215 225	— — —	145 190 175	140 — 160	150 200 165	— — —
Average Data of Flights of up to 5 days of Voskhod 1, Voskhod 2 and Soyuz 3-9		M σ n	191 28 140	189 27 10	— — —	— — —	— — —	— — —	199 32 15

The blood sugar content was normal on the 5th and 15th days, with some tendency to decrease, but it increased sharply on the 22nd day, especially that of G. T. Dobrovolskiy. The direct causes of this increase could not be disclosed from the onboard log data. It is only known that, on this day, the astronauts were tired, since they had to transfer many times from one section to the other, preparing the spacecraft for descent. On the whole, the changes in blood sugar and urea content were close to those which occurred during simulation experiments.

In distinction from the usual increase in blood and serum cholesterol levels in simulation tests, the content of it in all astronauts decreased during the flight. In clinical practice, the cholesterol content is determined in the majority of cases, not in the whole blood, but in the serum or plasma, since the cholesterol concentration in the erythrocytes is relatively low and the dynamics of the content in whole blood turns out to be less indicative. It did not appear to be possible to obtain serum for analyses during a flight; therefore, only whole blood samples were taken.

The increase in blood urea content of the astronauts during the flight of the Salyut space station should not be surprising, since it agrees well with those shifts, which occurred in the model test and during the flight of the Voskhod spacecraft. This increase cannot be a consequence of acceleration or synthesis, since the excretory capabilities of healthy kidneys is very much higher than /181
the possible rate of formation of urea. This follows, if only from the fact that the hourly excretion of urea and other nitrogenous products fluctuates within considerable limits in the course of a day, and the maximum rate always proves to be much greater than the average. In connection with this, the cause of urea retention in the body may be only functional changes in the kidneys. Their functioning actually changes, both in flight and in hypodynamia tests. An increase in elimination of water and electrolytes in model tests has been demonstrated in many works of Gauer and colleagues (1971). According to our observations, the kidney function after a space flight and at specific stages of model tests also disclosed characteristic changes (I. S. Balakhovskiy, et al., 1971). Although, in general outline, the cause of increase in blood urea content is quite understandable, the specific pathophysiological mechanism and, mainly, the importance of this fact for evaluating the state of health of the astronauts remains unclear. It can be said confidently that these changes are of a functional nature, since, in simulation tests and in brief flights, the increase in urea content was reversible, the concentrating function of the kidneys did not suffer and the clinical analysis of the urine did not disclose signs of pathology.

Changes in degree of glycemia in hypodynamia is explained most simply of all by deconditioning of the body and the disturbances in regulation of blood sugar content caused by it. It is possible that the decrease in glucose consumption by the muscles and the nature of the food play a definitive role. According to a number of studies, the results of which were correlated by L. G. Leybson (1969), the glycemia level of well-conditioned athletes remains constant, even when performing large physical workloads. However, if the load does not correspond to the degree of conditioning of the human body, the blood sugar content initially increases and, at the end of performing the work, when the strength is already exhausted, hypoglycemia develops. Of course, nothing similar occurs during prolonged limitation of movement. As a result of deconditioning of the body, even small stimuli, which are unnoticed under normal conditions, prove to be capable of changing the blood sugar content. This can be explained by increase in the glycemia level at the end of a test and immediately after the end of it, in subjects, not employing prophylactic measures. Evidently, even the fact of finishing the test and changing from a horizontal position to the vertical was a significant stimulus for them. /182

There was a similar, but clearer picture during the space flight in the Salyut orbital station. We do not know all the circumstances, preceding blood sampling on the 22nd day of the flight, but it might be thought that, even if there was some reason favoring an increase in blood sugar content, it would not have caused such a sharp glycemia under other conditions. It is interesting that, on the 15th day of the flight, the sugar content did not increase. If such results are obtained in other space flights, the blood sugar content can be used as a test, for establishing that flight length, at which changes set in in regulation of the metabolic processes. Of course, this question can only be asked, from the data of one flight. /183

In a simulation experiment, with "pure" hypodynamia (series V), the nonesterified fatty acid content in the blood serum increased, when those examined assumed the vertical position. Using physical workloads and electrical stimulation during hypodynamia (series IV and VI), this increase was successfully prevented. Although the results of studies, carried out on only three subjects, are insufficient for final conclusions, it must be noted that a distinct increase was noted in all subjects, being much more than 1000 μeq/l in each one of them, i.e., an amount very rarely observed in healthy people. /185

Nonesterified fatty acids, just like glucose, are primary sources of energy for the tissues. Adrenalin is capable of increasing the concentrations of these acids, to the same extent as it increases glycemia. In the majority of functional states, the dynamics of nonesterified fatty acide concentration are the inverse of the glucose concentration dynamics (T. A. Orlova, 1969). These relationships can be observed in test series VII; both the sugar and acid content (see Table 51) were practically the same on the 10th and 20th days of the test as before the start of it, but the sugar content decreased sharply and the acid increased on the 29th day (day before the end of the test). From the functional point of view, these relationships are understandable, since both substances are a source of energy for the same processes. Since there was a simultaneous increase in both glucose and nonesterified fatty acid content after the end of the model test with hypodynamia (series V), it is most likely that both reactions are mediated through the adrenal system.

In simulation tests, when the subjects ate a ration similar to the onboard ration of the astronauts, 2700-2900 kcal per day, the increase in cholesterol content was distinct by the third week of the experiment; in some cases, it stabilized, and it continued to increase in others. After the end of the tests, the cholesterol level remained elevated for several more weeks. In the test series with regular hospital food, there was no increase in degree of cholesterinemia (series VII). In the majority of cases, brief flights led to a small increase in blood cholesterol content, but this increase was statistically insignificant overall (see Table 53). After the 18-day flight, the blood cholesterol level of A. G. Nikolayev increased from 206 to 226 mg %, and that of V. I. Sevast'yanov decreased from 170 to 136 mg %. It is interesting to note that the weight recovery of V. I. Sevast'yanov after the flight took place quite slowly, and that his loss during the flight was connected, not only with dehydration, but with protein catabolism processes. A. G. Nikolayev recovered weight considerably more quickly after the flight. Apparently, the different directions of the postflight changes in cholesterol content are connected with the facts observed. According to the data of American investigators, after the Apollo flights (Berry, 1971), the degree of cholesterinemia decreased. During the Salyut flight, the cholesterol content of the astronauts decreased. It is possible that this is connected with the fact that the actual food consumption was low, 1500-2000 kcal per day. The role of nutrition can be decided from the following example: The blood cholesterol content of all six participants in test series IV and V increased. Sh. had the smallest change in it (from 200 to 215 mg %). Nitrogen elimination of this subject, with the same ration during the entire test, was 16.9 g per day, on the average, while it was 13-14 g/day, for the remaining subjects in this series. Sh. was the most developed physically, and his energy expenditure in performing the physical workload was the largest; therefore, the calorie value of the ration apparently proved to be inadequate, in connection with which there was an increase in tissue protein catabolism.

As is well known, cholesterol forms in the body, in the intestines, liver and in the intima of the vessels; moreover, it comes in with food. According to the research of Malinow, et al., (1969), cholesterol breakdown is closely connected with muscle activity. Evidently, a decrease in it, with high energy value foods, is a direct cause of hypercholesterinemia. Electrical stimulation of the muscles, activating metabolic processes in them, creates a /186 unique imitator of muscle contractions, which, although it does not lead to the same consumption of energy as an actual muscle contraction, it is the starting mechanism of a complex change of metabolic processes, connected with cholesterol breakdown. Hypocholesterinemia, with hyperdynamia in the simulation tests, may also be connected with a decrease in the thyroid gland function. An indirect confirmation of this possibility is the decrease in basal metabolism under these conditions (M. I. Mikhasev, et al., 1960).

From the practical point of view, it is very important to give a correct evaluation of the results of studies of blood cholesterol content, although all aspects of the pathophysiological mechanisms of this phenomenon cannot now be interpreted.

The blood cholesterol level is not directly connected with the appearance of atherosclerosis; however, with a high content of it, the probability of various disturbances of the cardiovascular system increases. A sharp increase in blood cholesterol content during a period of several weeks is considered to be undesirable, since it may favor development of atherosclerotic lesions which remain after the cholesterol content becomes normal.

If the cause of hypercholesterinemia in simulation experiments is the energy excess of the ration, this question becomes especially urgent during flights. As a matter of fact, a nutritional insufficiency leads to a negative nitrogen balance, which apparently took place during the flight of Gemini 7 (Lutwak, et al., 1969), and an excess, to hypercholesterinemia. Both weaken the functional capabilities of the body.

It is difficult to precisely balance the energy consumption and calorie value of the ration: "earth" standards can be adopted, only with great reservations. An astronaut is overloaded with work during a flight, which requires neuroemotional stress. He must ensure navigation of the craft and performance of scientific research programs. The stay under weightlessness shows up in the equatorial function of the gastrointestional tract. This all leads to the situation, that the accustomed stimuli affecting thirst and appetite change. As a result, the very fine equilibrium between energy expenditures and food intake is disturbed; therefore, further working out of indices of sufficiency in nutrition is very important. The blood cholesterol level may possibly prove to be a useful criterion in this respect.

The informativeness of the research methods used can be noted in summarizing the work. Using them, it was successfully shown that the blood sugar content during a space flight and during simulation of it on earth is maintained with less constancy than under normal conditions, which may be connected with a decrease in conditioning of the body.

Similar results obtained in study of the nonesterified fatty acid content. The increase in urea content, which occurred both during the flight and in ground experiments apparently is connected with change in the functional state of the kidneys. The increase in cholesterol content is most correctly explained by the excess nutrition. This index can be used for evaluating the onboard rations.

7. Effect of Weightlessness on Mineral Saturation of Bone Tissue

N75 23121

In distinction from other tissues, bone tissue is rich in mineral salts. The skeleton not only provides the support-motor function, but it is a unique depot of the calcium and phosphorous salts, necessary to maintain the ionic equilibrium of the internal medium of the body. About 98% of all mineral salts of the body are in the bone tissue. /187

The shape and structure of the bones are continually in a state of dynamic development, and they are continually rebuilding and changing during the entire life of man and animals, depending on the internal and external influences. As the work of domestic investigators has shown, the support-motor function performed by it, as well as the constant action of the muscles on them, are of great importance in formation of the structures of individual bones (B. A. Dolgo-Saburov, 1930; A. T. Gorbunov, 1938).

The bony tissue reacts very sensitively to various functional shifts occurring in the body. The effect of the central nervous system, blood circulation, endocrine system, as well as nutrition and living conditions, on the structure of bones, is well known.

Demineralization of the skeleton unavoidably sets in, in patients forced to stay in bed a long time, i.e., osteoporosis develops. Osteoporosis is encountered quite often in the clinic. It is the almost constant companion of various diseases and traumatic injuries (S. A. Reynberg, 1964).

Disruption of the mineral metabolism in bony tissue and development of osteoporosis also is observed in a healthy man, if he is in a state of limited muscle activity for a prolonged period (bed rest, immobilization with plaster, submerged in water, etc.) (Ye. N. Biryukov, 1967; I. G. Krasnykh, 1969; Whedon, 1964; Vogt, et al., 1965; Mack, 1965; Dick, 1966; Rodahl, et al., 1966, and others). /188

Many investigators consider the cause of disruption of mineral metabolism in the bones under hypodynamic conditions to be functional underloading of the support-motor apparatus and the accompanying neurotrophic, hormonal, hemodynamic and other disturbances (S. A. Reynberg, 1964; Ye. N. Biryukov, 1967; Howard, et al., 1945; Frost, 1964).

On the basis of clinical observation data of domestic and foreign authors, at the beginning of the 1960's, when the conquest of space by man began, the hypothesis was expressed, of possible demineralization of the bony tissue, during a long stay under weightless conditions, in connection with a considerable underload on the skeleton. Subsequent studies of human bone density after returning from space completely confirmed the correctness of this hypothesis. Even a brief stay of man in weightlessness sharply affects the mineral saturation of bone tissue (Mack, 1966; Lutwak, 1966; Whedon, 1966). Thus, after a four-day stay under weightless conditions, the loss of calcium salts in the calcaneus of the Gemini 4 pilot and spacecraft /189 commander was 6 and 9.5%, respectively, and it was over 10% in the phalanges of the left hand (Klass, 1965). With an increase of flight duration to 8 days, the maximum decalcification of the skeleton of the Gemini 5 spacecraft commander was 15% in the calcaneus and 20% in the hands (Mack, 1966).

As Ye. N. Biryukov (1967), Ye. N. Biryukov and G. I. Kozyrevskaya (1967) showed, the loss in the mineral component of the calcaneus of two dogs, which were in space in the Kosmos 110 biological satellite for 22 days, was 10 and 11%.

In our research, the dynamics of change in mineral saturation of the bone tissue of the Soyuz 4, Soyuz 5, Soyuz 9 spacecraft and the Salyut orbital station crews were studied.

Determination of the degree of mineralization of the bone tissue was carried out by X-ray photometry (Mack, et al., 1927, 1939, 1949). This method allows the mineralization of bony tissue to be estimated quantitatively, by the degree of darkening of the X-ray film, with respect to the density of a graduated reference wedge, made of ivory, and photographed on the same X-ray photo as the bone being studied. This method makes it possible to record shifts in mineralization of the bone tissue on the order of 1-3% (Mack, et al., 1939; I. G. Sharabrina, 1958; R. S. Abrosimova, 1954, 1956, 1958).

We determined the mineral saturation of the bone tissue of the astronauts in the right calcaneus and in the basilar phalanges of the right hand, i.e., of bones of the skeleton under different functional conditions. Besides, it was important for the research that the layer of soft tissues covering these bones be small.

X-ray photography of the right calcaneus was carried out in the lateral, and of the right hand, in the anterior-posterior projections, together with the reference wedge, made of cattle bones with previously determined bone density, expressed in milligrams of phosphorous-calcium salts per mm^2 in each section of it.

X-ray photography was carried out on the same equipment, with identical voltages and current strength on the tube, as well as exposures and filters, on film of a single series. A developer, prepared the day before the study was used for development; development time was strictly maintained, in this case.

Photometry of the X-ray photos was carried out, using a MF-2 microphotometer, of the X-ray image of the right calcaneus, in the central segment and at the bases of the first phalanges of the right hand.

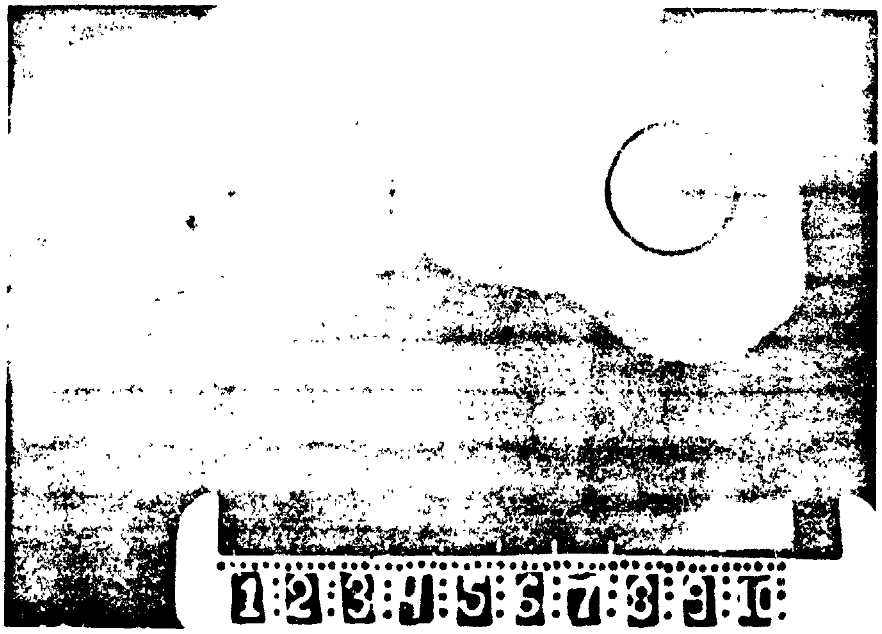

Fig. 51. X-ray photo of right calcaneus with reference wedge. Photometry was carried out in the section of the central segment of the bone designated.

100-150 points were determined in the central segment of the right calcaneus (Fig. 51) and 25-30 points, at the bases of the first phalanges (Fig. 52). The data obtained on all points in each bone were summed, and the average density was then calculated. On the basis of comparison of the average densities before and after a flight, the percent decrease or increase in mineral saturation of the bone tissue was calculated.

The results of study of mineral saturation of bone tissue of the Soyuz 4, Soyuz 5 and Soyuz 9 spacecraft crews are presented in Table 54.

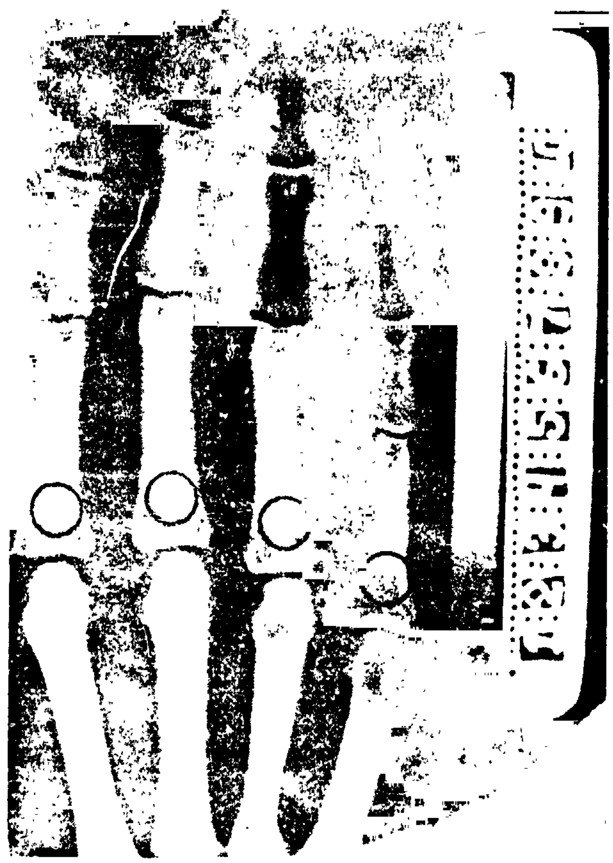

Fig. 52. X-ray photo of right hand, with reference wedge. Photometry was conducted in the designated sections of the bases of the first phalanges of fingers II-V.

It is evident from Table 54 that the degree of mineralization of the right calcaneus of V. A. Shatalov, B. V. Volynov and Ye. V. Khrunov decreased negligibly, by 4.65%, on the average, after three day's weightlessness. That of A. S. Yeliseyev remained at the preflight level. In the basilar phalanges of fingers II-V of the right hand, the changes were still smaller than in the calcaneus, 1.3-2.5%, on the average. The optical density of the calcaneus of A. G. Nikolayev and V. I. Sevast'yanov was 8.5 and 9.6%, respectively, below the initial level. Unidirectional changes, indicat- /190 ing loss of calcium and phosphorous salts, were noted in the basilar phalanges of fingers II-V of the right hand, as well. These losses were 3.7-6.8%, on the average. Examination on the 22nd day of the period of readaptation to earth conditions disclosed an increase in density in all parts of the skeleton studied. However, this period proved to be insufficient for complete recovery of the initial level of mineralization of the bone tissues. This can be explained partially by the fact that the functional load on the support-motor apparatus also was limited in this period, to a certain extent. Similar observations were noted earlier by Klass (1965), after the flight of Gemini 5. Complete recovery of the initial level of bone mass of the crew members had not occurred, even by the 50th day of the postflight period.

Before analyzing the data of the research on bone tissue density of the Salyut orbital station crew, the following remark must be made: Only the right calcaneus was studied in the postflight period. Moreover, for reasons beyond the control of the author, it was not possible to carry out radiological studies in the postflight period, which were identical to those of the baseline studies. In this connection, the reliability of our data may be reduced to a certain extent.

TABLE 54

CHANGE IN MINERAL SATURATION OF BONE TISSUE (in %) OF SOYUZ 4, SOYUZ 5 AND SOYUZ 9 SPACECRAFT CREW MEMBERS

Astronaut	Day After Flight	Calcaneus	Basilar Phalanges of Fingers			
			II	III	IV	V
V. A. Shatalov	7	−4.7	−1.2	−1.4	−1.8	1.5
B. V. Bolynov	7	−4.8	−1.8	−1	−1.2	±0
A. S. Yeliseyev	7	0	−1.6	−2.1	−3.2	−3.2
Ye. V. Khrunov	7	−4.4	−2.1	−1.9	−1.6	−2.2
A. G. Nikolayev	2	−8.5	—	−5	−3.1	−4.7
	22	−4.5	—	−2.5	+0	−1.6
V. I. Sevast'yanov	2	−9.6	−4.1	−5	−4.3	−8.9
	22	−3.4	±0	−5	−1.4	−4.4

Note: 1. - is a decrease; +, an increase in mineral saturation of bone tissue. This refers to all subsequent tables. 2. Study of the Soyuz 9 crew members was carried out jointly with Ye. N. Biryukov.

After the flight of the Salyut orbital station, the calcaneus optical densities of all crew members was below the initial level: that of G. T. Dobrovol'skiy by 18.2%, of V. N. Volkov by 18.7%, of V. I. Patsayev by 13.7% and an average of 16.8%.

Thus, the increase in stay time of man under weightless conditions also led to an increase in the degree of decalcification of bone tissue.

While the losses of mineral salts were negligible in crew members of the Soyuz 4 and Soyuz 5 spacecraft, the flight length of which was three days, with a sixfold increase in flight duration (18 days), decalcification of the calcaneus of the Soyuz 9 crew members doubled on the average and in the hand, almost tripled. With further increase in flight duration to 24 days, the degree of decalcification of the calcaneus doubled again.

From the data examined, it is clear that the demineralization /191
process begins very early under weightless conditions and progresses rapidly. It is interesting that demineralization under these conditions takes place at a higher rate than during hypodynamia. According to the data of Klass (1965), to obtain the same degree of demineralization as that of the Gemini 4 spacecraft crew members, by control tests on earth, required 30 days of bed rest, with restriction of motor activity.

It is appropriate to introduce our data, obtained in observations of healthy people, staying under hypodynamia for a long time (bed rest) on earth, to compare them with the results obtained after a stay in space (Table 55).

TABLE 55

CANGE IN MINERAL DENSITY OF RIGHT CALCANEUS (in %) IN HYPODYNAMIA OF DIFFERENT DURATIONS

Duration of Stay in Bed		
20	70	100
(2) $\frac{-6.3-10.7}{-8.5}$	(2) $\frac{-10.3-13.0}{11\ 65}$	(3) $\frac{-23.2-28.5}{-26.1}$

Note: The numbers in parentheses is the number of subjects; average data are in the denominator.

It follows from Table 55 that hypodynamia for a period of 20 days and the same ration, as that consumed by the astronauts, led to the degree of demineralization of the calcaneus observed in Soyuz 9 crew members, during a long 18-day flight, and the average index of calcium salt loss in the calcaneus of the Salyut crew members was twice that on earth. The extent of decalcification with increase in duration of hypodynamia on earth, from 20 to 70 days, increased very slowly (3% in 50 days); in the next 30 days (100-day hypodynamia), it increased noticeably, and it was more than double the 70-day loss.

Consequently, in comparing data on loss of bone density, obtained in studies of spacecraft crew members, after the action of weightlessness on them, with materials obtained on earth during prolonged hypodynamia, it is clearly seen that the rate of increase in demineralization of the skeleton is accelerated under weightlessness. This appears especially in longer stays under space conditions. How reliable these data are or, to state it another way, are there common patterns, which will be confirmed by subsequent flights, in the small number of observations at the present time, the confidence in which cannot be stated. Accumulation and generalization of material on space flights of the same or longer duration is necessary. However, from our point of view, the loss of calcium and phosphorous salts in the bones of the Soyuz 9 and Salyut crew members studied can hardly be considered to be unexpected. A demonstration of this is the data of Mack (1966), mentioned above, which established that the loss of calcium salts by the bones of the Gemini 5 crew members in an 8-day stay in weightlessness was almost the same as that of the Salyut crew members, though the /192
stay time under weightlessness was one-third as long.

The question is, will the extent of decalcification increase in proportion to the increase in length of a space flight, as might be thought, or will it remain at some stable level? How do these changes in degree of mineralization show up in strength of the skeleton, and will they lead to damage to the bones in the g-forces upon return to earth?

It should be considered at the same time that, as a result of marked and long calcium disturbances, a number of other physiological functions of the body may also be disrupted (see section 1, Chapter 6). Moreover, prolonged calcinemia and increased elimination of calcium with the urine may cause formation of idney stones along the urine elimination pathways, calcification c the walls of the vessels, ligaments, muscles, etc. (L. I. Kakurin, V. S. Katkovskiy, 1966; Cockett, 1964; Berry, 1967, and others).

In the opinions of specialists studying bone pathology, the main links in the mechanism of decalcification of the skeleton on earth are neurotrophic disorders, removal of loads along the vertical axis of the body to the bone-joint apparatus and decrease in the effect of muscle contraction on it, local and general hemodynamic disorders, endocrine disorders, etc. (D. G. Rokhlin, 1945; A. V. Rusakov, 1947; G. A. Zedgenidze, 1953; Howard, et al., 1945; Dunning, Plum, 1957; Frost, 1964, and others).

It must be assumed that the same pathophysiological mechanisms as those which lead to depletion of mineral salts from bone tissue act under weightless conditions. However, individual aspects of these disorders are expressed more clearly under weightlessness than on earth. An example might be the complete removal of loads on the bone-joint and muscle systems. In all likelihood, the rapidly advancing and progressing demineralization of the skeletal bones in weightlessness should be explained by this.

It must be noted in conclusion that the experimental materials presented introduce the urgent necessity for conduct of further, comprehensive studies of calcium metabolism during space flights and in experiments on earth, and also of searching for effective prophylactic measures. In our opinion, prophylactic measures must be developed in the following areas. First, the possibility of preserving locomotor activity must be sought, by means of using physical exercises; second, pharmacological preparations must be prescribed and, finally, the possibility of use of the food ration to normalize calcium and phosphorous metabolism must be studied.

In carrying out prophylactic measures, it should also be ke t in mind that disruption of the calcium and phosphorous metabolism must be considered to be an individual link in the change of water-salt metabolism, which is appreciably disturbed under weightless conditions. In this connection, prophylactic measures, for prevention of loss of the mineral component of bony tissue, should be a component part of measures to normalize the general metabolism, including the water-salt.

N75 23122

CHAPTER 4

MOTOR REACTIONS IN WEIGHTLESSNESS

1. Methods of Body Orientation in Space in the Absence of Support Under Weightless Conditions

Orientation of the human body in space in the absence of a support under weightless conditions is one of the urgent problems of space biomechanics. Weightless conditions cause significant readjustment of the movement coordinating structure. The greatest changes in coordination are sustained in the unsupported position, when the possibility of the accustomed interaction with external forces disappears from an astronaut. It is not advisable in all cases, for an astronaut to use technical devices for stabilization of his body in the required position, for turns relative to the longitudinal (on course) transverse (pitch) and front-rear (bank) axes, for control of body torsion in "free floating." Early mastery of methods of orienting the body in unsupported space by the astronauts, which are simple to perform and effective in results, using special cycles of movement of the extremities, facilitates these tasks and, in a number of cases, frees the hands for performing work. /193

During extravehicular activity, even with a tether, control of rotation of the body about its three axes presented A. A. Leonov with certain difficulties. A detailed analysis of the kinematic picture of extravehicular activities has been performed by Ye. A. Ivanov, V. A. Popov and L. S. Khachaturyants (1968) (see Chapter 6 of this book).

V. Stepantsov, A. Yeremin and S. Alekperov (1965, 1969) theoretically substantiated and tested a number of methods of turning the body around its axes, using the basic principles of the biomechanics of the unsupported position, under experimental conditions, on the Zukovskiy "stool," trampoline and in brief weightlessness.

Before the fundamental studies of V. L. Kirpichev (1907), an indirect interpretation of the law of conservation of momentum (the law of constant areas) led biomechanicists to the conclusion that it was impossible to turn the body in unsupported space. V. L. Kirpichev proposed a method of turning the body around the longitudinal axis, by means of cone-shaped motions of one arm above the head. This proposal retains its importance in stabilization of the body and in twists of it in open space. For example, when a twist develops, it can be stopped by a rotary motion of the arms in the direction /194 of the twist in the same plane, since the remainder of the body will turn in the opposite direction. It is completely obvious that movements of both hands or legs, as well as other parts of the body, relative to each other, can be used for orienting the body in space. Turns can be executed around, not only the longitudinal, but the other axes of the body, the transverse and front-rear.

In order to work out efficient types (methods) of mutual movements of parts of the body, for the purpose of orienting it in space, the values and ratios of the moments of inertia of links of the body must be obtained in various combinations, first of all. The basic theoretical calculations have been carried out, in accordance with the theorem of Shteiner, by the formula:

$$I_0 = I_c + ma^2,$$

where I_0 is the moment of inertia of the body (link) relative to an arbitrary axis O, I_c is the moment of inertia relative to the axis passing through the center of mass of the body (link), m is the mass of the body and a is the distance from the center of mass to the O axis.

The moment of inertia relative to the axis passing through the center of mass of the body (link) was determined, according to the data of Braune and Ficher (1890), by the formula:

$$I_c = m \cdot 0.09 \cdot l^2,$$

where l is the length of the body (link).

We have determined the average moments of inertia of the body and individual parts of it, relative to various axes, and their ratios, for a man 168-172 cm tall, weighing 70-75 kg, by theoretical calculations and experimental studies (Table 56). In particular, the ratio of the moment of inertia of a straight arm to the moment of inertia of the remaining part of the body in the straightened position, relative to the transverse axis of the shoulder joints (X_s) is 1/20, on the average, i.e., 1.2 kgm^2 to 24 kgm^2 and, in the bunched-up position, 1/10. Based on the equality of the momenta of these parts of the body, the angle to which the body turns in moving the straight arms can easily be determined. Thus, rotating the arm by 180° upward in the sagittal plane turns the body in the opposite direction (forward) by 1/20 of the angle, by an angle of 9°. The decrease in moment of inertia of the body to half by bunching up permits an 18° turn.

The ratio of the moments of inertia of the extended arms and the remaining part of the body, relative to the front-rear axis of the shoulder joints (Z_s) is 1/44-1/50. With the body bent at the hips to an angle of 90-100°, the moment of inertia of the legs

TABLE 56

AVERAGE MOMENT OF INERTIA OF BODY AND ITS PARTS (kgm^2) RELATIVE TO THE AXES

Part of Body	Moment of Inertia Relative to the Axes			
	X	Y	Z	Other Axes
Straightened Body	1.2–1.4	17.0–18.0	17.0–18.0	
Head, Trunk and Arms	0.55–0.65	3.8–4.4	3.8–4.4	
Straight Arms				X_s 0.6 Y_s 0.6 Z_s 0.6
Straight Legs				X_1 1.9–2.2 Y_1 1.9–2.2 Z_1 1.9–2.2
Legs, Separated in "spread eagle" or "step" position at angle of 60-70° 120-140°	2.6–3.3 3.9–4.4			
Straightened body, with arms deducted				X_s 24.0–2[illegible].8
Body bunched up with arms deducted				X_s 12.0–14.4
Body with one arm deducted				Z_s 27.6–30.0 Y_s 3.6–3.8
Legs in "angle" position to the trunk	3.8–4.4	3.8–4.4	0.50–0.55	

relative to the longitudinal axis of the trunk (3.8-4.4 kgm^2) is approximately 7-8 times greater than the moment of inertia of the remaining part of the body (0.55 kgm^2) and, on the other hand, the moment of inertia of the head, trunk and arms relative to the longitudinal axis of the legs is approximately as many times greater than the moment of inertia of the legs relative to their longitudinal axis. The ratio of the moments of inertia of the straight arms extended to the side and the remaining part of the body, relative to the longitudinal axis of the shoulder joints (Y_s) is approximately 1/6. /195

Thus, for practical purposes, the ratios of the moments of inertia of interacting parts of the body must be known, and it must be remembered that their movements always are in opposite directions. It should also be pointed out that, in practice, work in space will most often encounter the need for turning the body around the longitudinal or transverse axis. With the body vertical, the plane of motion of the arms will be horizontal. In everyday life, movements in this plane are encountered most often, and the anatomical-physiological peculiarities of man favor completion of turns of the body around the longitudinal axis.

To precisely define and select the most efficient method of turning the body around its axes, in addition to the studies conducted earlier on the Zhukovskiy "stool" and the trampoline, a series of experiments were performed with 8 subjects in brief weightlessness, during flight in the aircraft-laboratory along a Kepler parabola and /196 on 4 subjects in a water medium, as one weightlessness simulator, where it is possible for the subjects to work out cycles of movements of the arms and legs without a time deficit.

In order to determine the angle to which a body turns in performance of tasks by the subjects in brief weightlessness, motion picture photography was carried out, at 24 frames per second, against a background of a scale grid, in which the body of the subject was located, so that the plane of the turn was parallel to the plane of the motion-picture film. In a number of cases, photography of motion was used, with different locations of the body relative to the motion-picture camera, for study of peculiarities of the turn, as well as for elimination of external forces, connected with "purity" of reproduction of the weightlessness mode.

Since, while performing tasks under weightless conditions, the subjects wore a protective parachute helmet on the head, parachute boots on the feet and a parachute system on the trunk, in making the comparison of the theoretical calculations with the experimental data, first, the additional equipment was taken into consideration and, second, inaccuracies in task performance, connected with a limited amplitude of movement and disturbances of strict perpendicular position of the plane of movement to the body axis. The moment of inertia of the head was calculated by the formula for a sphere:

$$I_g = \frac{2}{5}mr^2,$$

and the moment of inertia of the trunk, by the formula for a parallelipiped

$$I_T = \frac{\alpha^2 + \beta^2}{3},$$

where α and β are mutually perpendicular segments from the axis to the outside of the trunk, lying in a plane perpendicular to the axis under consideration.

TABLE 57

CHARACTERISTICS OF MAIN LINKS OF THE BODY

Body Link	Ratio of Masses of Body Link to Body		Distance from Proximal End to Center of Mass of Link			Length of Body Links of Subject B (cm), our data
	from Harless	from N.A. Bernshteyn	from Harless	from N.A. Bernshteyn	Our Data	
Shoulder	0.0324	0.0263	0.485	0.475		30
Forearm	0.0181	0.0182	0.440	0.414		24
Hand	0.0084	0.0064			0.48	16
Thigh	0.1118	0.1249	0.467	0.388		40
Calf	0.0439	0.0473	0.360	0.418		38
Foot	0.0183	0.0139			0.40	25
	Scale Measurements of Subject B (our data)					
Head	0.07				0.50	18
Trunk	0.3327				0.44	40
Pelvis	0.1336				0.273	22

Individual singularities of body structure also were evaluated; they were determined by scale measurements by the method of Bernshteyn. The relative mass of the pelvis, length of pelvis and location of center of mass of the pelvis also were determined. It turned out that the pelvis actually brings the legs up to half the /197 mass of the body. Consequently, the upper and lower halves of the body, like two links of a kinematic pair, equal each other in mass; their centers of mass are at equal distances from the common center of mass of the body, and they are naturally joined at the place of greatest flexibility of the spine (the waist). The characteristics of the links of the extremities were selected, depending on the individual singularities of the subject, according to Harless (1876) or N. A. Bernshteyn (1934) (Table 57). Thus, according to Harless, the relative mass of the hand was 0.0589, of the legs 0.174, and the distance from the proximal end to the center of mass of the link was 0.47 and 0.41 of its length, respectively.

With several examples, we analyze the basic principles of plotting movement cycles. Kinograms of orientation of the body around the longitudinal axis, by the schemes of V. L. Kirpichev (a, b) and R. V. Polya (c, d), are presented in Fig. 53. Thus, to turn around the longitudinal axis (on course) by 180°, by the method of Kirpichev and Polya, 5-6 cone-shaped movements of the arms have to be made. However, as an analysis of the kinograms of execution of these movements shows, the body, although negligibly, will turn around the other two axes. Moreover, wearing a spacesuit, with the additional limitations on mobility and with the necessity for additional efforts to overcome its resistance, execution of circular movements of the arms will encounter serious difficulties.

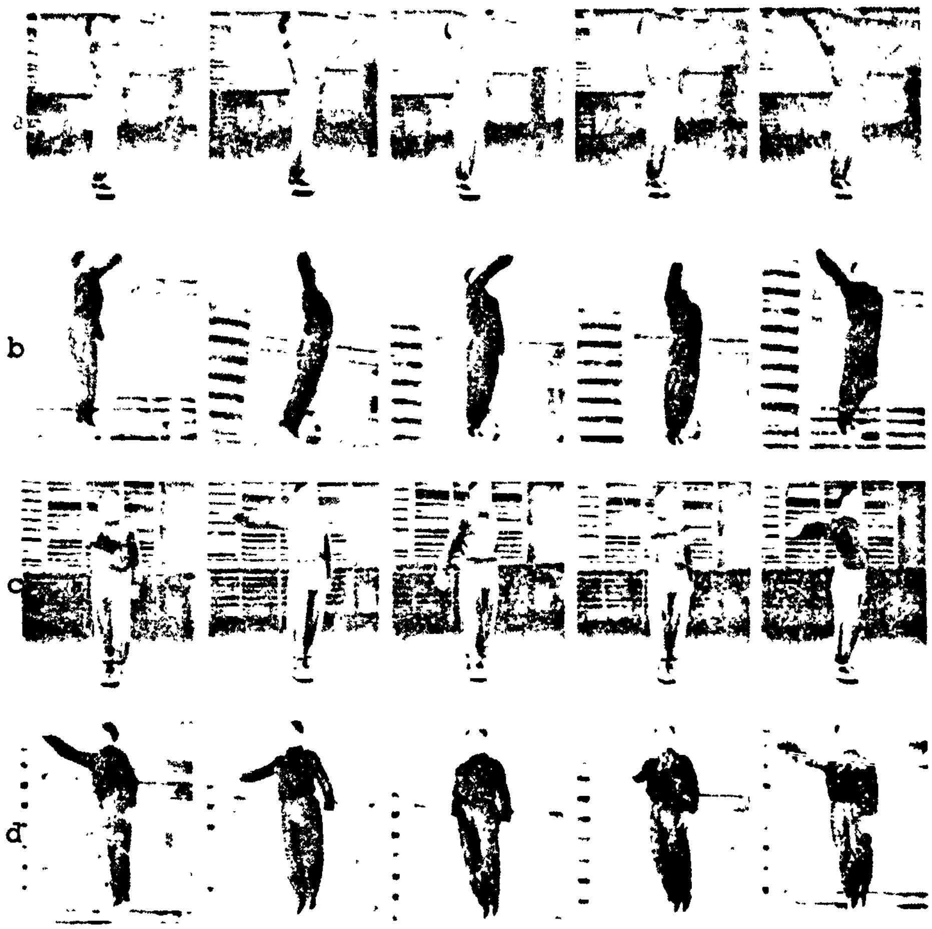

Fig. 53. Body orientation around longitudinal axis according to scheme of Kirpichev (a, b) and Polya (c, d): a, c) on Zhukovskiy "stool"; b, d) in unsupported position on trampoline.

As the experiments demonstrated, movements of the extremities in the plane perpendicular to the axis of rotation are more efficient and simpler to accomplish. In developing methods of turning, it is advisable to proceed from movements of two arms or legs in a single direction, opposite to the direction of rotation of the remaining part of the body, the basic motion of the cycle, but the preparatory motion of the cycle is characterized by returning the extremities to the initial position in opposite directions, in the plane parallel to the axis of rotation. Thus, for example, to turn to the left around the longitudinal axis, an initial position must be taken, in which the right arm is extended ahead and the left, as far back as it can be moved. One cycle of this turn consists

Fig. 54. Body orientation in unsupported position on trampoline, on course, method of Stepantsov-Yeryemin (a, arm motion, b, "scissors"), with subjects pitching (c) and banking (d).

of the basic and preparatory phase of arm movements. In the basic phase, the arms move full range to the right, in the plane perpendicular to the longitudinal axis of the body, i.e., by the side, so that the right arm occupies the backward position and the left, the forward, at the end of the basic phase (Fig. 54a, frames 1-3). If we return the arms to the initial position by the same path, the body again turns to the initial position. So that this does not happen, the arms are returned to the initial position in the preparatory phase in opposite directions, in planes parallel to the axis of rotation, i.e., through the down position (frames 3, 4). For orientation of 180° to the course by this method, about three cycles of movement of the arms must be made. As experience under weightless conditions has shown, a sufficiently trained subject executes one cycle of movement in one sec on an average, which permits him to turn 180° in 3 sec. On the trampoline, with good training, a subject succeeded in turning 160° in two arm movement cycles in 1 sec. Using the movement of one arm, he turned to a smaller angle (60-70°).

S. A. Alekperov (1954), studying the technique of executing two-arm turns on the bars, calculated a method of rotation around the longitudinal axis with alternating turns of the upper and lower halves of the body. In rotating the lower half of the body, the arms are moved out to the side, which increases the moment of inertia of the upper half of the body, and a turn of the lower half of the body to a larger angle takes place, than the turn of the upper /198 half of the body in the opposite direction. The arms then are brought to the trunk, and the legs are separated to the sides, and the man turns the trunk in the necessary direction. Here, the lower part of the body has a larger moment of inertia and its counter-rotation will be less. Calculations have shown that, by repeating these movements alternately, a man can turn 180° in three cycles. However, practically, this method is inefficient and difficult to execute, since coordination is complicated and turning by 180° requires more than 5 sec.

Turns around the longitudinal axis of the body by movements of the legs are more efficient and simpler to execute (V. I. Stepantsov, A. V. Yeryemin, 1969). In this case, two versions of the initial position can be recommended. In case it is necessary to turn on course by no more than 90°, it is advisable to separate the legs to the side ("spread eagle"), to an angle of approximately 60-70°, and then make the turn. In this initial position, the /199 moment of inertia of the legs relative to the longitudinal axis of the body is approximately 5-6 times larger than the moment of inertia of the remainder of the body. In connection with this, in turning the head, trunk and arms 90° in the required direction, the legs are moved in the opposite direction, to an angle, one-fifth or one-sixth of that, i.e., 15-18°, simultaneously completing the accompanying rotary motions in the direction of the turn around their longitudinal axes. Further movement of the legs in the same direction and, consequently, the turn itself are limited by the anatomical singularities of the structure of the motor apparatus of a man.

When orientation movements on course by more than 90° are required, the other version of the initial position should be used: separate the legs in the front-rear direction ("scissors") by an angle of 120-140°. In turning to the left side, the right leg must be forward (see Fig. 54b) and, inversely, in turning to the right /200 side, the left leg must be forward. A 160° turn can be made in one cycle from this initial position, since the moment of inertia of the legs in this case is 7-8 times greater than the moment of inertia of the remainder of the body.

Study of movements in a water medium has peculiarities. The basic peculiarity is that the subject must execute movements slowly and turn the hands, so that they do not form paddles. Besides, body stabilization in the initial position is improved in water, by the damping effect of the dense medium.

TABLE 58

BODY ORIENTATION AROUND LONGITUDINAL AXIS OF SUBJECT B BY VARIOUS METHODS IN WATER MEDIUM AND WEIGHTLESSNESS

Method of Turning Body	Performance Conditions	Calculated Body-Turn Angle in 1 Motion Cycle of limb, °	Number of Cycles of Movement of Extremities	Total Angle of Turn of Body, °	Average Angle of Turn of Body in 1 Cycle, °	Average Time of 1 Cycle, sec	Notes
By Kirpichev Cone-Shaped Arm Movements	Water	30	9	189	21	0.70	Body Straight, Tense, Bend at Elbow in Movement Above Head
			4	80	20	0.80	
			3	60	20	0.75	
	Weightlessness	30	2	46	23	0.40	
			3	75	25	0.45	
			3	69	23	0.40	
By Polya Arm Movements	Water	30	1	25	25	0.60	Body Straightened
			4	100	25	0.70	
			2	48	24	0.65	
	Weightlessness	30	5	135	27	0.30	
			3	86	29	0.32	
			3	82	27	0.28	
Stepantsov-Yeryemin: 2-Arm Movement	Water	60	1	45	45	1.20	Body Straightened
			2	86	43	1.15	
			3	144	48	1.10	
	Weightlessness	60	2	108	54	0.62	
			1	56	56	0.75	
			2	104	52	0.49	
Legs "Spread Eagle"	Water	Up to 90	4	240	60	1.60	Arms Pressed to Trunk
	Weightlessness		3	195	65	0.64	
"Scissors" with Legs	Weightlessness	160	2	228	114	0.48	Head Inclined Bend at small of back, incomplete spreading of legs
			2	240	120	0.52	
By Alekperov "screw" (bending-unbending)	Water	300	3	315	105	0.74	Arms pressed to body, small motions of legs
			2	410	205	0.40	
	Weightlessness	300	2	470	235	0.36	

Turns of the body around the longitudinal axis are of the greatest practical interest (Table 58). Moreover, torsion of the body arises more easily around the longitudinal axis, since its moment of inertia is approximately 1/13 that around the other axes. /201

The methods of Kirpichev, Polya and Stepantsov-Yeryemin were tested in a water medium. In executing body turns by other methods, the angle turns were less in all cases, than under weightless conditions, and the time for execution of a movement cycle increase by 1-1/2 - 2-1/2 times.

Body turns by movement of both arms is more effective. Thus, a body turn by the Stepantsov-Yeremin method was 52-56° in weightlessness and 43-48° in water. However, leg movements are more efficient, when the arms of the astronaut are free for motion-picture photography or for doing other types of work.

A 160° turn can be made, by using the "scissors" method. Subject B attained an angle of 120°, since he separated his legs in the front-rear direction insufficiently and bent them. The same error was typical of other subjects, which is additional evidence of the necessity for special training in both water and weightlessness. Moreover, the "small scissors" method is of great practical importance in performing body turns in open space, when the spacesuit limits movements of the joints.

It is advisable to carry out orientation of the body around the front-rear axis, i.e., banking, by movements of the arms, in connection with restricted mobility of the legs in the frontal plane (Table 59). The moments of inertia of the two arms is 1/20-1/23 of the remainder of the body in the straightened position, and 1/10-1/12, with the body bunched up. In those cases, when one hand is busy, the turn can be accomplished by circular movements of the other hand in the frontal plane, in the direction opposite to the turn of the body.

The calculations carried out and studies in weightlessness have shown that 4-5 circular movements of the arm must be made to turn the straightened body to a 35-40° bank.

If the moment of inertia of the arms is increased with a load (0.7 kg hammer), it is sufficient to make 1-1/4 turns, to turn about to the same angle (see Fig. 54d). When it is undesirable to carry the hands in front of the face and the turn must be accomplished more strictly in the frontal plane, movement of both arms in lateral arcs can be used. In the initial position, to turn to the left, the right arm is raised upward, the left is lowered, and the calculated angle of change of position of the arms in one cycle is 9° and 18°, when bunched up. This method also is more convenient with the spacesuit. In the auxiliary phase, the arm movements are accomplished towards each other, while bending the elbows and bringing the arms to the trunk, to the maximum extent possible.

TABLE 59

BODY ORIENTATION AROUND FRONT-REAR AND TRANSVERSE AXES OF THE BODY OF SUBJECT B UNDER WEIGHTLESS CONDITIONS

Method of Turning Body	Execution Conditions	Calculated Turning Angle of Body in 1 Arm Cycle, °	Number of Arm Movement Cycles	Total Turn Angle of Body °	Average Turning Angle in 1 Cycle, °	Average Cycle Time, sec	Notes
About front-rear axis							
Circular movement of arms in frontal plane	No load	7.2	8 6 10	44 34 55	5.5 5.7 5.5	0.25 0.38 0.18	Bending of arms at elbow in movement to chest; body straightened
Movement of both arms in lateral arcs	No load	9	2 1 3	14 8 22	7 8 7.3	0.9 0.7 0.9	Body straightened
	With load	20	1 2	17 32	17 16	1.1 1.1	
Lateral arc arm movement (body semi-bunched up)	No load	12	1 2 2	10 21 22	10 10.5 11	0.8 0.9 0.9	Legs bent 90° at knees
	With load	26	2 2	48 51	24 25.5	1.1 1.2	
About transverse axis							
Circular arm movement in sagittal plane	No load	7.4	4 8 3	22 48 20	5.5 6 6.7	0.35 0.25 0.32	Plane of movement of arms not maintained
Two-arm forward arc movements (body semi-bunched up)	No load	16	1 2 3	14 29 45	14 14.5 15	0.60 0.62 0.65	Forward turn Bend at waist
		16	2 2 2	26 28 29	13 14 14.5	0.54 0.52 0.50	Backward turn with forward bend of hips

Turns of the body around the transverse axis (pitch) by circular movements of one arm frequently causes a simultaneous turn of the body on course. The turning angle of the body is about 6 °, with a calculated angle of 7.4° (see Table 59).

Circular movements of both arms in the sagittal plane are most efficient with the body bunched up. To turn by an angle of 90°, depending on the mobility of the shoulder joint, requires 2-1/2 - 3-1/2 cycles and, in orientation of the straight body, but having tools in the hands, it can be turned by 45-50° in one cycle of arm movements (see Fig. 54c). While working in a spacesuit, it is more convenient to execute the arm movements in front arcs, returning the hands to the initial position through the side.

Thus, conduct of experiments on the Zhukovskiy "stool," /202
trampolines, in water and in weightlessness in Kepler parabola flights, have confirmed the correctness of the theoretical calculations and the possibility of orienting the body relative to three coordinate axes, exclusively by means of one's own muscular efforts, without the aid of technical devices. The best methods of body orientation relative to the longitudinal axes are the Stepantsov-Yeryemin methods: by movements of both arms, "spread eagle" and /203
"scissors" with the legs and, when wearing the spacesuit, the "small scissors" method. Body orientation around the front-rear axis must be accomplished only with circular movements of one arm or by the lateral arc method. In turning the body around the transverse axis, the most efficient method is circular movements of the arms with the body bunched up and, in the spacesuit, movements of both arms in front arcs. Having a tool, motion-picture camera or other additional mass in the hands facilitates turning of the body.

As a result of conduct of a comparative analysis of execution of body orientation in space in water and in weightlessness, by different methods, the advisability has been determined of using water as one of the stages of the training process, since there is no time deficit in water training, and the water resistance shows up negligibly in mastering the exercises, with low rates of movement of the extremities.

The experience accumulated in training subjects in methods of body orientation in space indicates the necessity of clear planning of the training process. After theoretical familiarization with the principles of body orientation in space and reviewing training films, practical mastery of the body orientation methods should begin with working out of the individual elements on the Zhukovskiy "stool." Then, the correctness and sequence of movements are carefully mastered in water, and the motor skills are then reinforced under time deficit conditions, on the vaulting bars, trampolines, and, in the concluding stage of training, the methods of orienting the body in space in weightlessness are worked out in laboratory-aircraft, with and without the spacesuit and with and without a load.

N75 23123

2. Motor Activity of Astronauts in Unsupported State

The unsupported position is possible, when a man is under weightless conditions, while reproducing them in ground test stands ("Roman turret," lifting devices, swings, etc.), during flights in flight vehicles along a parabolic trajectory and in artificial earth satellites. The longest unsupported state is provided by the latter method.

Quite extensive information has now been obtained on the physiological reactions of people in prolonged weightlessness (O. G. Gazenko, 1962; N. M. Sisakyan, V. I. Yazdovskiy, 1963, 1964; I. I. Kas'yan, et al., 1964a, 1964b, and others). However, the question of the reactions of people in the unsupported position, nevertheless, has been inadequately dealt with. As a rule, the astronauts have been well secured to the working places in orbital flights, and they have had support (chairback, halters, etc.) in performing one operation or another. In case the astronauts are not connected, they also could not move about the spacecraft cabin, because of the limited nature of the space. In connection with this, the orbital flights of P. I. Belyayev and A. A. Leonov, and of Ye. V. Khrunov and A. S. Yeliseyev, are of exceptional importance; during these flights, astronaut A. A. Leonov went out into circumterrestrial space for the first time in history, and astronauts Ye. V. Khrunov and A. S. Yeliseyev transferred from one craft to the other. As /204 is well known, the flight of P. I. Belyayev and A. A. Leonov in Voskhod 2 was preceded by a long preparatory period, during which the astronauts methodically worked out the flight task. Considerable information was obtained during their aircraft flights along a parabolic curve.

Examinations were carried out in a laboratory-aircraft, equipped with a Voskhod 2 mock-up and mock-ups of Soyuz 4 and Soyuz 5. Up to 25-30 sec of weightlessness was reproduced during a parabolic flight. In executing the basic stage of the flight task, going out of the spacecraft and returning to it, before entering the airlock, A. A. Leonov had to put on the backpack with automatic life support systems and hook himself up to it and, together with spacecraft commander astronaut P. I. Belyayev, conduct a check of the equipment, providing for going out of the spacecraft, and equalize the pressure in the airlock and spacecraft cabin. Then, A. A. Leonov went into the airlock, where he had to check the closure of the sealed helmet, the light filter position, spacesuit seal and oxygen supply. At this, P. I. Belyayev, closed the cabin hatch cover, dropped the pressure in the airlock and opened the exit hatch cover in the airlock. A. A. Leonov had to leave the craft through the airlock hatch, make the required number of moves away from and approaches to the airlock under weightless conditions and return.

It follows from an analysis of the task that approximately six working operations were performed by the astronauts while immobilized at the work place (pilots chair), eight operations in the unsecured state, in movement about the cabin and airlock, and four working operations in the unsupported position, after leaving the spacecraft mock-up, when the astronauts executed moves away from and approaches to the spacecraft airlock, "coiled up" the tether and worked with the motion-picture camera.

Peculiarities of the performance of work by the Soyuz 4 and Soyuz 5 crews in semiunsupported space (support by the hands only on the handrails attached to the spacecraft mock-up skin) should be considered to be the purposeful movement of the astronauts from the hatch of the passive to the hatch of the active craft and the necessity of performing a great amount of addition work (removal, transfer and installation of the motion-picture camera, inspection work, etc.), during the regular transfer from one craft to the other.

Continuous medical and procedural observations of the astronauts were carried out during the aircraft flights. In this case, the quality of task execution was evaluated, chronometry of the succeeding elements of the exercises was conducted, motion-picture photography was accomplished and the pulse and respiration rates were recorded.

As a result of the studies, it was determined that securing to the working place insures sufficiently high quality performance of the six exercises provided for in the program. In the first two flights, insignificant changes of finely coordinated movements, missing the target, etc., by A. A. Leonov and P. I. Belyayev were observed, and they were absent in succeeding flights.

Exercises under weightless conditions, with movements inside the craft and airlock, were more difficult to perform. This is explained by the fact that the astronauts were deprived of reliable support to a certain extent (they were in contact with the side of the craft) and the nature of the work was more complicated. It required at least 2-3 flights on a parabolic curve, to work out the movements through the hatch. Performance quality depended greatly on symmetry of pushes on the walls of the craft or airlock. With /205 strong pushes, slipping through the airlock was quite fast; however, the threat arose of striking surrounding objects: with weak pushes, the exercise frequently was not completed. A second complicating condition was the presence of special equipment, the spacesuit, especially when pressure was maintained in it. The fact that P. I. Belyayev required five repetitions to perfect the exit from the craft into the airlock evidently is explained by these causes. The criterion of correctness of performance of an exercise in the unsupported position, i.e., after leaving the airlock, was the smoothness of moving away and approaching airlock without turning and the length of time for performance of the task.

Skills in performing approaches and, especially, movements away were not worked out immediately. A. A. Leonov, developing skills in executing a smooth movement away without turning, made six attempts and, in approaching, four. In the first attempts, the moving away and approach movements were accomplished abruptly, with turns of the body in both the vertical and horizontal axes of it, and more time was taken to accomplishment than in the succeeding attempts (Table 60).

TABLE 60

QUALITY OF PERFORMANCE OF MOVEMENTS AWAY AND APPROACHES TO THE AIRLOCK BY ASTRONAUT A. A. LEONOV DURING PARABOLIC FLIGHTS IN SPECIAL AIRCRAFT

Move away from airlock chamber			Approach to airlock chamber		
Repetition number	Time, sec	Performance Quality (inaccuracies observed)	Repitition number	Time, sec	Performance Quality (Inaccuracies Observed)
1	20	Turn backward	1	6	Turn to side
2	19	» to side	2	7	Same
3	20	» »	3	6	» »
4	16	» forward	4	10	Approach smooth without turn
5	12	» to side	5	10	Same
6	12	Move away smooth without turn	6	10.7	» »
7	8	Same	7	9	» »
8	8	» »	8	10	» »
9	12	» »	9	10	» »
10	8	» »	10	10	» »
11	5	» »	11	10	» »
12	5	» »	12	7	» »
13	10	Slight turn toside	13	6	Sideways approach
14	8	Slight turn back	14	9	Approach smooth without turn
15	5	Move away smooth without turn	15	9	Same
16	6	Same	16	6	» »
17	6	» »	17	5	» »
18	8	» »	18	6	» »
19	6	» »	19	8	» »
20	6	» »	20	6	» »

Thus, in the first three attempts to move away from the airlock, A. A. Leonov took 19-20 sec and, in the succeeding attempts, approximately 6-8 sec. Somewhat different ratios were observed in chronometry of the approaches. He did not succeed in decreasing /206 the time, in repeating the operation. On the contrary, the time spent in performing approaches was less in the first attempts than in the succeeding ones, which was caused by great haste, with a reduction in quality of task performance. The subjects did not approach the airlock smoothly, but with jerks and side and even back turns. At the end of the training cycle, the movements away and approaches were smooth, with optimum time consumption (Fig. 55).

As an illustration, we present the report of astronaut A. A. Leonov, on his feelings in one of the last flights, while working out the flight program: "The flight was tolerated well. Felt no unpleasant sensations. Feelings the same as were observed earlier, during flights in weightlessness. The spacesuit limits movements somewhat, and the helmet decreases the field of view. Approaches to the airlock were performed easily, since I tightened the tether and, thereby, created a point of support and designated the direction of movement. Approaches and movements away should be done smoothly. Any work apparently can be performed in weightlessness, without noticeable disruption of motor coordination, with the most negligible point of support."

An analysis of the material, carried out by I. A. Kolosov and I. F. Chekidra (1967), showed that the time for performance of separate operations by Ye. V. Khrunov and A. S. Yeliseyev, during the transfer from one craft to the other, in the semiunsupported situation, also differed. Thus, in transferring the snap-hook from one handle to another, A. S. Yeliseyev and V. M. Kubasov took 24 and 22 sec, respectively, and Ye. V. Khrunov and V. V. Gorbatko, 3 and 3.5 sec. The transfer from the mock-up of one craft to the mock-up of the other also was executed in various times. While Ye. V. Khrunov and V. V. Gorbatko took 23 and 41 sec, respectively, A. S. Yeliseyev and V. M. Kubasov took 74 and 79 sec to perform this work. This can be explained by the fact that Ye. V. Khrunov and V. V. Gorbatko already had more experience in working under weight-

Fig. 55. Astronaut A. A. Leonov while perfecting movement away from airlock under conditions of brief weightlessness.

less conditions, at the beginning of the training sessions. Therefore, especially in the first parabolic flight, their motor coordination was better than that of the other crew members (Fig. 56).

Fig. 56. Transfer of astronaut Ye. V. Khrunov from mock-up of one craft to the other during brief weightlessness

It is interesting to compare this material with data on performance of these movements under space conditions, during the orbital flight in Voskhod 2. As is well known, A. A. Leonov accomplished five movements away and approaches in space, in which the very first movement away was made to a minimum distance, 1 m, for the purpose of orientation to the new conditions and the following ones were of greater extent. Movements away and approaches while "floating" free in space were performed in the same sequence as during brief weightlessness. There also were body turns to the side and backward in the first movements away, and the exercise was performed more correctly and confidently in subsequent movements away, which is evidence of the good adaptability of A. A. Leonov to weightless conditions and indicates a high quality of perfection of motor skills under parabolic flight conditions. In the words of astronaut A. A. Leonov, he "went out of the airlock, without the least difficulty or effort; there was a little torsion. The craft moved slightly to the side and I, to the other. There were no differences between weightlessness in the cabin and outside the craft.

It is more convenient to work outboard than in the craft. It was more difficult to return to the craft than to move away from it."

K. E. Tsiolkovskiy (1919) suggested that orientation would be disrupted in the unsupported situation: "It appears to man here, that up is where his head is and down is by the legs. However, since the direction of his body depends on how he establishes it, /207 he can establish it as he pleases, and up and down can be anywhere. There is nothing simpler than this, because there is no difference between them."

Experience demonstrated that A. A. Leonov, being unsupported in weightlessness, did not experience disturbances in orientation in space, and his movements were sufficiently coordinated. He followed the outer surface of the craft without difficulty, turned on the motion-picture camera and demonstrated it before returning to the craft, and he performed visual observations of the earth and circumterrestrial space, etc. It is appropriate to state that the American astronaut E. White noted approximately the same thing. During the four-day flight in Gemini 4, he, like A. A. Leonov, left the spacecraft capsule and stayed about 20 min in unsupported space. E. White was connected to the capsule by a 25-foot tether, was equipped with two motion-picture cameras and a "space pistol," permitting him to maneuver, by means of air jets. As follows from the preliminary reports, E. White moved actively in unsupported, circumterrestrial space, and he fulfilled the flight task; he did not note appreciable disturbances of orientation in space or of motor coordination, in this case. This is explained by the presence of a support, the tether and the near-by spacecraft. Data on accomplishing the transfer of astronauts from one craft to another is of definite interest. Thus, Ye. V. Khrunov, in his transfer in open space, reported: "While exiting, it was difficult to bring out the legs, the brackets were very close to the seat itself. I began to 'transfer' smoothly by the arms. In moving along the handhold, motor coordination was not disrupted. It was then necessary to pull out the camera, which did not come out of the socket. I began to rock it. I rocked with one hand and held the handle with the other and removed the movie camera. I transferred from one craft to the other without resting." A. S. Yeliseyev characterized his transfer thus: "In the transfer from spacecraft to spacecraft, there were no special difficulties; /208 there were greater difficulties in securing inside the craft. The securing straps for the legs were made according to our recommendations. In order to secure myself, it was necessary to lean on my heels and raise the toes. During the transfer, movement coordination was not disrupted in open space. The impression is the same as during a normal training exercise in the laboratory-aircraft; coolness was displayed and posture was controlled."

During the first familiarization-training flight in weightlessness, a distinct difference in behavior of the astronauts was displayed, although the program was executed by both of them. Thus, while motor and speech activity of P. I. Belyayev was reduced and the flight task was performed in longer times, A. A. Leonov performed the task, on a background of marked neuroemotional excitement, displaying hyperemia of the face and increased motor and speech activity. In subsequent flights, the differences in behavior practically disappeared, apparently because of extinction of the orienting reaction.

The basic data on the state of the cardiovascular systems of P. I. Belyayev and A. A. Leonov are presented in Table 61.

TABLE 61

CHANGE IN PULSE AND RESPIRATION RATE OF ASTRONAUTS DURING TRAINING PARABOLIC FLIGHTS

Astronaut		Pre-flight	Inflight: Horizontal part	Inflight: g-force	Inflight: Weightlessness	Inflight: g-force	Post-flight
Secured to work place							
P.I.Belyayev	1	84—90 / 18—24	90—96 / 15—18	100—114 / 18—26	70—89 / 16—18	102—120 / 19	84 / 18
A.A.Leonov	1	54—60 / 21—24	66—72 / 18—24	84 / 18	60—70 / 18—21	84 / 24	66 / 18
Working out elements of entry and exit							
P. I. Belyayev	1	64 / 12	72—78 / 14—14	80—88 / 16—16	76—78 / 14—14	84—88 / 16—18	70 / 12
	7	68 / 12	70—86 / 12—16	80—100 / 14—20	76—88 / 12—16	80—100 / 14—20	78 / 12
A.A.Leonov	1	68 / 12	79—90 / 14—22	80—102 / 16—24	76—90 / 14—20	80—108 / 18—26	80 / 14
	7	64 / 12	70—84 / 12—14	80—90 / 14—16	78—84 / 12—14	82—96 / 14—16	76 / 12

Note: Limits of variation of pulse rate (beats per minute) in numerator, respiration rate (cycles per minute) in denominator.

It is clear from the data presented that the pulse and respiration rates changed during flight, depending on the flight conditions. In the horizontal flight stage, these changes apparently were caused mainly by neuroemotional stress. In the g-force /209
the pulse and respiration rate also increased in all cases, being more significant in the period after the action of brief weightlessness on the astronauts. In repeated weightlessness, as a rule, the

pulse slowed down quite regularly from flight to flight, in the majority of cases. The arterial pressure changed in accordance with the heart rate. During the action of g-forces, the maximum arterial pressure increased by 10-30 mm Hg. Under weightless conditions, it decreased (sometimes to the initial level), on a background of slowing of the pulse. The minimum arterial pressure was practically unchanged.

In analyzing the data of Table 61, no significant differences could be found in the direction of change in pulse and respiration rates of the astronauts, depending on being secured. This apparently is explained by considerable neuroemotional stress in first flights and the different program of activity of the astronauts in the flight, as a result of which, the shift caused by immobilization of the astronauts kept to the background.

The physiological reactions observed in P. I. Belyayev and A. A. Leonov during aircraft flight along the parabolic curve, were practically the same as the reactions of other Soviet astronauts (I. I. Kas'yan, et al., 1964, and others). However, in performing work in the spacesuit (during the regular transfer from one craft to the other), for Ye. V. Khrunov and A. S. Yeliseyev, a more marked quickening of the pulse was observed, to 131.2±4.5 per minute, /210 compared with data obtained in control test flights (without spacesuit).

The same regularity was displayed in analysis of the results of the space experiments, with some singularities.

Thus, the pulse rate of Ye. V. Khrunov during the transfer from one craft to the other in open space varied within 104-154 per minute and that of A. S. Yeliseyev, 135-145 per minute. At the same time, the pulse of V. A. Shatalov increased to 94-100 per minute. The quickening of the pulses of the astronauts is connected, not only with great neuroemotional stress, but with performing various operations, during the transfer from one craft to the other.

During parabolic flights in weightlessness, the state of the motor analyzer of the astronauts also was studied. The time for performance of a specific movement, the length of time the "pencil" was in contact with the coordinograph contacts and the preservation of the assigned muscle effort of 750 g were measured. Considering that the method of examination has been described in detail (I. I. Kas'yan, et al., 1964, and others), we point out that the rate of performance of motor acts by A. A. Leonov during g-forces and weightlessness decreased from the initial value (Table 62).

In performing the test with a fixed muscle effort in various periods of flight, no significant differences were revealed in either astronaut. The time reflexes worked out by the astronauts

TABLE 62

MOTOR ACTIVITY OF ASTRONAUTS DURING KEPLER PARABOLA FLIGHT (average figures)

Astronaut	Total Time for Completion of Complex Movement on Coordinograph, sec				Contact Time of "Pencil" on Coordinograph Contact, sec			
	On Earth	g-Force after Weightlessness	In Weightlessness	g-Force after Weightlessness	On Earth	g-Force after Weightlessness	In Weightlessness	g-Force after Weightlessness
P. I. Belyayev	4.8	3.98	4.99	3.16	0.56	0.27	0.31	0.27
	4.72–4.88	—	4.08–4.50	—				
A. A. Leonov	3.9	7.12	5.18	7.22	0.25	0.45	0.36	0.39
	3.56–4.30	5.68–8.56	4.44–5.92	6.48–7.96				

Note: Range of fluctuation of indices in denominator, average data in numerator.

under ground conditions (20 sec intervals) were retained under weightless conditions.

Analysis of the state of the vestibular analyzers of P. I. Belyayev and A. A. Leonov showed that, after flights in weightlessness, the duration of the illusion of counterrotation and postrotational nystagmus decreased noticeably, with this phenomenon being more marked in P. I. Belyayev (Table 63).

TABLE 63

CHANGE IN DURATION OF POSTROTATIONAL NYSTAGMUS AND COUNTERROTATION ILLUSIONS (in seconds) BEFORE AND AFTER KEPLER TRAJECTORY FLIGHTS

Astronaut	Flight Number	Postrotational Nystagmus		Counterrotation Illusion	
		Before Flight	After Flight	Before Flight	After Flight
P. I. Belyayev	1	12	10	10	7
	7	9	6	8	5
A. A. Leonov	1	15	12	12	11
	7	10	6	9	5

The latter is explained by individual differences in resistance to vestibular effects. A. I. Gorshkov and Ye. M. Yuganov (1964) first noticed the difference in nystagmus time under weightless conditions. They expalined this by an increase in the reciprocal effects of the otoliths on the semicircular canals under weightless conditions. Somewhat later, I. A. Kolosov and V. I. Kopanev (1966) extended these ideas. It was determined in their studies that shortening of the period of nystagmus and counterrotation illusions depends greatly on the resistance of the subjects to weightlessness. In the case of reduced resistance, shortening is expressed to a significantly smaller degree or is not observed at all. The reciprocal effects of these persons under weightless conditions apparently either do not change or are even somewhat weakened. /211

It can be concluded from the results of vestibular examination of A. A. Leonov and P. I. Belyayev that their stability in weightlessness was quite high.

In a medical examination of the astronauts after aircraft flights on a parabolic curve, no significant deviations were disclosed on the part of the cardiovascular or respiratory systems. In the majority of cases, a negligible slowing of the pulse and some reduction of the maximum arterial pressure of A. A. Leonov were observed. In performing familiarization-training flights in the spacesuit, an appreciable quickening of the pulse was noted most frequently (Table 64).

The material presented on physiological reactions of the astronauts in the unsupported position showed that these reactions do not differ significantly from the reactions noted in Soviet astronauts, who had flown briefly under conditions of both brief (during the training period) and long (during orbital space flight) weightlessness. There were only differences of degrees in expression of the physiological shifts. However, it should not be forgotten, that neither A. A. Leonov, Ye. V. Khrunov, A. S. Yeliseyev nor E. White were in a truly unsupported position. The tether assisted A. A. Leonov and E. White in orientation in space and in accomplishment of the necessary working operations. Additional studies must clearly be conducted, for the purpose of developing the physiological reactions in the unsupported position in detail.

The time is now ripe for the necessary simulation of astronaut activities under ground conditions, building mock-ups of spacecraft and stations, by means of which docking units can be perfected in parabolic flight and repair work can be carried out inside and on the surface of the model (welding, riveting, cutting and severing metal, etc.). /212

The following conclusions can be drawn from study of the physiological reactions of the astronauts in unsupported space.

TABLE 64

PULSE AND RESPIRATION RATE AND ARTERIAL PRESSURE BEFORE AND AFTER PARABOLIC FLIGHTS

Astronaut	Flight Number	Pulse Rate, bear/min		Respiration Rate cycle/min		Arterial Pressure, mm Hg	
		Before Flight	After Flight	Before Flight	After Flight	Before Flight	After Flight
		Without spacesuit and passing through airlock					
A. A. Leonov	1	66	60	12	12	130/70	125/70
	2	66	60	12	12	128/70	120/60
	5	72	64	14	12	115/65	110/70
	10	60	56	12	12	115/70	115/70
	15	60	54	10	10	115/70	112/65
		In spacesuit, airlock stage					
	1	68	80	12	18	125/70	120/70
	2	76	80	12	14	125/70	125/70
	5	68	72	12	14	125/70	125/70
	10	60	60	10	10		120/70
	12	60	60	10	10	110/60	110/60
		Without spacesuit and passing through airlock					
P. I. Belyayev	1	78	72	18	18	125/85	125/80
	2	78	72	20	18	120/80	120/80
	5	72	70	18	14	[illegible]/70	110/60
	8	66	60	10	10	[illegible]65	105/65
		In spacesuit, airlock stage					
	1	64	70	12	12	110/60	110/60
	2	66	76	14	14	110/60	110/60
	5	68	78	12	16	110/70	115/70
	8	68	70	12	12	105/60	105/60

-- Upon leaving the craft in circumterrestrial space and transferring from one craft to another, coordination of movement, orientation and performance capacity of the astronauts were not significantly disrupted;

-- To perfect finely coordinated movements in moving away from the spacecraft and approaching it, at least 4-6 repetitions are necessary, under weightless conditions;

-- The direction of the physiological shifts are identical to the data obtained in training other Soviet astronauts, and it is characterized by an increase in pulse and respiration rate and an increase in arterial pressure under g-forces, a gradual decrease in these indices during repeated stays in weightlessness or during the prolonged effect of it, by a reduction of the length of post-rotational nystagmus and counterrotation illusions under weightless conditions and by negligible shifts in the motor analyzer.

N75 23124

3. Bioelectric Activity of Skeletal Musculature under Conditions of Alternating Action of g-Forces and Weightlessness

As is well known, the tonus of the skeletal musculature /213 creates the initial background for active motor activities of a man and is a response reaction to the effects of mechanical factors, first and foremost, the force of gravity. It is completely obvious that any change in the effect of gravity (increase or decrease) must cause corresponding changes in the muscle tonus, which, in turn, can be reflected in coordination of movement and performance capacity of a man in flight. Among many indices characterizing the tonus of the musculature, the bioelectric activity of the muscles is an important one. Electromyography, although it is not one of the methods of direct tonometry, it permits study of the effect of the central nervous formations on the muscles, as a result of which there may be change in tonus.

V. I. Babushkin and colleagues (1958), were occupied with study of the electrical activity of the skeletal musculature of man under conditions of increased weight; they found a definite dependence of change in biopotential amplitude on g-force value. According to their data, the biocurrent amplitude increased in conformance with the increase in g-force. In the majority of cases, an increase in amplitude was not observed at more than 4-5 g. During the action of g-forces of constant amplitude, the biopotential amplitude began to decrease after some time. The authors point out the the increase in biopotential amplitude indicates an increase of muscle tonus of a an under g-forces, and that it is connected primarily with change stimulation of the proprioceptors. It is logical that changes in the opposite direction may arise under conditions of decreased weight.

At present, there are only theoretical concepts of the possibility of change in muscle tonus under weightless conditions (Beckh, 1956, 1958; Clemedson, 1958; Lansberg, 1960; Graveline, et al., 1961; Lawton, 1960), and there is only one experimental work (Ye. M. Yuganov, et al., 1960), which is the first effort at solution of this problem, by means of mechanographical studies.

In our experiments, the bioelectric activity of the musculature of animals and man was studied, during alternating g-forces and weightlessness. The appropriate conditions were reproduced in flight along a parabolic curve; in this case, weightlessness lasting 25-30 sec alternated with g-forces of about 2 g magnitude. Some tests were carried out on animals during vertical flights of rockets, with weightlessness lasting 5-6 minutes and g-forces up to 6-7 g.

The studies were carried out with intact rabbits and dogs, as well as with decerebralized and labyrinthectomized cats.

The animals were labyrinthectomized 1-10 days before the experiment, by introduction of 1.5% solution of monoiodacetic acid to the middle ear. The effectiveness of the operation was determined by the behavior of the animal. Decerebration was carried out 1-2 hours before the flight, with preliminary ligation of both carotid arteries. In the experiments with rabbits, the biopotentials were tapped from the rectus muscles of the left eye, with lobe-shaped tantalum electrodes. The animals were immobilized on the right side. The electrodes were applied 2-3 hours before the flight. A cut was made in the mucous membranes of the eye (under local anesthesia), 1 mm from the limb, after which the mucous membrane /214 was stripped, revealing the upper and lower rectus muscles, and the electrodes were applied to them.

The bioelectric activity of the internal hip muscles of dogs was recorded, with the animal immobilized on the abdomen and on the back. Tests were conducted on intact and labyrinthectomized animals.

In tests with decerebralized and decerebralized-labyrinthectomized cats, the biopotentials were taken from the flexor and extensor muscles of the front limbs. The animals were immobilized on the back in the stand; the forepaws were freely extended upwards, and the head was located at an angle of 45° to the horizon.

In studies with human participation, the biological currents of the neck muscles, rectus muscles of the back and hip muscles were recorded. The subject sat, leaning against the back of the chair, and he was immobilized with straps in the region of the small of the back and in the region of the ankle joints. The biological currents were recorded through an amplifier, with a sensitivity of 5-10 μV on oscillographs, at a frame movement rate of 1[illegible], 60, 125 and 250 mm/sec, or on a tape recorder, with subsequent decoding in an analyzer.

Centrifuge tests were controlled, and they were performed with a gradual increase in g-forces from 1 to 7 g. In some cases, the rotation mode provided for a rapid increase in g-forces and a subsequent "plateau," in a period of 1 min, with 3 and 7 g. The experiments with rabbits were performed only in vertical rocket flights.

The biopotential of the lower rectus muscles of the rabbit eye was 30-40 μV before rotation, in the majority of cases, and the upper, 8-25 μV. With increase in g-force to 2.5-3 g, an increase of 1-1/2 - 2 times took place. With further increase in g-forces, the biopotential amplitudes remained at the same level or decreased somewhat, but they did not reach the initial values. In tests, with constant action of 3-7 g, with increase in them, the biopotential amplitudes also increased within these limits. However, on the "plateau," a decrease took place in the voltage, after 10-15 sec, to half the maximum value. This picture was retained subsequently, despite the prolonged effect of g-forces. With decrease in g-forces, a noticeable decrease in biological currents was observed, to the level of the baseline electromyograms. In some cases, the biopotential amplitudes turned out to be lower than the initial values after the action. This phenomenon was almost regular after repeated g-forces in the centrifuge.

The results of the rocket experiments demonstrated that, in the period of g-forces, increasing from 1 to 7 g, the total frequency of the rabbit eye muscle biopotentials was practically unchanged, at 70-100 Hz. The biological current amplitudes increased, in conformance with the increase in g-forces to 4-5.5 g. In the initial period of weightlessness, the frequency characteristics of the biological currents of the eye muscles were equivalent to the frequency of oscillations during g-force action. In proportion to the length of stay in weightlessness, some slowing of the biopotential frequency arose, with decrease in oscillation amplitude. This phenomenon is evaluated as the result of increase in synchronization of oscillations or the appearance of nerve impulses from the central hemisphere formations, primarily from the vestibular apparatus and motor analyzer.

The experiments with decerebralized and decerebralized-labyrinthectomized cats were carried out in aircraft flights. The decerebralized cat extensor muscle biopotentials, 20-60 μV in horizontal flight, increased to 30-120 μV under 1.8-2 g. In the first 5 sec of weightlessness, it decreased to 20-35 μV and, in the 6-20th seconds, to 15-25 μV, remaining at this level till the end of the effect. Upon ending the parabolic maneuver, it again reached values, characteristic of the preceding horizontal flight (20-55 μV). These regularities were noted in 12 of 16 experiments. /215

The changes in bioelectric activity of the flexor muscles in the corresponding periods were almost opposite. The amplitude increased negligibly in the g-force, or it remained practically unchanged. In the weightless state, the oscillations increased by 1-1/2 - 2 times, reaching 25-60 μV (Fig. 57). These changes reflect reciprocal interactions of their innervation. We propose that the phenomena observed, especially the decrease in extensor muscle biopotentials in weightlessness, are predominantly a consequence of reflex effects from the vestibular analyzer. To prove this proposal, studies were carried out of the activity of the corresponding muscles, in labyrinthectomized-decerebralized animals. It turned out that the biological current amplitude of the flexor and extensor muscles of these animals in weightlessness remained practically unchanged from the initial values in horizontal flight (Fig. 58).

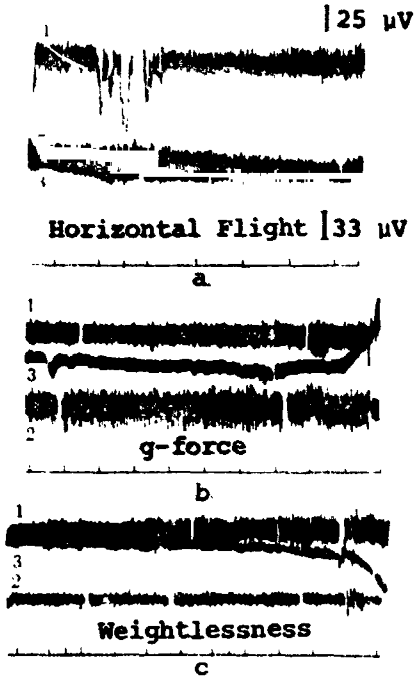

Fig. 57. Electromyogram of forelimb muscles of decerebralized cat: 1) flexor muscle biopotentials; 2) extensor muscle biopotentials; 3) accelerogram

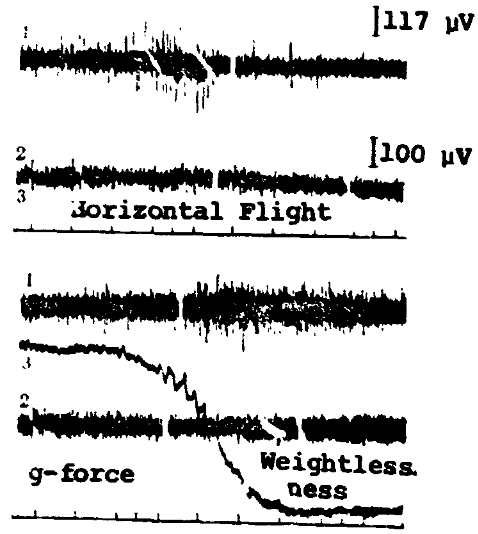

Fig. 58. Electromyogram of forelimb muscles of decerebralized-labyrinthectomized cats: designations same as in Fig. 57.

A decrease in the bioelectric activity of muscles in weightlessness was clearly defined in the experiments on dogs. Compared with the initial state, the biopotential amplitudes of the thigh /216 extensors of intact animals usually decreased by 1-1/2 - 2 times in weightlessness, which is illustrated by the data of Table 65.

An electromyogram of a thigh muscle, obtained in one of the experiments, shows that the oscillations increased by 1-1/2 times under the g-forces and decreased to almost half the initial level in weightlessness. Similar phenomena were not observed in studies performed on dogs with bilateral labyrinthectomies. In this case, the biopotential amplitudes of the thigh muscles in weightlessness /217 and under g-forces differed very much less from the initial values (Table 66).

The material obtained on labyrinthectomized animals (cats, dogs) permits expression of the hypothesis that the action of weightlessness,

TABLE 65

CHANGE IN BIOPOTENTIAL AMPLITUDES OF QUADRICEPS MUSCLES OF THE THIGH OF INTACT DOGS IN DIFFERENT SECTIONS OF PARABOLIC FLIGHT (in % of indices during initial horizontal flight)

Experiment No.	Horizontal flight before parabola	g-force before weightlessness	Weightlessness		g-force after weightlessness	Horizontal flight after parabola
			Start	End		
1	100	125	87	62	150	93
2	100	100	66	55	122	77
3	100	120	50	50	127	88

TABLE 66

CHANGE IN BIOPOTENTIAL AMPLITUDE OF QUADRICEPTS MUSCLE OF THIGH OF LABYRINTHECTOMIZED DOG UNDER g-FORCES AND WEIGHTLESSNESS (in % of indices in initial horizontal flight)

Experiment No.	Horizontal flight	g-force	Weightlessness		g-force	Horizontal flight
			Start	End		
1	100	128	100	86	100	100
2	100	114	100	100	128	128
3	100	100	100	82	82	82

with the vestibular analyzer cut off, is reflected to a considerably smaller extent in changes of tonus of the musculature.

Studies of human muscle biopotentials were carried out in experiments in aircraft. Quite regular changes in the bioelectric activity of various groups of muscles were disclosed under g-forces and in weightlessness. Thus, muscle biopotential amplitudes of 130-180 μV in horizontal flight, increased to 190-330 μV under g-forces. In the subsequent weightlessness, an abrupt reduction in osciallation voltage was observed (to 40-50 μV) and, in a number of cases, phenomena, similar to the picture of bioelectric "silence" were noted (Figs. 59 and 60). The data of Table 67 reflect these regularities.

Similar changes were observed in the bioelectric activity of the thigh flexor and extensor muscles. Equal to 30-37 μV in the initial state, the amplitude increased to 50-60 μV during g-forces. In the weightless state, the same picture of changes was observed, /218
as in recording the neck muscle biopotentials. Consequently, changes in bioelectric activity of the skeletal musculature have a

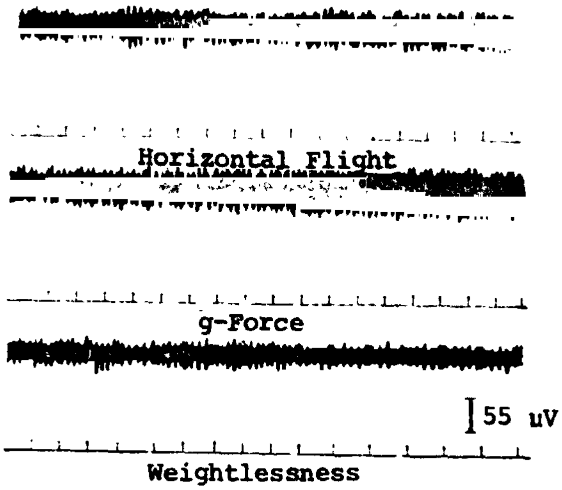

Fig. 59. Electromyogram of thigh extensor muscle of dog.

quantitatively opposite nature, under conditions of increased and decreased gravity. Under weightless conditions, a distinct decrease in bioelectric activity is noted. These data can be used in evaluating the nature of change in the tonic stress of the musculature, under these and other conditions. They indicate a possibility of reduction in tonus of the musculature in weightlessness, and they demonstrate a dependence of the changes observed on the singularities of functioning of the vestibular analyzer under these conditions.

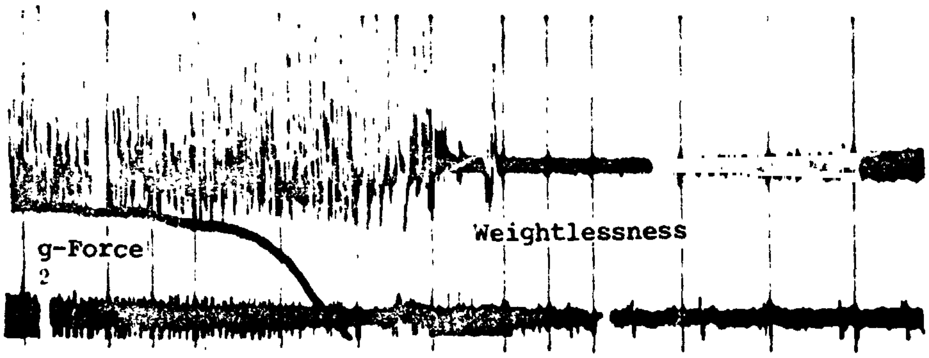

Fig. 60. Electromyogram of trapezius muscle of man: 1) biopotentials of upper bundle of trapezius muscle (right); 2) accelerogram

TABLE 67

CHANGE IN BIOPOTENTIAL AMPLITUDE OF HUMAN NECK MUSCLES UNDER g-FORCES AND IN WEIGHTLESSNESS (in % of indices during initial horizontal flight)

Experiment No.	Horizontal flight	g-force	Weightlessness		g-force	Horizontal flight
			Start	End		
1	100	150	0	33	130—180	116
2	100	175	0	23	105—140	105
3	100	105	0	16	—	—
4	100	233	66	66	166	100
5	100	130	37	37	100	75
6	100	142	42	42	142	85

N75 23125

4. Motor Activity under Weightless Conditions

The movements of man on the earth are accomplished in the sphere of action of the gravitational field, which naturally determines the nature of his activity. By analysis, movements can be divided into two components, as a rule: The first is the muscle efforts, which are a response to the action of mechanical forces, first and foremost, of the force of gravity and, second, direct locomotor acts. The static forces (first component) in any position are maintained at a level, adequate for movement in space. They only change, depending on the support area. If it is quite large, the muscle forces are moderately expressed; if the area decreases, without change in body weight, they increase, and vice versa. At the present time, the indices characterizing the static muscle forces which have been studied the most are the tonus of the skeletal musculature, which depends greatly on the force of gravity. Locomotor activity is diverse, and it is judged by many indices: rate of movements, their amplitudes, precision, etc.

During the long process of evolution, organisms have worked out definite compensatory structures (bone system, muscles, etc.) and mechanisms (orthostatic changes of the cardiovascular system, etc.), under the influence of the gravitational field of the earth, which are brought into action in any movements in space (by unconditioned reflex reaction mechanisms).

Completely different relationships arise under weightless conditions, when the constantly acting factor, weight, decreases or completely disappears. While, under earth conditions, a man applies force in any movements, adequate to the effect of the force of gravity, this movement stereotype can be a source of errors in weightlessness. Hence, the necessity for study of the peculiarities of motor activity of people under weightless conditions, which is of great practical importance, since the quality of movement determines the performance ability of a man in flight.

Since long ago, scientists have attempted to imagine the nature of the motor activity of man in weightlessness. K. E. Tsiolkovskiy, as early as 1883, pointed out that, in "free space" (under weightless conditions), the function of the legs as a support apparatus obviously changes. They will primarily execute movements, which are useful for given conditions: "grasping, like tweezers, for holding in place or repelling . . . ." Later, Haber (1951) noted that the absence of weight must seriously change the sensorimotor coordination, because of disruption of the interaction between the visual, /219 tactile and motor analyzers. Armstrong (1953) and Gaspa (1953) also pointed out the possibility of the onset of disruptions in coordination of movement, explaining it by the fact that a man will develop excess energy, corresponding to the earth stereotype of motion, under weightless conditions, which is not adequate to the new conditions. They considered that these disruptions would disappear quite rapidly, as a result of development of compensatory reactions. The propositions expressed were subsequently confirmed experimentally by other authors.

Effect of Brief Weightlessness on Functional State of Motor Analyzer

The research conducted by Lomonaco and colleagues (1957, 1960), in reproducing weightlessness in the "Roman turret," which was constructed by the authors, as well as of V. S. Gurfinkel and colleagues (1959), in the high-speed elevator of Moscow University, are extremely interesting. Lomonaco and colleagues (1957) studied the motor coordination of 30 healthy persons in weightlessness, lasting 1.7 sec. The subjects had to hit a target 15 cm in diameter with a pencil, with the natural rhythm of each. It was noted that they had considerable scattering of hits over the entire target, compared with control tests, which gradually decreased with repetition of the task in weightlessness. For the purpose of ascertaining the role of vestibular apparatus stimuli in the change of accuracy of movement, the authors also conducted studies on five deaf-mutes, and they found that they had less discoordination of movement. In this manner, the authors concluded that the labyrinth function was important in the genesis of motor disturbances. In later work, Lomonaco and colleagues (1960) determined that, although movements became less accurate in weightlessness, the sequence of accomplishment of them was not significantly disrupted.

Somewhat different data was obtained by V. S. Gurfinkel and colleagues (1959). In their tests, the subjects also hit a target; however, the accuracy of it was not changed significantly. Among the shortcomings of these works is the extreme briefness of weightlessness (not over 2 sec), alternating with accelerations, which greatly hindered analysis of the material.

More complete information on the nature of the motor activity under weightless conditions was obtained in parabolic flights. Thus, Grossfield (1951) and Ballinger (1952), in weightlessness lasting 15-25 sec, observed some difficulties of the subjects in hitting a target with the hand and, in individual cases, missing the target. Beckh (1954) complicated the experiment somewhat. In his test, the subjects drew crosses in special squares along a diagonal from top to bottom, with eyes closed and open. While, under ground conditions, the test was performed completely satisfactorily, in weightlessness, the subjects without control of vision, in the majority of cases, deviated from their handwritten lines after the third cross, by 90° to the upper right-hand corner. In the opinion of the author, this type of change was explained by predominance of tonus of the muscles raising the hand.

Approximately the same data were obtained by Gerathewohl and colleagues (1954, 1957), in a study of target-hitting accuracy. In the state of weightlessness, the subjects hit approximately /221 1 cm above and to the right of the target. The authors noted a great expression of movement discoordination at the start of weightlessness and compensation of the disruption after 5-6 repetitions. A definite role apparently is played by signaling from the tactile and visual analyzers, in development of the latter.

In our tests (Ye. M. Yuganov, I. I. Kas'yan, 1961-1963), an effort was made at a more complete study of the nature of the motor activity of people under brief weightlessness. In this case, the muscular force of the hands (dynamometry method), coordination of movement in a writing test and work on a special coordinograph, the precision of maintaining assigned muscle forces of 750 g, as well as the bioelectric activity of the musculature in static and phased movements, were recorded.

As a result of studies carried out on 26 persons, it was /222 determined that, of 266 measurements, the muscular force of the hands decreased by 4-22 kg in 82% of the cases, with an initial value of 45-65 kg. This direction of change was preserved, both with the subjects immobilized at the workplace and in free "floating" in the aircraft cabin. The authors explain these shifts by a reduction in tonic stress of the musculature, which was confirmed by the nature of change in the bioelectric activity of the muscles. As a rule, a marked decrease in biological current amplitude of the neck muscles and the flexor and extensor muscles of the thigh were observed under weightless conditions. The "writing test" data showed that a brief stay in weightlessness does not significantly affect the handwriting of the majority of subjects. In the opinion of the investigators, this was explained mainly by better immobilization of the subjects at

TABLE 68

MOTOR ACTIVITY OF SUBJECTS DURING KEPLER PARABOLA FLIGHT (average data)

Subject	Total Time of Performance of Complex Movement on Coordinograph, sec		Duration of Contact of of Pencil with Coordinograph Contact, sec	
	On Earth	In Weightlessness	On Earth	In Weightlessness
1	6.61 / —	7.45 / 6.26—8.64	0.46	0.48
2	4.8 / 4 72—4.88	4.29 / 4.08—4.50	0.56	0.34
3	3.16 / 3.04—3.28	3.83 / 3.52—4.14	0.18	0.21
4	4.65 / 3.7—5.6	5.72 / 4.72—6.72	0.26	0.33
5	6.58 / 5.8—7.36	7.9 / 5.76—10.04	0.46	0.54
6	5.38 / 4.8—5.96	6.05 / 5.32—6.78	0.38	0.36
7	5.42 / —	5.68 / 5.28—6.48	0.36	0.37
8	7.46 / 5 12—9.8	4.83 / 3.82—5.84	0.43	0.36
9	4.04 / 3.10—4.98	4.52 / 4.16—4.88	0.37	0.33
10	5.64 / 5.52—5.76	5.72 / 5.6—5.84	0.25	0.30
11	3.93 / 3.56—4.3	5.18 / 4.14—5.92	0.41	0.38
12	6.58 / 6.00—7.16	5.45 / 5.44—5.46	0.25	0.36
13	7.18 / 7.0—7.36	6.83 / 6.34—7.32	0 56	0.38
14	9.32 / 8.16—10.48	9.05 / 8.32—9.78	0.49	0.38
15	7.13 / 5.30—8.90	5.9 / 5.14—6.60	0.85	0.86
16	6.0 / 15.88—6.12	5.2 / 4.52—5.88	0.76	0.52
17	4.86 / 4.52—5.2	5.59 / 4.94—6.24	0.4	0.38
18	4.52 / 4.4—4.64	5.13 / 4.7—5.56	0.38	0.39
19	4.73 / 4.58—4.88	5.42 / 4.88—5.96	0.30	0.33
20	5.69 / 5.42—5.96	5.25 / 4.68—5.82	0.26	0.21

Note: Average data in numerator, limits of variation in denominator the workplaces during the flight experiments. As an illustration, samples of entries made by astronaut V. F. Bykovskiy during parabolic flights are presented in Fig. 61.

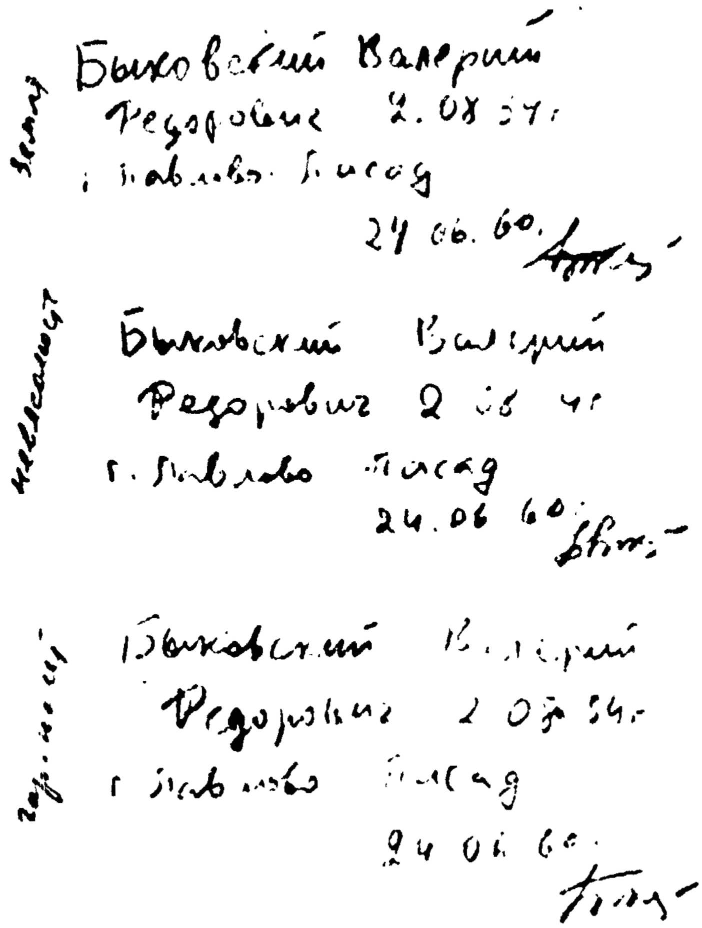

Fig. 61. Samples of handwriting of astronaut V. F. Bykovskiy on earth and during space flight.

Studies on the coordinograph allowed a decision on the time of performance of a complex movement and the length of delay in movements at given moment in the program. The results (presented in Table 68) show that some tendency to slow down the rate of performance of motor acts was noted in the majority of subjects (12 of 20), with no signs of discoordination.

Additional data were obtained by M. A. Cherepakhin, who conducted experiments on subjects well adapted to flight conditions

(13 men). The results of 52 experiments are presented in Table 69.

TABLE 69

ACCURACY OF HITTING ASSIGNED TARGET

Flight Conditions	Total No. of Movements	No. of hits and deviations from center of target				Number of Misses
		0	3 мм	7 мм	10 мм	
Horizontal flight	322	280	20	22	—	—
Weightlessness	371	316	31	22	2	—
Horizontal flight after Weightlessness	266	220	29	9	2	2

It is evident from it that, under weightless conditions, the accuracy of hitting a target with the finger, with visual control, is the same as in horizontal flight. The number of hits in the center was 86% in weightlessness and 87% in horizontal flight. The size of the deviations from the center of the target in both horizontal flight and in weightlessness was not over 10 mm. The author also was interested in the question of precision of movements, accomplished without visual control. For this, a cardboard screen was placed between the subject and the electrical target, with a 1 mm opening at the same level as the target center. The possibility of observing the hand movements was eliminated. In performing this task, the subjects were given instructions not to go beyond the limits of the target, and that hitting the center of it was not necessary.

In these tests, the hit accuracy decreased: while there were four misses in 140 movements in horizontal flight, there were eight misses in 100 movements in weightlessness. In other tests, the /223 subjects performed the same task with eyes closed, i.e., with complete elimination of visual control of both the start and the process of movement of the hands. As a result, there were 8 misses in 45 movements in horizontal flight and 15 misses in 33 movements in weightlessness.

Data on the time of performance of standard movements, obtained in work with the electrical target are presented in Table 70. 1389 movements in all were analyzed. The time of execution of the movements in weightlessness and in horizontal flight was practically the same. The differences recorded are not of significant value and are statistically insignificant.

TABLE 70

TIME OF EXECUTION OF TARGET-HITTING MOVEMENTS (in milliseconds)

Flight Conditions	Movement			
	From front knob to target	From target to side knob	From side knob to target	From target to front knob
Horizontal flight	730	814	771	715
Weightlessness	725	801	754	730

Thus, under conditions of brief weightlessness, the accuracy and time of experimental movements of persons adapted to the alternating action of g-forces and weightlessness and immobilized in the chair, was practically unchanged. A negligible increase in number of misses under weightless conditions, with visual control cut off, cannot be attributed to the specific effect of this factor.

Interesting data have been obtained by Ye. M. Yuganov and colleagues in determination of the precision of maintenance of given muscular effort (Table 71). They showed that the precision of static work was preserved unchanged in weightlessness by only 4 of 14 men, and that errors of 150-1250 g were observed in the remaining persons, always in the direction of increase in the effort. Under weightless conditions, the reflex time was shortened in the majority of subjects (10 of 14 men).

TABLE 71

MAINTENANCE OF GIVEN MUSCULAR EFFORT (750 g) AND TIME REFLEX (20 sec) UNDER GROUND CONDITIONS AND DURING BRIEF WEIGHTLESSNESS

Subject	Muscular Effort, g			Time Characteristics	
	Ground Conditions	Weightlessness		Ground Conditions	Weightlessness
		Flight 1	Flight 2		
1	750	750	1200	20.8	15.8
2	760	750	—	20.5	19.8
3	750	800	750	21.0	21.7
4	750	850	750	19.1	19.8
5	780	900	1000	19.0	14.4
6	770	1000	--	19.5	19.1
7	750	1000	--	19.0	18.4
8	750	1000	900	18.1	17.4
9	750	1600	900	20.0	17.4
10	750	1200	1200	20.6	19.1
11	750	1200	1000	20.2	20.6
12	750	1300	1200	21.1	17.8
13	780	1700	--	19.0	20.2
14	750	2000	1500	21.0	19.7

Somewhat later, M. A. Cherepakhin carried out refined studies. The subject, fastened in the pilot's seat, had to maintain a tension of 400 g on an electrodynamograph, with small efforts, during the entire time of a weightlessness parabola flight.

The tests were conducted with eyes open and closed.

18 men, from 18 to 43 years old, were examined. The majority of the subjects had repeatedly participated in weightlessness parabola flights before the examination; they included astronauts A. G. Nikolayev, V. G. Bykovskiy and P. I. Belyayev. One subject was participating for the first time in parabolic flights. All subjects had not had preliminary training in maintaining a force on the electrodynamograph, but received only familiarization instructions, 15-30 minutes before takeoff of the aircraft.

The results of the test showed that maintenance of a given static force, under conditions of periodic transformation of the force of gravity, was quite an easy task for all the subjects, if /224 they performed under visual control. With visual control eliminated, the precision of maintenance of a given force depended on the degree and nat[illegible] of change in body weight of the subject: an increase in the gra[illegible]g force on the electrodynamograph lever was observed in g-forces and a decrease in it under weightlessness. In the horizontal flight section, the subject maintained the force with sufficient accuracy. This precision was disrupted each time, when the acceleration of gravity differed from 1 g. Appropriate reductions in the force by subjects participating in the weightlessness parabola flight for the first time, even with visual control, during the transition to weightlessness in the first seconds of its onset attracted attention. True, after a few repetitions, they beg[illegible] to perform the experimental task accurately.

TABLE 72

MAINTENANCE OF A GIVEN FORCE (in grams) BY SUBJECTS WITH EYES CLOSED

Statistical Index	Horizontal Flight (control)	g-force before Weightlessness	Weightlessness	g-force after Weightlessness	Horizontal flight after weightlessness and g-force
M	383	390	367	382	364
σ	62	105	83.4	95.6	104.9
m	5.6	8.00	5.0	7.5	9.6
t		0.7	2.13	1.06	1.44

Note: M is the arithmetic mean; σ is the root mean deviation; m is the average error of the arithmetic mean; and t is the confidence factor.

The results of statistical processing of the data obtained in performance of the task by the subjects with eyes closed are presented in Table 72. A decrease in the force is evident in weightlessness, with respect to the corresponding force in horizontal /225 flight and in the g-forces.

In this same work, an electromyogram (EMG) of several postural muscles of three subjects, the trapezius muscles of the neck in particular and, for comparison, the large chest muscles, was recorded in one period of tests. The importance of the initial working posture for effectiveness of any motor act is well known. The postural musculature performs specific static and dynamic work in motor activity of man, which is caused predominantly by the effect of the force of gravity. A decrease to zero of the force of gravity led to a reduction in bioelectric activity of the neck muscles (trapezius) in all subjects. The electrical potential of the large chest muscle, recorded for a baseline, increased somewhat during the transition to weightlessness, and it remained practically without change in weightlessness.

Thus, a detailed analysis of the mechanogram and statistical processing of the material obtained disclosed a persistent tendency towards change in the static force, in connection with the transition of the subjects to g-force and weightless conditions and during the action of these factors. It turned out that the magnitude of the force reflects the general direction of the transformation of the force of gravity. With increase in body weight of the subject, the force of squeezing on the electrodynamograph lever increased, if the g-force vector coincided with the direction of the force; with decrease in weight, the squeezing force decreased. Consequently, there is a direct relation between the squeezing force on the electrodynamograph lever and body weight. With elimination of visual control, this relation is disclosed more strongly. However, the extent of the effect of change in force of gravity on the static force differed in different subjects. M. A. Cherepakhin revealed a change in precision of muscular force on degree of training.

An acceptor effect was formed in trained subjects, in tests with brief weightlessness, and it still was not formed in the untrained. The acceptor effect, with increase in the kinesthetic component of all subjects, led to the situation that the falling off of adequate stimulation in weightlessness caused a compensatory activation of the muscle groups participating in execution of the experimental task. In this manner, there was no model of the nerve stimulator of the sensory standard, which, by means of comparison of it with the composition and nature of the reverse afferentation, would signal success in accomplishment of the task. However, the phenomenon noted was complicated by the process of formation of the acceptor effect. It is completely evident that, in a familiarization session, and in the first stages of a flight, when the fixed force was maintained under visual control, proprioception participated in the acceptor effect being formed. The nonuniformity of the static force, during transition from g-force to weightlessness and, on the other hand, from weightlessness to g-force, as well as the increase in bioelectric activity of the muscles of the working arm, are evidence of this.

There is a basis for considering that this phenomenon is caused by a change in nature of the experimental activity of the subjects. In conformance with instructions, the subjects had to precisely maintain a given force, consciously suppressing any impulse to change this force They succeeded quite easily in doing this during horizontal flight; the corresponding mechanogram curves of maintenance of the force coincided quite closely with a straight line. In the /226 transition period, the mechanograms became broken lines; the static force of the subject was complicated by dynamic components. It can be assumed that this explains the increase in bioelectric activity of the muscles, to a definite extent. Moreover, it is possible, in connection with the disappearance of weight, that supplementary arm muscle forces can be developed, for compensation of the pressure on the electrodynamograph lever, created by the weight of the hand in horizontal flight. To precisely define this situation, the authors conducted a series of tests, with the hand immobilized at the elbow and wrist joints, thereby eliminating participation of weight in the pressure on the dynamograph lever. The results turned out to be as before: the bioelectric potential of the muscles increased. Finally, with onset of this phenomenon, participation of the general orienting reaction to the change in weight is beyond a doubt. In other words, the cause of the increase in bioelectric activity of the arm muscles in our test was multivalent.

In analysis of data on motor disorders under weightless conditions, it should be kept in mind that their nature depends on the degree of immobilization (Henry, et al., 1952; Clark, et al., 1960, and others).

K. E. Tsiolkovskiy had already pointed out that, in the absence of immobilization, slight movements of a man (even the act of breathing) could cause involuntary movements of the body in space. This has been confirmed experimentally.

In experiments on animals, it turned out that the nonimmobilized animals rotate quite randomly in space, apparently as a consequence of the peculiarities of stimulation and interaction of the analyzers (V. I. Yazdovskiy, et al., 1960; Ye. M. Yuganov, et al., 1962; Henry, et al., 1952; Beckh, 1954). The test subjects behaved approximately the same, which significantly affected the nature of motor activity. The subjects could move about the aircraft cabin, only by means of tight cables or by pushing away from the cabin wall. In essence, they could not write, and they performed simple operations with difficulty (Ye. M. Yuganov, et al., 1962; I. I. Kas'yan, 1963; Simons, Gardner, 1961; Lowrey, Ray, 1963; Zally, 1966).

Analysis of the writing of V. F. Bykovskiy in brief weightlessness has shown that the astronaut could not write an assigned text while "floating" freely in the aircraft cabin. In a quite short interval of time (about 25 sec), V. F. Bykovskiy changed position in space several times.

At present, a more complete study of the motor activity of people in weightless conditions in the unsecured state is necessary, since, in future flights, the length of which will be months and years, the astronauts will primarily move freely in all directions, both inside and outside spacecraft.

Effect of Prolonged Weightlessness on Functional State of Motor Analyzer

During the first space flights with animals, using television and contact-rheostat sensors, a quite complete study was made of the motor activity of animals under weightless conditions for a long time. It turned out that the motor activity of dogs increased some in the first period of weightlessness. Subsequently the behavior of the animals was peaceful. Without particular difficulties, they moved forward and backward, to and from the automatic feeder. Head movements were free and quite coordinated. All this indicated full preservation of rapid and adequate reactions of the dogs. Weightlessness also did not prevent the recovery of old and the acquisition of new motor acts. Nevertheless, B. A. Zhuravlev (1962), analyzing materials on working out of the skill of standing in place by a dog, under weightless conditions, concluded that the formation of new motor skills and preservation of old ones apparently requires much time and repetition. /227

It might be thought that the nonuniform extent of motor activity in the initial period of weightlessness and the various adaptation capabilities of the animals could indicate individual sensitivity of their neuroregulatory apparatus to the absence of gravity and differing functional mobility of their nerve structures (V. I. Yazdovskiy, et al., 1960).

It has been determined in manned space flights that the motor activity of the astronauts did not change significantly. Nevertheless, it cannot be concluded from this that the motor activity of the astronauts is constant, since they were immobilized in the majority of studies conducted, and they carried out working operations, the precision of execution of which was commensurable with possible disruptions of movement indices. Therefore, V. I. Yazdovskiy and colleagues (1963), having studied the sensorimotor coordination of astronauts in prolonged weightlessness, concluded that the state of weightlessness does not decrease the quality of coordination in the specific form of it, which occurred in actual space flights. Material has now been accumulated on the fact that, under weightless conditions, coordination acts are disrupted to a certain extent. /229

Thus, A. I. Mantsvetova, I. P. Neumyvakin and colleagues (1964), analyzing 132 entries in the log by A. G. Nikolayev and 75 entries by P. R. Popovich, concluded that the coordination of movement of the astronauts in flight was changed somewhat. The greatest changes were noted in the first 40-50 minutes of their stay in weightlessness. In the opinion of the authors, such changes are caused, in all likelihood, by the unusual external conditions of writing, and they are not a consequence of any disruption of central nervous system functions.

TABLE 73

PROPRIOCEPTIVE SENSITIVITY OF A. G. NIKOLAYEV WHILE MAINTAINING A GIVEN MUSCULAR EFFORT (Fi) OF 600 g FOR 10 SEC IN ORBITAL FLIGHT

Orbit or Date	Day of Flight	Time of Study	Before physical workload, g		Proportioned Workload	After Workload	
			Eyes open (Fi)	Eyes closed (Fi)		Eyes open (Fi)	Eyes closed (Fi)
In Flight							
69	5	4^{00}	600	610	Pumping out condensate	590	580
						580	580
						610	640
163	11	23[illegible]	620	650	2 min	620	550
			650	570	30 movements	650	570
			670	630	with loads to	640	[illegible]
241	16	19[illegible]	670	650	10 kg	650	620
			600	640		670	600
			620	580		620	650
After Flight							
27 Jun 1970	—	10^{00}	550	670	Expander	580	[illegible]
			600	620	30 movements with	610	590
			610	620	loads to 10 kg	620	62[illegible]

There is interest in the data on motor activity of astronauts, obtained under conditions of long weightlessness, of up to 18-24 days. The muscle-joint feeling, kinesthetic sensitivity and muscular effort of the hands were studied. Analysis of the material has shown that astronauts A. G. Nikolayev and V. I. Sevast'yanov maintained a given muscle effort of 600 g in orbital flight, with eyes opened and closed; the fluctuations were ±10-70 g. The fluctuations in force were most often in the direction of increase from the assigned force. Thus, the errors of A. G. Nikolayev reached +70 g on days 11 and 16 of the flight (Table 73).

It should be emphasized that performance of various proportioned workloads did not lead to appreciable change in the indices, when working with the DP-2 dynamograph. On the basis of the data obtained, it can be concluded that delicate operations with various units, instruments and scientific apparatus can be performed in prolonged weightlessness. Working with manual controls, designed for a 600 g-force, the precision of muscular efforts under these conditions can be somewhat changed. Although this position is based on a small number of experiments (15 tests) and only on two astronauts, it cannot be left out of consideration, in compiling assignments to perform various working operations in longer weightlessness.

Very convincing data also have been obtained, in a study of kinesthetic sensitivity, while sustaining a fixed muscular force /230 of 20 kg. 50 tests in all were carried out, with 4 men participating. The results of the experiment show that, in a majority of cases, the number of errors increased significantly in orbital flight, both with the astronaut secured in the seat and in the unsupported state, compared with indices recorded before launch.

The indices of A. G. Nikolayev fluctuated most of all in the 102nd, 150th, 182nd and 262nd orbits and those of V. I. Volkov, in the 954th orbit (Tables 74 and 75). In performance of a similar experiment by V. I. Sevast'yanov and V. I. Patsayev, errors in /231 maintaining the force were considerably less, with both the right and left hands. The data obtained still do not permit specific conclusions to be drawn; however, it is completely obvious that these materials will be of definite importance, for evaluation of the capabilities of performing planned work, while assembling, installing and manually joining various units in space, where it will be necessary to sustain a force on the order of 20 kg.

The functional state of the motor apparatus also was evaluated, by means of hand dynamometry. The experiments were performed with the right and left hands, with the astronaut firmly secured to the seat and while in the unsupported position. Four astronauts participated in the tests. 29 experiments (85 measurements) were carried out in all. The resulting data show that the maximum muscular force of the hands of the four astronauts decreased, under orbital flight conditions in all tests (Figs. 62, 63 and 64). This was especially pronounced in V. N. Volkov and V. I. Patsayev. Somewhat smaller changes were observed in A. G. Nikolayev and V. I. Sevast'yanov.

It can be assumed that one of the reasons for a decrease in muscular force of the hands is a reduction in tonic stress of the skeletal musculature in orbital flight; this also is in agreement with data, which we obtained earlier in brief weightlessness.

In tests with hypokinesia lasting up to 30 days, the muscle force of the hands also decreased appreciably, in the majority of cases; however, expression of the indices was considerably less than in orbital flight.

In all likelihood, during the stay of the astronauts in longer weightlessness (over 24 days), still more significant reduction in tonus of the skeletal musculature may set in, which will be reflected to some extent in the motor efficiency of the astronauts.

TABLE 74

KINESTHETIC SENSITIVITY OF ASTRONAUTS A. G. NIKOLAYEV AND V. I. SEVAST'YANOV WHILE MAINTAINING A FIXED MUSCULAR FORCE (Fi) OF 20 kg IN ORBITAL FLIGHT OF SOYUZ 9

Orbit, Day of Flight	Time of Study	Right hand	Left hand
A. G. Nikolayev			
Prelaunch period			
22 May 1970	23^{00}	20 22	20 20 22
In flight			
38th orbit 3rd day	6^{00}	20	20
70th orbit 5th day	5^{00}	20	20
102 orbit 7th day	4[illegible]	25	18
150th orbit 10th day	4[illegible]	28	17
182nd orbit 12th day	4[illegible]	25	23
214th orbit 14th day	3[illegible]	22	22
262nd orbit 17th day	3^{00}	20	15
After flight			
22 Jun 1970	10[illegible]	20	20

Orbit, Day of Flight	Time of Study	Right Hand	Left Hand
V. I. Sevast'yanov			
Prelaunch period			
22 May 1970	24^{00}	20 21	20 20
In flight			
53rd orbit 4th day	4[illegible]	23	18
86th orbit 6th day	4[illegible]	23	23
116th orbit 8th day	1^{13}	22 22 22	20 20 20
134th orbit 9th day	4^{10}	22	23
182nd orbit 12th day	4^{10}	20	20 22
198th orbit 13th day	3[illegible]	23	23
230th orbit 15th day	2[illegible]	23 21 22	23 20 19
241st orbit 16th day	19^{30}	22 23 20	23 20 21
246th orbit 16th day	3^{00}	23 22 20	24 20 21
After flight			
27 Jun 1970	10^{00}	23 20 21 24 21	19 20 20

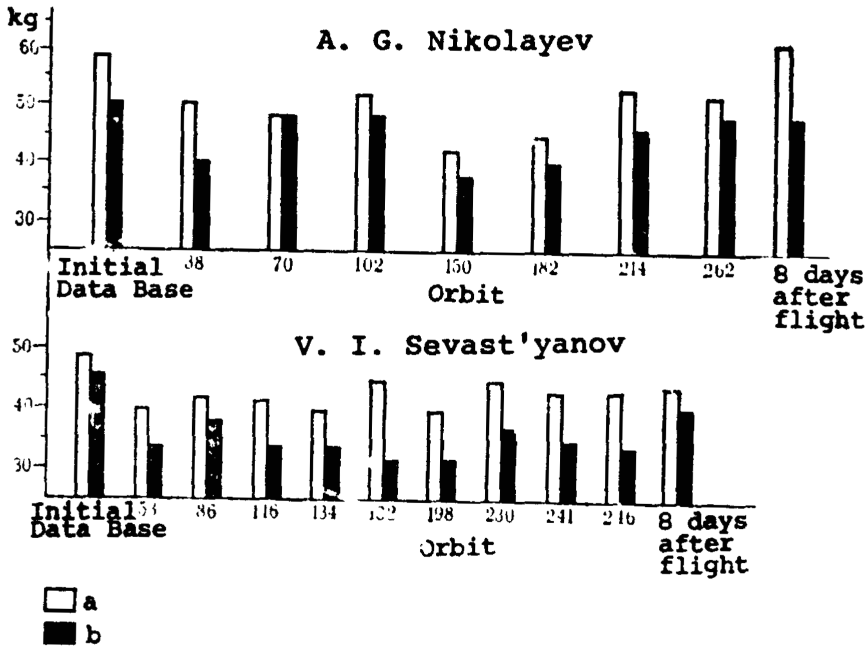

Fig. 62. Change in muscular force of the hands of astronauts A. G. Nikolayev and V. I. Sevast'yanov before, during and 8 days after flight of Soyuz 9: a) right hand; b) left hand

This indicates the necessity for use of quite efficient load and other measures, for prophylaxis of the unfavorable effect of weightlessness, in future flights.

Condition of Motor Analyzer Before and After Flight

M. A. Cherepakhin, together with V. I. Pervushin, to evaluate the state of the neuromuscular systems of A. G. Nikolayev and V. I. Sevast'yanov before the flight and in the period of readaptation to earth conditions after the end of it, conducted a study of the reflex excitability, tonus and contracting power of the muscles.

The reflex exictability was determined by recording the bioelectric activity of the muscles participating in execution of the knee tendon reflexes. The biopotentials were taken off, by means of electrodes on the skin, and they were recorded on the tape of an optical oscillograph. The reflexes were induced by a neurological hammer, by means of multiple, proportiored blows (15-20 times).

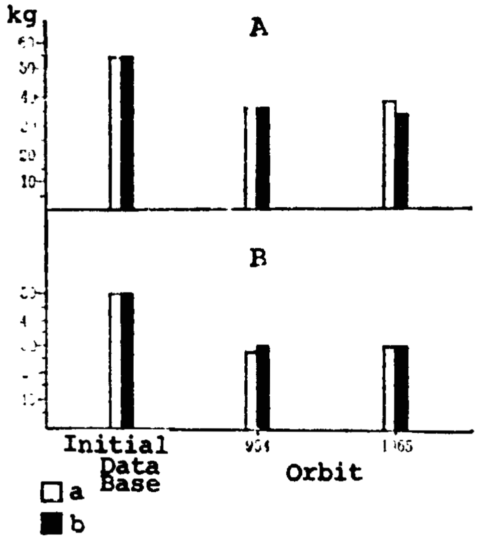

Fig. 63. Change in muscular force of hands of V. N. Volkov during flight in Salyut orbital station: A, right hand; B, left hand; a, with astronaut secured to seat; b, in unsupported state

The muscle tonus was studied by two methods: The tibialis anterior, quadriceps femoris and biceps brachii by the method of Sirmay, and the total tonus of the thigh, calf and shoulder muscles, by the method of Uflyanda. The contractile power of the muscles was decided on the basis of dynamometry of the trunk extensors and the hand flexors.

After the flight, the astro- /232 nauts complained of general weakness, painful sensations in the leg and back muscles, and uncertainty in maintaining the vertical posture. They rushed to sit down during the examination. On the first day of the examination, it was noted that the biopotentials of the muscles participating in the knee reflex /233 of A. G. Nilolayev doubled over the preflight data and, of V. I. Sevast' yanov, tripled. Both astronauts felt pain at the moment of the blows of the neurological hammer on the tendon. The intensity of these feelings weakened with each succeeding examination; they disappeared 7 days after the flight. On the 36th day after the flight, the reflexes were induced in both astronauts with difficulty.

The muscle tonus, on the basis of their hardness after the flight proved to be decreased in both astronauts (in the legs). The strength of the hand flexors after the flight was the same as before the flight. The central force decreased in A. G. Nikolayev by 40 kg on the 3rd day after the flight and in V. I. Sevast'yanov, 65 kg.

In measurements of the extremity perimeters, a moderate decrease was found in the circumferences of the calves and thighs. The shoulder perimeter remained practically unchanged. On the 11th day after the flight, the circumferences of the limbs corresponded to the initial ones. The decrease in limb perimeters, in all likelihood, involves muscle atrophy This consideration is in agreement with the results of biochemical studies, conducted after the flight, which indicated a disruption of the nitrogen and calcium balance.

On the basis of the data obtained after the 18-day flight, it can be proposed that the increased reflex excitability of the neuro-

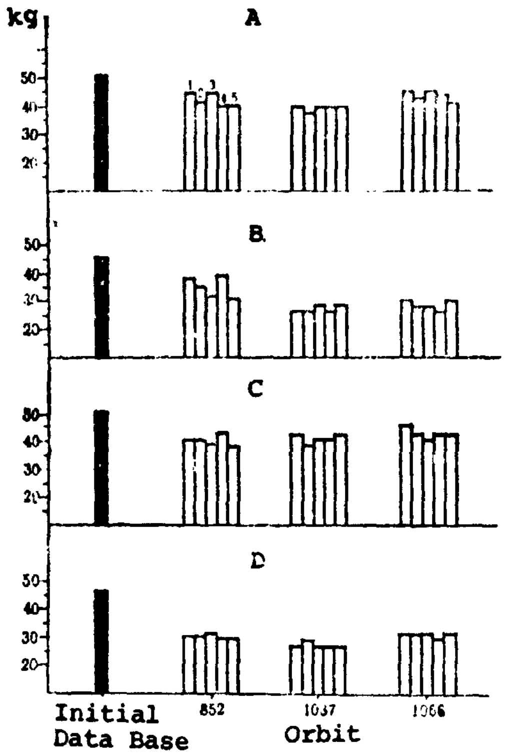

Fig. 64. Change in muscular force of hands of astronaut V. I. Patsayev during flight in Salyut orbital station, with astronaut secured to seat: A) right hand; B) C) left hand, and with astronaut in unsupported state: D) right hand; E) left hand; 1-5, order of conduct of measurements

muscular apparatus and the painfulness at the sites of blows of the neurological hammer are symptoms of deterioration of the functional state of the nervous system, caused primarily by gross drops in afferentation, arising at different stages /234 of the flight and during the period of readaptation to earth conditions.

It is known that the most characteristic element for study of the motor reactions of a man is walking, as an example of cyclic locomotion. In study of the cyclic locomotion, it is important to analyze the movement during one cycle and to determine the cycle repetition rate or movement rate. The movement cycle includes periods of support and of motion or stepping. The length of the support period of a normal man in walking is 10% greater than the length of the motion period, on the average. The walking of A. G. Nikolayev and V. I. Sevast'yanov was recorded before and after the flight by motion-picture photography, at a rate of 24 frames per second. The motion-picture camera was installed, so that its lens was approximately at the level of the center of gravity of the astronaut and at a distance, approximately equal to the length of the course of the movement studied. The chronogram of the astronauts' walks was plotted by the generally adopted procedure, using measurements of each motion-picture frame. The results obtained are presented in Fig. 65.

It is evident from the chronogram that the duration of the front support phase or shock absorption (setting the foot on the ground, with the toes ahead of the body center-of-gravity line), of A. G. Nikolayev and V. I. Sevast'yanov was 0.42 and 0.38 sec, respectively, before the space flight, with the duration of the binary support phase of both astronauts being 0.21 sec. After the flight, the front support phase increased somewhat, to 0.5 and /235 0.54 sec, respectively. The binary support phase increased to 0.37 and 0.42 sec, respectively. The duration of the pushing-away phase

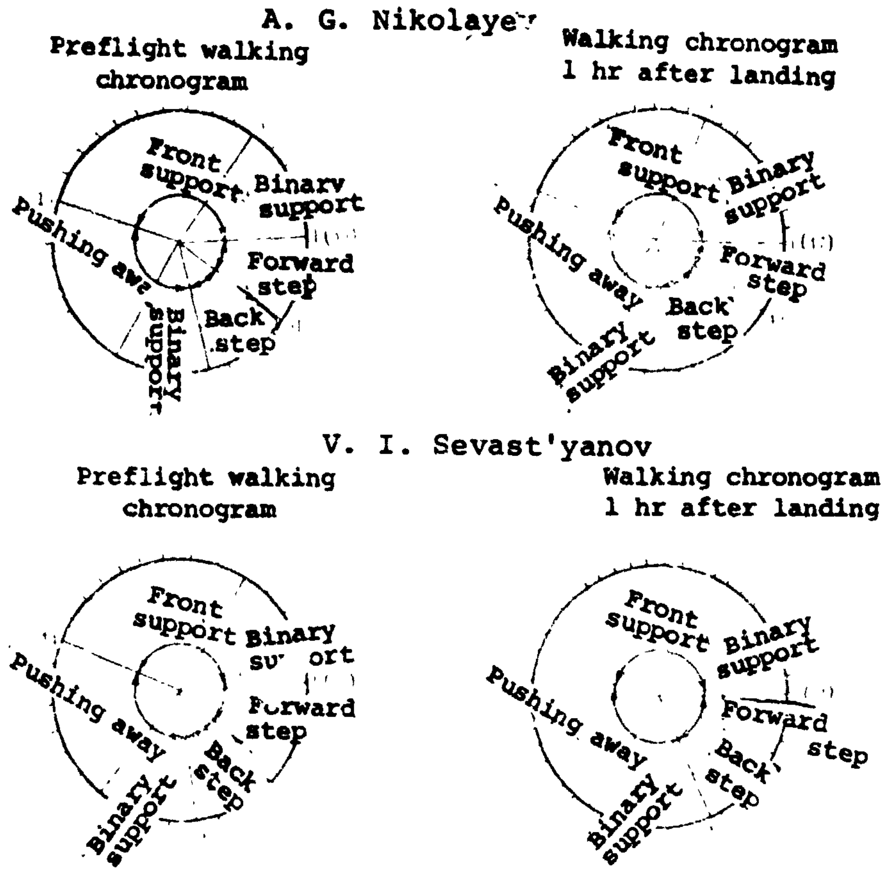

Fig. 65. Chronogram of walk of A. G. Nikolayev and V. I. Sevast'yanov before and after Soyuz 9 flight

(the body center-of-gravity line is ahead of the support) of A. G. Nikolayev and V. I. Sevast'yanov was 0.33 and 0.3 sec, respectively, before the flight, and the length of the binary support phase of pushing away of both of those examined was 0.17 sec. After a long flight, the pushing away phase increased to 0.37 and 0.42 sec. The duration of the binary support phase also had a tendency to increase, to 0.25 and 0.33 sec, respectively.

As is well known, another characteristic element of walking is the rear and front step. In analysis of motion-picture material, it was determined that the time of the rear step of A. G. Nikolayev and V. I. Sevast'yanov after the flight was 0.3 and 0.25 sec, respectively, and of the initial step, 0.17 sec. The duration of the front step of both astronauts before and after the flight remained unchanged (0.17 sec). Thus, the material obtained leads to the conclusion that a stay in orbital flight, lasting up to 18 days, causes a noticeable change in the nature of the walk of the astronauts, with the total time of the walking cycle of both astronauts increased by 44%, on the average.

The duration of the front step phase increased by 30% and the binary support phase by 88%. The pushing away phase increased by 25% and the rear step by 50%. After the flight, a tendency was noted in both astronauts toward a pronounced slowing of the walk, owing to a decrease in all phases of the motor cycle, especially because of an increase in the time of the binary support phase.

Thus, the material presented on the motor activity under weightless conditions (brief and long) leads to the conclusion that it is not significantly disrupted, if those being examined are secured at the workplaces. Some discoordination of movement, moderately expressed disruption of the precision of reproduction of assigned muscular forces, etc., were observed in them. The subjects successfully performed working operations, not requiring great precision. The opposite was observed when not secured. During free "floating" under weightless conditions, the subjects attempted to maintain the body in a certain equilibrium, with respect to the surrounding objects. It is completely clear that, in this case, performance of more or less delicate motor acts became impossible, since each movement disturbed the equilibrium and moved the body in space.

At present, the physiological mechanisms of motor disturbances still have not been studied fully. Experimental materials and data in the literature lead to the thought of a straight (direct) and indirect (mediated) effect of weightlessness on the human body (I. I. Kas'yan, et al., see section 3, Chapter 1 of this book). The direct effect is understood to be the complex of reactions, caused by the significant decrease in body weight of a man, as a result of which, the tonus of the skeletal musculature decreases, the afferentation of many analyzers changes (vestibular, motor, etc.), and movement coordination is disrupted. These phenomena are aggravated by the fact that, under weightless conditions, the concordance of the work of the analyzers participating in analysis /236 of spatial relationships is disrupted (G. L. Komendantov, 1959; G. L. Komendantov, V. I. Kopanev, 1962). In this case, there also is a mediated effect of weightlessness on the nature of the motor activity, as a consequence of disturbance of the functional system in the work of the analyzers. It is difficult to state at present the degree of importance of one mechanism or another, in the genesis of motor disorders; however, their presence should be pointed out again.

The majority of the investigators have noted that motor disorders decrease significantly, in proportion to the length of stay under weightless conditions. This apparently takes place, as a consequence of formation of a new functional system, adequate to the conditions of weightlessness.

Tests on intact and labyrinthectomized animals (see section 1, Chapter 2) have demonstrated that signaling from the inner ear receptors, which is very necessary to orientation under ground conditions, is superfluous in weightlessness, since it promotes the onset of disruptions in the combined work of the position analyzers.

TABLE 75

KINESTHETIC SENSITIVITY OF ASTRONAUTS V. N. VOLKOV AND V. I. PATSAYEV WHILE MAINTAINING A FIXED MUSCULAR FORCE (Fi) OF 20 kg IN ORBITAL FLIGHT OF SALYUT

Orbit of Flight Date, Work before Study	Right hand, kg		Left hand, kg	
	Secured to Seat	Unsupported State	Secured to Seat	Unsupported State
Prelaunch period				
V. I. Patsayev				
27 May 1971	21	21	20	20
Orbital flight				
10 Jun 1971	24	22	21	22
Systems monitoring	21	22	19	21
852nd orbit	20	20	20	18
	21	21	21	19
	21	20	21	20
22 June 1971	22	20	20	20
Television reporting	20	18	18	20
	22	20	20	20
	18	22	18	18
	20	20	18	20
24 June 1971	22	20	20	20
Rest	22	22	20	20
1066th orbit	22	20	20	20
	22	22	20	20
	22	22	20	20
V. N. Volkov				
Prelaunch period				
25 May 1971	22	22	21	21
Orbital flight				
Physical training	24	24	25	18
	30	26	16	18
954th orbit	24	24	20	22
	22	26	18	20
	26	22	20	20
24 June 1971	26	24	18	20
1065th orbit	22	22	18	20
	24	22	20	19
	24	20	24	18
	22	20	19	18

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CHAPTER 5

PATHOGENESIS AND PROPHYLAXIS OF UNFAVORABLE EFFECTS OF WEIGHTLESSNESS

1. Pathophysiological Analysis of the Effect of Weightlessness on the Body

In preceding sections of this book, the results of observations of the effect of weightlessness on the bodies of man and animals have been presented. These observations were carried out, both during brief weightlessness, created in parabolic aircraft flights and during longer flights of spacecraft. However, the prospects of growth of astronautics requires elucidation of the effect of prolonged weightlessness on the body, and it requires creation of a complete conception of the processes taking place in the body, under the influence of weightlessness. To develop effective measures for prophylaxis of the unfavorable effect of prolonged weightlessness, the action of weightlessness on the body must be analyzed, from the viewpoint of pathological physiology, a science occupied with study of the effect of the basic etiological factor and of the conditions in which it acts, as well as with elucidation of the chain of development of the basic links in pathogenesis and establishment of the connections and vicious circles, which can arise in these cases. The task of pathophysiological analysis also includes determination of the total changes of both individual systems and the entire body of a man. Nevertheless, very few efforts have been made at such an analysis up to now. /237

This principle of approach to the problem can be useful, since it provides the possibility of a stricter prognosis of one disruption or another and, consequently, of a more purposeful selection of ways to protect from the unfavorable aftereffects of weightlessness and of their prophylaxis.

A complete solution of this problem is very complicated and unusual. In the history of medicine, one pathological process or another, one disease or another, as a rule, has been observed completely, from start to finish, without time limitations. Only after this have physicians proceeded to study of it and attempts at treatment. Other conditions are accumulated at this stage of the study of weightlessness. We have data on comparatively long (up to 84 days) effects of weightlessness on the body, but, simultaneously /238 with active prophylaxis of the unfavorable effects of it, during the flight in the Skylab orbital station.

The logical necessity arises for constructing even hypothetical schemes and general pictures of development of the process and individual links of it, without protective measures. In this case, the missing facts and their consequences have to be supplemented for the time being, with purely logical construction. However, it seems to us that it is not necessary to be particularly afraid of this, since the entire course of development of natural science and a number of its cardinal problems was built initially on hypotheses and assumptions.

We attempt first of all to briefly characterize the basic etiological factor, the decrease or absence of the action of the force of gravity on the body. I. Newton (1687) proved that a mutual attraction exists between all bodies in the universe. Two bodies attract each other with a force, directly proportional to the product of their masses and inversely proportional to the square of the distance between them. Based on the universal law of gravitation, all bodies on earth, as is well known in everyday practice, have a force of gravity, i.e., a force of attraction to the center of the earth. On the basis of Newton's law, it is easy to understand that the force of attraction differs in various sections of our planet or above its surface, since the distance to the center of the earth differs in different places on the planet. The weight of a body, upon rising 1 km above the earth decreases its value by 0.0003 (consequently, if a man weighs 100 kg, during flight in an aircraft at an altitude of 10 km, he will weigh 300 g less than on earth). At the poles of the earth, we weigh somewhat more (by 0.005 of our weight) than at the equator, since the earth is flattened at the poles and, moreover, centrifugal forces also act at the equator, also decreasing the weight.

We briefly characterize the forces which act on the body while it is on earth. The force, with which a body presses on a support, is called the force of weight or gravity. The action of this force is manifested only when there is a support. In this case, the body presses on the support and on sections of the body adjacent to the support, and the force of gravity is the greatest, since all parts of the body located higher press against it. Consequently, the body is as if irregularly "loaded" with forces, acting downward in the direction of the support: the lower sections of the body (legs and especially feet) endure a greater load, and they are subject to greater deformation; the entire body is as though it were compressed, when a man is standing in a vertical position. Deformation is a very important characteristic of the effect of the force of gravity on the body. Changes in living structures, and specific deformations and compressions of them are actually illustrated by the decrease in height of a man in the vertical position, by 3-5 cm, compared with him in the prone position. Still another important circumstance should be noted: in standing, the blood and lymph, as well as other fluids, positioned in planes, in the vertically situated major vessels of the body, press downward and create a hydrostatic pressure of a column of liquid, which also deforms the vessels and tissues somewhat. This is the first and general characteristic of the effect of the force of gravity on a living organism. The main feature here is the creation of deformation and of a definite stress on the structure.

What takes place in weightlessness? Weightlessness is the name of the state, in which the effect of loss of weight or cessation of the action of the force of gravity arises. Consequently, the main etiological factor in this case is the termination of the action of the force of gravity on the body and elimination of structural deformation and stress. It must be remembered that the force of gravitation, with which the earth acts on any body, even before its contact with a support (for example, in falling on earth), is a massive force, i.e., this force simultaneously acts on all cells, molecules and atoms of the organism and creates a uniform acceleration in falling. When there is no support, there is no compression of the body, there is no deformation of it, and there are none of those effects, which are characteristic of the action of the force of gravity on the organism. More than that, during a free fall on earth in an airless space (when there is no slowing down by the air), with the acceleration of the gravity of earth, inertial forces, directed against the acceleration, arise at each point in the organism, in accordance with Newton's law. These inertial forces also are massive, i.e., they arise at all points of the body simultaneously, without exception, and they appear to equalize those forces of compression of the lower part of the body by sections lying higher, which can arise in falling. Compression does not occur, since the force of gravity acts simultaneously and uniformly on all points of the body. Consequently, in this case, weightlessness and the absence of deformation also arise in falling; this is the so-called dynamic weightlessness. There is a similar type of weightlessness in orbital flights of spacecraft. Another type of weightlessness exists, which could arise at a sufficient distance from earth or other celestial bodies; this type of weightlessness is called static. /239

We turn to the question of the effect of weightlessness, as the main etiological factor of space flight, causing specific changes in the body. Of course, there is a difference in the conditions, under which any etiological factor, including weightlessness, acts. If g-forces and vibrations acted on the body before this, a general state of excitation is noted, the effect obviously will be somewhat different than during the action of weightlessness itself alone, without this background. In an actual space flight, we unfortunately always have to do with the effect of a set of factors and, therefore, these conditions must be taken into consideration with the effect of the main etiological factor, althought the main etiological factor, as follows from the basic assumptions of general pathology, determines the specifics of the disruptions observed and the process overall.

It should be taken into consideration that gravitational fields apparently can have a definite effect on electromagnetic oscillations and, consequently, their action on the deepest and most elementary foundations of life, at the molecular, atomic and electron level, cannot be eliminated. As many investigators think, it is precisely at these levels that the most important functional, structural and energy cycles, determining the course and direction of the life processes, take place (L. Pauling, 1947; Szent-Gyorgyi 1963; B. Pülman, A. Pülman, 1965; A. Lehninger, 1966; D. Riegel, 1967, and others). The ideas expressed by Szent-Gyorgyi (1971) deserve particular attention in this regard. Since the gravitational fields, based on unified field theory, in all likelihood, may have some common features with electromagnetic and magnetic fields, the action of which on living objects has already been precisely determined, and particularly intensive study has begun recently, both in our country (A. L. Chizhevskiy, 1963; Yu. A. Kholodov, 1966; A. S. /240 Presman, 1968, and others), and abroad (Beischer, 1962; Barnothy, 1964; Haber-ditzel, 1967; Michaelson, 1967; Hameman, 1967, and others), a definite effect of a gravitational field or its interaction with the electromagnetic fields and their mutual action on living objects cannot be eliminated.

At the IV International Biophysical Congress, Yu. M. Svirezhev and V. V. Verigo (1972) presented interesting calculations, which prove that, if living cells are in an unstable state, variations in intensity of the gravitational field can cause a noticeable effect. In addition, in the opinion of these authors, weightlessness can affect the dynamics of the flow of cyclic autocatalysis reactions. This effect can be expressed by a change in reaction rates, because of differences in the probabilities of encounters of molecules of differing masses in the body of a cell, which also is determined by the laws of Brownian motion and diffusion. These are the possible deep aspects of the effect of absence or change in gravitation, on the atomic, molecular and subcellular levels. However, it must be considered that everything expressed here, with respect to the effect of gravitation on a body at these levels still is only of hypothetical importance, but the thought is forced that the absence or weakening of the gravitational field cannot be considered only as the absence of weight and removal of deformation, since other, still obscure effects of gravitation may be disclosed at the atomic and molecular levels.

Proposed Pathogenesis of the Effect of Weightlessness on the Body

Let us attempt to consider, what the specifics of the action of the main etiological factor causing changes in the body in space flight are and the conditions under which this etiological factor acts.

It is well known that the normal state of the body exists, until the proper, or more precisely, the adequate balancing of the organism with the external medium is disrupted by appropriate causes and conditons. In other words, a limit must be established, beyond which adaptation of the organism to the medium becomes incomplete and inadequate (I. R. Petrov, 1966). This is the fundamental assumption of classical pathophysiology. Under normal conditions of life, either the appearance of new environmental factors, not previously existing (for example, the appearance of a new microbe) or a sharp increase or decrease in a constant factor (for example, temperature or oxygen content in the air) can induce a pathology. In normal life on earth, gravitation is such a constant factor. In a space flight, the etiological factor capable of causing a disruption is the complete or almost complete absence of the action of the force of gravitation on the body. It is important that the force of gravity stops acting in weightlessness, on all organs, tissues, cells and even molecules, since this is a mass force, as was stated above. The conditions in which this principle acts may be preceding neuro-emotional stress, as well as g-forces and vibrations in the powered section of the flight. In a long flight, in addition to weightlessness itself, as the main etiological cause, there may be additional conditions and effects of a number of other factors, such as, /241 for example, hypokinesia, a changed gaseous environment, disruption of the biological rhythms, radiation, etc. However, it must always be remembered that the main cause of a pathology determines the primary specifics of an observed process, of its primary quality, without which a given pathological process cannot exist (I. R. Petrov, 1966). In our specific case, we consider the main cause to be prolonged weightlessness. Consequently, in an effort to carry out an analysis, based on the principles of pathophysiology, it should be clearly understood that we are dealing, not simply with a set of factors, but with the action of the main etiological factor (weightlessness) and with the conditions under which it acts. We understand well that, as is normal in life, the main etiological factor may affect the overall process more or less, depending on the conditions under which it acts.

All these considerations are not simply theoretical conjectures, but principles of approach to analysis of a chain of cause-effect connections, without which it generally is difficult to analyze the processes arising in an organism in space flight. A shortage of facts and of their common connections must be compensated for here, to a certain extent, by efforts to construct logical schemes and hypothetical interrelationships.

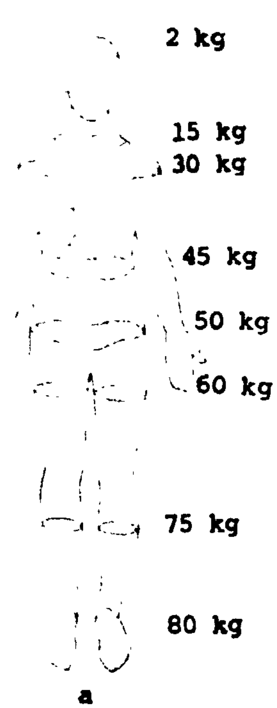
We have already discussed the fact that the effect of the force of gravity shows up in deformations generated in a man in individual parts and sections of the body. They can be very small and be measured, not in centimeters, but in millimeters or even microns. However, the body is far from indifferent to this. It should be considered that the deformations take place to a certain extent, even when a man is simply lying in bed. Of course, they are smaller, since the supporting plane is distributed over larger areas and the direction of the force of gravity on the body is different, than in the vertical position, but it exists and causes a definite effect of deformation and compression. For a graphic idea of loads created on the body by the force of gravity, exemplary values of the weights of individual parts of the body, pressing down on sections of the body below, in its vertical and horizontal locations, are shown in Fig. 66.

Normal compression, deformation and stretching of individual sections of the body and displacement of organs, caused by the force of gravity, lead to creation of constant functional loads on the body. This is primarily the generation of a flow of afferent information from various receptor formations (vestibular, tactile, proprioceptive, interoceptors, etc.). These are small displacements of vessels and nerves of underlying tissues, tightening of ligaments, loads on the skeletal elements of the body, displacement of parts of an organ, redistribution of body fluids, the appea ance of hydrostatic pressure, the generation of muscle tension and tonus, etc. In the past decade, original data have appeared, indicating that pressure and microshifts, even in such dense tissues as structural elements of the bones or crystals in the otoliths of the vestibular apparatus induce generation of a small electrical potential, which can cause a chain of subsequent changes in body (Basset, 1965; Morris, Kittleman, 1967) and, in particular, stimulate trophism and growth of bones.

Under weightless conditions, all these deformations and shifts disappear. The load on the entire body and all of its systems decreases abruptly. It should be considered here that such an etiological factor as weightlessness can act over the entire extent of development of the pathological process, although its role /242
evidently is not the same at different stages of the process, i.e., it can first weaken and then strengthen.

In analyzing the effect of weightlessness, the reactivity of the body must be taken into consideration. Many centuries of clinical experience and results of a tremendous number of experimental studies are convincing evidence that the reactivity of the body and its resistance play a tremendous role in the emergence of a pathology and of its course. As is well known, the reactivity of the body is closely connected with regulation of the constancy of the internal medium (homeostasis), carried out by the nervous and endocrine systems. The problem of study of the reactivity of the body, during the action of a number of factors of space flight, including weightlessness, has begun to receive more attention recently, and appropriate special studies are being conducted (V. V. Parin, B. M. Fedorov, 1969; P. V. Vasil'yev, et al., 1969; P. V. Vasil'yev, V. Ye. Belay, et al., 1971; Ye. A. Kovalenko, P. V. Vasil'yev, 1971).

Thus, we proceed to an effort to construct a general scheme of pathogenesis of the effect of weightlessness on the body. It follows from what has been said above, that the changes caused by the absence of deformations in the body, caused by the force of gravity, can be considered to be the leading ones in pathogenesis. One of the basic, principal links in the pathogenesis is the same shift of the body fluids, first and foremost of the blood, which have lost weight. In turn, this leads to a decrease and



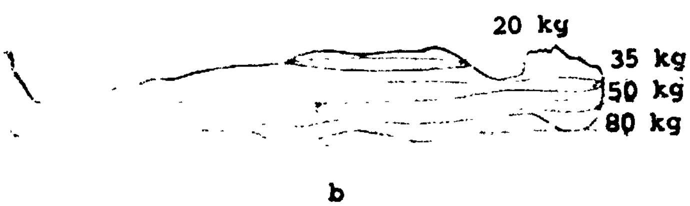


Fig. 66. Approximate distribution of compression forces of overlying parts of the body on underlying parts in the vertical (a) and horizontal (b) position of a man

change in the functional loads on a number of systems (derivative links in pathogenesis). A decrease and change in the afferent impulses from a number of systems and organs takes place: from the otoliths, from the tactile sensitivity receptors, from the proprioceptors, from the interoceptors of all organs and tissues losing deformation, including the vascular regions, tubular organs, etc. From everywhere that the force of gravity caused a constant flow of information, on the deformations, stresses and tensions taking place, this information disappears or changes.

Removal of deformation leads to a decrease in the muscle tonus, the necessary and constantly maintained tension of one group of muscles or another, preventing the action of the force of gravity (first and foremost, the tonus of the support muscles, according to Rademacher). This causes a change in metabolism of the muscle and bony tissues.

One of the chief links in the pathogenesis is the shift of body fluid, first and foremost, the blood, which have lost weight. /243
Redistribution of a large amount of the circulating blood in the vascular channels of the upper half of the body takes place, some change in pressure of the cerebrospinal fluid in the spinal column and cranial cavity can occur: specific shifts in the lymph flow are possible, because of removal of the hydrostatic pressure and because of loss of tonus of the muscles and other tissues, etc. The entire volume of body fluids is as though partially moved to the upper part of the body. The volume of blood flowing to the heart changes, a flow of information arises from the volume receptors of the upper half of the body and the flow of it from the lower sections of the vascular channels of the body decreases. Following this, the next link in pathogenesis is switched on, such, for example, as change in regulation of the water-salt metabolism.

One of the main links in the pathogenesis of a possible effect of prolonged weightlessness, the absence of the stimulating action of the force of gravity on the energy and plastic metabolism of the body, is more hidden in analysis of the change of evolving events. This is one of the major links, and it must be taken into consideration, without fail.

All of the discussion presented is still hypothetical, of course but, if we are to carry on a discussion as is accepted in pathophysiology, i.e., that if the leading pathogenetic links of the effect of prolonged weightlessness, the decrease in deformation and shift of body fluids, are eliminated, it can be assumed that the entire chain of subsequent mechanisms of development of the disruption is not disconnected. It also must be said that the concept of deformation itself (a term usually accepted in physics and mechanics) is not deep enough in the consciousness of biologists and physicians. In thinking through the essence of it and the biophysicial effects appearing in detail, it very completely and comprehensively characterizes the singularity of the effect of the force of gravity or absence of it on the body. It cannot be forgotten that, from the point of view of physics, our bodies are a unique set of elastic, solid and liquid media, undergoing deformation or shifts, like any other physical body. The specifics consist of the unique combination of these differences in biophysical properties of the body. In general form, the effect of the etiological factor and the primary, main link in pathogenesis is shown schematically below (Diagram 2).

We now proceed to the characteristics of the proposed mechanisms of action of weightlessness on a number of body systems.

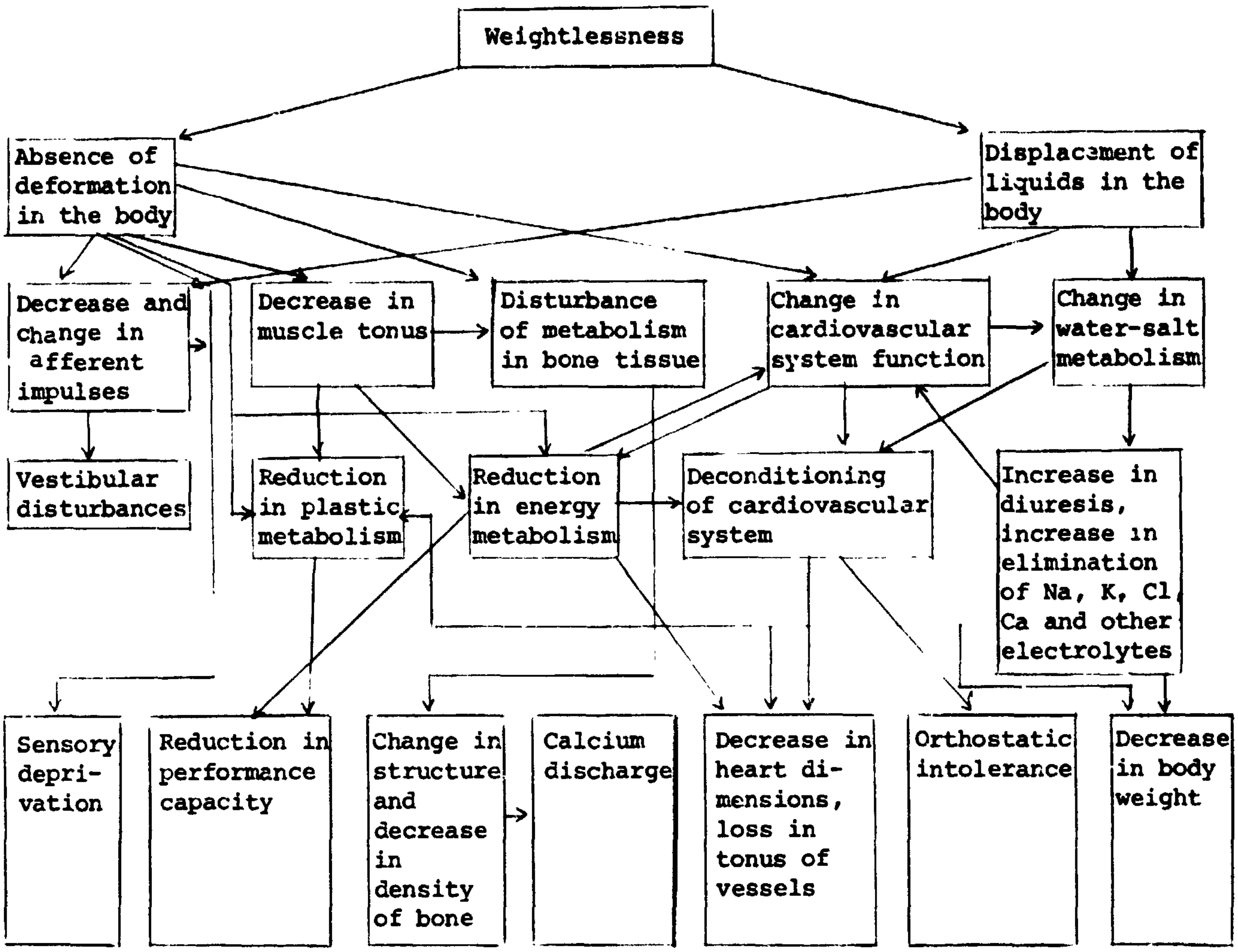


Diagram 2: Proposed scheme of pathogenesis of the effect of weightlessness on the body (principal etiological factor and basic links in pathogenesis)

Vestibular and Sensory Changes in Weightlessness

The entire process of evolution has taken place in the gravitational field or the earth. Life in the gravitational field has forced the body to take a strictly defined position, with respect to the gravitation vector. Moreover, situations always arise in real life, when some deviation of the body axis from the strictly directed gravitation vector has to be created. As a result, a well-matched system has been put together, permitting man to quite distinctly orient himself in space. This system is dependent on the activity of a number of receptor formations, and it depends primarily on the function of the main gravitation receptor, the vestibular apparatus. Simultaneously with information from the vestibular aparatus, signals from the skin-tactile receptors, proprioceptors and a number of interoceptors come in, as well as signals of visual perception of the surroundings. The entire set /244 of these signals assist man in orienting himself well in space, because of their clearly coordinated information. However, the main special orientation organ, with respect to the direction of the gravitational field of earth is the otolith apparatus. Under weightless conditions, this delicately coordinated and well-settled system of interaction of the orientation analyzers, first and foremost, the otolith apparatus, begins to give false information. The only signal correctly informing as to the body position under weightless conditions is vision, and the otolith apparatus, skin-tactile receptors, proprioceptive signals and interoceptors can return distorted afferent signals. All this leads to illusory feelings of the body position, a feeling of the upside-down position, the feeling of floating, rotating, etc.

Space flight experience has shown that sensory disruptions arise in some Soviet and American astronauts (see Chapters 1, 2, 7). The situation is complicated by the fact that the disruptions of orientation and illusory disturbances are joined to distinct vegetative disorders, in the form of dizziness, nausea, vomiting, changes in pulse rate, paleness of the face, fluctuations of arterial pressure, etc.

What is the cause and what is the pathogenesis of the observed deviations in reactions of the analyzers, mainly, of the sharp vegetative disorders?

The interaction of the analyzers providing orientation in space, formation of the correct posture and motor acts undergo sharp changes under weightless conditions. Despite the lack of knowledge on functions of the vestibular analyzer and the interactions of individual parts of it, on the basis of the work of A. N. Razumeyev and A. A. Shipov (1969), Ya. A. Vinnikov, O. G. Gazenko, et al., /245 (1971) and a number of other studies, it can be assumed that the otoliths stop fulfilling the role of stimulators of the neural gear of the vestibular apparatus in weightlessness. Since there is a mutual influence between the semicircular canals and the otoliths, expressed by inhibition of the function of the cupulo-endolymphatic system, the semicircular canals, freed of the inhibiting effect of the otoliths, become more sensitive to adequate stimuli (G. L. Komendantov, V. I. Kopanev, 1962; Graybiel, Kennedy, 1969, and others). However, another opinion is known. In particular, Ye. M. Yuganov (1968) considers that, in the absence of gravity, no functional deviation of the otolith apparatus occurs, but, to the contrary, a "negative stimulus" for the otoliths is generated. As a result of the constant "negative" stimulation in weightlessness, motion-sickness symptoms appear.

A number of authors hold to the point of view that vestibular disorders in weightlessness do not depend on the stopping of stimulation of the sense organ receptors, and they introduce into evidence the fact of preservation of spontaneous electrical activity of the labyrinth in this case. It is interesting that severing of the vestibular nerves causes other symptoms, but not those which are noted in the absence of gravitation.

Vegetative disturbances are naturally a consequence of vestibular disturbances, especially in those periods when the active movements required for work are made. True, under the prolonged effect of weightlessness, the vegetative disturbances caused by vestibular disturbances gradually weaken. More than that, almost complete acclimatization to weightlessness can take place, and these disturbances are not repeated (Graybield, 1971). A good illustration of this is the almost complete acclimatization to weightlessness, observed in a period of 2-3 days in A. G. Nikolayev and V. I. Sevast'yanov (V. I. Vorob'ev, A. D. Yegorov, et al., 1970).

Analysis of the condition of a man in open space shows that, as A. A. Leonov and V. I. Lebedev (1968) consider, the primary importance in orientation and movements in weightlessness in open space is acquired, first and foremost, by vision, then tactile and, finally, muscle-joint feeling. Signals from the vestibular and interoceptive analyzers are of less importance. Consequently, the mechanism of the disruptions arising in weightlessness consists, not so much of disruptions of the function of some one analyzer (even such a specific one as the vestibular), as in breaking up of the usually well-coordinated effect of the set of analyzer systems: vestibular, proprioceptive, skin-tactile, visual, etc. Possible connections and mechanisms of the disturbances arising are shown in Diagram 3.

For a detailed disclosure of the mechanism of vestibular disruptions, one of the most important evidently is precise determination of the functional connections between the vestibular apparatus itself and different sections of the parasympathetic and sympathetic systems. This problem has not been solved conclusively up to the present time, although the effect of the vestibular receptors on singularities of brain blood circulation has been clearly demonstrated in the works of B. N. Klosovskiy and Ye. N. Kosmarskaya (1961) and A. N. Razumeyev and A. A. Shipov (1969).

The problem of the mechanisms of the functioning of the vestibular apparatus in weightlessness undoubtedly has a number of complications, the more so that there still is no complete concept now, even about such important and fundamental aspects of the problem, /246 as the function of the otolith. There is not a single opinion as to whether the otoliths are stimulated by sliding or compression or, possibly, tension (Corvera, Hallpike, Schuster, 1958; Miller, 1962). If, for example, compression or tension of the otoliths takes place, the otolith crystals may generate electrical potentials in specific cases, i.e., have the properties of piezocrystals. These potentials

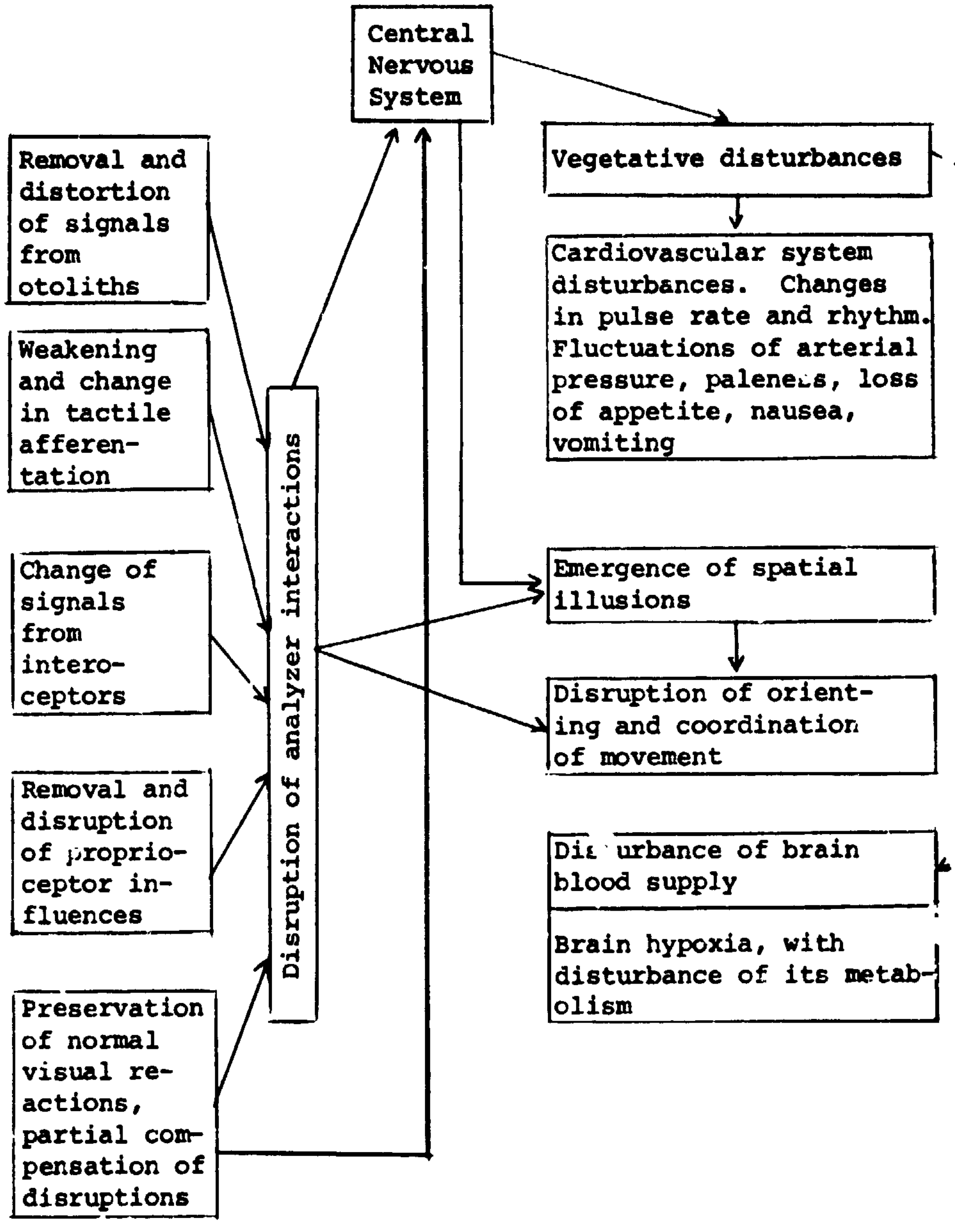


Diagram 3: Proposed scheme of pathogenesis of vestibular and sensory changes in weightlessness: solid lines established connections; dashed lines, hypothetical connections

can play a part in creation of signals and the function of the otolith apparatus itself (Morris, Kittleman, 1967). There also are data that a unique "yellow spot" exists in the otolith apparatus, analogous to "blind spot" in the retina of the eye. This considerably expands our conceptions of the functions of the otolith in weightlessness (Nelson, 1968); in those cases, when the otolith falls on the "yellow spot," there may be a greater change in the afferent impulses.

Despite intensive study of this link in pathogenesis of the effect of weightlessness in recent years, the main problem of the precise mechanisms and nature of the connections between the effect of weightlessness on the vestibular function and the vegetative disorders induced here has not be conclusively solved.

Possible disruptions of the vestibular apparatus, leading to distortion of orientation in space, as well as to a number of vegetative disorders, are shown in Diagram 3. /247

Speaking of the sensory reactions in weightlessness, of the changes in afferentation arisin.., the significant changes in pulses from the tactile receptors, because of removal of the pressure in contact of the skin surface with the support and with surrounding objects, cannot be forgotten. Together with this, changes in the proprioceptive pulses take place, arising in connection with the absence of the effect of gravity and deformations, which were spoken of earlier.

Thus, on the basis of data now existing, on the effect of comparatively brief weightlessness, it can be considered that one of the leading pathogenetic links is disruption of the well-coordinated interactions of various analyzers, providing correct orientation in space under ground conditions. The leading part in this case is played by disruption of afferentation of the vestibular analyzer. The vegetative disorders, especially disturbances of the brain blood supply, caused by stimulation of the vestibular nuclei, are of significant importance here.

Mechanisms of Disruption of Cardiovascular System Function in Weightlessness

In examination of the principal links in pathogenesis of the effect of weightlessness on the body, it has been noted that there apparently are two links, on which development of the entire subsequent chain of disruptions depends, to a great extent. Under weightless conditions, deformation is removed from a number of systems of the body and, in addition, the weight of the blood disappears, which leads to redistribution of the circulating blood.

We attempt to examine the mechanism of changes observed in the cardiovascular system in greater detail. When our body is in the vertical position on earth, the pressure of the weight of the vertical column of blood, i.e., hydrostatic pressure, is added to the pressure created by the work of the heart in the large vessels located on the longitudinal axis of the body. The magnitude of this pressure is very significant. If the height of a man is assumed to be about 180 cm, the distance from the heart to the feet is approximately 135-140 cm and, from the heart to the brain, 45-40 cm. It is easy to calculate here that the blood pressure in the vessels of lower part of the legs will be 135-140 cm H_2O greater than at the level of the heart. If these data are recalculated to a mercury column (specific weight of mercury 13.6), the pressure is about 100-150 mm Hg. Thus, it turns out that the total pressure in the large vessels in the lower part of the legs will not be 115-120 mm Hg, as it usually is normally at the level of the heart or, say, in the shoulder arteries, but 220-225 mm Hg. In other words, it is as though there were a unique "hypertonia," but this is the absolute standard for the vertical position of the body and vessels of the legs. The elastic properties of the vessel membranes, the elasticity of the walls of the arterial circulation and the turgor of the adjacent tissues all create a corresponding counterpressure to the increased blood pressure and, therefore, no particular dilation of the vessels of the legs takes place. However, there are two main factors in the entire system, preventing dilation of the vessels and deposition of the blood in the lower half of the body in the vertical position. The first factor is contraction of the muscles of the limbs and abdominal wall. An increase in tonus of the abdominal /248 musculature increases the intraperitoneal pressure and leads to compression of the vessels of the abdominal cavity, and the vessels of the legs are squeezed by contraction of the musculature of the legs. Together with this, rhythmic contraction of the muscles causes movement of the blood along the veins, since the venous pump begins to act here (Gayton, 1963, and others).

The second factor is the usually well-regulated reflex increase in tonus of the vessels of the legs and the entire lower part of the body.

However, with change of body position under normal earth conditions, a definite deposition of part of the blood takes place, in the somewhat dilated vascular channels of the lower half of the body. According to the data of Gayton (1963), the normal degree of elasticity of the vessel walls (in volumetric values) is 0.02 ml per 1 ml of blood, on the average. In normal arising from bed, the minute volume of the heart decreases by 20-40%. These shifts would undoubtedly be greater, if the entire system of the compensation mechanisms indicated did not participate as a set in preventing the displacement of blood by the force of gravity. The venous portion of the blood circulation deserves special attention under these conditions, since there is normally considerably more blood in it (80%) than in the arteries. The hydrostatic pressure of the venous blood column is directed against its movement to the right auricle, i.e., there exists a seeming obstacle to venous return of the blood to the heart. Normally, this phenomenon usually is well compensated for by the tonus of the walls of the veins, by muscle contractions compressing the veins, by the presence of venous valves, the sucking action of the thoracic cage and by a small residual systolic pulse of the heart transmitted by the blood passing through the capillaries. In the region of the head and upper part of the body, on the other hand, the force of gravity on the blood promotes return of the venous blood to the superior vena cava and to the right auricle . For a clear representation of this picture, it can be represented, in the form of the schematic model of the circulatory system and the effect of the force of terrestrial gravity on it (Fig. 67).

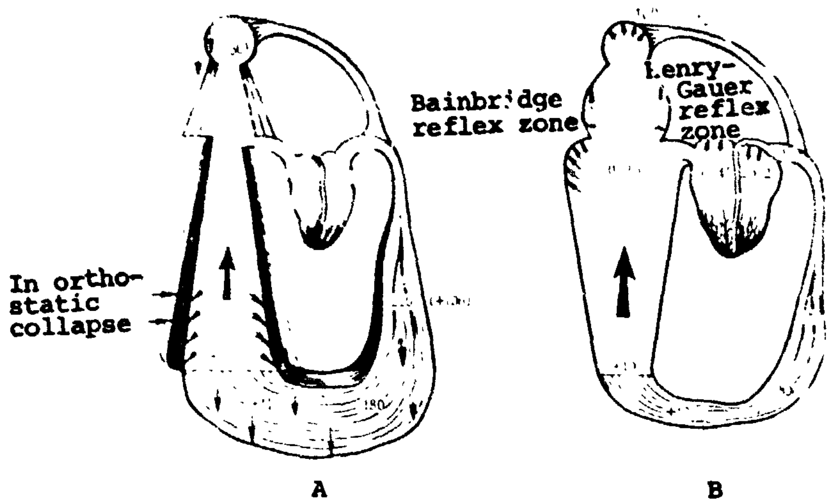


Fig. 67. Diagram of effect of hydrostatic pressure on blood circulation and of the absence of it in weightlessness: numbers are the blood pressure in different parts of the circulatory system; A. at normal hydrostatic pressure (the additional capacity of the circulatory system, formed by deconditioning after a stay in weightlessness, is shown in black); B in weightlessness

What takes place when the body enters weightlessness? We present simply a situation, in which a man assumes the horizontal position, since the horizontal position of the body partially simulates the changes in hemodynamics arising in weightlessness, and this is widely used (Miller, et al., 1964; Giovanni, et al., 1964; Vogt, et al., 1966, 1967, and others). In the horizontal position, the primary, large main vessels, located along the longitudinal axis of the body, become perpendicular to the gravitation vector and the hydrostatic pressure of the blood decreases. A redistribution of the circulating blood takes place; blood filling of the legs can decrease by up to 50%, and blood pressure on the vessels of the lower half of the body disappears. The blood supply to the brain increases by almost 20%. The venous return of the blood from the lower half of the body increases considerably, since the hydrostatic pressure opposing the blood flow to the heart disappears. In the opinion of Gayton (1963), the minute volume of blood may increase by 20-40% and, according to the data of Lamb (1964, 1965), in changing from the vertical position to the horizontal, the minute volume of the heart increases from 000 to 5000 ml and more per minute. Under these conditions, the blood filling of the entire upper half of the body increases and the load on the circulation system of the lower half of the body and legs decreases sharply. Moreover, when a man lies down, the leg muscles relax, the tonus of the abdominal muscles decreases and the intra-abdominal pressure decreases and, consequently, the pressure on the vessels located in these sections of the body. /249 If this state is continued sufficiently long and daily exercising of the circulatory system does not take place, by changing from the horizontal position to the vertical, deconditioning of a large and very capacious section of the circulatory system arises. The possibility of rapid and adequate switching on of reflex regulation of the tonous vessels will be lost, the tonus of the muscle system will be lost, and the general turgor of the tissues will decrease, i.e., changes will take place, which are usually observed after a long stay in bed. The result of this, in changing to the vertical position, may be development of orthostatic hypotension and even collapse.

A similar situation arises after a long stay in weightlessness. As experience demonstrates, upon return from weightlessness even with a comparatively short space flight (Berry, 1966, 1967, 1969), as well as after a long stay in bed, orthostatic hypotension develops, as a rule, i.e., a situation when vascular tonus is lost and deposition of part of the blood in the deconditioned circulatory system of the lower half of the body takes place. Still another circumstance is important. The development of orthostatic intolerance after a stay in weightlessness or a long bed rest can be explained, not only by redistribution of the blood in the deconditioned circulatory system, but by a decrease in blood plasma volume, which has repeatedly been recorded. It apparently arises, as a result of increase in stimulation of the baroreceptors of the central veins, and this, in turn, promotes suppression of secretion of antidiuretic hormone and aldosterone (Henry-Gauer reflex), causing an increase in sodium and water diuresis (Anderson, et al., 1959; Gauer, Henry, et al., 1961; Mills, 1965; Kleman, Fichman, 1967).

A definite part may be played in weightlessness by the decrease in production of the hypothetically so-called third factor, regulating, as it is thought, at the nephron level, glomerulus- /250 tubule filtration (Bricker, 1967). Experimental data and calculations carried out by Hyatt (1970) show that in hypokinesia, simulating weightlessness, in the horizontal position, the loss of volume of intravascular fluid before the test in the vertical position was 500 ml in a man and, in changing to the vertical position during the orthostatic test after hypokinesia, another approximately 500 ml of the liquid part of the plasma, discharged from the circulatory system, is lost, since filtration of fluid from the deconditioned vessels is increased. In this manner, the blood volume can decrease by 1000 ml, and not by 500 ml, as is normal in the vertical posture, without preliminary hypokinesia. This significant reduction in volume of circulating blood, together with deposition of blood in the vessels of the lower limbs, which have lost tonus, causes a sharp anemia of the brain. Interesting data on significant change in the blood filling of the head in weightlessness and in the orthostatic test have been presented by Yu. Ye. Moskalenko and colleagues (1971). An experiment, carried out on 2000 rats, kept 100-130 days under hypokinesia, indicates elimination of part of the fluid from the body. A 70-80% increase in diuresis, compared with control data, was successfully found here (Ye. A. Kovalenko, V. L. Popkov, et al., 1971). Consequently, even in animals, which, as is well known, are primarily in the horizontal position all the time, prolonged hypokinesia in itself leads to significant increase in elimination of fluid from the body and, consequently, to a decrease in blood mass. This fact shows that, under weightless conditions, in which a definite degree of hypokinesia will always be observed, to one extent or another, this circumstance also must be considered to favor a decrease in mass of the circulating blood. This emphasizes the importance of physical training in flight, for prophylaxis of the unfavorable effects of weightlessness, which is discussed in detail in section 3 of this chapter. In addition, the loss of fluid takes place, not only from the plasma, but from the fluids of other spaces. In simulation of weightlessness by bed rest, the volume of extracellular fluid (determined by ^{35}S) and the total volume of water in the body decrease (Vogt, Johnson, 1967), and it has been shown, by incorporation of labeled bromine (^{82}Br), that the total volume of extracellular fluid decreased by 300 ml (Hyatt, 1970).

Thus, it is evident that, in weightlessness and conditions simulating it, an increase in elimination of fluid from the body is clearly observed; a decrease in the volume of circulating blood can take place, because of this phenomenon.

Thus, as a result of deposition of blood in the vertical position of the body and decrease in mass of it because of dehydration, anemia of the brain and loss of consciousness can occur, i.e., that which is called orthostatic collapse. In these cases, as a rule, the pulse pressure decreases, blood filling of the legs increases and compensatory quickening of the pulse sets in (Berry, 1966, 1969, and others).

Consequently, one of the main concluding links in pathogenesis of orthostatic collapse should be development of an oxygen insufficiency of the brain. This phenomenon has been reproduced, to a certain extent, in an experiment, with establishment of the vertical position of the body, even without preceding weightlessness and only with partial simulation of it by prolonged hypokinesia. In tests on animals (rats), after long (100-day) hypokinesia, in changing from the horizontal position to the vertical, a significant reduction in oxygen pressure right in the brain tissues was recorded (Ye. A. Kovalenko, A. V. Ryazhskiy, 1972, A. V. Ryazhskiy, /251

1973). The presence of hypoxia of the brain, in orthostasis after hypokinesia, was directly and successfully demonstrated by these tests.[5]

We examine still other aspects of possible consequences of redistribution of the blood and changes in the blood flow arising in weightlessness. Upon entering weightlessness, a redistribution of the blood and an increase in blood filling of the vena cavae, right auricle, pulmonary circulation and left auricle takes place. As a result of the increase in venous return of the blood, a specific rearrangement of all the interactions of the cardiac and vascular reflexes, which were well balanced on earth, may begin. As a rule, astronauts almost always note a feeling of blood rushing to the head, heaviness of the head, as well as some hyperemia of the skin of the face and of the sclera, upon entering weightlessness (Berry, 1969, 1970, 1971; V. I. Vorob'yev, Yu. G. Nefedov, et al., 1970a, 1970b). These data are evidence of perceptible subjective symptoms of an increase in blood filling of the upper part of the body, especially, of the head.

In response to the increase in blood filling of the circulatory system of the upper half of the body, an increase in reflex depressor effects may arise in the sinocarotid zone, and overfilling of the vena cavae may increase the effect of the reflex component of the Bainbridge reflex. The interaction of these reflexes may have an opposite effect, to a certain extent. The depressor reflex, upon overfilling of the carotid artery, will be directed toward some slowing down of the pulse rate. It is interesting that the slowing of the pulse and some decrease in arterial pressure actually was noted in nearly all astronauts, during the first hours in weightlessness. This permits the thought of such a depressor reflex mechanism. The more so, that a reduction in physical load takes place in a number of systems and, consequently, in the requirements on the hemodynamics function. Under these conditions, some dominance of vagus tonus, i.e., predominance of the parasympathetic influences sets in (N. M. Sisakyan, V. I. Yazdovskiy, 1962; P. V. Vasil'ev A. A. Voskresenskiy, et al., 1965; Johnson, 1971, and others). Together with this, the reflex effect from the vena cavae (Bainbridge reflex) is directed toward discharging the increased amount of blood flowing to the right side of the heart. This can increase the heart rate and lead to periodical quickening of the heart rate. These mutually opposite effects, inadequate to the clearly coordinated

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[5]In free maintenance of the rats (in the control), they frequently assume the vertical posture, and in this case, they condition the brain blood supply mechanism, but this does not occur in prolonged hypokinesia.

reflex interactions on earth, may cause instability and a very labile change in the heart rate in weightlessness. The general picture of change in cardiovascular system regulation may be complicated still more, because the muscle function and discharge of adrenalin and, especially, of noradrenalin into the blood decreases sharply.

All this is a basis for considering that a very important link in pathogenesis of the disturbances caused by weightlessness is a decrease in oxygen, more precisely, the energy requirement of the tissues of many body systems in the absence of the effect of gravity. This is an extremely important circumstance, since that is an opinion in physiology that the "oxygen regulatory mechanism" in the tissues can sometimes play an even greater part than the neuro- /252 regulatory mechanisms. The latter has been proved, by means of complete resection of the vegetative nerves of the muscles; regulation of the muscle blood flow, depending on the oxygen requirement of a given tissue, was strictly preserved, in this case (Gayton, 1963).

A decrease in oxygen demand with decrease in load on the muscular system may lead to a slowing of the pulse and reduction in arterial pressure and, further, to a change in such an important and essentially central hemodynamics indicator as the minute volume of blood. True, initially, in the first period of weightlessness, to the contrary, the minute volume will increase, by virtue of redistribution of the blood and increase in venous return. However, in proportion to adaptation to weightless conditions and reduction in oxygen demand, it can then decrease.

We have already partially discussed the problem of change in plasma and the fluid volume in the body in weightlessness, which can aggravate the disturbances of the hemodynamics. The reduction in load on the cardiovascular system, caused by the decrease in oxygen demand, can cause deconditioning of the left side of the heart and a decrease in tonus of the peripheral circulation vessels, including the tonus of the arterioles, veins and capillaries.

There already are some facts on this. In X-ray photographs of the thoracic cage of 19 of 27 astronauts in the Apollo crews, a decrease has been found in the size of the heart shadow. Its transverse diameter was decreased by 0.5-3 cm from the preflight data. Clinical electrocardiograms made after the flight showed a decrease in T-spike amplitude in a number of astronauts; a shift of the QRS complex and T-spike took place in some astronauts.

The change in heart rhythm of the American astronauts in the Apollo 15 flight is very interesting. As is well known, the members of this crew performed quite a large amount of physical work and were subjected to very significant emotional stress during the flight, especially while out on the moon. After 157 hours from the start of the flight, a ventricular extrasystole was noted in J.

Irwin, the lunar module pilot and, after 179 hours of the flight, before separation of the lunar module, bigeminy (12 double beats of the heart per minute) was detected in him (Berry, 1972). In this case, the lowest pulse rate recorded from the astronauts also was observed, which, in the opinion of Berry (1972), can reach 30 beats per minute during sleep in weightlessness. Five days after this flight, the metabolism of labeled potassium (^{42}K) in the body was successfully traced. A 10-15% decrease in total content of potassium participating in the metabolic processes was established (Johnson, Hoffer, Wolthuis, Gowen, 1972; Alexander, 1972).

The heart rates of the Apollo crew members, measured after the flight at rest, was considerably higher in 13 of 18 astronauts than before the flight (Johnson, 1971). These data confirm that the heart function and, possibly, its morphology and microstructure react in a specific manner to reduction in oxygen demand and change in hemodynamics during and after a stay in weightlessness. At the same time as this, significant change in vessel tonus is observed, which is especially graphically demonstrated during conduct of the postflight orthostatic test, by a marked decrease in orthostatic tolerance, right up to development of a prefainting condition. In particular, data on orthostatic tolerance of the Apollo 10 - Apollo 14 crew members (pulse rate, indices or arterial pressure and blood /253 filling of the legs, as well as subjective symptoms) indicate that orthostatic tolerance is decreased after a stay in weightlessness (Berry, 1970, 1971, 1972). After the still longer flight in Soyuz 9, dizziness, weakness and a noticeable acceleration of the heart beats of astronauts A. G. Nikolayev and V. I. Sevast'yanov was noted, during a change to the vertical position immediately after the flight (Ye. I. Vorob'ev, A. D. Yegorov, et al., 1970, as well as section 5 of Chapter 5). Important data have been obtained in simulation of weightlessness by prolonged (for a period of 28 days) bed rest /254 (Hyatt, 1970). Conduct of a passive orthostatic test on a tilting table (turned to 70°) after this, also led, in a number of cases to such a threatening phenomenon, as stopping of the heart for several seconds (with complete absence of ventricular contractions). The outcom could be very serious, in development of this phenomenon. It cannot be forgotten that marked, developing anemia and hypoxia of the brain can take place at this time, because of outflow of blood into the vessels of the lower half of the body, which have lost their tonus. The combination of anemia of the brain and hypoxia of its vitally important centers (vascular and respiratory) and even a brief stopping of the heart can cause tragic consequences. It is difficult now to predict precisely what disturbances of the cardiovascular system might develop, after still longer flights and stays in weightlessness. The chain of these changes and the disruptions observed can lead to definite pathological changes, in the form of dystrophy of the cardiac muscle and even to some decompensation of cardiovascular activity, as well as to congestion phenomena in the veins of the peripheral and pulmonary circulation. The outcome of this may be disruption of the oxidative processes in various tissues and organs which, with prolonged action, can cause degenerative phenomena in the tissues of the parenchymatous organs (Diagram 4).

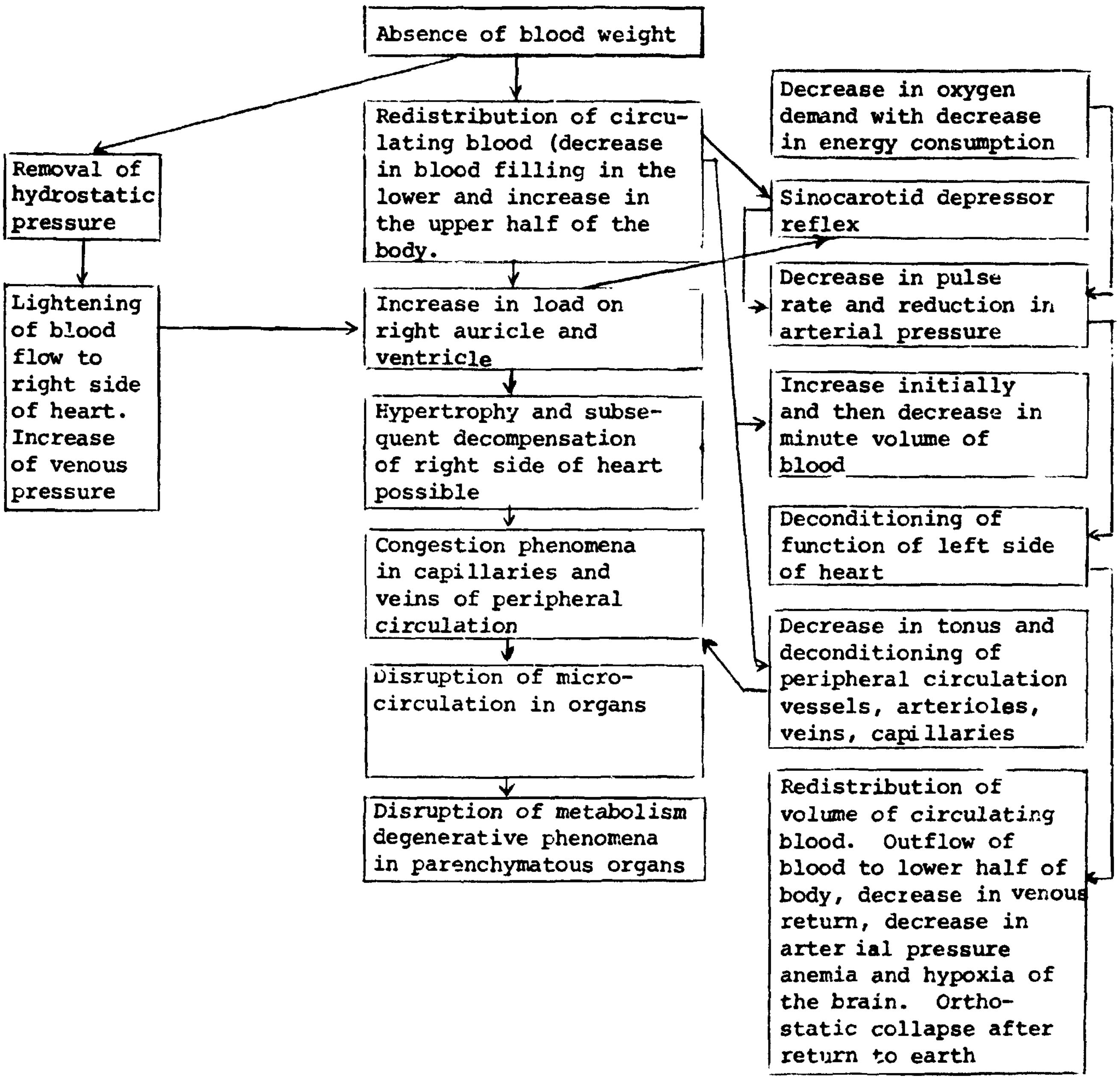


Diagram 4: Proposed scheme of pathogenesis of disturbances of the cardiovascular system in weightlessness and following weightlessness

All these conjectural disturbances apparently can develop, if the process of deconditioning of the cardiovascular system in weightlessness progresses, and does not remain at some new, even changed, but stable level, and if no protective and prophylactic measures are taken. In any case, this danger must be thought of, so that it is not permitted and that it can be learned how to prevent it ahead of time or combat it.

In discussion of the pathogenesis of disturbances of the cardiovascular system in general form, we still have not been concerned with one important link in the chain of changes observed. By redistribution of the blood and increase in the amount of it in the upper section of the body, especially in the intrathoracic section, the volume of blood in the blood circulation organs located inside the thoracic cage increases significantly. To a certain extent, this situation is analagous to the state, in which an increase in mass of circulating blood in the body takes place and, of course, it is assumed that the mechanisms providing for decrease in mass of blood, in order to return it to the normal homeostatic standard, must be switched on, to maintain the normal volume of circulating blood.

In a series of detailed studies, conducted by Gauer and Henry (1956, 1963, 1968, 1970), it was clearly demonstrated that an increase in intrathoracic blood volume switches on reflex mechanisms, in particular, it stimulates the baroreceptors of the heart and leads to an increase in diuresis, i.e., elimination of fluid from the body. In this way, a close connection is formed between the pathogenetic links of the cardiovascular system and the link regulating water-salt metabolism.

Mechanism of Change in Water-Salt Metabolism in Prolonged Weightlessness

As has already been noted, in weightlessness, astronauts usually experience an immediate increase in blood filling of the vessels of the face and head. There is some basis for thinking that, in these cases, blood filling of the uppper sections and of the large /255 vessels of the heart increases, approximately the same as occurs in changing the body position from the vertical to the horizontal or to head-down position. In such cases, the venous return of blood to the heart increases and, as we have already said, an increase takes place in the minute volume of blood. Increased blood filling of the vessels of the upper half of the body and of the intrathoracic vessels leads to some dilation of the vessels and tissues. In turn, all this increases stimulation of the vascular receptors and volume receptors of the entire upper half of the body. However, it is just local accumulation of blood in large sections of the intro-thoracic blood circulation system, which is particularly important. This causes dilation of the auricle and stimulates the so-called Nonidez-Paintal receptors in them (Gauer, 1972), as well as the network of nerve fibers without myelin membranes, located in other sections of the heart, which have been found in recent years, by more delicate anatomical and physiological methods of investigation (Johnston, 1968; Öberg, White, 1970; Malliani, et al., 1971). The receptor impulses are transmitted from here, through the vagus, to the central nervous system. An increase in diuresis sets in after this. Tests have shown that the pathway is precisely this, since diuresis clearly was decreased by resection of the vagus nerve (Gauer, Henry, 1956; Gauer, Eckert, et al., 1967).

All this chain of afferent effects, coming in from the stretched receptor zones of the heart and, in all likelihood, from other, still insufficiently precisely established volume receptors, is called the Henry-Gauer reflex. In keen-witted tests of human respiration under a low negative pressure and, consequently, with increased intrathoracic blood filling, these authors showed that a marked increase in diuresis sets in. These investigators obtained similar data, when the subjects were submerged in an immersion liquid and redistribution of the blood from the surface sections of the body to the inner ones took place, as a result of the hydrostatic pressure of the liquid on the body surface. Diuresis also increased here (Gauer, Henry, 1963, 1970; Gauer, 1968, 171).

The chain of processes developing in weightlessness can be represented in the following manner. Redistribution of the blood leads to an increase in blood filling of the intrathoracic vessels, heart and the entire upper half of the body. This produces a flow of pulses to the central nervous system. The incoming information causes suppression of the antidiuretic hormone center. Less antidiuretic hormone begins to enter the blood from the hypophysis; the latter increases diuresis, leads to discharge of water and of sodium with it; definite dehydration of the body takes place. Together with dehydration, some decrease in weight occurs. As is well known, a loss of weight is noted in nearly all astronauts after a flight, quickly proceeding on earth.

Still another circumstance must be noted. Since, under normal conditions on earth, the arterial pressure in the lower part of the body, in the vertical position, is increased, because of the hydrostatic pressure, the fluid part of the blood escapes from the circulatory system at the arterial ends of the capillaries. This occurs, because the arterial pressure exceeds the oncotic and osmotic pressure retaining the blood fluid. The picture is different in the venous section of the capillaries. The oncotic and osmotic pressure begin to exceed the reduced blood pressuresin the venous section of the capillaries and the fluid part of the blood escaping from the capillaries is again sucked into the blood circulation. This phenomenon has long been known in physiology by the name of /256 the Starling effect. Under weightless conditions, the added hydrostatic pressure is absent, and leaking of the liquid part of the blood at the arterial end of the capillary will not take place to the same extent as on earth. As a consequence of this, some hydremia of the blood and, besides, an increase in mass of circulating blood may set in, in the initial period of weightlessness. Of course, compensatory mechanisms, directed toward maintenance of an adequate blood volume, corresponding to the new capacity of the circulatory system, also is switched on here. In turn, this increases the fluid eliminated from the body but, since the increased blood filling of the large thoracic vessels and heart in weightlessness continues, this can lead, not only to compensation of the plasma volume, but to an excess elimination of the fluid part of the blood and to thickening of it. The latter actually was found in both Soviet astronauts, in the Soyuz 3 - Soyuz 5 flights (Ye. I. Vorob'ev, Yu. G. Nefedov, et al., 1969; see Chapter 3 of this book), and in American astronauts, after the Gemini 5 and Gemini 7 flights (Berry, 1969), and it was particularly distinctly established in dogs, after the 22-day flight of Kosmos 110 (V. N. Pravetskiy, et al., 1966).

The hematocrit of the American astronaut W. Schirra increased from 44 to 47% after 9 hours of weightlessness and that of G. Cooper, from 43 to 49%, after 34 hours of weightlessness. They had a weight loss of 2-3.4 kg. On the average, the American astronauts lost 3-8% of their weight during flights (White, et al., 1971). Thus, as a result of the apparent compensatory decrease in circulating blood mass, a significant loss of body fluid takes place. Actually, a 398-910 ml decrease in blood volume was found in the American astronauts flying in Gemini 4, Gemini 5 and Gemini 7 (Berry, Catterson, 1967). Consequently, a vicious circle can arise in the disruption mechanisms caused by weightlessness. Disturbances of redistribution of the blood lead to a reflex increase in dehydration of the body and, in turn, this decreases the amount of circulating blood and aggravates the disruption of the hemodynamics still more. With elimination of considerable amounts of fluid and the disruption of the electrolyte balance connected with it, definite changes in the acid-alkali equilibrium of the blood can set in. The latter was found in dogs, after the 22-day space flight in Kosmos 110 (I. N. Kotov, 1969).

Subsequently, a decrease in aldosterone production evidently can be included in the chain of disruptions generated. In immersion tests on dogs, partially simulating weightlessness, it was clearly demonstrated that a sharp decrease in excretion of aldosterone with the urine takes place in a period of 6 hours: up to one-sixth of its control value (Epstein, Saruta, 1971). A similar reduction in angiotensin II level was found in these same studies. Other authors also indicate a reduction in aldosterone discharge during immersion (Behn, Gauer, Kirsch, Eckert, 1969, and others). A decrease in renin content in the blood takes place at the same time as that of aldosterone and angiotensin II. Consequently, there is a basis for thinking that marked changes in status of hormones controlling water-salt metabolism regulation in the body arise in weightlessness. In the opinion of Gauer (1972), with increase in intrathoracic volume of blood in weightlessness and in an immersion medium, the following chain of unidirectional changes may develop: sympathetic nervous tonus decreases and the content of noradrenalin in the blood decreases; the latter inevitably shows up as a reduction in tonus of /257 the vessels, and this can remove the tonus of the precapillaries and, by increasing the blood flow in the capillaries, increase filtration of the liquid part of the blood (i.e., as though to compensate for the increase in the Starling effect) and, ultimately, it leads to a decrease in plasma volume. As a result of the decrease in plasma volume, the orthostatic tolerance of the body decreases, because the mass of circulating blood decreases. In other words, a vicious circle, joining the cardiovascular system function, again arises. A prolonged decrease in circulating blood mass also can cause deconditioning of the entire cardiovascular system to loads imposed on it upon return to earth.

It must be noted that, since the secretion of renin-angiotensin II and aldosterone, as well as of the antidiuretic hormone, decreases in weightlessness and, consequently, diuresis increases, the discharge of not only water, but of sodium, potassium and calcium, increases. Dehydration begins to develop, but, with dehydration, regulation of the blood volume cannot be accomplished, because of the irre- /258 versible discharge of fluid through the kidneys. In this case, movement of the plasma begins into the interstitial space, and a change in intracellular fluid content cannot be excluded in this case. We recall that there is a quite strict homeostatic ratio of water and solid substance in the body. Water constitutes 61% of the body weight, 36% of it is in the intracellular fluid, 20% in the interstitial and 5% in the plasma. This strict ratio can be disrupted in weightlessness, but to what extent, we still do not know precisely. It can be considered to be established at present that a reduction in body weight and a definite decrease in plasma volume takes place. Definite tissue dehydration also is possible.

Together with data on the water dynamics in the body, the data of Berry (1971) on decrease in total amount of potassium in the body after the space flight of Gemini 7, Apollo 13, Apollo 14 and Apollo 15, deserves particular attention. The exceedingly important role in the body (among a number of other electrolytes) of just the normal potassium content must be remembered. It has a significant effect on a number of systems and functions in the body. The hypothesis of change in potassium content in the body in weightlessness has /259 been confirmed by a detailed study of the amount of labeled ^{40}K in the Apollo 13 and Apollo 14 crew members. Gamma-spectrometry of the entire body demonstrated a significant reduction in the total potassium content of the American astronauts from the preflight data. A decrease in total potassium content in the body was observed in the Apollo 15 crew members, in a postflight evaluation, using labeled ^{42}K. As a rule, a reduction in excretion of potassium, sodium and chlorides is noted after all flights, which indicates a tendency of the body to retain fluids and electrolytes in the body, to compensate for the decrease in volume of them occurring during a flight. Similar phenomena of sodium and chlorine retention in the blood and, as a consequence of this, an increase in osmotic concentration of electrolytes has been found in the Soviet astronauts making the flights in Soyuz 3, Soyuz 4 and Soyuz 5 (Ye. I. Vorob'ev, Yu. G. Nefedov, et al., 1969; see also section 3 of Chapter 3).

Were these phenomena caused by an increase in diuresis and elimination of electrolytes only by the state of weightlessness and redistribution of blood in the body, or could they be the result of still other elements of the effect of weightlessness? Specially conducted sets of experiments simulating weightlessness (long, up to 130 days, hypokinesia in rats) clearly demonstrated that diuresis increases significantly in hypokinesia and the elimination of sodium, potassium, chlorine, and, especially, calcium from the body increases (Ye. A. Kovalenko, V. L. Popkov, et al., 1970). Consequently, the phenomena of dehydration of the body and elimination of electrolytes have a great simularity, both under weightless conditions and in simulation of it, even on animals. Apparently, still another unexplained internal mechanism of these changes is concealed here, which ultimately is due, not only to the Henry-Gauer reflex, but to the presence of hypokinesia itself, since redistribution of the blood will not take place in animals, primarily situated horizontally.

As is evident, the entire chain of disruption of the water-salt metabolism depends on the initial reflex effects on the cardiovascular system and on a number of other factors. In the final analysis, disruptions of the water-salt metabolism, in turn, affects the function of the cardiovascular system, reducing the adaptational and functional potentials of the body. The latter is demonstrated well, after the body again enters terrestrial gravitation. After this, as we saw earlier, the functional capabilities of the body decrease sharply.

Thus, weightlessness can have a very significant effect on the water-salt metabolism in the body (Diagram 5).

Effect of Weightlessness on Muscular System

The effect of weightlessness on the muscle system can show up in several areas. First, the tension function of the muscles, ensuring a specific body position in space and counteracting the force of terrestrial gravity, decreases in weightlessness (Fig. 68). Second, there always is a muscle force component, directed to overcoming the force of terrestrial gravitation in almost all body movements on earth; this component will be absent in weightlessness and, consequently, the total demand on muscle functions decreases. Third, under weightless conditions, a change in afferentation from /260 the muscles takes place. In turn, all this leads to a general reduction in tonus of the body musculature, ensuring both maintenance

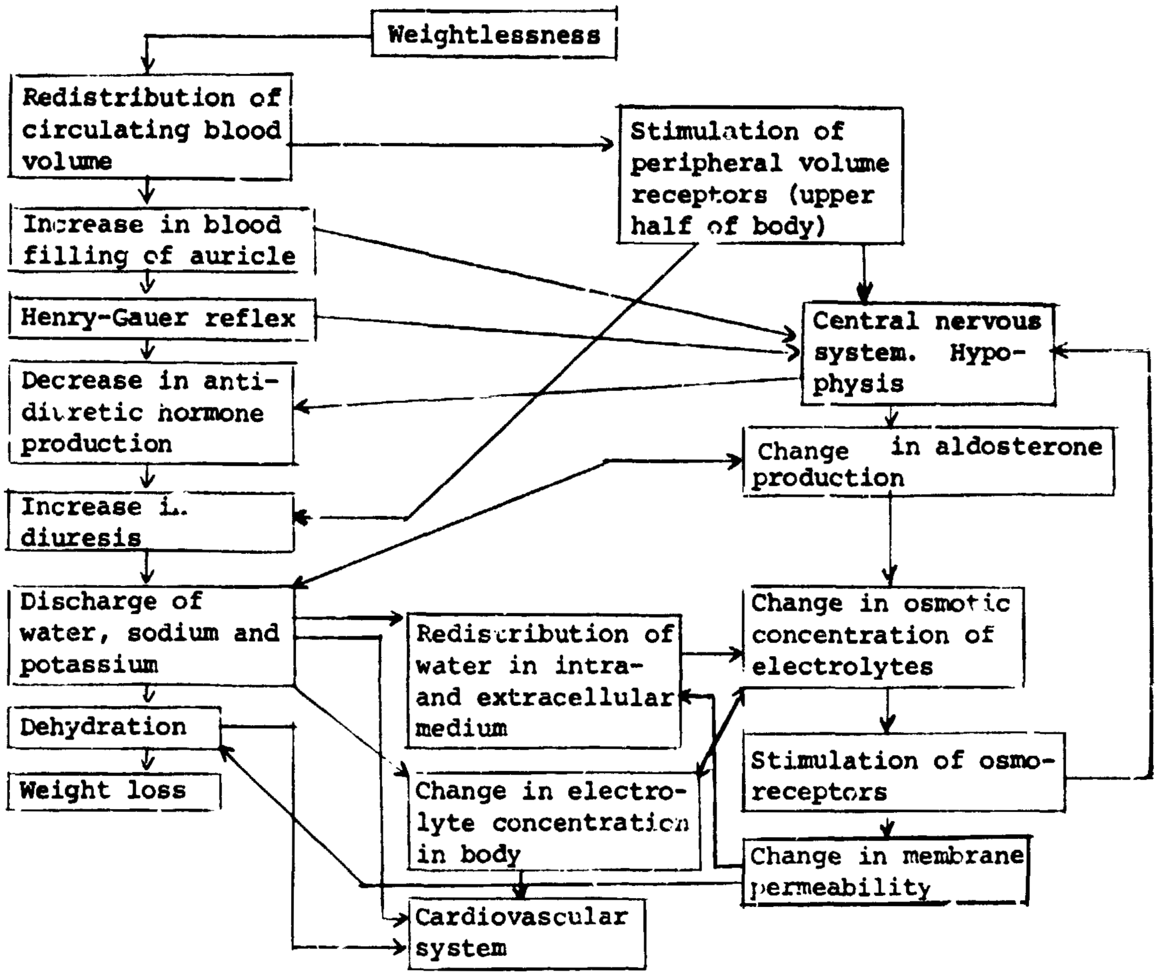


Diagram 5: Proposed scheme of pathogenesis of disruption of water-salt metabolism in weightlessness

of the vertical posture and the entire extent of motor activity. As Ye. Yuganov, I. I. Kas'yan and B. F. Asyamolov demonstrated in 1963 (see Chapter 4 of this book), the voltage of the oscillations decreases sharply in weightlessness and even a picture of "bioelectric silence" of the antigravitation musculature is observed. Moreover, the decrease in muscle activity may be intensified by the limited space in the spacecraft cabin. As a result, a definite degree of supplementary hypokinesia may also set in. Consequently, the amount of muscle contraction and of muscle effort itself, and the tonic tension of the muscles may decrease sharply in weightlessness.

It is well known that the act of movement is composed of a number of well-coordinated elements. Under weightless conditions, as experience demonstrates, a disruption of movement coordination may occur. Despite the fact that the astronauts have a full capability

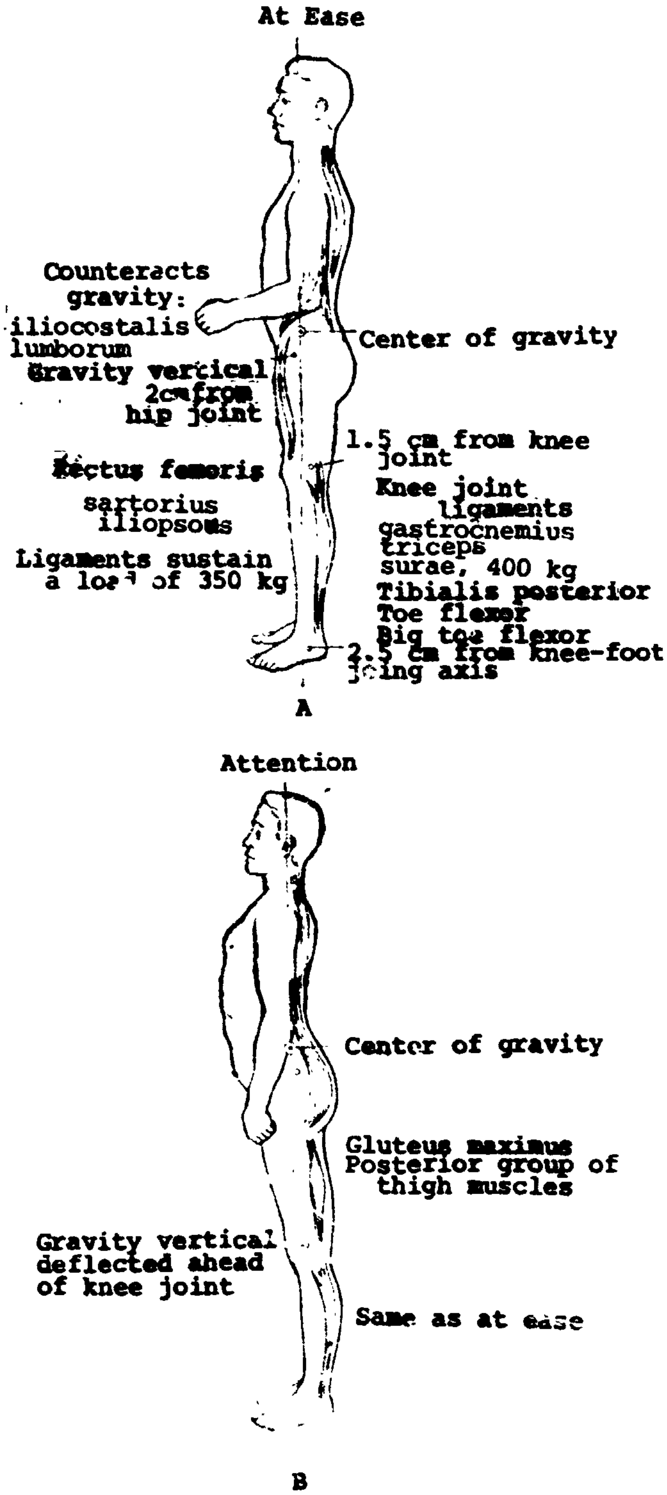


Fig. 68. Increase in functions of a number of muscle groups in vertical body position on earth, in "at ease" and "attention" postures; displacement of center of gravity vertical of body in these postures, with respect to support plane of feet

of executing movements and of retaining the ability to estimate the position of their bodies or separate parts of them in space, definite disruptions are found. Thus, at the start of the flight, G. T. Beregovoy noted some increase in the intervals between the intention to accomplish an action and the act of movement itself. A. G. Nikolayev and V. I. Sevast'yanov, in executing movements in weightlessness at the start of the flight, experienced difficulty in estimating the muscle force necessary to execute the corresponding movement; therefore, movements turned out to be disproportionate, but the astronauts acquired the necessary precision of movement by the 3rd or 4th day of the flight (Ye. I. Vorob'ev, Yu. G. Nefedov, et al., 1969; G. I. Vorb'ev, A. D. Yegorov, et al., 1970; see Chapter 4 of this book). In other words, in actual space flights, specific motor discoordination of varying natures can arise. In special studies of voluntary movements during parabolic aircraft flights (Ye. M. Yuganov, 1968), significant errors were found in determination of the accuracy of muscle force of 10 to 14 men, during the period of brief weightlessness. It is still not known precisely how all the biomechanics of movement change in a prolonged stay in a spacecraft and in unsupported space, when inertial mass remains, but the body and surrounding objects have no weight. Execution of even a simple, precisely controlled movement in weightlessness, according to the data of Ye. M. Yuganov (1968), required a long time (0.32-1.32 sec) for 12 of 20 subjects.

In an analysis of human motion, two components are usually distinguished: the muscle effort itself, which is a response to the action of mechanical forces, primarily the force of gravity, and the direct locomotor act. Both components change in weightlessness. On earth, a man applies a force in all movements, which is adequate to the force of gravity. In weightlessness, this stereotype can become the source of errors. An increase in time of execution of motor tasks, an increase in number of errors in movement, definite difficulties in executing them, especially in the first period of weightlessness, have been noted by many investigators and the astronauts themselves, as a rule. Moreover, an increase in errors in work is observed (O. G. Gazenko, A. A. Gyurdzhian, 1967; A. V. Korobkov, T. I. Goryunova, 1971; see Chapter 6 of this book). Much data indicate the correctness of the disruption mechanisms mentioned.

As the experience of longer flights demonstrates, man gradually becomes accustomed to matching the necessary muscle forces to the new relationships of reduced gravity (Ye. M. Yuganov, P. K. Isakov, et al., 1962; Yu. A. Gagarin, 1969). During the flight of Soyuz 9, A. G. Nikolayev and V. I. Sevast'yanov learned again to move around the spacecraft cabin, after a 3- 4-day stay in weightlessness. By pushing away with the legs, they could easily control the body position and move in the required direction, practically without controlling their actions. Television observations also confirm that no serious disorders were noted in the motor sphere or in disruption of movement coordination. Motor acts were not limited in extent or rate, i.e., definite adaptation set in (Ye. I. Vorob'ev, A. D. Yegorov, L. I. Kakurin, Yu. G. Nefedov, 1970). However, it must be considered that there also is fine coordination in movements, dependent on precise information from the tactile, visual, vestibular and motor analyzers. The systematic interaction between these analyzers, as well as the constant feedback of the proprioceptive information in movements in weightlessness can, nevertheless, be disrupted. During free movement in weightlessness, the absence of the accustomed tactile sensations and the change in proprioceptive signals coming from the skeletal muscular or motor-support apparatus, and the presence of inertial moments in abrupt movements lead to discoordination of movement, especially during the first periods of weightlessness. Sweeping motions, disruption of precise reproduction of given muscle forces and disruption of movement coordination are observed. The establishment of new coordination relationships, active correction of efforts during purposeful activity and the necessity for maintaining the required body position with respect to the surrounding objects and instruments, can cause a feeling of fatigue, which actually was observed in, say, A. G. Nikolayev and V. I. Sevast'yanov, after 10-12 days of flight. The disruption of the functional system of the analyzers during movement can lead, not only to disruption of performance ability, but to development of the so-called space form of motionsickness, right up to nausea, with corresponding symptoms in the cardiovascular system. /261

It is understandable that, under these conditions, not only can a sharp disturbance of the muscular apparatus function set in, but a significant reduction in the performance level (N. S. Molchanov, et al., 1970; Berry, 1971, and others). According to the data of Berry, the performance capacity of 48 astronauts decreased to 73% of the initial value after a flight, on the average. Under weightless conditions, as in simulation of it by prolonged hypokinesia, not only can movement coordination be disrupted, but more profound changes in the very structure and function of muscle tissue. We have made an attempt to indicate some links in pathogenesis of disruption of the muscle system (Diagram 6). It is important to emphasize only selected, most important events in this process.

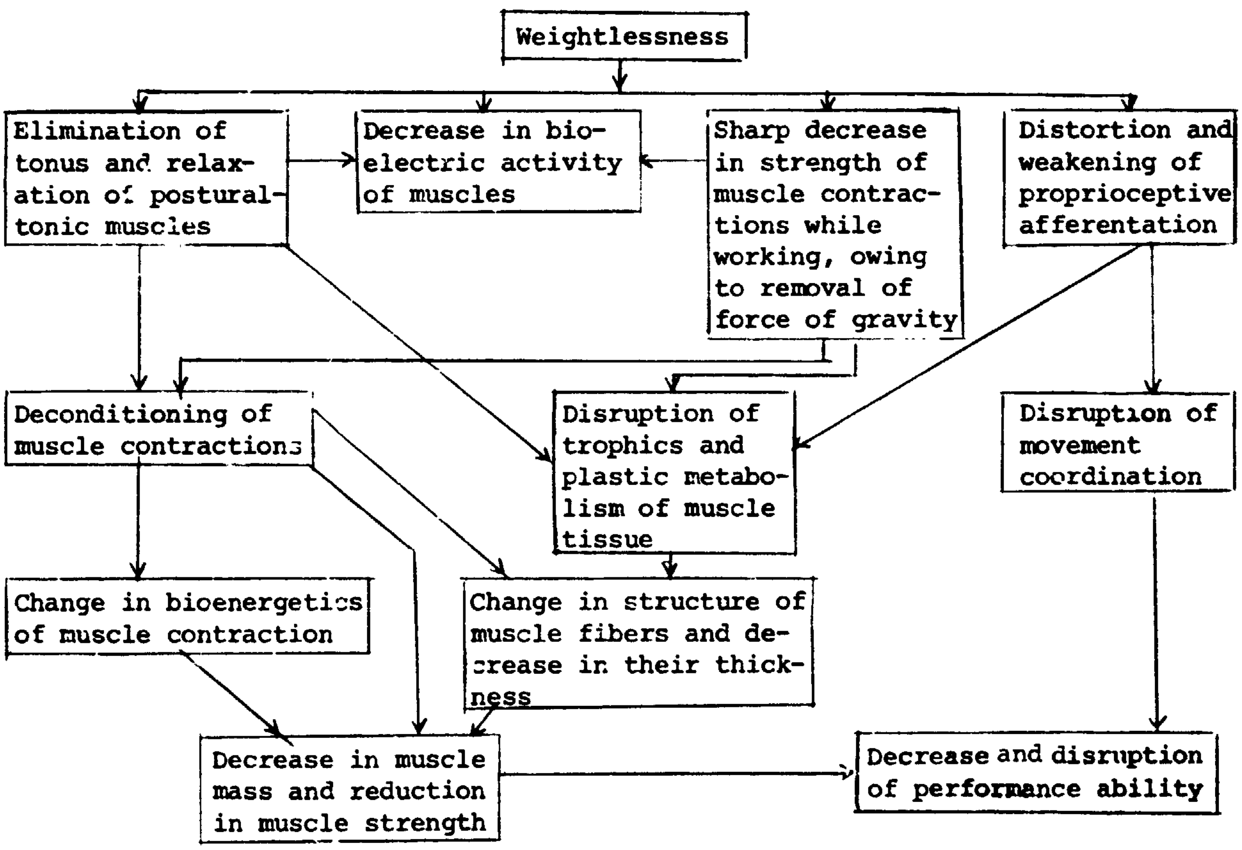


Diagram 6: Proposed scheme of pathogenesis of disruption of function of muscle system and coordination of movement in weightlessness

In prolonged hypokinesia, considerable muscle atrophy can develop. Deitrick and colleagues (1948) noted an increase in elimination of nitrogen with the urine and muscle atrophy of the hands and legs of 2-12%, in subjects in a bed rest test. In hypokinesia, as in weightlessness, the transverse dimension of the heart can decrease (I. G. Krasnykh, 1969). In simulation of weightlessness by a long (100-130 days) stay in hypokinesia, in the tests of Ye. A. Kovalenko and colleagues (1970, 1971) on rats, a pronounced /262 decrease in both heart mass and in the entire muscle mass of the body was clearly demonstrated, with a sharp reduction in capability of performing dynamic and static work. In a test carried out by Lynch and Jensen and colleagues (1967), on 44 subjects, it was determined that, in a 28-day hypodynamia, in addition to a decrease in the muscles, a loss of nitrogen, phosphorus and a number of electrolytes (sodium, chlorides, calcium, etc.) takes place. In all these cases, definite atrophy of the muscle apparatus sets in, the so-called disuse atrophy. With sharp restriction of muscle activity for a period of even 2-6 weeks, part of the muscle tissue is lost. A sharp restriction on muscle activity (hypokinesia), in itself, causes an extensive complex of polymorphic disorders, leading to a sharp reduction in resistance of the body to a number of unfavorable factors.

A combination of partial hypokinesia, because of the decrease in movement in the comparatively limited space of the spacecraft cabin, and the effect of weightlessness itself can be noted in weightlessness. A definite muscle atrophy (especially in the lower limbs) after a stay in weightlessness is expressed by a reduction in circumference and volume of the thighs and calves, as well as in a clearly recorded reduction in weight of almost all astronauts. In particular, Berry (1971, 1972) presents data on the weight reduction of a Mercury, Gemini and Apollo crew members. It varied from 1.3 to 4.7 kg, on the average. This weight reduction takes place, not only because of dehydration of the body, passing quickly after the flight, but, in all likelihood, because of the decrease in muscle mass, which, as is clear from measurements of the circumference and volume of the limbs, decreases (see Chapter 7 of this book).

It must be noted that elimination of not only nitrogen, but of such an important element as potassium, in which the muscle cells and, especially, the heart are rich, can take place in muscle atrophy. With the catabolic processes predominant in the body, potassium leaves the muscle cells and enters the interstitial space and further, it can be intensely eliminated with the urine. In this case, the plasticity of the muscle function can also be disrupted, as a consequence of reduction in stimuli, causing intensive anabolism. A special study of this problem, in a complex experiment on a large number of animals (rats), under conditions simulating weightlessness by 100- 130-day hypokinesia (which is about one-sixth of the lifetime of a rat), demonstrated a sharp disruption of many aspects of plastic and energy metabolism and an overall one-third reduction in weight of the animals, compared with the controls (Ye. A. Kovalenko, V. L. Popkov, et al., 1970a, 1971a); an increase in elimination of nitrogen, sodium, potassium and chlorides with the urine was noted, in this case.

In this respect, we must dwell briefly on the important general biological phenomenon of change in the processes of structural exchange in the body, since this phenomenon, as is evident, can occur in weightlessness or in simulation of it under ground conditions by prolonged hypokinesia. As is well known, destruction of biological structures continually occurs in many living organisms, and constant renewal of them proceeds, by means of synthesis of molecules, organelles, cells and tissues. This phenomenon, one of the most basic processes of all living systems, is as though in a continual dynamic equilibrium. The more intensive the functioning of a given organ or part of it, the more intensive the renewal and new construction of the structure. With increase in physiological function of the cells, activation of the genetic apparatus of the cells /263
increases and, in these cases, a function can, as it were, "demand" the proper plasticity for itself (F. Z. Meyerson, 1967). With the decrease in functional loads in weightlessness, in particular, the load on the functioning of the muscle system, regulation of the structural exchange and plasticity of the function can lead to atrophic changes in the skeletal muscles, as well as in the heart. Usually, normal functioning of a muscle fiber is determined by the ATP, the energy reserve of the current moment, existing in the muscle, and the bulk of the muscle mass, which can provide the muscle function through finished myofibril proteins present, is, as it were, a plastic reserve of a given performance level. A stimulus for building a new structure is an increase in rate of functioning of a given structure, a greater expenditure of energy and a greater breakdown of proteins in the muscle cells while working.

An increase or decrease in rate of functioning of a structure stimulates or suppresses the genetic apparatus of the cells and, in accordance with modern concepts of molecular biology, regulation of the function of the DNA-RNA-protein synthetic apparatus takes place (Jacob, Monod, 1962). When the load of the muscles is decreased, their function, energy consumption and the stimulation of the genetic apparatus (translation, transcription and replication) connected with them decrease. All this leads to a decrease in construction of protein molecules in the muscles. A significant decrease in incorporation of labeled amino acids in muscle tissue has been demonstrated in prolonged hypokinesia of animals (I. V. Fedorov et al., 1968). In our studies with prolonged hypokinesia, simulating weightlessness on animals, it has been determined that, together with the general significant decrease in weight of the rats, a primary decrease in just the muscle tissue takes place (Ye. A. Kovalenko, V. L. Popkov, et al., 1970). A reduction in synthesis of mitochondria is possible.

Still another circumstance is important. In the classical works of V. A. Engelhardt and M. N. Lyubimova (1939), it was demonstrated that the contractile substrate of the muscle, myosin, /264
acts as an enzyme. It splits off a phosphate group from adenosinetriphosphate (ATP) as a result of which, the energy necessary

for contraction is liberated. The absence of constant exercising of this biochemical process or a definite insufficiency of it, in prolonged weightlessness or prolonged hypodynamia, can lead to serious disruptions of one of the central energy channels for obtaining energy in the body. In these cases, adenosinediphosphate (ADP), which increases respiration of the mitochondria and accelerates the new ATP synthesis process, will not form again continually, to a sufficient extent and as efficiently. The presence of unused ATP and the absence of a constant and sufficient amount of its decay product, ADP, even if partially and for a long time, inhibits passage of electrons along the chain of respiratory carriers, and, consequently, inhibits the rate of consumption of oxygen in the mitochondria. Moreover, here, as in hypokinesia, a definite interruption of the respiratory chain and the chain of synthesis of energy in the form of ATP cannot be excluded, which has been demonstrated in hypokinesia (Ye. A. Kovalenko, et al., 1970, 1971). The number of mitochondria may decrease here.

These may be some deep-seated mechanisms of disturbances of the basic types of biological oxidation in the muscle system which are possible in weightlessness. It must also be considered that the contractile and ATP-ase activity of the myofibrils is regulated by the free Ca^{2+} concentration in the sarcoplasma. Each myofibril fiber is coated with an electrically polarized membrane. Contraction is induced by a pulse, moving along the nerve to the end plate, which is in contact with the fibers. During passage of the impulse, depolarization of the membrane occurs, and an activating substance, calcium ions, is released over the entire fiber. After disappearance of the pulse or fatigue of the muscle, the activating substance, in the form of a calcium salt, is bound to the sarcoplasmic reticulum i.e., by interweaving of fine tubules inside the muscle fiber (A. V. Hill, 1972; W. Hasselbac, H. Weber, 1964). Thus, muscular contractions have a direct and extremely close connection with normal calcium metabolism, which, as is well known and as will be demonstrated subsequently, can be disrupted significantly in hypodynamia (A. A. Prokhonchukov, Ye. A. Kovalenko, et al., 1970; A. A. Prokhonchukov, et al., 1970) and in weightlessness (Ye. N. Biryukov, et al., 1970). All these facts show how closely individual links in pathogenesis of the development of disruptions caused by weightlessness or by simulation of it can be connected. Despite the considerations expressed here, it must be kept in mind that, in weightlessness itself, after even partial adaptation to it sets in, it becomes possible to accomplish nearly all operations. More than that, the astronauts note even a certain ease and capability of freely accomplishing various movements, right up to acrobatics. As experience demonstrates, with a sufficiently good selection of candidates for astronaut and, chiefly, with comprehensive training under weightless conditions, a man can quite successfully overcome specific obstacles in weightlessness and perform purposeful movements and work. Thus, A. A. Leonov did not experience disruptions in spatial orientation in weightlessness, even in unsupported space, and his movements were adequately coordinated. During a still longer stay in space (for a period of 18 days), this was observed with A. G. Nikolayev and V. I. Sevast'yanov (Ye. I. Vorob'ev, et al., 1971; see Chapter 4 of this book). The same thing was noted with American astronaut E. White. He actively moved in open space and did not detect appreciable disruptions in orientation and coordination of movement. True, in these cases, control remained, by means of vision and orientation relative to the hull of the craft. Leaning against the hull and also using the tether, the astronauts could coordinate their movements. /265

As is clear from everything stated, muscular disturbances and discoordination of movement in weightlessness can be overcome, to a definite extent, with appropriate training. However, what changes will take place in the muscle system during a longer stay in weightlessness and, mainly, how this will show up in the condition of a man after descent to earth, still is obscure.

In tests on dogs after the flight of Kosmos 110, i.e., with an adequate duration (22 days) of stay of the animals in weightlessness, a significant loss (up to 30%) of muscle mass was established (V. N. Pravetskiy, N. N. Gurovskiy, et al., 1966; N. N. Gurovskiy, et al., 1968). A considerable reduction in performance ability was noted in the crew members of Soyuz 9, after the 18-day flight, as well as after the 14-day flight of the American astronauts in Gemini 7 (Berry, 1966, 1967) and after the Apollo flights (Berry, 1969, 1970, 1971).

After the flights of the Soyuz series spacecraft, a distinct deterioration in regulation of the vertical posture, a reduction in tonus and strength of the antigravity muscles, progressing with increase in flight duration (see Chapter 3 of this book), was observed in the astronauts. Upon leaving the spacecraft cabin, five astronauts of the ten crew members of Soyuz 6, Soyuz 7 and Soyuz 8, after a 5-day stay in weightlessness, felt "oscillation of the earth beneath the feet"; unsteadiness and uncertainty in walking was noted in them. On the day after the 5-day flight, a significant increase in amplitude of oscillation of the common center of gravity of the body could be clearly recorded on the stability platform. Disruption of coordination of fine movements remained in the first 3-4 days after the flight, in performing accustomed movements, as well as during tennis and billiard games (Yu. N. Purakhin, V. S. Georgiyevskiy, V. M. Mikhaylov, 1972).

A prolonged decrease in muscle function of the body in weightlessness leads to still another disruption. With a sharp reduction in muscle contractions, a sharp decrease in adrenalin, especially noradrenalin production is possible.

It is known that the pressor activity of catecholamines suffers in an unbalanced electrolyte ratio. The latter, as we saw above, can occur in disturbance of the electrolyte metabolism in weightlessness. Conditions are created, when, without any decrease in adrenalin or noradrenalin production, in a long, monotonous flight, a decrease in their production is aggravated by hypodynamia and weightlessness. All this will lead to a decrease in the pressor activity of the basic regulator of vascular tonus. As a result, a sharp reduction in muscle function can create still another vicious circle, causing a prolonged loss of vascular tonus and disturbance of the hemodynamics. Thus, there is another connection here with other links in pathogenesis.

Effect of Weightlessness on Bones and Calcium Metabolism

As has already been stated, one of the main pathogenetic links in the effect of weightlessness on the body is removal of the functional load on a number of systems and a decrease in macro- and microdeformations in different parts of the body. This apparently concerns, to the greatest extent, the system which fulfills the main support and maintenance function of the body, i.e., the entire skeleton and various structures connected with it, such as the cartilage and ligaments, skeletal elements of the organs, etc. /266

In 1638, Galileo first of all directed attention to the relation between the mass of the bones and soft tissues in the body and the effect of gravity on it. In 1892, Wolf demonstrated the dependence of bone structure, orientation of its structural elements and the masses of its component substances on the strength and direction of the mechanical load. It turned out that the deforming force causes a change in the bone structure, which is necessary to most adequately resist this force. A legitimate question arises: What can serve as a signal, causing one change or another in the bone? It is natural that the first signal, as in any other action in the body, may be impulses from the nerve endings located in the periosteum or in the region of the vessels, or in elements of the bone itself. These impulses, of course, include the appropriate trophic effects and the entire set of fine regulation of the bone structure, the protein and, especially, the calcium metabolism, in particular, through the hormone activity of the parathyroid gland (parathyroid hormone), as well as through the function of the thyroid gland itself, as a result of changes in production of thyrocalcitonin. This hormone is of particular importance in regulation of calcium metabolism. As a result, a change can set in, first and foremost, in the protein, phosphorus, magnesium and, then, the calcium metabolism. Particular attention should be given, in this chain of disruptions, to synthesis of such important amino acids as glycine and oxyproline, which actively participate in formation of the bone matrix, i.e., its protein base. Based on contempary conceptions of the function of the bone, some authors express the opinion that the cause of change in bone structure may consist, not only of nerve effects (they can be completely preserved, but bone metabolism is disrupted) and not even in changes in the vascular system (increase or lessening of the blood flow), but, apparently, mainly change in the mechanical stress and compression of the bones, which always occurs under gravitation (Abramson, Delagi, 1961; Forst, 1964).

In this area, the fundamental discoveries made by Yasuda (1953) and, then, Bassett (1965) deserve much attention. It was found that the bone acquires an electrical charge under a mechanical load or in bending and that the bone structure can act as a piezoelectric transformer of mechanical stress into electricity. The latter is well corroborated by the presence of two closely connected crystal systems in the bone -- crystals of hydroxyapatite and crystals of collagen constituting the basic substance of bone, its matrix. Since collagen crystals have more electrons than hydroxyapatite crystals, in loading and bending, the surfaces of these crystals form a specific potential difference, with the source of this electricity able to form immediately at the many contact points of the /267 tremendous number of hydroxyapatite and collagen crystals. The original research of Bassett demonstrated that the primary signal regulating bone structure is a mechanical deforming force. This signal generates a piezoelectric effect, i.e., an electrical potential is generated in the bone, the magnitude of which is proportional to the deformation force applied. In turn, this can be the origin of electrical reactions, generated on the bone surface and stimulating or suppressing the functions of the osteoclasts and osteoblasts. The sections of bone undergoing the greatest deformation acquire a strict polarity. It is interesting that bone growth is increased precisely where negative charges, leading to accumulation of osteoblasts predominate. On the other hand, osteoclasts leading to partial resorption of bone tissue, predominate where positive charges accumulate. If a compressing force acts, directed along the axis of the bone structure and causing a definite deformation, the change may consist only of an increase in density and thickness of the bone mass, but if the force acting on the bone is directed at an angle to the longitudinal axis by muscle forces or loads perpendicular to it, a shift in the bone and regrouping of the elementary particles of the bone structure are generated, i.e., approximately the phenomenon, which was also described by Wolf (1892).

The fact that movement of tissue fluids and the oxygen dissolved in them in bone tissue is very difficult is very important. The majority of osteocytes in bone are located quite far from the blood vessels. Narrow channels, along which the tissue fluid and blood can move in the bone, are not over 2.5-3% of the entire surface of the bone cross section. In other words, the entire system of supplying the bone cells with nutrient substances and oxygen has very limited capabilities, and the osteocytes in the bone are on a minimum supply schedule. The systematically changing direction of electrical impulses and polarity in the bone, arising under these conditions, is a unique "electrical pump," ensuring an inflow of charged molecules, mineral ions and chemical radicals. Such a supply mechanism can be provided by joints between the hydroxyapatite and collagen crystals, which possibly are multimillions of tiny potential generators in bones. Consequently, the supply of bone tissue and removal of metabolism products is improved.

In weightlessness, with a sharp decrease in the effect of deforming forces on the bone and the limited muscle activity in the comparatively limited space of the spacecraft cabin, as a result of considerable decrease in electrical activity of the bone tissues, death of part of the osteocytes can occur, as a consequence of inadequate provision. More than that, accumulation of osteoclasts, destroying the bone tissue at precisely those places, where a decrease or complete disappearance of electrical signals occurs, is possible. Bassett (1967) considers it to be almost completely proven that the electrical potential generated in the bone under mechanical loads regulatesthe change in orientation of bone elements and the mass of bone tissue. Removal of the deformation of the bone in weightlessness can apparently produce a sharp reduction in electrical potential in the bones, a reduction in nourishment and oxygenation of the bone, and predominance of the function of the osteoclasts over that of the osteoblasts. All this can cause a change in the bone structure and leaching out of the calcium /268
already in the bones.

The logic of our analysis shows that the subsequent pathogenetic links in the process must be an increase in calcium content of blood, a decrease in density of the bone tissue and an increase in elimination of calcium from the body, i.e., distinct signs of disruption of the calcium metabolism (Diagram 7). In fact, these phenomena are observed, to one degree or another, both after space flights and after partial simulation of them by prolonged bed rest, stays in immersion media or prolonged hypokinesia. Berry and colleagues (1967) note that the calcium and oxyprcline content of the blood of the astronauts increases noticeably after a 14-day flight. Oxyproline is irreplaceable for synthesis of collagen from amino acids; therefore, it is considered that an increase in elimination of it must be accompanied by increased demineralization and can lead to disruption of the bone structure. Similar data were observed in the dogs Veterok and Ugolek, after the 22-day flight in Kosmos 110. Their blood calcium content increased to 14.8-15.6 mg % (Ye. N. Biryukova, et al., 1967).

It has been demonstrated further by many investigators that the bone density decreases after space flights (by 10-20% from the initial value in individual bones) (Hattner, McMillan, 1968; Berry, 1970, 1971, and others).

Finally, and this was demonstrated especially convincingly in the interesting work of Brodzinski and colleagues (1971), in a study of the results of elimination of the Apollo 7 - Apollo 11 crews. It was found that the daily calcium loss of a man amounted to 635 mg on the average, potassium, 269 mg and iron, 6.4 mg. These investigators draw attention to the situation that calcium amounts

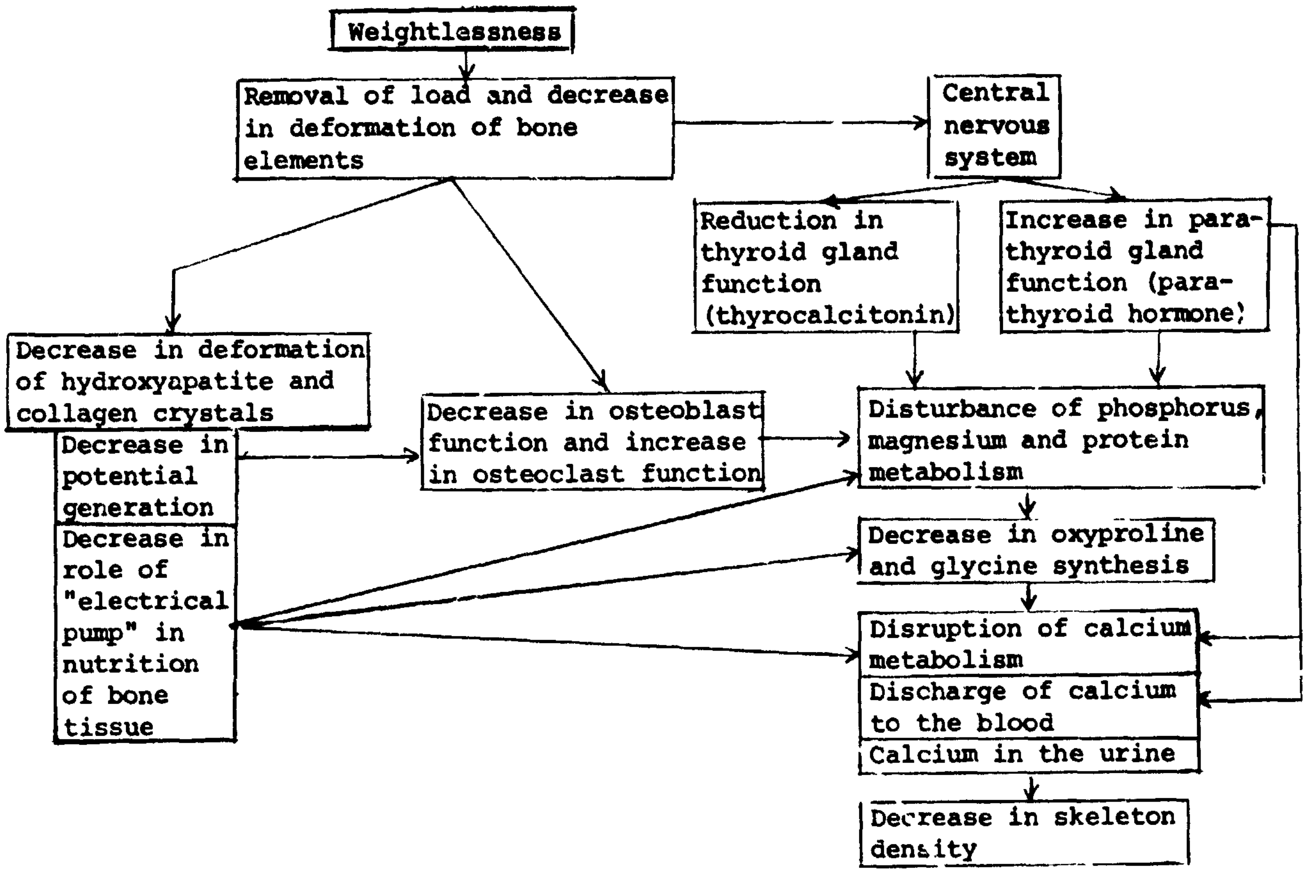


Diagram 7: Proposed scheme of pathogenesis of change in bone system.

to up to 20% of the weight of the skeleton and about 1.5% of the weight of the entire body. A loss of 635 mg per day of calcium by an astronaut weighing 70 kg means loss of 0.0605% of the entire calcium of the body, which amounts to about 1% in a 16-day flight. With a calcium loss rate of 220 mg per day, the total calcium loss by the body is 0.021% per day, i.e., 1% in a 48-day flight. Higher rates of elimination of calcium from the body were found by I. S. Balakhovskiy and colleagues (1969). According to their calculations, up to 10% of all the calcium in the bones can be washed out of the body in a 100-day flight. It is understandable that all this reasoning can be true, only in the event the rate of leaching out of the calcium is constant. However, no one has succeeded in proving up to the present time that the calcium leaching process depends on flight duration. True, in a number of cases, measures are taken to prevent calcium loss; therefore, the calcium output results may be somewhat hazy (Berry, 1971).

Thus, after a stay in weightlessness, three sequentially occurring phenomena can be observed: An increase in calcium content in the blood, a decrease in bone tissue density and an increased elimination of calcium from the body with the urine and excrement. To what consequences can these phenomena lead?

The blood calcium content is a very important indicator; blood coagulability can depend on it and, consequently, a predisposition to hemorrhage or, on the other hand, to thrombus formation. With a prolonged condition of increased calcium level in the blood, increased calcification of the vessels can be observed. The calcium ion dynamics can affect the nature of muscle fiber contraction.

To what can a decrease in density and, consequently, of strength of bone tissue lead, after a long stay in weightlessness? /269
During comparatively brief flights such calcium losses (not over 10% of the total content) can be tolerated, on condition that this loss is distributed uniformly over the entire skeleton. But the danger may be that, in some critical sections of the skeleton, the exchange takes place more intensively and the greatest mechanical load is created precisely here, and the mechanical load can increase sharply upon return from a space flight to earth. Among these sections are trabecular bone, with its extensive surface per unit weight, the long bones of the legs, especially the bodies of the vertebrae, as well as the calcaneus. Consequently, after prolonged weightlessness and entry into the descent g-forces, as well as during the subsequent stay on earth, the prerequisite may appear for bone fractures and trauma. This is an important situation, and, although there still are no clear data on this, the strength characteristic of bone should be investigated, in experiments on animals in simulated weightlessness.

An increase in calcium content in the urine also deserves /270
serious attention. It is known that, with an increased calcium content in the blood and tissues, as well as with disruption of the calcium metabolism, kidney-stone disease can arise (O. L. Tiktinskiy, 1972). This cannot be ignored in long space flights. Still another series of questions arises in a detailed study of this problem. Are the changes in calcium metabolism in weightlessness a regional process, involving only those parts of the skeleton in which the load is decreased in weightlessness, or is this a systemic process, concerning all or the majority of calcified tissues in the body? A partial answer to this question was obtained by simulation of weightlessness with hypokinesia, created in rats for a period of 100-130 days. A reduction in incorporation of labeled calcium (^{45}Ca) was established in the teeth of the animals (by 15.6%), the lower mandible (by 19.4%) and in the thigh bones (by 21%). (A. A. Prokhonchukov, Ye. A. Kovalenko, et al., 1970; Ye. A. Kovalenko, A. A. Prokhonchukov, et al., 1970). In addition, the presence of distinct and earlier changes in phosphorus and glycine metabolism were found in these tests: by the 100th day of hypokinesia, incorporation of ^{32}P in the teeth and thigh bones decreased by 13.8-33.5%, and, of [$2^{14}C$] glycine, by 5.9-35.5%. Thus, a systemic change in calcium metabolism and a disruption of the phosphorus and protein metabolism closely connected with it are observed in prolonged hypokinesia. Of course, study of the thyrocalcitonin

and parathyroid hormone in the blood, as the leading regulators of calcium metabolism, deserves special attention in all these studies. As we see, a close connection may exist between the change in calcium metabolism and other links in the pathogenesis of the effect of weightlessness on the body.

Effect of Weightlessness on Respiratory and Energy Metabolism

One of the main physical characteristics of life is the constant thermodynamic equilibrium with the surroundings. To maintain it, even in a state of complete rest, requires a continuous inflow of energy. In performing physical work, as is well known, the consumption of additional energy always is necessary. One of the central questions in the problem of the effect of weightlessness on the body arises in this connection: What is the fraction of the energy consumption of the body for constantly overcoming the force of gravitation of the earth? There still is no precise answer to this question. Moreover, it is evident that nearly all types of energy consumption of man at rest and during activity includes consumption of energy to overcome the gravitation of the earth. What takes place under weightlessness conditions, when this consumption and all systems, providing for its adequacy, i.e., mainly the cardiovascular and respiratory, as well as systems providing ATP synthesis, do not receive the appropriate and constant stimuli of activity requiring energy consumption and, consequently, the processes of the biological oxidation? This is one of the major questions of the entire problem. As an illustration, we attempt to make an approximate calculation of the simplest energy consumption for the most elementary type of muscle activity in weightlessness. Under earth conditions, energy consumption in performing work in raising some body, i.e., work directed toward overcoming the force of gravity and inertia, can be expressed by the following equations:

$$A_e = mgh + \frac{mv^2}{2} \cdot 2 = mgh + mv^2 \qquad (1)$$ /271

where A_e is the energy consumption on earth, m is the mass of a given body, h is the distance to which the body is raised above the earth, and v is the speed, at which this body is lifted.

Under weightless conditions, the energy consumption may be expressed by the equation:

$$A_w = \frac{mv^2}{2} \cdot 2 = mv^2 \qquad (2)$$

Multiplication by 2 is carried out, because a movement impulse must be given at the start of lifting, and it must be extinguished at the end.

The difference in energy consumption on earth and in weightlessness ($A_e - A_w$) will be mgh. We now establish the ratio of energy consumption in weightlessness and energy consumption on earth:

$$\frac{A_w}{A_e} = \frac{mv^2}{mgh + mv^2} = \frac{mv^2}{m(gh + v^2)} = \frac{v^2}{v^2\left(\frac{gh}{v^2}+1\right)} = \frac{1}{\frac{gh}{v^2}+1} \qquad (3)$$

On the basis of the the derivation of formula (3), we examine the following extreme cases:

1. In moving a body an infinitely long distance ($h = \infty$), the energy consumption ratio would become:

$$\frac{A_w}{A_e} = \frac{1}{\infty} = 0$$

2. In moving with an infinitely great velocity ($V \to \infty$)

$$\frac{A_w}{A_e} = 1,$$

i.e., the energy consumption ratio would be the same as on earth.

Based on this, we examine a specific problem: $h = 1$ m, $v = 1$ m/sec, $m = 1$ kg and, rounded off, we take g equal to 10. Then,

$$\frac{A_w}{A_e} = \frac{1}{10 \cdot \frac{1}{1} + 1} = \frac{1}{11} = 0{,}09$$

under weightless conditions, with a one-kilogram weight, and a rate of movement of 1 m/sec, the energy consumption in the task would be one-eleventh that on earth, or 9% of that on earth, but if we gave a speed 10 times greater,

$$\frac{A_w}{A_e} = \frac{1}{\frac{10 \cdot 1}{100} + 1} = \frac{1}{\frac{1}{10}+1} = \frac{10}{11} = 0{,}9,$$

i.e., the energy consumption would be 90% of that under ground conditions.

Consequently, under weightless conditions, slower and smoother movements while working produces a very large profit in energy consumption.

It is clear from this example that all types of energy consumption, directed toward overcoming weight, in the form of supporting the body, movements of the arms and legs, the work of the heart, movements of the thoracic cage and diaphragm and, especially, all types of muscular work of man, including the component overcoming terrestrial gravity, a completely different, significantly lower value is obtained in weightlessness. The production of energy in the body and systems providing for ATP synthesis is designed /272 for another, higher level. (Here, we do not examine the question of the additional energy consumption, necessary at first in working out the new coordination of movement.) The necessity arises from this of precisely defining the energy consumption in weightlessness and, obviously, in reviewing the many established classical calculations of energy losses of the body under normal ground conditions. The possibility is not excluded that, under these conditions, the need arises for reconsideration of the calorie value of the food ration. No wonder it is known that, of the 2500 kcal ration, the American astronauts ate only 1465-1649 kcal of food during the Apollo 9 flight (Berry, 1969). Perhaps other, not precisely known, heat losses take place from the body, under these conditions. Apparently, under weightless conditions, a new energetics must develop and, possibly, a different heat regulation of the body, adequate to the new living conditions.

Still another circumstance is important. At the beginning of a period of prolonged weightlessness, the general deconditioning and asthenization of a number of systems of the body can be well compensated by the significantly decreased energy demands of the body. As a result, complete well-being is noted and, after some adaptation, movement coordination will feel very easy, and the necessity for the stress function of the body in performing the same physical work as on earth, becomes superfluous, especially in performing slow and smooth movements. The absence of increased demands on all systems for oxygen supply, ATP synthesis and removal of the products of intensive metabolism while working, gradually leads to another level of functioning and deconditioning of the compensatory capabilities of the body. All this causes a further reduction in body function and further mutual asthenization of the functions themselves and their energy supplies. Besides, an unusual vicious circle can develop, if this process does not stop or if radical measures are not taken to break this circle, by various protective and prophylactic measures.

However, for the time being, these are theoretical considerations. There still are extremely few facts supporting them and, sometimes, these facts even contradict the theoretical premises.

As research has shown, during a stay under brief weightlessness, created in aircraft flights, some increase in pulmonary ventilation of the subject is observed, from 8.4 to 8.9 l/min. Simultaneously, there is an increase in oxygen consumption, from 320 to 533 ml/min, and an increase in discharge of CO_2 from 260 to 412 ml/min (P. K. Isakov, Ye. M. Yuganov, I. I. Kas'yan, 1964; see Chapter 3 of this book).

According to the data of I. I. Kas'yan, G. F. Makarov and B. V. Blinov (1967), in the initial period, the oxygen consumption of six men was 214-330 ml/min, and it was 306-549 ml/min in weightlessness, i.e., an increase in oxygen consumption occurs. In accordance with this, the energy consumption increases from 0.16 to 1.08 kcal per minute. These authors present similar results on increased respiratory metabolism in weightlessness. However, it must be considered that these data were obtained under conditions of very brief /273 weightlessness (in a period of 40-45 sec) and immediately after considerable g-forces, preceding weightlessness. It is hardly correct to consider that they were caused by weightlessness alone; they probably reflect the aftereffects of g-forces and the beginning of the period of entry into weightlessness, which is unusual for the body, especially considering that respiratory metabolism has some inertia. It apparently must also be considered that a specific period of stay in weightlessness, the unusual nature of the situation, the absence of movement coordination, the effect of inertial, initially very poorly regulated momentum in a complicated piece of work, all can initially lead to a considerable increase in respiratory metabolism and energy consumption.

It is interesting that, not only in brief weightlessness, but in longer simulation of it on the unsupported stand, while performing special work, there was a rise in respiratory metoblism, from 356 ±9.4 ml/min (1.75 ±0.04 kcal/min) to 462 ±11.4 ml/min (2.28 ±0.6 kcal/min), while working on the stand, compared with normal conditions of work without the stand. More than that, even during simulation of weightlessness by water immersion, similar changes took place (I. I. Kas'yan, G. F. Makarov, V. I. Sokolkov, 1971). The previously mentioned basic features of the effect of weightlessness, a reduction in the energy consumption demand of the body and, hence, significant change in respiratory metabolism can develop only in subsequent, longer stages of weightlessness.

As respiratory metabolism research shows (M. I. Mikhasev, V. I. Sokolkov, M. A. Tikhonov, 1969), the basal metabolism of 15 subjects in a 70-day bed rest decreased by 5-21% from the initial level. A similar pattern was established in the tests of V. S. Katkovskiy (1967), in a shorter hypokinesia (for a period of 20 days). Basal metabolism decreased by 7-22% (by 10% on the average). In specially conducted tests on dogs, during a long (60-day) hypokinesia, there was significant reduction (by 20-25%) also in respiratory metabolism in the state of rest (Ye. A. Kovalenko, V. L. Popkov, et al., 1971).

In all the tests with both people and animals, a drop in respiratory metabolism occurred mainly during the first month of hypokinesia, and some stabilization of it was then noted. However, it is completely evident that, in weightlessness, where the gravitational effects are removed, this effect can be more pronounced. Berry and colleagues (1967) present interesting data. It turned out that the calculated average energy consumption in discharge of carbon dioxide of the astronauts in the Gemini 4 flight was 2400 kcal, 2010 kcal in Gemini 5 and 2219 kcal per day, in Gemini 7. This energy consumption turned out to be greater than the calorie value of the food eaten; therefore, the spacecraft commander and 2nd pilot lost 2-3.8 kg in the first case, 3.4-3.8 in the second, and 2.7-4.5 kg in the third case. It still is not clear, whether or not these losses of weight are only due to dehydration.

Berry (1966, 1967, 1969) considers that a definite tendency is noted for reduction in energy consumption, in proportion to increase in flight lengths under weightless conditions. While the energy consumption reached about 500 BTU/hour (126 kcal) during the brief Mercury flights it amounted to about 300 BTU/hour (75.6 kcal) on the 8th day of the flight of Gemini 5. As is clear, these date confirm the correctness of the thought that there is a gradual reduction in energy metabolism under weightless conditions. In a study of /274 energy consumption under partially reduced gravitation, during the stay and work on the moon by the Apollo 14 crew members, a quite significant decrease in energy consumption also was noted. In these cases, like during extravehicular activity in a spacesuit, there might even be an initial sharp rise in respiratory metabolism in overcoming resistance generated by the imperfect design of the spacesuits themselves. Energy consumption decreases significantly, in proportion to improvement in spacesuit design (Berry, 1971, 1972). This situation must also be taken into account inside the craft, when putting on the spacesuit.

The results of postflight processing of the regenerated substances and data on dynamics of change in oxygen, carbon dioxide and water concentration in the air of the spacecraft cabins, conducted by A. M. Genin, G. I. Voronin and A. G. Fomin (1965), demonstrated that space flight does not have a great effect on human energy consumption in brief flights. According to the average data, the energy consumption in these flights was: 85.8 kcal/hour by A. G. Nikolayev, 97.2 by P. R. Popovich, 83.5 by V. V. Tereshkova and 84.6 kcal/hour by V. F. Bykovskiy. In the opinion of these authors, the basic indices of metabolism should decrease in long space flights. All this confirms the correctness of the thought expressed earlier that energy consumption gradually decreases in weightlessness, although it may be increased at the beginning of a flight and reduction in it takes place only in proportion to adaptation.

The data obtained by Wortz and Prescott (1966) must also be presented. They are from a human respiratory metabolism study in a special test stand, simulating reduced gravity on earth of one-quarter, one-sixth and one-eighth of earth gravity. It was found that, when a man walks on a treadmill installed in this trainer at a speed of 6.4 km/hour, a reduction in energy consumption takes place, by 48, 56 and 60% of the initial value under normal earth gravity, respectively. Consequently, even with a partial decrease in the effect of weight, respiratory metabolism changes are very significant, and energy consumption decreases linearly with decrease in gravitation. It follows from this that, even on the moon, where the gravity is one-sixth that of earth, energy consumption may decrease by more than half. Similar data, on the reduction in energy consumption of approximately half, while walking on an inclined test stand, with the effect of weight decreased to one-sixth that of earth, were presented by A. S. Barer and colleagues (1972). This all agrees with the opinions of Margaria and Cavagna (1964) and Berry (1970, 1971), who also consider that energy consumption may decrease during movements under reduced gravity.

There is still another interesting study. A respiratory metabolism study of Soviet astronauts P. I. Belyayev and A. A. Leonov (I. I. Kas'yan, V. I. Kopanev, 1967) has shown that the oxygen consumption of A. A. Leonov increased by 206 ml/min. This is completely understandable, in connection with the great stress and performance of certain operations (extravehicular activity). The oxygen consumption of P. I. Belyayev decreased by 72 ml/min from the initial, preflight consumption. To a certain extent, the latter confirms the hypothesis of a reduction in metabolism in weightlessness. Unfortunately, the unique data are extremely few, and it is early now to make the final conclusion.

Under weightless conditions, some reduction apparently is possible in temperature, since the tonus of the muscular system (especially in the state of rest) will be reduced. A reduction in body temperature of A. A. Leonov in the state of rest was observed /275 to 35.2°, 35.4° and 35°, during the 4th, 7th and 15th orbits of the flight (I. I. Kas'yan, D. G. Maksimov, I. G. Popov, et al., 1971). Consequently, it cannot be excluded that a change in muscle tonus, which is especially important for heat production of the so-called temperature regulation muscle tonus (K. P. Ivanov, 1968) leads to a change in the nature of heat regulation under weightless conditions. The latter also is closely connected with respiratory and energy metabolism of the body.

We attempt to represent in detail the chain of possible changes in the entire energy metabolism in weightlessness. Obviously, removal of the effect of gravitation leads to a decrease in energy consumption. Consequently, the requirement for macroerg production is reduced. Inasmuch as synthesis of macroergs and, first and foremost, ATP takes place mainly as a result of biological oxidation, the oxygen and oxidation substrate supply requirement decreases. In turn, this decreases the load on the oxygen and oxidation substrate supply system, as well as on removal of products of metabolism. In other words, deconditioning of the cardiovascular system and, possibly, subsequently, the respiratory function begins. More deep-seated processes may develop at the sites of biological oxidation itself, i.e., in the mitochondria and enzyme systems. "Deconditioning" of the biological oxidation process itself is possible, in connection with the fact that there will not be a continuous and adequately intensive stimulation of ATP resynthesis by its breakdown products, ADP in particular. The latter has been successfully demonstrated, to a certain extent, in model tests after prolonged hypokinesia of rats, in studies of the respiration of mitochondria removed from their tissues. It turned out that, in these cases, interruption of oxidative phosphorylation begins, and changes in structure of the cristae of the mitochondria were found morphologically, right on the surfaces and membranes, on which biological oxidation proceeds (Ye. A. Kovalenko, V. L. Popkov, et al., 1970a, 1970b; E. S. Mailyan, et al., 1970; L. G. Grinberg, 1972). It cannotbe excluded that similar qualitative changes in biological oxidation takes place under actual weightless conditions. Further, these changes can lead to disruption of adequate synthesis of macroergs and disruption of the oxygen budget of the body in hypokinesia and weightlessness. Respiratory metabolism efficiency and economy during work are disrupted (Yu. S. Galushko, 1972). The oxygen demand and the oxygen debt increases, and the coefficient of recovery of the oxygen budget of the body also decreases. All this leads to a sharp disruption of the oxygen regime of the body (A. V. Ryazhskiy, 1972) and to a reduction in performance capacity (Diagram 8).

This chain of events is easily traced in model tests during prolonged hypokinesia, which we and our colleagues carried out on animals (rats) over a period of 100-130 days (Ye. A. Kovalenko, V. L. Popkov, et al., 1970, 1971; E. S. Mailyan, et al., 1970; Yu. S. Galushko, 1972; L. G. Grinberg, 1972; A. V. Ryazhskiy, 1972). Similar phenomenon of significant reduction in performance capacity and respiratory and energy metabolism economy of the body are seen in astronauts, after they have been in weightlessness. Berry (1971) noted that a reduction in performance capacity and the considerable deterioration in ability to utilize oxygen and, consequently, to perform assigned work, were observed in all crew members of the Gemini and Apollo spacecraft.

After the flights of the Soviet astronauts in Soyuz 4 - Soyuz 8, it was determined that, after 2- 5-day flights, in performance of measured physical work on the bicycle ergometer, at a rate of 600/276 kgm/min, an increase was noted in oxygen consumption, from 1384-1567 ml/min before the flight to 1399-1621 ml/min after it. A greater increase of heart rate and decrease in oxygen pulse took place simultaneously. In performing still more work (1400 kgm/min), the oxygen consumption changed from 2079-2804 before the flight to 2172-2783 ml/min after it; the pulse and respiration rate changed still more markedly, and the oxygen pulse also decreased (B. S. Katkovskiy, G. V. Machinskiy, et al., 1972). In analyzing the results of the flights of the entire Soyuz series, Yu. G. Nefedov, L. I. Kakurin and A. D. Yegorov (1972) point out a reduction in performance capacity and general asthenization and fatigue of the astronauts, as well as a reduction in strength and tonus of the antigravity muscles. With increase in flight duration, these phenomena progressed.

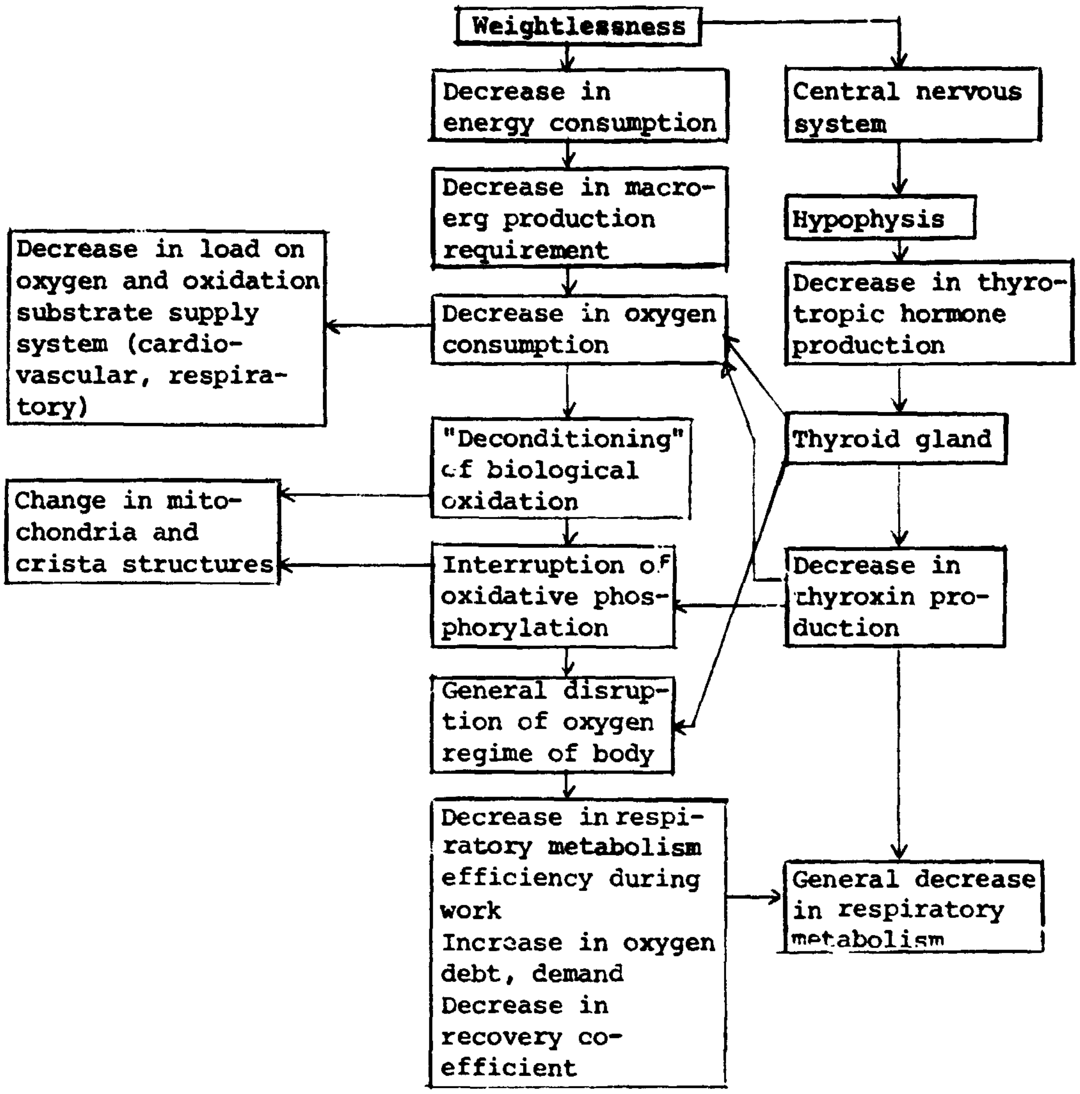


Diagram 8: Proposed scheme of pathogenesis of changes in energy metabolism under weightless conditions

Still another circumstance must be noted, a reduction in afferent effects, coming to various sections of the central nervous system under weightless conditions. The general decrease in load on the body and decrease in afferentation and reduction in stimulation of the reticular formations and, further, a decrease in stimulation of the hypophyseal system, lead to a decrease in thyrotropic hormone production; all this can then cause a general reduction in function of the thyroid gland and a drop in thyroxine output. In turn, the latter also will favor disruption of the rate of oxygen utilization in the tissues, with asthenization of the body. As a result of all these changes, in all likelihood, further changes in thyroid gland function will take place, and this will cause a reduction in oxygen consumption of the tissues. Since there are cells producing thyrocalcitonin and thyroxine in the parenchyme of the thyroid gland, disruption of the oxygen and calcium metabolism may somehow be mediated through the change in function of this gland. There are direct data; a distinct uncoupling effect of the mitochondria function is noted in the cell, with an increase in calcium level (L. G. Grinberg, 1972). Consequently, there also may be a connection between disruption of energy and calcium metabolism regulation in weightlessness, both at the level of the thyroid gland and at the level of the final structures of biological oxidation, i.e., in the mitochondria. These are important and unstudied aspects of the pathogenesis of the intimate aspects of metabolism in weightlessness.

Evidently, still another structural aspect of metabolism must be dwelt on. Performance of all functions in our body continually requires, not only energy supply to them, but, without fail, plasticity (F. Z. Meyerson, 1967). Breakdown and buildup of new systems continually takes place in our body. The existence of this dynamic structural equilibrium of the body is always maintained by corresponding demands for preservation of structure of the organs and tissues. When a prolonged increase in their functions is necessary, the predominance of anabolism over catabolism develops, since an increased load on the structure is generated and the mass of the necessary functional structural units increases. In weightlessness, with changes and decreases in functional loads, as the main link in pathogenesis, together with a reduction in energy consumption, catabolism can prevail over anabolism, as a result of the absence of intense stimulation of anabolism. Disturbance of the protein synthesis function develops in the cells, and the DNA-RNA-protein /277 system will function to a lesser extent, not receiving the proper stimulation impulses. The latter leads to decrease in enzyme and protein synthesis.

A gradual increase in mass of organs and tissues develops and, as a result, a decrease in volume and weight of the muscles. Does this process take place in a man in actual space flights? It apparently does. It was stated above that, for example, the circumference of the thighs and calves of the astronauts decreases after flights. More than that, a decrease in heart dimensions was noted. The phenomenon of general loss of weight of almost all astronauts after a flight is well known. The weight loss, as a detailed analysis shows, cannot be completely attributed only to loss of /278 fluids. In other words, a loss in tissue structure and, of course, mainly of the muscle system, is noted. This is simulated very well in hypokinesia tests.

We still know little of the peculiarities of change in hydrocarbon and fat metabolism in weightlessness. However, this phenomenon cannot be eliminated, as a transition, in a number of cases, of matter and energy metabolism, from more intensive and productive to less intensive, for example, a change of the normal hydrocarbon metabolism to the pentose cycle and formation of lipid metabolism products. Changes in lipid metabolism are possible, as a result of which, the structure and permeability of the biological membranes of the cells and their organelles can be disrupted, and this leads to a change in the water and electrolyte metabolism in the cell, etc. In other words, in the examination here of various aspects of metabolism in weightlessness, the possibility of the development of vicious circles and their close connection with other links in pathogenesis arises.

There still are few concrete data, in this entire chain of hypothetical changes, on singularities of neuroendocrine regulation under weightless conditions, but we have attempted to examine a number of possible pathways of change in this regulation. It can be assumed overall that this major function of the body gradually changes its active adjustments. Stressor effects, caused by the start of the flight, decrease. Gradual change to predominance of parasympathetic effects on a number of functions and systems takes place. This situation can be replaced by periodic readjustments of sympathetic and stressor type regulation, depending on the specific stresses of the space flight situation.

In setting forth the proposed pathogenesis of the effect of prolonged weightlessness on the body, we have scarcely touched on questions connected with possible adaptation of the body to this factor. This aspect of the problem will be examined in succeeding chapters of the book. Problems of adaptation are discussed in sufficient detail, in the analysis of performance capacity of the astronauts in Chapter 6. We have limited our task to examination of possible aftereffects of weightlessness, from the point of view of pathophysiology.

In conclusion, we would like to emphasize again that all the considerations we have expressed on the proposed pathogenesis of the effect of weightlessness on the body are very hypothetical and are actual to a greater extent, if no means of prophylaxis and protection are used. Since the same means are used and, of course, will be used in flights of man, with an increase in degree of activity, many of these disruptions and links of pathogenesis, in all likelihood, simply will not occur, which has been demonstrated by the successful accomplishment of long (up to 84 days) flights of three crews in the Skylab orbital station. However, all the experience of medicine indicates and urgently requires of us an approach, in which pathophysiological analysis of the mechanisms of the observed changes in the body is necessary, in order to better understand possible disturbances and, hence, to not permit or to limit manifestations of them.

2. Prophylaxis of Unfavorable Effect of Weightlessness on the Human Body

20 years of experience has significantly enriched our knowledge of the effect of space flight on man. It has now been solidly established that flights 2-3 months long do not cause serious functional disruptions, which would sharply worsen the performance /279 capacity, or of explicit pathological disorders, which could be recorded by the medical monitoring methods used.

As is well known, one of the factors continually acting in space flight and least studied, because of the impossibility of full reproduction of it over a long period of time under earth conditions, is weightlessness. Analysis of clinical-physiological data obtained in actual flights and during simulation of the effects of weightlessness under laboratory conditions has resulted in a description of the phenomenology of the unfavorable effects of weightlessness, development of some pathogenetic mechanisms of its effect and determination of the direction of work to find means and methods of prophylaxis. However, it should be noted that there is not a unified point of view at present, with respect to possible aftereffects of long space flights, and of the importance of adaptation of the body to weightlessness (P. V. Vasil'ev, et al., 1969; Ye. A. Kovalenko, P. V. Vasil'ev, 1971; Berry, 1971, and others). Meanwhile, it is extremely important to know the physiological systems in which adaptation is observed and the ways in which it is accomplished, as these transformations may be reflected in the reactivity of the body to external and internal stimuli, including pathogenic agents, the extent to which adaptation to weightlessness subsequently limits the adaptive capabilities and performance capacity of a man after he lands, etc. It also is important to know, Is accumulation of unfavorable effects observed in any system, and what are the consequences to which it can lead? The competence of asking all these questions is strengthened by the results of the 18-day flight of A. G. Nikolayev and V. I. Sevast'yanov (O. G. Gazenko, P. V. Vasil'ev, 1970). Prognosis of the directions of these changes in various physiological systems (Fig. 69), made by Dietlein (1965), is not without substantiation, and can be the subject of special discussion and study. Of course, convincing answers to these questions will be obtained only in space flights, with a considerable increase in duration of them. They will permit a more rational approach to synthesis of a complete system of prophylactic measures.

However, efforts have already been made to develop means of preventing or considerably mitigating the unfavorable manifestations of the effect of weightlessness. It should be noted that all these studies have been conducted and are being conducted in experiments, with simulation of weightlessness, by means of prolonged restriction of motor activity in bed rest or by submerging in immersion media.

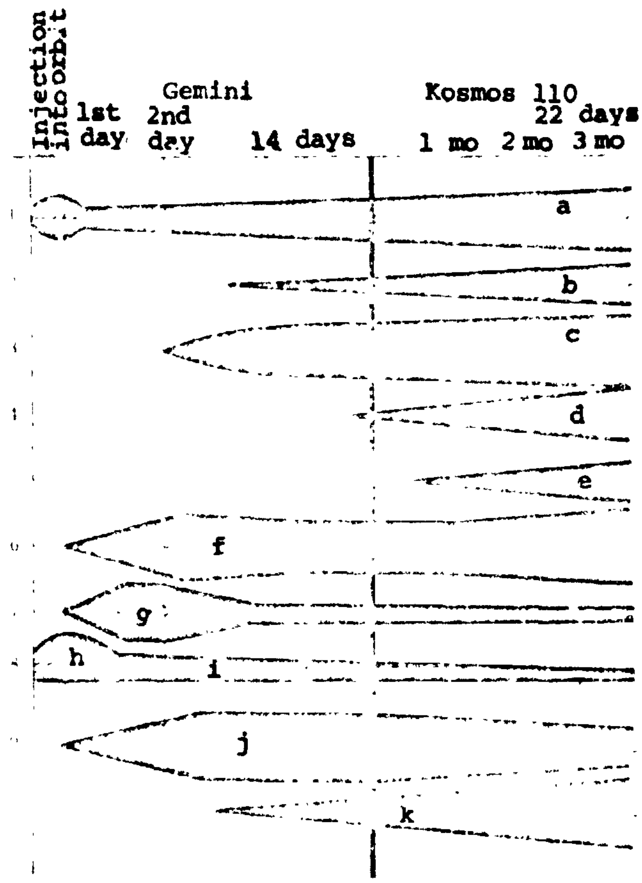


Fig. 69. Hypothetical picture of disruption of body functions during prolonged stay under weightless conditions (further development of scheme of L. Dietlein, 1964): a. disruption of cardiovascular system activity; b. muscle atrophy; c. disruption of water-salt metabolism, dehydration of body; d. disruption of calcium metabolism, bone demineralization; e. disruption of hemopoiesis, f. digestive disorders; g. vestibular disorders (nausea, dizziness); h. change in basal metabolism level; i disruption of respiratory-energy metabolism; j. sleep and change in daily rhythm; k. general asthenization, caused by the set of flight factors (weightlessness, hypokinesia, monotony of the situation and living environment).

It is known that the most reliable and effective are etio-pathogenetic means of both treatment and prophylaxis of any pathological process.

The polymorphic nature of clinical-physiological, biochemical, immunobiological, histological and histochemical disturbances indicate the unusal universality of the etiological factor, having an effect on different systems of the body (Ye. A. Kovalenko, et al., 1970; McCally, 1968; Berry, 1971, and others). The overall picture of disruptions in a prolonged stay under weightless conditions is characterized by general asthenization, suppression of immunobiological reactivity, deconditioning of the striated, especially antigravity, musculature and readjustment of the hemodynamics, protein, mineral and water metabolism (Yu. M. Volynkin, P. V. Vasil'ev, 1965; Ye. I. Vorob'ev, et al., 1970; O. G. Gazenko, P. V. Vasil'ev, /280 1970; O. G. Gazenko, et al., 1972; Berry, 1970, and others). It was discussed in detail in the preceding section.

Three driving links can be distinguished in the pathogenesis of the disorders observed in weightlessness:

-- removal of hydrostatic pressure of the fluids, especially the blood;

-- decrease in gravitational (force) load on the skeletal muscular apparatus (hypodynamia) and motor activity (hypokinesia);

-- change in gravireceptor functions.

The complex interrelationship between these links, the specific importance of which in manifestation of one disruption or another changes at different stages of a flight, determines the overall picture of the developing disorders. By acting on these pathogenetic links, the unfavorable effects of weightlessness can be decreased. /281 Ways and methods of prophylaxis are presented in Diagram 9.

It is evident from the diagram presented above that artificial gravitation is the single, universal method of prophylaxis of the negative effects of weightlessness. The thought of creating artificial gravity in spacecraft was first expressed by K. E. Tsiolkovskiy (1911). However, theoretical and experimental studies of this problem began only at the moment of the launch of the first artificial earth satellites. Two questions in this problem require a strictly scientific substantiation: determination of the minimum effective artificial gravitation and determination of the rotating system parameters permissible for man, by medical indications. In all likelihood, it will be possible to solve these problems, only by a reasonable compromise.

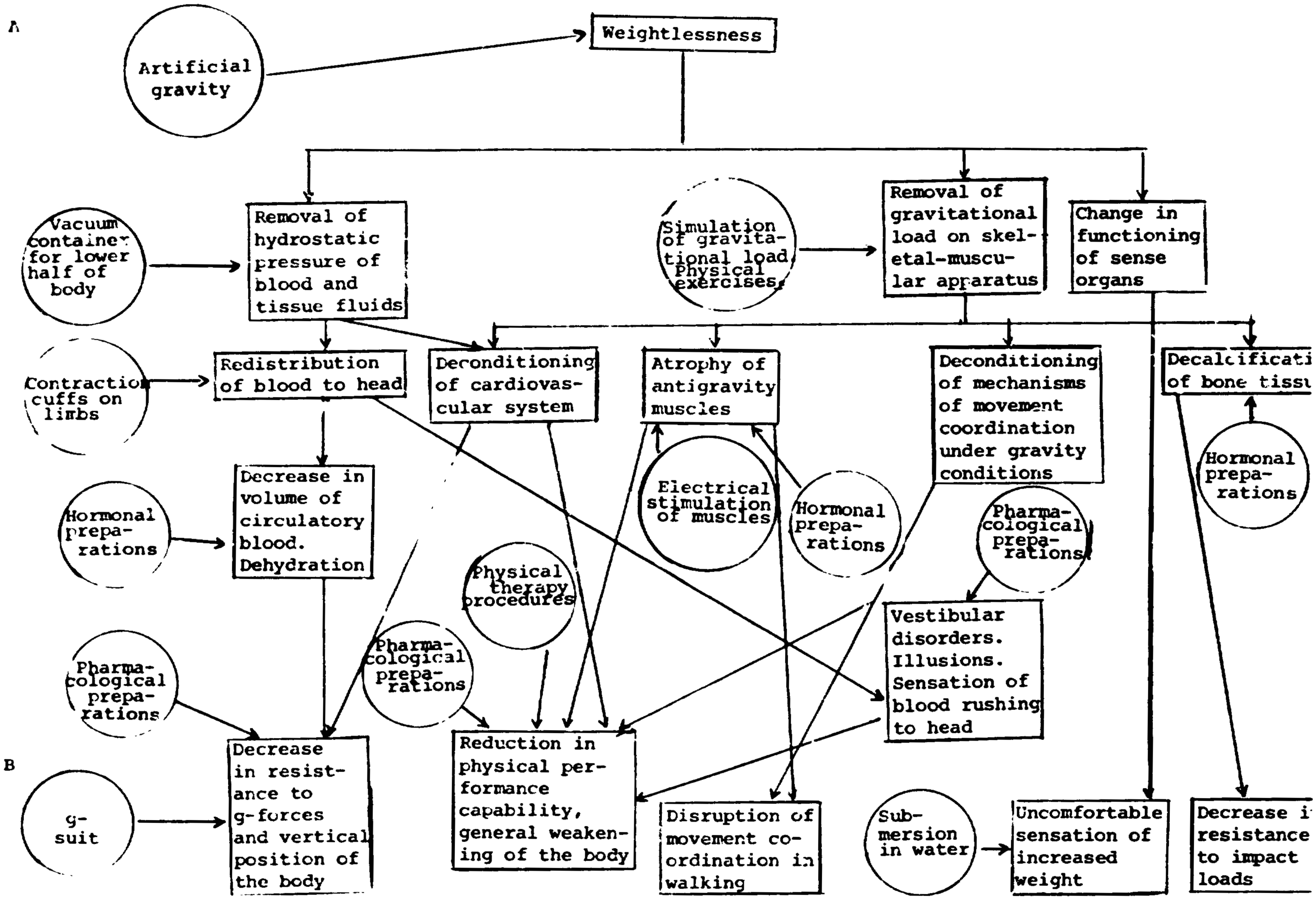


Diagram 9: Basic links of mechanism of action of weightlessness on the human body and methods of prophylaxis of these effects: A, during flight; B, in postflight period (according to A. M. Genin and I. D. Pestov, 1972).

Ye. M. Yuganov and M. D. Yemel'yanov (see last section of this chapter), on the basis of analysis of existing data on the resistance of man to a prolonged stay in rotating systems, reach the conclusion that with a permissible rotation rate V = 10°/sec, the optimum radius of rotation of spacecraft must be R = 90 m, in which the variations in weight of an astronaut, under conditions of his movement in the direction of rotation does not go beyond 0.25-0.35 g. However, these data may be subject to significant corrections under real flight conditions (A. M. Genin, 1965). The complexity of the physiological problems, arising in development of artificial gravitation, is no less than the complexity of the technical problems facing the spacecraft designers, in this case, as well as the absence of an acute need for artificial gravitation in the flights accomplished, according to medical indications; all this is delaying further advance and the bringing of existing projects of the very promising area of prophylaxis of negative consequences of weightlessness into being. /282

Technically simpler and more accessible methods of prophylaxis, true, directed only towards individual pathogenetic links or even symptoms of the unfavorable effects of weightlessness, are being extensively developed at present and have been approved in real space flights in part (A. M. Genin, I. D. Pestov, 1971; Vogt, 1966; Taylor, David, 1966; McCally, 1969, and others).

It is known that removal of the hydrostatic pressure of the blood and tissue fluids observed under weightless conditions, and reproduced in laboratories by a long stay of a man in a horizontal, low-mobility position or by submerging him in a thermally indifferent liquid, leads primarily to redistribution of the blood in the body, with an increase in the amount of it in the upper part of the trunk. Increased diuresis develops here, which is caused by switching on of neuroendocrine mechanisms (Gauer, 1971), and loss of water and electrolytes occurs; the volume of circulating blood decreases significantly; dehydration of the body develops. During a long stay under reduced hydrostatic pressure, in addition to plasma loss and decrease in volume of circulating blood, deconditioning of the cardiovascular system and its regulatory mechanisms, directed towards maintaining the basic hemodynamic characteristics, sets in. A consequence of this deconditioning is a reduction in tolerance of g-forces and the vertical posture.

To prevent these disorders, caused by the reduction in hydrostatic pressure of the blood, a number of methods are being developed. Among them are impact-inertial exercises in physical trainers, occlusion cuffs on the limbs, regulating the inflow of blood to the heart and conditioning the vascular system, respiration under excess pressure, placing the lower half of the body under vacuum, short-radius centrifuges and pharmacological preparations, keeping the water-salt metabolism normal and stimulating the cardiovascular and central nervous systems. Each of these methods has quite convincing proof of effectiveness of use of them (see the next section).

In laboratory studies with man, it has been determined that, by means of impact-inertial exercises, the hydrodynamic impact reproduced has a powerful conditioning effect on a number of body systems, first and foremost, on the cardiovascular system (Whedon, et al., 1949; Miller, et al., 1964, and others). The effectiveness of these training exercises has been confirmed in orthostatic loading tests/283 All persons trained during hypokinesia on the impact-inertial test stand tolerated orthostasis considerably better than persons in the control group, both over time and by degree of expression of physiological reactions (Chase, et al., 1966).

Numerous tests of foreign and domestic authors are convincing evidence of the possibility of successful use of pneumatic cuffs on the limbs, under certain conditions. These cuffs make it difficult for the return of venous blood to the heart and, in this manner, simulate the effects of hydrostatic pressure, to a certain extent (P. V. Buyanov, et al., 1966; Graveline, 1962; Vogt, 1965, 1966, and others). Use of this method under optimum conditions favorably affects vascular tonus, neurohumoral regulation of the blood circulation and water-salt metabolism. Thus, for example, Vogt and Johnson (1967), in studies of 14-day hypokinesia, using the occlusion cuffs, noted their favorable effect on retention of blood plasma in the vascular system. In fact, while the plasma volume of the control group in the experiment decreased by 12.6% on the average, that of persons using the cuffs was only by 4%. According to observations of McCally and colleagues (1968), the cuffs favored maintenance of normal elimination of noradrenalin with the urine (Fig. 70), which has a direct relationship to the functional state of the sympathetic-adrenal system. Vogt (1965) found a favorable effect of these cuffs on the weight and diuresis indices. In 70-day hypokinesia, V. G. Voloshin and colleagues (1971) observed that persons conducting training, use of occlusion cuffs, applied to the upper third of the thigh, prevented reduction in the flexible-elastic properties of the vessels of the lower limbs, to a considerable extent. The tolerance of orthostatic loads and the effect of accelerations was decreased. True, according to the data of Vogt (1965), in studies with the subjects in an immersion medium, use of the cuff decreased the number of losses of consciousness in conducting the orthostatic test, and it favorably affected the cardiovascular system. Thus, it is shown in Fig. 71 that loss of consciousness was observed in the orthostatic test, without use of the cuff, at the 25th minute.

Consequently, the question of the effect of the pneumatic cuffs on orthostatic tolerance and tolerance of g-forces still remains controversial; the data on this question are contradictary. The conduct of further tests is necessary, for the purpose of finding the most effective training conditions and the optimum localization of application of the cuff.

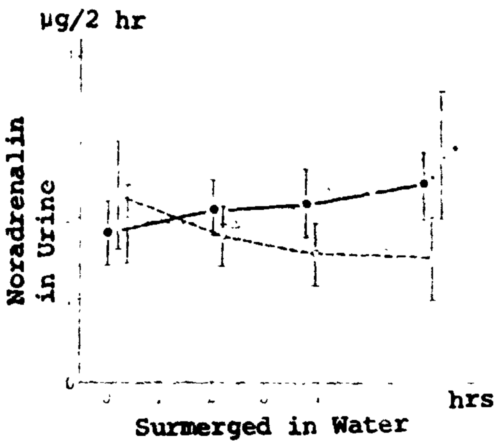


Fig. 70. Dynamics of noradrenalin elimination with the urine (in micrograms) in 2 hours of persons in a chair (1), submerged in water without the occlusion cuffs (2) and with the occlusion cuffs (3) (from McCally, et al., 1968)

To simulate hydrostatic blood pressure during a space flight, several versions of a unit for decompression of the lower part of the body are being developed and tested: a special chair (Fig. 72), a cylindrical container, a special coverall trousers. In creating a vacuum under these conditions, a double effect develops: a power load is created in the direction of the longitudinal axis of the body, which simulates weight to some extent and redistribution of blood and accumulation of it in the lower part of the body takes place, which is characteristic of being in the vertical position on the ground. Both effects, judging from the results of the study, have a conditioning action on the body, and they present the development of sharp disruptions in the readaptation

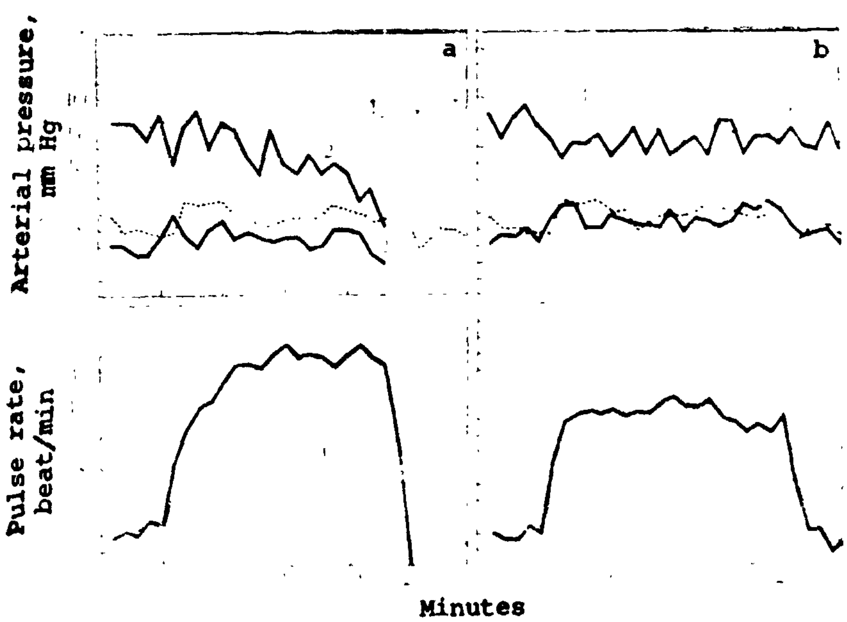


Fig. 71. Blood pressure and heart rate before, 1, and after, 2, water immersion in orthostatis (start at 5th minute): a, without cuff; b, using cuff (from Vogt, 1965).

Fig. 72. Vacuum chair to create negative pressure on the lower half of body (from Genin and Pestov, 1972).

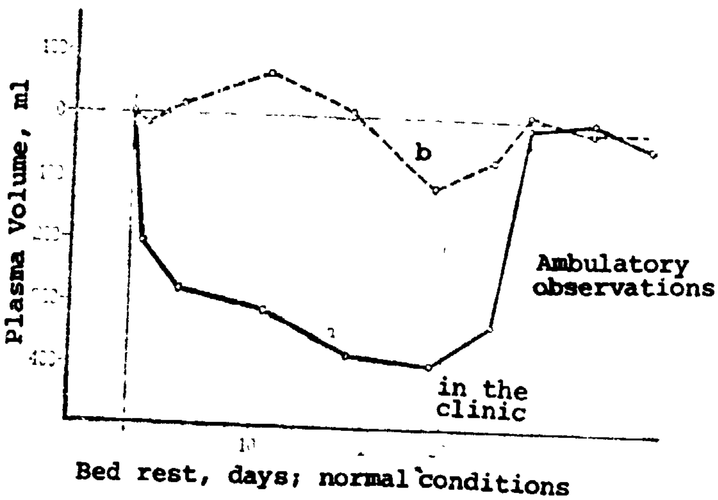


Fig. 73. Change of plasma volume (average data) of persons in control (a) and LBNP conditioned (b) groups in 26-day hypokinesia (from Stevens, et al,., 1966)

period, first and foremost in the hemodynamics. A favorable effect of use of these designs on the fluid content of the body has been clearly determined: a higher level of the plasma volume is maintained /284 (Fig. 73), diuresis decreases, secretion of the antidiuretic hormone increases, and the activity of the sympathetic nervous system is stimulated (the blood catecholamine content increases).

The application of negative pressure to the lower part of the body (LBNP) of from 20 to 40 mm Hg, to persons in bed for a long time, has restored the leg volume, reflecting redistribution of fluids to the level observed in the vertical posture under earth gravity conditions (Musgrave, et al., 1969). The respiratory function of the lungs (Dewell, et al., 1969; Potanin, et al., 1969) and kidneys (Gilbert, et al., 1966) under LBNP, also /285 approached the level of functioning characteristic of the vertical human position. In experiments with prolonged hypokinesia, application of a vacuum container, to create LBNP under certain training conditions, increased the tolerance of an orthostatic load or the acute action of LBNP, of up 70 mm Hg.

In studies of Stevens, Miller and colleagues (1966), carried out with six subjects in 26-day bed rest, it was noted that the conditioning effect of negative pressure on the lower part of the body prevented loss of consciousness under orthostatic loads and decreased the stress on cardiac activities. Thus, the pulse rate of persons in the control group increased by 29 beats per minute after bed rest, while standing passively, and that of those subjected to LBNP, a total of 12 beats per minute. Similar results have been obtained by other investigators in similar experiments (I. D. Pestov, B. F. Asyamov, 1972; Miller, et al., 1965; Stevens, Lynch, et al., 1966; Cramer, 1971).

The vacuum container was used on the 24-day flight of the Salyut orbital station, and it received a favorable rating from the astronauts. The crew members willingly used this device, and they noted that training in it gives very pleasant sensations (A. M. Genin, I. D. Pestov, 1972). There is no doubt that the vacuum container used in Salyut requires further improvement, both in design and in its planned operating conditions aboard the spacecraft.

The principles of creation of negative pressure in the region of the lower part of the body can be used in flight, as a functional test, for expert evaluation of the state of health of the astronauts, primarily of the cardiovascular system, in solving the problem of the possibility of continuing the flight. Consequently, the /286 vacuum container is a useful and promising means of prophylaxis of the unfavorable effects of weightlessness.

The biochemical and physiological mechanisms of the effect of LBNP on the human body must be studied more deeply in laboratory investigations, so as to more rationally constitute the conditions for its use in space flights.

The most significant physiological shortcoming of LBNP prophylaxis is the absence of a hydrostatic pressure gradient along the body vertical. Although technically, creation of such devices is completely practicable, they are complicated in design and considerably less convenient in operation, especially under flight conditions in spacecraft.

American authors (Blockley, 1970, and others) have obtained reassuring results, by combination of respiration under excess pressure, using a special suit, having a counterpressure gradient on the body (Fig. 74); this method merits special experimental study.

A comparison of the pathogenetic mechanisms of disorders in hypokinesia and weightlessness and the physiological effects of respiration under excess pressure indicate the advisability of deeper study of this method of prophylaxis of these disorders. The first tests conducted by I. D. Pestov indicate the possibility of obtaining quite favorable results.

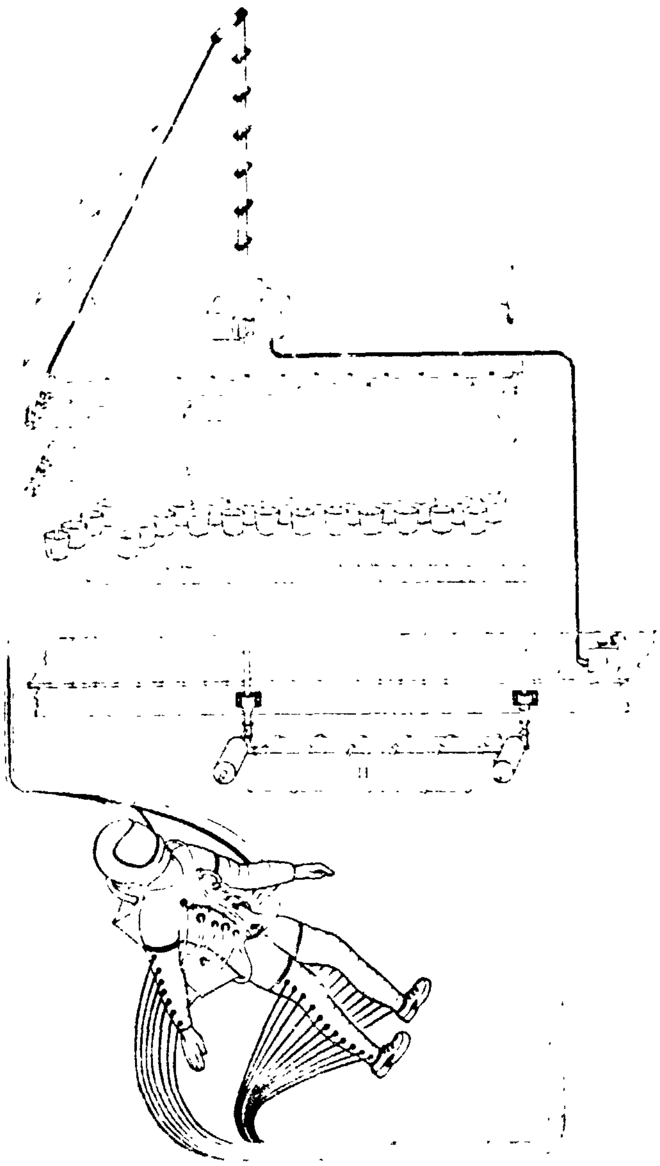


Fig. 74. Suit for prevention of unfavorable effects of deconditioning of cardiovascular system under orthostatic loads (from Blockley, 1968)

The question of the advisability of use of centrifuges with a small shoulder radius in space flights, to reproduce the effects of gravitation, remain insufficiently studied. However, the first work in this area indicates the necessity for expanding these studies (Middleton, White, 1968, and others).

A search for pharmacological means of keeping /287 water-salt metabolism normal, maintaining the volume of circulating blood, preventing demineralization of the bones and increasing the orthostatic tolerance and tolerance of g-forces also is justified; existing data indicate the advisability and competence of this area of work. Thus, Gauer and colleagues (1965), by slow administration of vasopressin, at a dose of 0.25 units per kg of weight, observe a return to normal diuresis and elimination of Na^+ and K^+ (Fig. 75), caused by prolonged submersion of man in a thermally indifferent liquid. Similar results have been obtained by Eckert (1964), Hunt (1967) and McCally and colleagues (1968). Eckert (1964) noted a decrease in diuresis, with administration of vasopressin antidiuretic hormone, at a dose of 0.5-1 unit per kg of weight, instantaneously or by prolonged infusion at a rate of 0.25 unit/kg in 30 min. Administration of vasopressin not only prevented polyurea, but it promoted recovery of plasma volume and favorably affected the orthostatic test indicators (Fig. 76). Infusion of the preparation, even in doses not affecting the total blood pressure, prevented development of orthostatic collapse in four out of five cases.

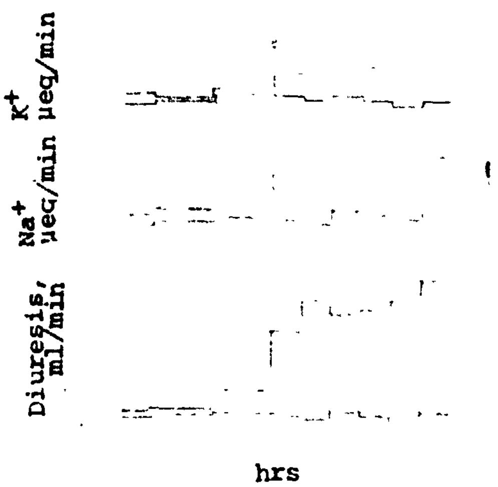


Fig. 75. Effect of intravenous administration of vasopressin (0.25 unit/kg) on dynamics of K^+ and Na^+ elimination and overall diuresis during immersion of subject (Gauer, et al., 1965): 1, control; 2, test; moment of administration of preparation shown by arrow

These data were extended by the authors in subsequent studies, with bed rest duration from 28 to 78 days (Stevens, et al., 1966). It was demonstrated here that the use of 9-FF is equally effective in both early and later periods of bed rest (Fig. 77). An important section of this work was determination of the orthostatic tolerance of subjects at various times in bed rest, before and after use of 9-FF. The criteria for evaluation of orthostatic load tolerance (90° up to 30 min) were the time of onset of loss of consciousness and heart rate. According to the data of the authors, 9-FF did not have a clearly expressed effect on tolerance of orthostasis, although some tendency towards slowing of the heart rate was observed here. The latterfact, a decrease in tachycardia, was convincingly confirmed in the work of Bohnn and colleagues (1969). In experiments on 8 subjects, in the course of 10 days of strict

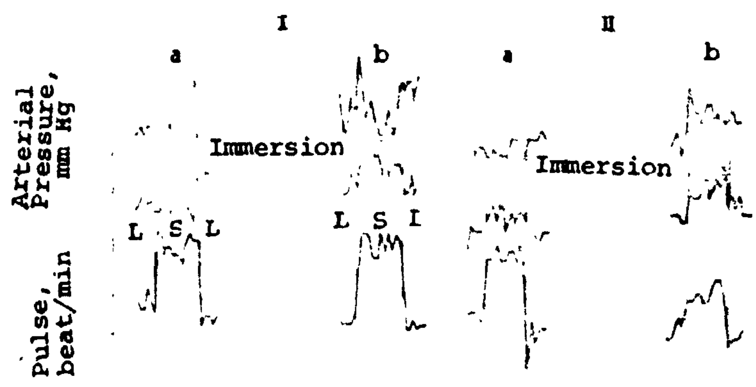


Fig. 76. Effect of 6-hour immersion on orthostatic tolerance, according to pulse rate and arterial pressure data, in change from "prone" position, L, to "sitting" position, S: I, without preparation; II, using preparation; a, baseline; b, after immersion (from Gauer, et al., 1965)

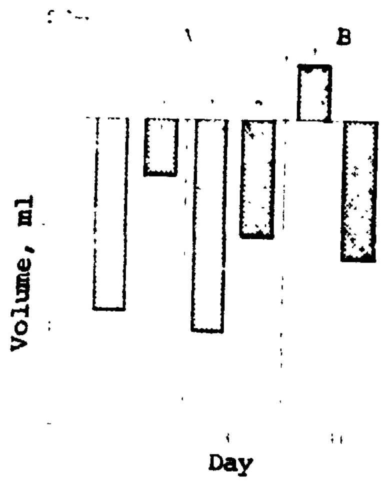


Fig. 77. Change in plasma volume (1) and erythrocyte mass (2) at various times in bed rest and effect of 9-FF on them: A, without preparation; after administration of 9-FF for 2 days (from Stevens, et al., 1966)

bed rest and use of 0.2 mg of the mineral corticoid 9-FF, the authors demonstrated that the reaction of the cardiac contractions of the subjects were less pronounced, and recovery took place more quickly, than in persons receiving placebo. The effect of use of 9-FF on body weight, diuresis, plasma volume and elimination of sodium and potassium was favorable, and itdid not differ from the results of the tests Stevens and colleagues (1965, 1966).

Keeping in mind the important role of aldosterone in the mechanism of disruption of water metabolism and blood circulation, Ditzel and colleagues (1964) tested its effectiveness in /288 orthostatic hypotension. Favorable results were obtained in all cases here. This allows this preparation to be recommended for broader experimental testing, especially in hypodynamia.

As was noted above, in hypodynamia and weightlessness, significant disorders of calcium metabolism, the physical importance of which in the body is difficult to overestimate, are observed. Calcium metabolism in the body and preservation of a constant level of it in the blood is regulated by the parathyroid hormone and thyrocalcitonin (B. V. Aleshin, 1969; Siggler, et al., 1967, and others). Here while the parathyroid hormone, increasing the activity of the /289 osteoclasts and increasing the number of them, leads to destruction of hydroxyapatite crystals and discharge of calcium and phosphorous ions into the blood, which is accompanied by hypercalcinemia, thyrocalcitonin, on the other hand, decreases the calcium content in the blood circulation. Based on the mechanism of action of thyrocalcitonin and keeping in mind the existing concepts of the genesis of disruptions of calcium metabolism under weightlessness, Gittes and and Wells (1967) proposed use of this preparation in space flights. The rationale of this proposal is partially confirmed in the work of Wynston and Perkins (1968), who showed that administration of thyrocalcitonin to white rats, at a dose of 0.315 mg per animal, decreased the extent of decalcification of immobilized limbs. The results of our experiments on rats with prolonged hypokinesia were similar (A. I. Volozhin, et al, 1972).

The experimental studies of Wynston and colleagues (1967), carried out on rabbits, guinea pigs, rats and chicks, showed that parotin does not reduce the calcium level in the blood. However, it seems to us that tests of parotin must be carried out in pro- /290 longed hypodynamia, when distinctly expressed shifts in regulation of calcium metabolism develops and there is an increase of its content in the blood, i.e., on the background of changed reactivity of the body, for a final answer.

To prevent protein breakdown, losses of amino acids and decalcification of bone, substances can be tested, which, by systematic use, stimulate protein synthesis, improve amino acid uptake and change the negative nitrogen balance to a positive one, and also inhibit loss of calcium by the body. The anabolic effect of such a type of preparation is widely used in the clinic, for treatment of osteoporosis and to accelerate consolidation of bones in fractures. Several groups of anabolic agents are known at present: anabolizing steroids (dianabol, nerobol, etc.), biogenic anabolizers (apilak, etc.), those mainly stimulating synthesis of proteins, as well as purine (meradine) and pyrimidine (cytosine, orotic acid, etc.) bases and certain vitamins (B_{12}, folic acid). Study of the effect of these preparations on the amino acid and calcium balances, in an experiment with prolonged hypokinesia, would be fully substantiated theoretically (V. V. Parin, et al., 1969).

In the studies of colleagues of our laboratory, the effectiveness of multiple use of phenamine, caffein and strychnine or securinine was studied in orthostatic tests and the effects of g-forces, before and after prolonged bed rest or immersion. These preparations, having a tonic effect on the cardiovascular and respiratory systems, the cortex and subcortical vegetative centers, the spinal cord and the striated muscle, was prescribed in the following doses: phenamine 0.01 g, caffein sodium benzoate 0.2 g, strychnine 0.001 g or securinine, 0.002 g.

In 18-hour immersion tests, the set of pharmacological agents is used an hour before performing the orthostatic test. A distinctly expressed effect is obtained here. In fact, while collapse of four of seven subjects developed after the orthostatic test in the control studies (immersion without prophylaxis), in the series using the medicinal preparations, similar phenomena were not noted in a single one of the men (I. D. Pestov, 1968).

The effectiveness of these preparations also was manifested in a 70-day bed rest experiment. Thus, at the end of the experiment, four subjects of the control group developed collapse in the orthostatic test, while in subjects receiving the set of stimulators /291
during hypodynamia and before the final orthostatic test, the physiological shifts in the vertical position were of a compensated nature. This was expressed by a somewhat lesser degree of tachycardia during orthostatis and less pronounced shifts in pulse pressure and systolic volume, in persons receiving the medicinal preparations (Fig. 78).

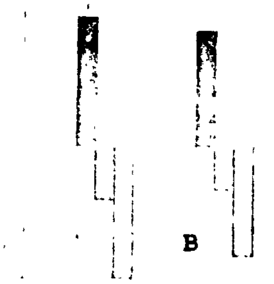


Fig. 78. Reaction of cardiovascular system to pharmacological agents in orthostatic test after 70-day hypokinesia: A, control; B, using medicinal agents; 1, pulse rate; 2, pulse pressure; 3, systolic volume of blood. The indices are expressed by the ratio of the reaction before hypokinesia to the reaction after hypokinesia (in%) (from I. D. Pestov, et al., 1969)

In determination of tolerance of lateral accelerations before and after bed rest, a favorable effect of these pharmacological agents was disclosed (Table 76).

The analysis of the resulting materials is convincing evidence that use of a set of medicinal agents almost completely ensured preservation of the general tolerance of g-forces, compared with the initial indices (A. R. Kotovskaya et al., 1969). The higher tolerance of orthostasis and g-forces of persons taking this set of medicinal agents evidently is explained by their favorable effect, primarily on different links of reflex regulation of the cardiovascular system. Moreover, the fact that the use of the pharmacological agents in three cycles of four days each for the duration of 70-day hypodynamia, to a considerable extent, prevented decrease in mass of the circulating blood, the minute volume, heart volume and blood cycling time should be noticed. Consequently, the initial functional state of persons in this group, according to the indices enumerated, was more favorable before conduct of the orthostatic tests or the action of g-forces. It is not excluded

TABLE 76

EFFECT OF PHARMACOLOGICAL AGENTS (phenamine + caffein + securinine) ON TOLERANCE OF ACCELERATIONS AFTER 70-DAY BED REST (maximum tolerances, A. R. Kotovskiy, 1970)

Subject Group	Subject	Before Bed Rest	After Bed Rest	
			Day 1	Days 24-32
Control	Mo	12.2*	9.3	9.0
	Ko	11.5	9.8	9.5
	Avg	11.8	9.5	9.2
Pharmacological agents used	Bu	12.5	12.5	11.1
	Gu	12.0*	11.8	13.0*
	Br	10.0*	11.2	10.0
	Avg	11.5	11.8	11.4

Conventional symbols: the * is the relative bradycardia; heavy figures, "black shroud"; underlined figures "gray shroud."

that the increase in tolerance of these functional loads also is /292 explained, to a certain extent by an increase in resistance of the body to hypoxia, which has an important part in the mechanism of the disorders in orthostasis and accelerations.

As is well known, in study of the effect of space flight on the electrolyte balance, a considerable decrease in total potassium content in the body was established (Berry, 1971), which has an important part in the function of the myocardium. A comparison of the nature of the disturbances of cardiac activity with change in potassium content has led American specialists to recommend the use of potassium preparations in flight. According to an estimate of Berry, this measure proved to be quite effective in the Apollo 16 and Apollo 17 flights.

Thus, the materials presented above indicate the promise of the search for pharmacological agents for maintaining normal water-salt, protein and other types of metabolism, disturbances in hypodynamia and weightlessness, and increasing the tolerance of the body, especially the cardiovascular system, of functional loads (orthostasis, accelerations), connected with the g-forces of the descent to earth and the action of terrestrial gravitation.

One of the main links in the genesis of disorders developing in weightlessness, as is evident from Diagram 9, is a decrease in gravitational load on the support- motor apparatus. Analysis of existing materials shows that loss of a load on the skeletomuscular system causes a whole range of changes, beginning with scarcely noticeable deviations in enzyme system activity to severe muscular atrophy. The most significant shifts are the reduction in weight and slowing of growth, atrophic and dystrophic changes in the striated muscles, redistribution of the blood, change in the function of the cardiovascular system, dyskinesia of the intestines, change in tissue respiration and total respiratory metabolism rates, disruption of oxidative processes (decrease in phosphorylation level and interruption of oxidative phosphorylation), disruption of mineral and protein metabolism and suppression of antibody formation. Moreover, the functional state of the regulartory systems of the body, the central nervous system and the endocrine, changes distinctly; in prolonged hypodynamia, depletion of the hypothalamus - hypophysis-adrenal system is observed, and inhibition develops in the nervous system. These changes lead to disruption of the dynamic and static performance capability, to disruption of coordination of motor acts and to decrease in tolerance of accelerations and resistance to infectious diseases (P. V. Vasil'ev, 1968; McCally, 1968; Berry, 1971, and others).

It is completely obvious that motor activity approaching normal activity of an "earth" man in amount, involving the muscle groups and power loads, is a radical method of preventing these disruptions.

Both domestic (V. V. Bazhenov, V. I. Chudinov, 1965; A. V. Yeremin, et al., 1969; V. I. Stepantsov, et al., 1972, and others) and foreign investigators (Graveline, 1962; Brannon, et al., 1963; Müller, 1963; Cooper, et al., 1966; Treibwasser, et al., 1970, and others) are developing various means and methods of physical training of astronauts, suitable for use in spacecraft. A special section of this book is devoted to this question. It should only be noted that, of the numerous proposals for physical training, the CPT (complex physical trainer, see next section) physical trainer, /293
developed by a group of authors (V. I. Stepantsov, et al., 1972), which allows performance of isometric and dynamic exercises of varying amounts and rates, accustomed locomotor acts (walking, running), inertial-impact actions on the longitudinal axis of the body (springs) and working of the antigravity musculature, merits the greatest attention. The average energy "costs" of physical training in the CPT, with a force of attraction to the "treadmill" (simulation of weight load) of 50 kg, is 300-350 kcal.

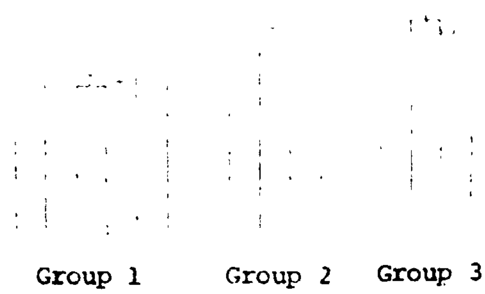


Fig. 79. Maximum g-force tolerance after hypokinesia (average data): group 1 hypokinesia; group 2 hypokinesia-stimulators; group 3 hypokinesia + physical training; 1, initial data base; 2, on 1st day; 3, on 17th day; 4, on 23rd-32nd days; 5, on 62nd day of hypokinesia

The results of studies conducted in various institutions under prolonged bed rest conditions, show that purposeful physical training in a prone position increased physical performance capacity, decreased the reaction of the cardiovascular system to an orthostatic load, increased resistance to accelerations (Fig. 79), and improved the condition of the kinematic and dynamic characteristics of accustomed locomotor acts (V. S. Gurfinkel', et al., 1969; V. G. Skrypnik, 1969). A CPT trainer was installed in the Salyut craft. As is known from radio traffic, the astronauts willingly exercised on the trainer, tested the requirements for increase in training time on it and evaluated it highly overall. In connection with this, there is every basis for thinking that CPT, perhaps with individual modifications, is one of the means of prophylaxis of the unfavorable effects of weightlessness.

A number of domestic and foreign investigators are giving much attention to development of a special bicycle ergometer, suitable for installation in a spacecraft. Various designs of it, frequently with a set which should provide a favorable emotional charge (television accompaniment with images of countrysides on earth). The device developed by the Lockheed Missiles and Space Company is interesting; it consists of a combined bicycle ergometer and vacuum container for the lower half of the body. It can be admitted that such a gymnastic apparatus for training under weightless conditions is very promising. As is well known, bicycle ergometers permit assigning a strictly measured energy consumption; they are compact and convenient in operation. The most significant shortcoming is a certain unilateral nature of the load on the skeletomuscular apparatus. A hydrostatic load cannot be reproduced with them (there is no impact-inertial effect), and it is difficult to sustain natural locomotor acts. Moreover, the latter is especially important, in the case of landing after long flights, in unplanned regions in emergency situations.

To reproduce axial physical loads on the basic muscle groups /294 and skeleton, a number of models has been developed, which are very close in design to loading suits. The majority of them has demonstrated quite high effectiveness in laboratory tests. Two models of suits, developed by Soviet authors, were tested and received a good evaluation from the astronauts, during the long flight of the Salyut orbital station. Design improvements of these suits are being made at the present time, for the purpose of selecting locations of the rubber tension shock absorbers, which is the optimum in loading characteristics.

For exercising muscle systems, a method of electrical stimulation of the muscles and vibromassage are being developed.

Multichannel bioelectrical stimulation of the neuromuscular system of man allows programming of coordinated involvement of various muscles in work, simulating various conditions of human physical training. With appropriate selection of quantities, frequencies and shapes of the electrical signals, unpleasant sensations can be avoided and the structure of muscle contractions, observed in natural motor acts, can be closely approximated. In this case, the heart rate increases, the blood pressure increases, energy exchange is intensified, and the volume of muscle mass and strength indices increase. Systematic electrical stimulation in hypokinesia leads to an increase in orthostatic tolerance, physical performance capability and the functional capacities of the cardiovascular system (B. B. Yegorov, et al., 1969; I. S. Balakhovskiy, et al., 1972, and others).

Consideration of the possibility of use of an active synthetic gaseous environment, to prevent deconditioning of a number of physiological systems of the body, due to the effect of a prolonged stay in weightlessness and hypokinesia, have been expressed in a number of works (A. M. Genin, 1964; A. M. Genin, Ye. Ya. Shepelev, 1964; P. V. Vasil'ev, N. N. Uglova, 1967; Lamb, 1965). Actually, as tests on animals and studies with human participation indicate, purposeful change in the gaseous atmosphere can be an effective method of prophylaxis of the development of a number of manifestations of the hypodynamic syndrome and of the unfavorable effect of weightlessness. Thus, P. V. Vasil'ev and colleagues (1971a, 1971b) determined that conditioning of animals and men in hypokinesia to increasing hypoxia increases the tolerance of accelerations and acute

oxygen starvation. This evidently is explained by their retention at a high level of the adaptation capabilities of the functional systems of the body (respiratory, cardiovascular system, blood, etc.) functions, responsible for oxygen transport to the tissues. In this case, we demonstrated, in tests on rats, that a periodically created oxygen deficit (405 mm Hg) in an artificial gaseous atmosphere decreases the unfavorable effects of hypokinesia on calcium metabolism in the bones (Fig. 80) and the function of the gastrointestinal tract. Lynch and colleagues (1967) noted a positive, favorable effect of a rarefied atmosphere on calcium, phosphorus, nitrogen, sodium, potassium and chlorine metabolism in people in bed for a long time. However, in the studies of V. V. Portugalov and colleagues (1972), according to the cytochemical indices of muscle tissue of hypodynamic rats, conditioning by means of fractional hypoxic hypoxia was not successful. If these facts are confirmed in subsequent work, it will be necessary to conclude that the /295
favorable effect of hypoxic conditioning appears nonuniformly in different functional systems of the body.

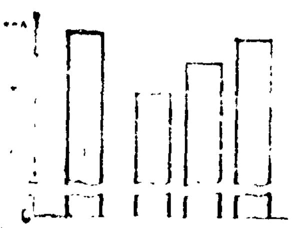


Fig. 80. Effect of hypoxia on ^{45}Ca content in tibia of rats (in % of control group): 1, biological control; 2, hypokinesia; 3, hypoxia; 4, hypokinesia-hypoxia.

Consequently, the results of these operations indicate the necessity for further development of this area of work, for the purpose of determination of the optimum composition of the gaseous environment and conditions of its employment under actual flight conditions.

Considerable difficulties developed in an effort to develop means of prevention of the disorders caused by removal of adequate stimuli of the gravirecptors. It is known that even partial deafferentation causes disturbances of spatial orientation, coordination of movements, etc. Cutting off the function of such receptor fields as the otolith part of the vestibular apparatus, large skin surface, proprioceptive sensitivity of the skeletal muscular system and receptor zones of the internal organs all lead to development of a complicated symptom complex, characterized by disruptions of motor sensitivity and the vegetative sphere (V. V. Baranovskiy, et al., 1962). Because of these disruptions, the performance capacity of a man can decrease and the fulfillment of the flight program can be significantly disrupted. Prophylaxis of sensory deprivation and the entire range of disorders caused by this can be reliably provided, as was pointed out above, only by creation of an artificial gravitational field. However, to prevent individual disorders caused by disruption of the interrelationships in the analyzer systems, in particular, to eliminate motionsickness symptoms, pharmacological agents are being developed. According to ground experiment data, considerable success has been achieved in this area by both domestic and foreign investigators. A significant contribution to working out this problem was made by Graybiel (1968), who conducted tests of a large number of pharmacological preparations (Fig. 81). It was shown here that complexes (formulas) consisting of sympathomimetics and parasympatholytics (scopolamine + amphetamine) are the most effective. There are a number of other prescriptions for elimination of "motionsickness" symptoms, which have a better prophylactic effect in laboratory studies (P. V. Vasil'ev, 1971).

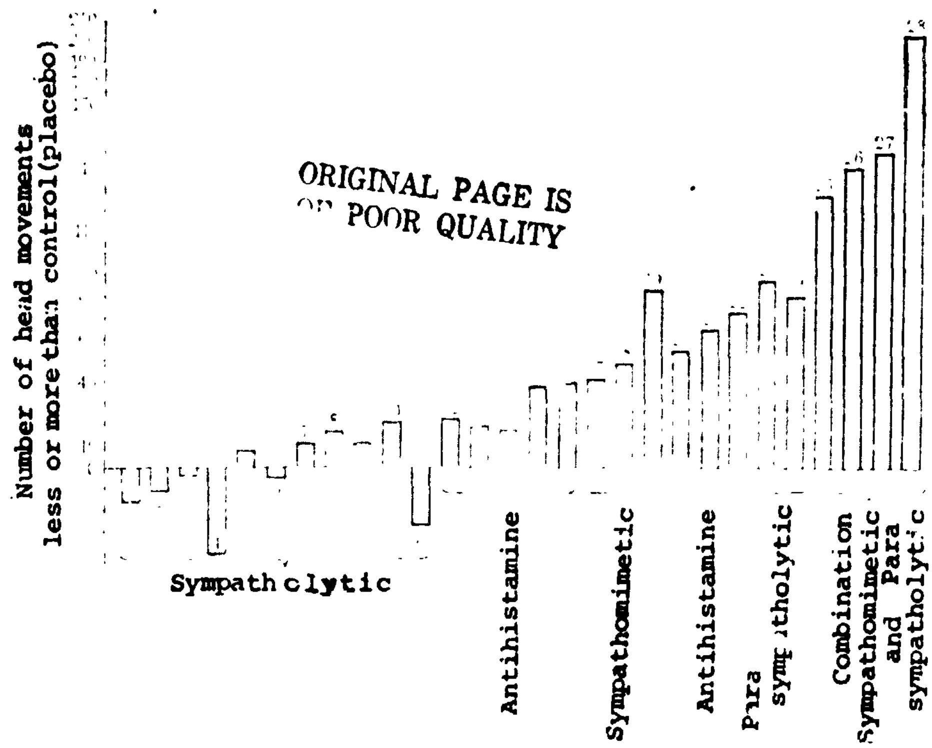


Fig. 81. Effect of pharmacological agents on tolerance of Coriolois acceleration by vestibular apparatus (from data of Graybiel, 1968): 1, phenoxybenzamine, 20 mg; 2, meprobamate, 400 mg; 3, triethylperazine, 10 mg; 4, triethylperazine, 30 mg; 5, trimethylbenzamid, 250 mg; 6, trimethylbenzamid, 750 mg; 7, chlorpromazine, 25 mg; 8, prochlorperazine, 5 mg; 9, prochlorperazine, 15 mg; 10, EKSP-999, 10 mg; 11, EKSP-999, 25 mg; 12, meclizine, 50 mg; 13. meclizine, 50 mg + amphetamine, 10 mg; 14, meclizine, 150 mg; 15, cinnarazine, 150 mg; 16, cyclizine, 50 mg; 17, ephedrine, 50 mg; 18, amphetamine, 10 mg; 19, amphetamine, 20 mg; 20, dimenhydrinate, 50 mg; 21, diphenidol, 50 mg; 22, promethazine, 25 mg; 23, scopolamine, 0.6 mg; 24, scopolamine, 1.2 mg; 25, scopolamine, 0.6 mg + ephedrine, 50 ml; 26, scopolamine + amphetamine, 25 mg; 27, scopolamine, 0.6 mg + amphetamine, 10 mg; 28, scopolamine, 1.2 mg + amphetamine, 20 mg.

A number of unfavorable reactions of the vegetative and psychic spheres during motionsickness, in all likelihood, can also be eliminated by prescription of medicinal preparations from the broad group of psychotropic agents. However, these problems require the conduct of special studies.

Undoubtedly, physical training, decompression of the lower part of the body and other methods spoken of above have a favorable effect with respect to these disorders.

A number of general measures, directed towards creation of an optimum hygienic environment and microclimate, building up a favorable schedule of work and rest, complete satisfaction of the requirements of the body for high-quality, high-calorie food and /297 water, creation of the necessary conditions for a favorable emotional background, undoubtedly all will prevent or alleviate development of asthenization, fatigue and the specific symptomatics connected with the effect of weightlessness.

Attention should now be given to the necessity for deeper study of the peculiarities of the clinical-physiological course of the readaptation period and acceleration of development of means, which promote recovery of the function of physiological systems to the initial level after landing and to increasing the performance capacity of the astronauts. This question can be particularly acute in the first hours and days after landing, when a reduction in tolerance of orthostatic loads is observed. To prevent unfavorable reactions and to increase resistance of the body to terrestrial gravitation, a number of methods have been proposed. The question is discussed in the literature, of the possibility of use of submergence of a man in an immersion medium, the use of g-suits and elastic underwear and socks for this purpose. The taking of tonic pharmacological agents before landing on earth may be fully substantiated.

According to the data of Miller and colleagues (1964, 1965), owing to use of the g-suit (chamber pressure 60 mm Hg) before the orthostatic test following prolonged hypokinesia decreased the frequency of loss of consciousness, and it decreased the stress of the cardiovascular system (Fig. 82) and respiration. Similar results have been obtained by A. M. Genin and I. D. Pestov (1972), who observed appreciable return to normal of the cardiovascular system during orthostatic loading, in water immersion studies, in subjects wearing g-suits. According to the data of the authors, g-suit chamber pressures from 35 to 50 mm Hg proved to be the most highly preferred. At this pressure, a man can perform a number of jobs for a period of many hours. Under somewhat different experimental conditions, a favorable effect of the g-suit was observed by Filcescu (1969).

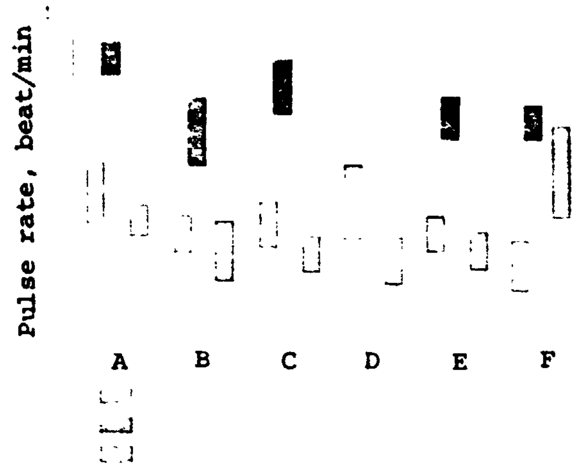


Fig. 82. Pulse rate in orthostatic test of subjects (A, B . . . F) before (1) and after hypokinesia: without using g-suit (2) and using g-suit (3) (from material of Miller, et al., 1965)

McCally and colleagues (1968) note that the use of elastic underwear, put on immediately before orthostasis on the inclined table after 8-hour immersion, turned out to be the most effective of all methods tested by them (occlusion cuffs, LBNP, immersion in cold water, injection of antidiuretic hormone) the mechanism of action of these means consists of limitation of deposition of blood in the vessels of the lower limbs and abdomen, while in the vertical posture.

Thus, purposeful studies are being carried out, both in our country and abroad, to find means and methods of prophylaxis of the unfavorable effects of a long stay in weightlessness. A number of effective measures have been developed in model experiments, which permit support of the basic biochemical and physiological indices at a level close to normal, preservation of orthostatic tolerance, physical and mental performance capacity and resistance to g-forces. Of course, combination of various prophylactic means in a single protective set is important, since each of them separately creates only partial effects and does not provide a harmonic conditioning effect.

The effectiveness of the proposed measures, their convenience of use in a spacecraft, simplicity in use, the necessary time, energy consumption, size-weight characteristics, etc., must all be evaluated under actual flight conditions. Of course, the specific /298
tasks of the flight, its duration, crew composition, tactical-technical data of the flight vehicle, etc., will be taken into consideration here. However, the basic characteristic, which undoubtedly will determine the selection of prophylactic means and methods will be preservation of health and performance capacity of the astronauts, both during the flight and after landing on the earth or another planet.

Having examined the basic areas in the search for means and methods of preventing the unfavorable effects of a stay in weightlessness, unfortunately, we cannot confidently answer the question of the conditioning and prophylaxis means it is most reasonable to use, with what duration and with what changes in the body, should these means be used at the very start of flights lasting several weeks or a month, thereby preventing adaptation of the body to its new living conditions or is it more advisable to include them in the preparation for return to earth, etc.

These questions become particularly acute in landing on planets, with a different (less or greater) gravitational field than the field of earth. However, answering them is the task of future experimental studies and future flights.

N75 23128

3. Means and Methods of Physical Conditioning of Man in Long Space Flights

The successful progress of astronautics is developing prospects for increasing the distance and duration of space flights. However, as follows from numerous works and the preceding sections of this book, even the relatively short orbital flights of recent years have shown that a stay of man in weightlessness can cause certain changes in the condition of the body, in particular, in the functional state of the locomotor and cardiovascular systems.

In numerous experiments simulating prolonged weightlessness (hypodynamia, immersion media), it has been determined that these conditions unfavorably affect the condition of the body of a healthy man. In this case, the overall and physical performance capacity is significantly disrupted, orthostatic tolerance decreases, coordination of accustomed locomotor acts is sharply disrupted, right up to partial or complete loss of the ability to move independently, the quantity of circulating blood decreases, atrophy of the skeletal muscles (especially of the lower half of the body) and demineralization of bone tissue take place, etc.

True, all these changes, expressed to a lesser extent, have been observed after space flights. This demonstrates the adequacy of simulation of the basic effects of weightlessness under ground conditions. Many authors, not without grounds, consider one of the basic causes of the development of functional disorders to be restriction of muscle activity (A. Korobkov, 1968; Miller, Johnson, Lamb, 1964, and others). Therefore, precisely for the purpose of prophylaxis of hypodynamic changes of spacecraft crews, various sets of physical exercises are proposed (Graveline, Barnard, 1961; /299
Graybiel, Clark, 1961; Lawton, 1962, and others).

It has been demonstrated that, to retain muscle strength, a brief (5-7 sec), maximum tension of the muscles once a day is sufficient (Müller, 1962; Dietlein, 1964). However, this type of exercise did not prevent other changes, in particular, reduction in orthostatic tolerance (Graveline, 1962). The combination of isometric stresses with dynamic exercises and with cyclic work on the bicycle ergometer, under conditions of prolonged bed rest, resulted in preservation of nearly all the basic physical qualities of a man, at a level close to the initial one. However, in these cases, after ending the experiment, sharp disruptions of orthostatic tolerance and walking disorders were observed (V. V. Bazhanov, V. I. Chudinov, 1965; A. V. Yeremin, et al., 1969, 1970; Birkhead, 1964; Triebwasser, Lancaster, 1971, and others).

On the basis of the results of analysis of data in the literature and of our experiments, the suggestion can be introduced that, to preserve orthostatic tolerance after a long stay in actual or simulated weightlessness, special actions on the vessels of the lower half of the body, reproducing the blood pressure on the walls of the vessels, are necessary. Under normal conditions, preservation of the normal vascular reaction is provided principally by means of a combination of hydrostatic and hydrodynamic blood pressure. The hydrostatic pressure is created in the vertical body position, on the principle of the pressure of a column of fluid on the walls of the vessels. However, it along still does not guarantee a normal reaction of the vascular system. More than that, a prolonged static action can cause temporary weakening of the pressor reactions (for example, the so-called fainting for show). In our opinion, hydrodynamic pressure, created by locomotor acts (walking, running), by means of inertial movement of blood, acting according to the principle of hydrodynamic "hammers," plays a significant role in regulation of vascular tonus. The fact is that in locomotion, by means of the reciprocating motions in the vertical plane, the human body (its solid and liquid media) experience inertial impact actions, the vector of which always is directed along the longitudinal axis of the body from the head to the feet. The daily quantity of such loads, even for a man living in a relatively immobile life style, is 20-24 thousand cycles per day, which corresponds to 10-12 thousand steps.

From the point of view of this hypothesis, the causes of the insufficient effectiveness of physical exercises proposed by various authors, for use in actual or simulated weightlessness, become understandable. These exercises have been mainly directed toward preservation of muscle strength and overall endurance, and they have included static tension, exercises with an expander and cyclical work of the pedalling type. Of course, they did not reproduce the hydrodynamic component of blood pressure on the vessel walls, the inertial-impact loads experienced by the support-motor apparatus, and they did not promote preservation of orthostatic tolerance and coordination of movement in locomotion. In other words, this means that the human body, under conditions of prolonged weightlessness or simulation of it, must receive a definite minimum of dynamic and kinematic loads, corresponding to those which occur under ground conditions.

Based on the theoretical considerations stated, we have developed a basic system of physical exercises for conditions of prolonged weightlessness, and we have created means of physical conditioning, which could provide for performance of physical exercises by spacecraft crews, for solution of the following problems: /300

-- creation of favorable emotions and improvement of performance capacity during a space flight;

-- prophylaxis of muscular atrophy, especially of the anti-gravitation musculature, and demineralization of bone tissue;

-- preservation of muscle strength and the power and general endurance of the body;

-- returning the reactions of the cardiovascular system to normal in the orthostatic body position and preserving the capacity for accomplishing natural locomotion (walking, running) after return to earth.

The set of physical conditioning means provided for performance of varying amounts and intensities of exercises of an isometric and dynamic nature, for practically all muscle groups; accustomed motor acts (walking, running); inertial-impact actions along the longitudinal axis of the body, by means of reciprocating movements in jumping, running, walking and squatting; static work of the anti-gravity musculature, dynamically adequate to the load, which this musculature experiences in retaining the vertical posture under ground conditions.

Fig. 83. CPT unit in pseudo-gravity test stand for training in horizontal position.

The means developed for these purposes were subsequently combined in an onboard complex trainer for physical training, CPT (Fig. 83), which included: 1) running path(treadmill) with electric drive; 2) gravity system; 3) conditioning-loading suit (CLS); 4) special footwear; 5) movable crossbar; 6) set of multilink expanders. /301

The treadmill permits assigning a forced running rate, at a speed of 10 km/hour. By switching off the electric drive, one can walk or run on it, resting on the handrails or elements of the gravity system. In performing jumps in place and various exercises, including those with expanders, the "running path" is locked.

The gravity system, in the form of elastic cords and the conditioning-loading suit, permits a load to be provided along the longitudinal axis, similar to the body weight and a "support effect" to be created, in actual or simulated weightlessness. The force of attraction to the treadmill is regulated over a broad range, from 0 to 70 kg.

Fig. 84. Conditioning-loading suit included in CPT trainer set.

The conditioning-loading suit is lightweight overalls with short sleeves and legs (Fig. 84). Rubber tapes, the degree of tension of which is regulated, are installed longitudinally in it, in the trunk region. The basic purpose of the suit is to provide for connection to the treadmill and to distribute 30% of the simulated weight load, created by the gravity system of the trainer, over the upper part of the body.

The special footwear (see Fig. /302 84) has reinforced, elastic soles, to damp the vibration loads and decrease heating of the soles of the feet, generated by movements along the roller conveyer of the CPT treadmill, and half-rings on the side, to fasten the foot-loading elements of the special, long-legged Athlete flightsuit. The movable crossbar, secured by eccentrics to elements of the gravity system, and the set of expanders allow performance of various speed-power exercises.

To use the CPT in laboratory experiments, with subject in the horizontal position, a so-called pseudogravity stand was developed, in the form of a welded truss. A CPT trainer treadmill was fastened to it in the vertical position; the subject, suspended by means of a system of cables, shock absorbers and soft support, was drawn to it by the gravity system (see Fig. 83).

In connection with the fact that any mechanical system of simulation of a gravitational load cannot provide ideal distribution of it over individual parts of the body, studies were carried out, to determine the optimum values of the loads along the longitudinal axis of the body. In addition, these studies were necessary to precisely define the weight and dynamic characteristics of the complex onboard trainer, considering the necessity for a maximum decrease of its weight, while retaining the operating qualities of the CPT. The studies were carried out under laboratory conditions in the vertical position, on the pseudogravity stand, as well as in parabolic flights in the laboratory-aircraft. The amounts of the loads along the longitudinal axis of the bodies in individual series of experiments were:

a) with subjects in the vertical position:

-- normal weight (without gravity system), normal gravity;

-- body weight +20 kg (by means of the CPT gravity system), hypergravitation;

b) on the pseudogravity stand:

-- "normal weight," simulating the force of attraction equal to the natural weight of the subject;

-- 50 kg (which is 60-70% of the weight of the "average man"), "hypogravitation";

-- "hypogravitation," simulating one-half and one-sixth of earth gravitation, i.e., with a force of attraction of one-half and one-sixth of the weight of the subjects);

c) In laboratory-aircraft flights, the load (by means of the pull of the CPT) for the subjects was 50 kg.

The studies were conducted with 24 volunteer men, 20-35 years old participating; 14 of them participated in the ground experiments and 10 men in the aircraft flights.

As should have been expected, in the first tests of work on the CPT, even with the subjects in the vertical position and without using the gravity system, the kinematic and dynamic characteristics, i.e., the biomechanics of locomotion, were somewhat changed. This frequently was connected with the limited size of the treadmill (85 cm long, 40 cm wide), but, mainly, with the lack of the skills of the subjects of walking and running on a moving belt. Similar changes were observed while working on the pseudogravity stand and in aircraft flight, when the body weight was simulated by the pull of the rubber shock absorbers in moments of weightlessness. However, these changes were brief. All the subjects easily and quickly adapted to moving on the treadmill. In studies under conditions of brief weightlessness (flights in the laboratory-aircraft), execution of movement was mastered in the first weightlessness cycles. Visual observations, as well as detailed biomechanical analysis of the motion picture and photographic cyclograms, shows that, after brief training, the kinematic characteristics of walking and running in the CPT were practically the same as in moving under normal conditions on earth. This was true, not only while preserving normal weight loads, but while decreasing it by up to 50%. /303

TABLE 77

KINEMATIC INDICES OF WALKING AND RUNNING ON CPT TREADMILL UNDER NORMAL CONDITIONS, IN HORIZONTAL POSITION AND IN WEIGHTLESSNESS

Index	Walking			Running		
	Normal conditions	Pseudo-gravitation 1/2 body wt	Weightlessness 50 kg pull	Normal conditions	Pseudo-gravitation 1/2 body wt	Weightlessness 50 kg pull
Rate, steps per min	120	125	122	180	176	178
Avg rate of movement, m/sec	1.30	1.27	1.27	2.58	2.52	2.54
Length of double step, cm	130	122	125	144	150	146
Duration of single support, sec	0.39	0.36	0.38	0.28	0.31	0.30
Duration of double step, sec	1.00	0.96	0.98	0.64	0.72	0.68
Duration of double support, sec	0.12	0.12	0.11	-	—	—
Duration of airborne interval, sec	—	—	—	0.04	0.05	0.05
Foot reaction angles, °:						
Front thrust	74	76	75	81	80	79
Rear	73	71	71	70	71	72
Vertical swings of joint, mm;						
Hip	40	35	37	95	100	98
Knee	95	85	88	145	135	140
Ankle	180	175	177	230	250	242
Angles between links, °:						
maximum forward thrust of hips (from vertical)	32	29	30	31	32	30
same, backward	11	13	14	14	12	13
forward thrust of shins (from vertical)	3.0	4.0	3.7	0	0	0
same, backward	60	61	62	77	82	79
minimum knee angle	108	106	107	92	87	90
forward tilt of body (from vert.)	6.0	4.5	6.5	12	11	13
Maximum rate of movement of joints, m/sec:						
longitudinal components:						
knee joint	1.250	1.375	1.350	2.000	1.575	1.950
ankle "	2.250	2.375	2.325	2.875	2.750	2.800
Vertical components:						
knee joint	0.875	0.625	0.775	1.000	0.875	0.925
ankle "	1.000	1.125	1.100	1.500	1.375	1.425

The kinematic characteristic of walking and running on the treadmill under normal conditions and on the pseudogravity stand, simulating one-half the body weight (subject N), as well as during flights in the laboratory-aircraft (subject S), are presented in Table 77.

The data obtained indicate that exercises on the CTP, even with a considerable decrease in weight load, do not change the coordination mechanisms of locomotion, which are inherent in man under normal conditions. This permits it to be recommended as an onboard physical training facility.

In addition, studies have shown that, in simulation of the total weight load, unpleasant sensations of strong pressure develop in a number of cases and, sometimes, fraying of the skin at the locations of the elastic elements of CLS and the CPT gravity system connected to it. These unfavorable phenomena were successfully avoided by decreasing the pull, but, in return, the energy "cost" of the load decreased. The most acceptable compromise solution was to decrease the simulated weight to 50 kg (60-70% of the natural weight). In this case, a 15-20% reduction in energy "cost" of the load was compensated by an increase in duration and intensity of the physical exercises.

The metabolic and energy "costs" of the set of exercises were the subject of a special study; knowledge of them is necessary, for evaluation of the caloric adequacy of the food ration and calculation of the life support system. For this purpose, respiratory metabolism parameters (oxygen consumption and carbon dioxide discharge) of the subjects were continuously recorded, using the Spirolit metabolograph, during a typical training exercise, for a period of an hour, with two different "gravitational loads": natural body weight in the vertical position and with a 50 kg "gravitational" load in the horizontal body position. The data obtained are represented in Table 78 and in Fig. 85.

TABLE 78

ENERGY CONSUMPTION vs. BODY POSITION AND GRAVITATIONAL LOAD

Subject	Body Position	Body wt. (pull) kg	Oxygen consumption in 1 exercise (60 min), l			Energy consumption in 1 exercise (60 min) kcal		
			Total	Rest level	Above rest level	Total	Rest level	Above rest level
B	Vertical	68.8	75.3	14.4	60.9	368	70	298
	Horizontal	50.0	64.0	13.8	50.2	314	67	247
N	Vertical	72.2	78.34	18.0	60.34	384	87	297
	Horizontal	50.0	66.7	16.8	49.9	328	81	249
Sh	Vertical	84.6	88.5	20.2	68.3	432	99	333
	Horizontal	50.0	74.8	18.0	56.8	366	87.5	278

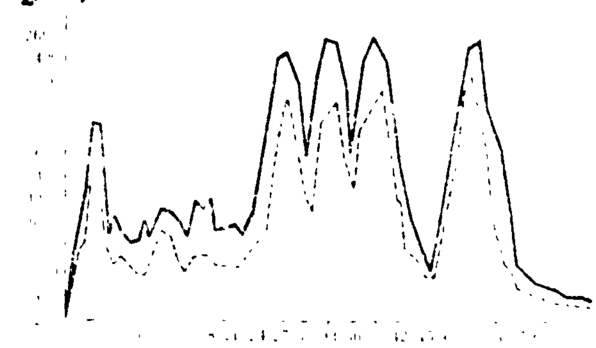


Fig. 85. Dynamics of oxygen consumption in training exercise on CPT: 1, vertical position, body weight 72.4 kg; 2, horizontal position, 50 kg pull

It follows from Table 78 that, in calculations for the "average" man, weighing 70 kg, the oxygen consumption and energy consumption above the rest metabolism level in a 2-1/2-hour training exercise under normal earth conditions, was 145 l of oxygen, or 710 kcal, respectively. In the horizontal position and with a "pull" to the plane of the treadmill, with a force of 50 kg, the identical load had an oxygen "cost" of about 120 l, and its energy equivalent was about 580 kcal. In the period from 1965 to 1971, we conducted numerous complex experiments, in which the effect on the body of long (from 30 to 100 days) hypodynamia was studied, and various means of prophylaxis of the hypodynamic disorders were approved. Tests of the effectiveness of physical conditioning resources were carried out in five studies, with 30 healthy men, 20-27 years of age participating; five experiments served as the control.

TABLE 79

CHANGE IN CERTAIN INDICES OF PHYSICAL CONDITION AND PERFORMANCE CAPACITY OF SUBJECTS AFTER PROLONGED HYPODYNAMIA (70-100 days)

Physical Condition Indicator	Group	
	Control	with Physical Exercises
Amount of change in body wt., kg	from -2.0 to -6.4	from -0.5 to -2.6; in 3 cases, from +0.5 to +0.8
Physical performance capacity (on bicycle ergometer)	decline by 34-91%	practically unchanged
Locomotor acts (walking, running)	considerable disruption, right up to lack of ability to move and stand	" "
Orthostatic tolerance	decline to collapse	unchanged or slight reduction (improvement in 3 cases)
Power endurance	34-80% decrease	Unchanged or increase up to 134%
Static endurance	24-60% "	unchanged or increased by 30-100%
Work efficiency (by oxygen consumption and oxygen "cost" of loads)	appreciable decline	practically unchanged

TABLE 80

CHANGE IN ABSOLUTE MUSCLE STRENGTH OF SUBJECTS AFTER 70- 100-day HYPODYNAMIA (average data in kilograms)

Muscle Group	Control Group			Exercise on CPT		
	Before	After	Δ, %	Before	After	Δ, %
Shoulder flexors	24.3	22.5	−7.4	34.8	37.2	+6.9
Forearm "	25.2	23.7	−6.0	28.7	33.9	+18.1
Hip "	24.9	28.0	+12.4	29.1	30.0	+3.0
Trunk "	23.3	21.6	−7.3	35.4	36.6	+3.3
Shin "	36.8	38.9	+5.7	42.2	40.2	−4.7
Antigravity:						
trunk extensors	189.3	104.2	−44.4	165.7	157.9	−4.7
hip "	120.1	82.6	−31.2	133.4	122.4	−8.2
shin "	16.8	12.7	−24.4	18.5	20.7	+11.9
Foot flexors	114.9	55.5	−51.7	133.7	143.8	+7.6

The results of the study are convincing evidence that, owing /306 to the proposed physical training system, using the CPT trainer, manifestations of the hypodynamia syndrome have been significantly decreased and some of them have been almost completely prevented. Thus, the physical condition of subjects performing exercises on the CPT, in distinction from persons in the control group, is practically unchanged from the initial state (Table 79). More indicative was the fact that, having trained on the CPT, by the end of the experiment, they could almost immediately walk and run normally. Biomechanical studies have not disclosed significant changes in locomotion. At the same time, subjects of the control groups, depending on the length of hypodynamia, either could not only not walk at all, but could not maintain the vertical position (after 100 days of hypodynamia), or moved with difficulty with a loose walk, leaning on surrounding objects with the arms or using the assistance of other people. They complained of pains in the feet, calves, thighs and buttocks. An outward return to normal of the walk took place only by the 10th-14th day. Delicate biomechanical indices of locomotion were restored only after 1 - 1-1/2 months. The subjects could perform such exercises as the half-squat or squat, only on the 6th to 11th day after leaving the state of experimental hypodynamia.

A significant indicator of the effectiveness of physical exercises in the CPT is retention or negligible reduction in the initial level of orthostatic tolerance, while that of people in the control groups decreased sharply and, after 70-100 days of hypodynamia, orthostatic syncope was observed.

The change in strength of various muscle groups, especially the antigravity ones, is very characteristic (Table 80). The strength of the shoulder, forearm, hip, calf and trunk flexors changed negligibly and in different directions, especially in control group subjects. This apparently was connected with differing degrees of muscular activity in performing everyday operations (eating, reading, toilet, etc.). No distinct regularities could be noted here.

In a comparison of the change in antigravity musculature, the considerable reduction of strength in the control group is striking. It amounted to 85-90% of the initial value in some subjects (for the foot flexors). In the group of subjects performing physical exercises on the CPT, either a small reduction or even an increase in /307 strength was noted.

The results of functional tests with graded workloads on the bicycle ergometer indicate a marked functional stability of subjects exercising on the CPT: the metabolism level and the stress of the cardiovascular system under load and in the recovery period, characteristic of each subject and group overall, were practically unchanged during the entire experiment with hypodynamia. For the control group people, after 100 days of hypodynamia,the total amount of workload (6600 kgm) proved to be infeasible. In this case, the basic physiological indices increased considerably, which indicates a reduction in performance capacity and work efficiency (Fig. 86).

Everything stated above, as well as the emotional attraction of physical exercises on the CPT, of which all subjects spoke permit this trainer to be recommended for use aboard a spacecraft.

The set of training exercises developed for use in a space flight and tested in model experiments was compiled on the basis of a cycle of three workload days and one day of active recreation (3 + 1 cycle). The exercises of each of the three workload days were primarily directed toward solution of specific problems.

First day: preservation of the speed-strength quality and orthostatic tolerance; amount of workload small, rate submaximum and maximum, energy "cost" 380-420 kcal.

Second day: maintenance of strength endurance and preservation of orthostatic tolerance; amount of workload medium, rate medium, energy "cost" 450-500 kcal.

Third day: maintenance of overall endurance of the body, preservation of orthostatic tolerance, overall coordination of movement; large volume of work, low intensity, energy "cost" 550-580 kcal.

Fourth day: active recreation, performance of functional tests; workload low, intensity as desired by subjects; energy "cost" about 150 kcal.

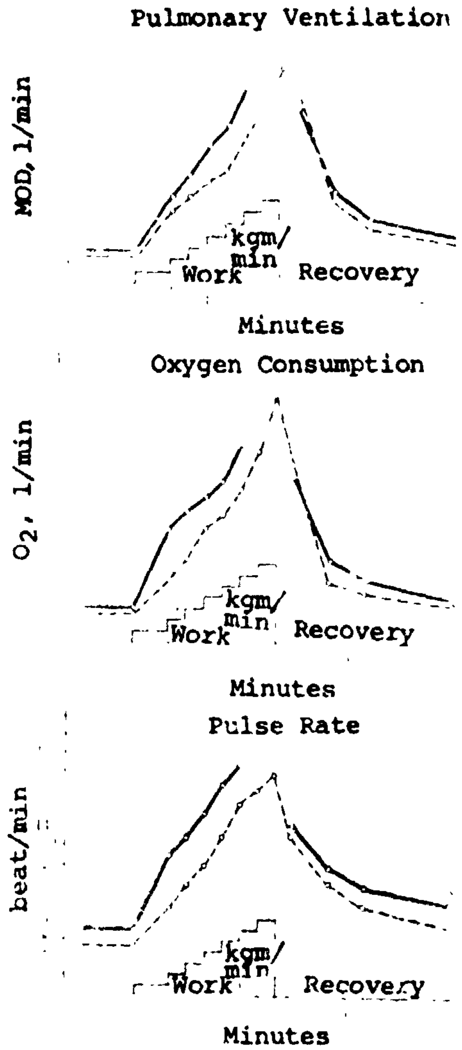


Fig. 86. Performance capacity and work efficiency of subjects after 100-day dynamia: a, control group; b, physically conditioned group

It was specified that, in flight, each astronaut would exercise on the CPT twice daily for one hour each and one time for 30 min (morning gymnastics and evening walk). The total daily workload in the four-day cycle was 450 kcal, on the average.

Some elements of the physical trainer were first used in prolonged weightlessness, in the 18-day flight of A. G. Nikolayev and V. I. Sevast'yanov in Soyuz 9. The training program specified performance of physical exercises twice a day, for 30 min each. For this, a collapsible platform and shock absorber binding system were placed in the living section of the craft. The astronaut, dressed in the CIS-1 conditioning-loading suit (Fig. 87), attaching the shock absorber binders to the latter, provided himself a support with a force of 20 kg and, standing on the platform, could walk and run in place, perform jumps, squats, tilts, exercises with special rubber shock absorbers and coordination exercises.

As should have been expected, the physical workload proved to be insufficient. From the results of functional tests with measured physical workloads, performed /308 periodically by the astronauts during the flight, as well as at the request of the Soyuz 9 crew members themselves, A. G. Nikolayev and V. I. Sevast'yanov, the in-flight physical training program was changed: the duration of each exercise was increased to 60 minutes, certain exercises were replaced, the duration of performance of the most heavily loaded exercises was increased, etc. The calculated energy "cost" of the training exercises amounted to about 240 kcal per day, on the average, in this case, i.e., approximately one-fifth of the usual terrestrial motor activity of a man. Of course, this amount of workload could not replace the deficit of terrestrial muscle activity of the astronauts and prevent asthenization of the body.

Fig. 87. Sc... 9 spacecraft commander before performing physical exercises.

The results of the preflight examinations of A. G. Nikolayev and V. I. Sevast'yanov are reported in the appropriate publications (O. G. Gazenko, P. V. Vasil'ev, 1970; I. F. Chekidra, et al., 1971; L. I. Kakurin, et al., 1972; Yu. G. Nefedov, et al., 1972, a others; see also section 3, Chapter 3 and other parts of this book); therefore, we limit ourselves to mention of the reduction in orthostatic tolerance, decline in physical performance capacity and locomotion biomechanics. Inadequate loading of the antigravity musculature led to atrophy of it: the thigh and calf perimeters decreased by 2-4 cm; the muscle strength decreased considerably (Table 81). According to the reports of the astronauts, for a period of a week after the flight, they felt a gradually disappearing sense of increased heaviness of the entire body and individual parts.

Following special readaptation measures, movement coordination was gradually recovered, muscle strength increased, painful sensations in the region of the back, hips and hand gastrocnemius muscles disappeared.

However, even two weeks after the flight, the leg muscle mass was still reduced. Symptoms of asthenization of the body were observed 25-30 days after the flight. Nevertheless, despite the insufficient amount of physical workload and the limited nature of /309 the onboard conditioning facilities, the astronauts evaluated physical exercises favorably. They noted an improvement in well-being and performance capacity after the exercises. In this case,

TABLE 81

CERTAIN INDICES OF PHYSICAL CONDITION OF SOYUZ 9 CREW MEMBERS

Physical Condition Index	A. G. Nikolayev		V. I. Sevast'yanov	
	Preflight	After	Preflight	After
Body weight, kg	65.0	62.3	68.0	64.5
Perimeters. cm:				
right arm	26.7	26.8	26.7	26.3
" thigh	45.1	47.0	54.8	50.6
" calf	34.5	33.1	35.2	33.2
Hand dynamometry				
right	74	74	44	44
left	52	52	46	36
Central force, kg	170	120	190	125
Static endurance, half-squat exercise, sec	80	25	64	42
Pulse reaction to 2-minute step test, relative units	100	79	116	84

it was considered that the pulling force must be at least doubled and the exercisetime increased.

Fig. 88. Long-legged Athlete conditioning loading suit

Considering the results of the 18-day flight of Soyuz 9, the recommendations of the astronauts and, also, the results of the many-day experiments conducted up to this time, using means of prophylaxis of hypodynamic disorders, the physical training set for the Salyut space station was expanded. The CPT multiple trainer was installed aboard the station, for performing physical exercises under actual flight conditions. The binding system provided a total pull to the treadmill path of 50 kg. It was planned that the astronauts would perform physical exercises on the trainer to the full extent, with the exception of the first 3-5 days of the flight (adaptation period), when a decrease in workload to 50% was permitted. Moreover, for more complete compensation of the deficit of accustomed terrestrial activity of the antigravitation musculature, the most "unloaded" in weightlessness, and to create axial loads on the skeleton, the use of the Athlete conditioning- /310 loading suit by each crew member was specified (Fig. 88). These suits had to be used in place of the flight clothing, in the intervals between training sessions, i.e., during the hours of occupational work. Periodic turning on of the power system of the suit, between three and six sessions per day, for 40-60 min each, depending on the conditions and nature of the occupational activity, was prescribed by special instructions.

During the flight of Salyut, for technical reasons, running was eliminated from the set of physical exercises performed on the CPT trainer. In this connection, the following corrections were made in the physical training program: the released time devoted to running, as well as the additional 30 min for each crew member eliminated from the overall schedule, was used for walking exercises, so as to ensure a planned level of energy consumption in physical training. For this purpose, it was recommended that the brake of the running path be engaged twice per exercise, for 1 minute of the walking time.

Thus, during the flight of Salyut, the astronauts were occupied with physical exercises three times a day (two times at 75 min each and one time at 30 min), with the exception of the active recreation periods (every 4th day of the 3+1-cycle), when functional tests were conducted with physical workloads on the CPT trainer, after which the selection, amount and nature of the physical exercises were determined as the person exercising desired. Moreover, by request of the astronauts, they were permitted to use the Athlete costume, with the loading system "switched on," all day long, with the exception of sleeping periods. The degree of tightness of the elastic loading elements was regulated independently by the crew members.

Unforeseen situations arising during flight led to the situation in which the astronauts sometimes omitted physical training, replacing them to the full extent. The sequence of exercise, worked out by day of the 3+1 training cycle also was disrupted. Moreover, because of breakdown of the movable crossbar of the trainer, certain exercises had to be canceled.

Of course, everything stated above decreased the effectiveness of the physical training and hampered analysis of the medical telemetry obtained from onboard. However, during radio conversations and in entries in the logs, the Salyut station crew members favorably evaluated both the exercises on the CPT and the conditioning-loading /311 suits. Understanding the importance of physical training, the astronauts applied every effort to fulfill the prescribed schedule of physical workloads as much as possible. According to the reports of the astronauts, the physical exercises generated pleasant feelings. There were no limitations on performance of the exercises. Fatigue connected with the physical workload did not accumulate. It should be noted particularly that, by the end of the flight, the physical exercises became a need of the crew.

TABLE 82

CHANGE IN CERTAIN ANTHROPOMETRIC INDICES OF SALYUT ORBITAL STATION CREW MEMBERS

Name	Body weight, kg		Perimeters, cm					
			Upper Arm		Thigh		Calf	
	Before flt	At End of flt	Before flt	At End of flt	Before flt	At End of flt	Before flt	At End of flt
G. T. Dobrovolskiy	[illegible]	77.[illegible]	[illegible]	31.5	59.5	56.5	[illegible]	34.0
V. N. Volkov	83.3	80.[illegible]	[illegible]	30.5	56.5	55.0	38.5	36.5
V. I. Patsayev	74.6	70.[illegible]	28.5	28.5	56.0	53.0	37.0	35.0

The tragic end of the flight of the Salyut crew significantly hampered detailed analysis of the effectiveness of physical training in flight, as a means of prophylaxis of disorders caused by the effect of weightlessness. However, a number of physical condition indices, change in body weight and limb perimeters in particular (Table 82), indicate that the prophylactic means used considerably weakened development of the weightlessness and hypodynamia syndrome. The weight loss was 2.74, 3.73 and 3.9 kg, i.e., they did not exceed the losses observed in other, shorter flights of Soviet and American astronauts, as well as of subjects in ground experiments, simulating the conditions of prolonged weightlessness (see Table 79). /312

As should have been expected, the upper arm perimeter was practically unchanged during the entire flight (the measurements were made periodically during the flight, by the crew members themselves). The thigh perimeter decreased by 1.5-3 cm and that of the calf, by 2 cm.

Altogether, the results of the Soyuz 9 and Salyut orbital station space flights permit one to speak of the favorable effect of the proposed physical exercise system, applicable to weightless conditions, on the general condition and state of health of the astronauts, as well as of the advisability of use of the CPT trainer and the conditioning-loading suits as onboard physical training resources.

The recommended sets of physical exercises do not cause overtiring, overtraining or unpleasant subjective feelings, under prolonged space flight conditions, and, to a considerable extent, they prevent development of the hypodynamia syndrome. Space flight experience and the numerous experiments, with laboratory simulation of weightlessness, carried out in the Soviet Union and abroad, have created a sound theoretical basis for solution of a number of practical problems of development and introduction of means for reducing the unfavorable effects of prolonged weightlessness on the human body. Materials have been obtained, which are necessary for plotting a scientific prognosis of the expected aftereffects of a prolonged stay of man in the state of weightlessness, the mechanisms of formation of individual disruptions have been studied, and promising directions for prophylaxis of these disruptions have been determined.

The results of medical examination of the Soyuz 9 crew permit it to be asserted that the previously made prognoses have been confirmed and that, consequently, such problems of practical importance as testing prophylactic means can be successfully solved in laboratory models of weightlessness.

The group of disruptions, for which development and use of prophylactic measures are particularly necessary, has now been clearly defined.

The disruptions described, as the majority of investigators state (A. M. Genin, P. K. Sorokin, 1969; A. V. Korobkov, 1968; A. V. Yeremin, 1969, 1970; V. I. Stepanstov, et al., 1972; Graveline, 1962; Lamb, et al., 1965, and others), and as they have been described in detail in the first section of this chapter, are based on a number of pathogenetic mechanisms, the main ones of which are removal of gravitational loads on the body and the absence of hydrostatic blood pressure flowing from this and the redistribution of the blood in the body connected with the latter, as well as the decrease in energy consumption in moving, maintaining posture and other processes

The absence of the accustomed amount of inertial-impact loads along the longitudinal axis of the body and, correspondingly, the hydrodynamic component of blood pressure are of great importance. /313

Each of these mechanisms is a trigger, it entails formation of a chain of mutually dependent secondary effects, which ultimately leads to development of the disruptions, combined under the concept of "hypodynamia syndrome."

The experimental research carried out indicates that shifts, predominantly caused by the unfavorable effect on the body of prolonged hypodynamia (decrease in volume and strength of muscles, physical performance capacity, orthostatic tolerance, mineral saturation of the bones, coordination of movement in locomotion), are quite effectively prevented by use of the principles, means and methods of physical training.

In this respect, the official CPT trainer for physical exercises aboard spacecraft is promising, from the point of view of both preservation of the primary qualities of the locomotor system and physical performance capacity of the body, and of a significant decrease in disruption of orthostatic tolerance, owing to the presence of the hydrodynamic component of blood pressure, generated in locomotor acts on the CPT (walking, running, jumping).

Methods of prophylaxis of disorders caused predominantly by reduction or absence of hydrostatic blood pressure in weightlessness and in experimental stimulation of it (readjustment of the water-salt metabolism, relative dehydration, disruption of competence of the cardiovascular system with respect to orthostatic loads, etc.), also are adequately substantiated. Two theoretically possible approaches to prophylaxis of this type of disorder should be examined here: the use of methods of simulation of the effect of hydrostatic blood pressure in flight and decrease in the gravitational redistribution of blood to the lower part of the body in the postflight period.

In particular, the method of negative pressure in the lower region of the body, use of which during experiments with simulation of weightlessness gave favorable results, is promising (A. M. Genin, I. D. Pestov, 1972; Lamb, et al., 1965; McCally, et al., 1966; Stevens, et al., 1966, and others).

A significant decrease in orthostatic disorders after completion of such experiments also was achieved by use of g-suits or other types of special clothing, producing excess pressure on the lower part of the body (I. D. Pestov, et al., 1972; Miller, et al., 1964, 1965; Vogt, Johnson, 1967).

Thus, the effectiveness of prophylactic measures, in our opinion, is determined by their complexity and multiplicity of action on the body.

In this case, in prolonged weightlessness, maintenance of the functional capabilities of various body systems and preservation of the complex integration of physiological mechanisms, determining the fine and precise coordination of motor and vegetative functions necessary in the activity of man in earth gravity, must be ensured.

4. Problem of Artificial Gravity from the Point of View of Experimental Physiology

N75 23129

In finding ways and means to provide for preservation of the /314 health and adequate performance capacity of astronauts upon their return to earth after a long stay in weightlessness, two directions are conceivable at the present time:

-- development of a set of methods and means, used immediately upon the landing of the astronauts, so as to quite quickly and painlessly restore the functioning of their different physiological systems to the "earth" level;

-- development of a set of methods and means, which must be used in flight and, thereby, prepare the human body before landing, for its "earth" level of functioning.

The methods and means which were spoken of in the preceding sections may be included in the latter set. Among the methods of prophylaxis of the unfavorable disorders under weightless conditions and, therefore, in the period of readaptation to the gravity of earth also are the creation of artifial gravity (AFG) in spacecraft and orbital stations.

The idea of use of this method of control of the unfavorable effect of weightlessness was first expressed in the scientific world by K. E. Tsiolkovskiy.

In the work *Study of Universal Space* (1911), he wrote: "Even if it turned out that people cannot live without gravity, it would be easy to create it artificially in an environment where it does not exist. For this, the habitation of man, even if a rocket need only have rotational motion imparted to it; then, as a consequence of the centrifugal forces, an apparent gravity is formed, of the desired magnitude, depending on the dimensions of the habitation and its rotation rate. This gravity is all the more convenient, but it can be arbitrarily small or large and can always be annihilated and again renewed."

Examination of different versions of orbital stations with AFG began only 50 years later, in connection with the flight of Yu. A. Gagarin. However, the authors of these plans contemplated creation of artificial weight, guided only by technical considerations.

From the point of view of experimental physiology, two questions are of significant value for solution of the AFG problem. First and foremost, it must be ascertained what minimum acceleration should be used in space objects, to create relatively effective artificial body weight and, second, not only the spacecraft rotation rates permissible for a man must be determined, but the possibilities of life and activity in long-term rotating systems.

The latter question involves the nature of development of motionsickness under prolonged complex accelerations, and it involves one of the complex general problems of the physiology of adaptation of the body to stress.

The first work on the experimental-physiological basis of the minimum effective AFG, necessary for maintenance of normal body posture and movement coordination, were conducted in 1961, in the Soviet Union (Ye. M. Yuganov, P. K. Isakov, et al., 1962). The studies were c[illegible]ied out with animals The magnitude of the /315
centripetal fo[illegible], at which the position and nature of movement of the animals were similar to their normal laboratory behavior, was adopted as that, necessary to create the minimum effective AFG.

An analysis showed that, in weightlessness, the animals rotated at random, in various planes, sometimes, in two or three simultaneously.

The rotation rate around the longitudinal axis of the body was 0.5-1.5 for the rats and 1.0-3.0 turns per second, for the mice. In creating AFG, with acceleration from 0.05 to 1.0 g, the nature of the motor activity of the animals changed significantly: corresponding to an increase in the magnitude of the accelerations produced, the movement approximated the terrestrial type more and more. With small accelerations, the animals were directed to the wall of the apparatus; however, up to 0.08 g for the mice and up to 0.18 g for the rats, half-turns around the longitudinal axis of the body were still observed now and then. At high accelerations (up to 0.28 g), the animals rested the limbs on the surface of the apparatus and made attempts to move along the walls; however, the paws slipped, the movements were very peculiar and the direction of movement continually changed.

In creating accelerations of over 0.28-0.3 g, the behavior of the animals in flight was the same as under laboratory conditions. The animals occupied the "sitting" position characteristic of them or moved slowly and quietly. Beyond this limit, their movements were smooth and quite coordinated, in all cases.

Though the motor activity of mice and rats in weightlessness differed, the magnitude of the accelerations required for complete recovery of coordination of their movements and posture turned out to be the same in both cases. On this basis, an acceleration of 0.3 g was acknowledged to be the minimum effective value, necessary for creation of artificial weight.

The considerations presented were considered to be preliminary. They were refined in subsequent experiments on other animals, in which the criterion of the acceleration necessary to create AFG were not only the motor acts, but other indicators, characteristic of the condition of the motor system of the body. In particular, in experiments (Ye. M. Yuganov, 1967), in which the bioelectric activity of the muscles was recorded, it was found that the first signs of increase in it, compared to the activity of muscles in weightlessness, developed at a AFG of 0.15 g. Between 0.15 and 0.28 g, the biopotentials increased, in parallel with increase in the transverse g-forces. The amplitude characteristic of the bioelectric activity in artificial gravity turned out to be equivalent to the value characteristic of normal earth conditions, with a force of gravity of 0.28-0.31 g.

Subsequently, despite the increase in magnitude of the effective g-force to 0.6-0.7 g, no noticeable increase in biopotential amplitude was found; their values equaled the actual amplitude at 0.28-0.31 g.

Therefore, on the basis of data on keeping the electrical activity of the skeletal muscles of the animals normal, it also was concluded that an acceleration of 0.28-0.31 g can be acknowledged as the minimum effective value of the artificial gravity.

Applied to the activity of man in a space flight, this position, of course, requires additional proof. The competence of these conclusions was confirmed by the work of American investigators. According to their statement, an acceleration of 0.277 g can be considered to be an adequate value, not only for prevention of motor disorders in animals, but to bring the motor reactions of man to normal (Loret, 1963). /316

In examining the physiological problems of AFT, we considered that the magnitude of the latter would depend on the singularities of the functions and interactions of various analyzer systems, first and foremost, the role of the vestibular analyzer in this functional system. The assumption of that maintenance of normal motor activity at 0.3 g depends primarily on this analyzer and that labyrinthectomy leads to an increase in the acceleration required for AFT, appeared to be right. For labyrinthectomized animals, the latter could be determined primarily by the reactions of the neuroreceptor formations of the tactile and motoranalyzers to the action of mechanical forces.

In connections with this, studies were carried out on animals (mice), with bilateral permanent labyrinthectomy (Ye. M. Yuganov, D. V. Afanas'yev, 1964). The animals were used in the experiment, only in the period of complete compensation of the motor disorders. It turned out that, in this case, the mice did not rotate at all in the state of weightlessness. They quietly "sailed" in the air in any body position relative to "up" and "down," they preserved some similarity of normal posture and did not make abrupt movements. When they were brought in contact with the walls of the container, by the transiently developing very low accelerations in the aircraft, the animals even attempted to move; in this case, their movements were smooth and coordinated, although the paws slipped on the surface of the glass.

These facts are in agreement with Beckh's data (1954). In his tests, labyrinthectomized mice, with compensation of motor disruptions, retained the natural posture and moved about normally over the wall of the container, in parabolic aircraft flights with artificial gravity, created by a total acceleration of 0.1 g, while 0.3 g was required for this, in tests with intact animals.

This can be explained in the following manner. In permanently labyrinthectomized animals, compensation of motor disorder indicates creation and reinforcement of a new form of integration of the function of the remaining analyzers. The newly formed interactions of the afferent systems of the test mice were not significantly disordered in weightlessness, since the most sensitive indicator of change in the force of gravity (the otolith apparatus) was absent in the new functional structure. The action of weightlessness on the tactile and motor analyzers showed up considerably less in the integral activity; therefore, the magnitude of the acceleration sufficient for retention of normal posture and movement turned out, in this case, to be one-half or one-third that in experiments with intact animals.

Considering this factor, we can conclude that the peculiarities of function of the vestibular analyzer in weightlessness are not promoted, but the formation and normalization of motor acts are prevented and an increase in the necessary AFG is determined. In connection with this, it can be assumed that the necessary artificial gravity of 0.3 g for intact animals is determined mainly by /317 disruption of the interaction of the analyzers, owing to the unusual effect of weightlessness on the vestibular apparatus.

Another circumstance confirms this thought. The action of weightlessness creates a picture of disorders characteristic of acute disruptions of vestibular analyzer functions. Disorders of motor activity and postural reactions of the animals do not differ outwardly in any way from similar disorders, caused by experimental cutting off of the labyrinth.

Thus, studies of domestic and foreign authors demonstrate that, in weightlessness, for orientation of the body in space, preservation of movement coordination, as well as for maintenance of the necessary level of certain physiological indices, the measure of artificial gravity in space objects of the future may be preliminarily determined by the range 0.28-0.31 g, i.e., one-third of normal earth gravity.

Creation of this range of artificial weightiness is possible, with various angular accelerations of rotation of the satellite, as a function of the radius of rotation.

A limited amount of work has been devoted to study of the activities and processes of adaptation of man, under conditions of prolonged rotation. They were begun in the Soviet Union and abroad in the 1960's (A. V. Lebedinskiy, et al., 1963; R. R. Galle, M. D. Yemel'yanov, 1967; Graybiel, Clark, Zarriello, 1960; Clark, Graybiel, 1961; Kennedy, Graybiel, 1962).

In the first stages, a large portion of the studies were conducted with rotation, not exceeding 1-2 days in length. In 1964, Guedry and colleagues (1964) carried out a two-week experiment with continuous rotation, at a rate of 18° per second.

Graybiel and collagues (1960) published the results of experiments, with rotation at a rate of 60° per second and lasting 12 days.

Newsom, Brady and Goble (1964) observed slackening of the symptoms of motionsickness in a revolving space station simulator (MRSSS) during a five-day experiment, with rotation at a rate of 36° per second. R. R. Galle and M. D. Yemel'yanov (1967), during studies in a MVK-unit, noted the onset of persistent adaptation to rotation at a rate of 10° per second and partial acclimatization at a rate of 40° per second, in an experiment seven days long.

Graybiel (1969) could summarize all these and later data, in the form of the following characteristics of tolerance of rotation by a healthy man, with a stable vestibular function (with radii between 1.5 and 7 m and centripetal accelerations up to 0.3 g):

60° per second, 4 hours;
40° " " 7 days;
36° " " 14 days (persistent adaptation).

Disruption of performance capacity and development of the motionsickness syndrome are connected primarily with the effect of Coriolis acceleration. The maximum permissible rotation, of course, decreased with decrease in stability of the vestibular analyzer.

Considering the numerous labyrinth and extralabyrinth factors determining the development of adaptation to rotation, as well as the statements of the investigators listed, relative to the result of the experiments, the rate of 10° per second could be proposed as the initial, optimum, tolerable magnitude of prolonged rotation. Subse- /318 quent significant refinement of this value, in accordance with our expanding knowledge on the functions of the analyzers in weightlessness, is not excluded.

There is a basis for thinking that, if the sensitivity of the static-kinetic analyzer to linear and angular accelerations under weightless conditions changes, this might be reflected in the parameters defining AFC (A. M. Genin, 1965).

It follows from the data on the dependence of angular velocity on radius of rotation (the radial acceleration is assumed to be 0.3 g) that an increase in radius leads initially to a sharp decrease in angular velocity of rotation; the curve of the function then changes smoothly, i.e., further increase in radius has almost no effect on angular velocity. Considering the experimental data on the permissibility of a rotation rate V = 10° per second, we think it possible, from the medical point of view, to consider the optimum radius of rotation of objects to be R= 90 m, in which variations in weight of the astronaut as he moves in the direction of the rotation does not exceed 0.25-0.35 g.

N75 23130

CHAPTER 6

PERFORMANCE CAPACITY OF MAN IN WEIGHTLESSNESS

1. Training of Astronauts in Laboratory-Aircraft Under Weightless Conditions for Work in Space

The basic task of training astronauts for occupational /319 activity in space is optimization of the interaction of man with various spacecraft designs. Of course, maintenance of identity of training conditions and actual performance of work creates the greatest guarantee of reliability and efficiency of reactions of man in space. In training the first astronauts for flights in the Vostok spacecraft, training in weightlessness, conducted in special aircraft, for the purpose of revealing the effects of weightlessness, both directly on the human body and indirectly on his activities, occupied a significant place. The importance of these studies is dependent on a number of circumstances. For example, in performing work in free space, the development of disproportionment speeds by an astronaut in pushing away from a support may lead to trauma. An inadequate level of adaptation and individual intolerance of the effects of space flight factors threatens loss of performance capacity, since the conditions of existence become less favorable for the body.

The initial period of the conquest of space was characterized by study of the simplest (psychophysiological) forms of interaction between the body of the astronaut and the unusual living environment and with elucidating the question of the possibility of human activity under weightless conditions. The experience of the space flights of Vostok 1 - Vostok 6 and Mercury craft demonstrated the possibility of an active life, but work in space in these flights was not of primary importance. In accordance with this, the training exer- /320 cises of the astronauts in weightlessness before a space flight were carried out, for the purpose of familiarization with weightlessness, finding out the possibilities of performing the simplest everyday acts (eating food, drinking water) and certain work operations (conduct of radiocommunications, one- and two-component object movements), as well as study of the psychophysiological reactions to alternate g-forces and weightlessness. The transition period in the conquest of space was characterized by study of complicated forms as physical interactions, such as an astronaut staying and moving inside and outside the craft (Voskhod - Voskhod 2 flights). The successful extravehicular activity of A. A. Leonov became the beginning of the conquest of space, when, together with continuation of the study of psychophysiological and physical interactions, the principal attention is given to active occupational activity of the astronauts inside and outside spacecraft, using special equipment (spacesuits, backpacks, etc.), gear and tools.

The qualitative complication of space flight programs led to the necessity for finding new, adequate methods of training astronauts under ground conditions. Laboratory-aircraft flights in weightlessness permitted solution of the problems posed in the best way. The training was conducted by a support team, which included representatives of various occupations, including physicians and methodologists. Various motor and vegetative reactions were recorded in the training process. Indices of vitally important functions were produced on videoscopes in numerical values, which made it possible to monitor and correct the course of training in good time. The correctness of the direction adopted was confirmed by the experience of successful fulfillment of the missions of astronautics, under space flight conditions.

The following work can be carried out in flying laboratories:

1. Working out a procedure for training astronauts, in accordance with the singularities of forthcoming space flights;

2. Working out the optimum methods of performing piloting operations, applicable to typical spacecraft, in mock-up sections;

3. Testing of special equipment, units and tools by the astronauts;

4. Work to efficiently match man and technical systems (design changes, in accordance with the requirements of anthropotechnics and biomechanics, as well as use of methods of performing work, applicable to the design features of spacecraft);

5. Familiarization-training flights by the astronauts in weightlessness, for the purpose of general familiarization and expert-prognostic study of individual psychophysical reactions;

6. Training of astronauts in mock-up sections of spacecraft in brief weightlessness. The astronauts proceed to this type of work, after successfully passing through a number of stages of ground and flight training. Ground training includes general physical, special vestibular and theoretical training for weightlessness.

During the final training exercises, the astronaut perfects the following types of work:

1. Conduct of scientific-techanical experiments;

2. Preparatory operations inside the craft for extravehicular activity; /321

3. Putting on and removing special gear;

4. Extravehicular activity (going through the airlock, exiting through the airlock hatch, moving away and approaching the hatch on a safety tether -- Voskhod 2);

5. Movement in open space (transfer from craft to craft, transportation of freight);

6. Assembly-disassembly and repair work in open space;

7. Actions of astronauts in special cases (impossibility of independent movement, breakdown of life support system, etc.).

While performing these types of work, special attention is given to efficiency of the spacecraft systems, convenience of placement of equipment and fastening of instruments and tools, securing of the astronauts while working, accessibility of control levers, design of the compartment interior, correspondence of the special gear to the physiological, biomechanical and anthropometric peculiarities of the human body. This type of work made it possible to work out the engineering-psychological requirements for spacecraft design.

The work of man in space is a new type of work activity, which is performed under unusual conditions. The defensive-adaptive capabilities of the body must, on the one hand, provide for physical and mental efficiency and, on the other, compensate for the effect of the unusual conditions of the outer environment on the body. Reliability of the work of an astronaut, interacting with technical systems, is of tremendous importance here. The experience of training astronauts in laboratory-aircraft has shown that the success of work activities and a decrease in probability of errors by a working astronaut depend on the following factors:

1. Tolerance of the unusual conditions of the outer environment and the degree of adaptation to it by the astronauts;

2. The degree of convenience of use and efficiency of design of technical systems, in accordance with the requirements of anthropotechnics, biomechanics and engineering psychology;

3. Selection of optimum methods of performing work, with decrease in labor cost;

4. The persistence and dynamicity of the occupational skills of the astronauts.

To decide on the tolerance of the alternating effects of g-forces and weightlessness by astronauts, as well as the complex effects of weightlessness and angular accelerations, we worked out special tables, by which the degree of adaptation of the astronauts to weightlessness, level of efficiency and degree of mastery of motor skills were evaluated. On the basis of these evaluations, recommendations were made on design of training exercises in the final stage, with the individual peculiarities of the body taken into consideration.

Accomplishment of work activities in flights in weightlessness places increased requirements on the body of the astronaut; in this case, the functioning of various systems is characterized by a number of transitional states and maximum stress of the compensatory-adaptive mechanisms. As the final result, adaptive rearrangement of the functions takes place, providing for successful activity under extreme conditions. It stands to reason that the nature of the activity in itself affects the level of stress on the compensatory-adaptive mechanism to a considerable extent, and nonconformance of the adaptive capabilities to the load of work performed can lead to a decrease in reliability of the astronaut. In connection with /322 this, it becomes necessary to evaluate different types of work activity by difficulty and reliability of performance. This evaluation may be based on the experience of classification of ground work (W. Woodson, D. Conover, 1968), and it will have the following appearance.

A. Work inside a spacecraft.

1. Single work operations, with adequate securing and the absence of limitations on mobility of the astronauts by special gear.

2. Sets of working operations, performed with adequate immobilization and without special gear.

3. Sets of work operations performed with inadequate securing.

4. Sets of work operations requiring evaluation of the situation, decision-making and choice of method of action.

5. Sets of work operations performed in special gear, with inadequate immobilization.

6. Sequential sets of work operations, including coordinating actions with other astronauts and performed in special gear.

B. Work outside a spacecraft.

1. Sets of work operations performed in special gear under randomly changing conditions in the unsupported position.

2. Sequential sets of work operations, including coordination of action with other astronauts, performed in special gear, under randomly changing conditions, in the unsupported position.

Analysis of the complexity and severity of forthcoming work and coordination of methods of performance with the actual capabilities of the astronaut at each stage of training is one of the underlying principles of rational construction of the study-training process in flying laboratories.

In the initial period of training, the astronauts have to master working operations, characterized by a high degree of reliability and, in proportion to their mastery, proceed to performance of more complicated tasks (with a lesser degree of reliability), requiring more stress on the compensatory-adaptive mechanisms of the body. Thus, for example, sequential sets of working operations accomplished by Ye. V. Khrunov and A. S. Yeliseyev, during the joint transfer from craft to craft in free space, should be among the complicated types of activities. The astronauts performed purposeful movements, carried out various types of assembly-disassembly work, scientific experiments and motion-picture photography (Figs. 89 and 90).

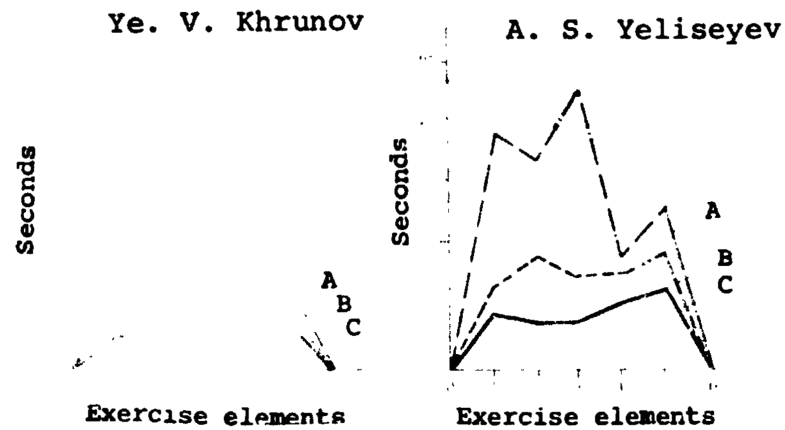


Fig. 89. Time and motion charts of accomplishment of transfer from craft to craft by astronauts Ye. V. Khrunov and A. S. Yeliseyev at start (A), middle (B), and end (C) of training cycle in laboratory-aircraft flights: elements of transfer (exercises): 1, occupation of initial posture for transfer; 2, transfer to first handhold; 3, transfer from one handhold to another; 4, transfer to second handhold; 5, occupation of initial posture for entry into hatch of orbital station.

The work was performed in spacesuits under excess pressure, which bound movement, hampered heat regulation and increased energy consumption, because of the application of additional efforts to overcome the resistance of the spacesuit shell, and it decreased the

Fig. 90. Motion-picture frames of process of exit from craft (A), transfer to other craft (B), and entry into other craft (C) by astronaut A. S. Yeliseyev in brief weightlessness.

visual field of view. Ye. A. Karpov (1966), analyzing the activity of the Voskhod 2 crew, concluded that, for all its complexity, success was predetermined by the content of the preflight training. Ye. A. Ivanov and colleagues (1968), conducting a comparative biomechanical analysis of the performance of extravehicular activity by A. A. Leonov in the last training sessions in the flying laboratory with the third exit from the craft under actual conditions, concluded that the training exercises had a significant favorable affect on /323 forming the skills of controlling orientation and movement of the body in space. Thus, the success of the training program worked out in the laboratory-aircraft ensures a high quality of task performance under actual conditions; the sequence in mastery of the operations of various degrees of complexity is of decisive importance here.

An increase in reliability also is achieved by means of repeated exercises, until complete mastery of them under weightless conditions. Time and motion charts of execution of the transfer from craft to craft by Ye. V. Khrunov and A. S. Yeliseyev, at various stages of the training process, are presented in Fig. 89. A decrease in time for performance of individual elements of the exercise and a rise in evaluation of the quality, in proportion to mastery of the skills by many repetitions of the exercise, is common to both astronauts. The considerable expenditure of time in performance of individual elements and the entire exercise by A. S. Yeliseyev at the start of training attracts attention. This is explained by the fact that A. S. Yeliseyev, in distinction from Ye. V. Khrunov, had no experience working in weightlessness. This circumstance confirms again the importance of observance of the principles of constructing the training process reported above. The vegetative reactions of A. S. Yeliseyev at the start of the training cycle were more pronounced than those of Ye. V. Khrunov. The recovery reaction time of the cardiovascular and respiratory systems of A. S. Yeliseyev, after working in weightlessness, was 1-2 min longer than the recovery reaction time of Ye. V. Khrunov. These differences were smoothed out in the concluding stage.

It has been determined in a number of studies that, as the astronauts work out the actions, an adjustment of the motor-skill structure, applicable to the conditions of absence of body weight takes place simultaneously (I. F. Chekidra, 1967, 1968). During the training process, the coordination structure of special purpose movements of the arms of the astronauts, of varying complexity, was studied by the photocyclogrammetric method. It was shown that, in the first flights in weightlessness, the coordination structure of movements is complicated, compared with normal weight conditions: muscle forces and the amplitude and number of correcting signals sent from the central nervous system to the periphery during movement increase. By the 4th-5th flight, the structure of the test movements in weightlessness approximates that under normal gravity. Between the 20th and 30th flights, stabilization of the movement structure takes place, which is expressed by a decrease in applied muscle forces and, which is particularly interesting, a decrease in magnitude and number of correcting movements, compared with normal weight conditions. Owing to recording of the biomechanical characteristics (speed, acceleration, forces, muscular moments in microintervals of time), objective criteria for evaluation of the speed of adjustment of the motor skills were successfully worked out. Recording was carried out in a parallel study of the overall work activity, by means of analysis of motion-picture materials, time and motion charts, psychophysiological reactions, performance capacity and quality of work performance.

The complex evaluation of activities results in revealing difficulties, arising in performing various elements of a task, and in controlling the process of forming a stable dynamic stereotype of occupational activity of an astronaut, worked out in mock-up sections of spacecraft under weightless conditions.

The experience accumulated has shown that efficient matching /324 of astronauts with the technical system must be based on the following principles of engineering psychology:

1. To evaluate equipment, from the point of view of convenience in work;

2. To scrupulously and attentively approach evaluation of details of the work of an astronaut;

3. To use objective methods of recording motor activity of an astronaut and the vegetative reactions of his body;

4. To evaluate performance capacity of an astronaut, on the basis of a complex analysis of psychophysiological reactions and success in task performance;

5. To evaluate the efficiency of work of an astronaut;

6. To predict the reliability of performance of work by an astronaut under actual space conditions.

The question frequently arises during training, as to how to evaluate various inefficient elements of design. The classification of W. Woodson and D. Conover (1968) seems reasonable to us; according to it, the following are distinguished: a) irrational elements, not having an effect on activities; b) reducing efficiency, but not eliminating the possibility of performance of the activity; c) leaving to the impossibility of performing the activity; d) causing an emergency situation.

From these considerations, various proposals for improvement of design were evaluated, in the training of the astronauts for the Voskhod 2 flight.

Generalizing what has been reported above, we consider it necessary to note that analysis of occupational activity of the astronauts in laboratory-aircraft flights permits the training of astronauts to be built on a scientific basis, and that this promotes further improvement and refinement of the methods of training and of work in space.

2. Preservation of Human Performance Capacity Under Prolonged Space Flight Conditions

N75 23131

The creation of orbital stations, as well as long space flights, especially to other planets, involves a prolonged stay of man in weightlessness or considerably reduced gravitation. The investigators are faced with the significant problem of preservation of the health and satisfactorily high performance capacity of crew members of spacecraft, orbital and, in the future, interplanetary stations, for a long time (possibly months and years). Preservation and maintenance of that level of efficiency which would ensure manual execution of precise and delicate maneuvers in docking craft in orbit, landing them on other planets or returning to intermediate or ground spaceports, is of particular importance. /326

In long space flights, work is the significant factor determining the lifestyle. The work of an astronaut is complicated and varied. By its nature, it is a variety of operator-type work. However, at the present time, it has a number of fundamental differences from the work of operators in other occupations. The main ones of them are that, first, the astronaut works under unusual external environmental conditions, to which man is not adapted in the process of phylogenesis and ontogenesis and, second (in all likelihood, this is a peculiarity of the present time), he is an operator, with an extremely extensive range of qualifications, and performance of operator functions frequently is not an end in itself, but only a necessary prerequisite creating conditions for conduct of scientific research, i.e., for accomplishment of cognitive activities, in the interests of a large number of scientific disciplines.

The complexity of performing many tasks, which an astronaut works out during a space flight, places investigators of performance capacity in a very difficult position, since the criteria for such evaluation will be diverse and frequently contradictory.

In recent years, study of the condition characterizing performance capacity has become one of the basic problems of space biology and medicine, especially in solution of the problem of increasing reliability of man, as a major link in an ergonomic system.

It should be noted that in both biology and medicine and in engineering psychology, there is a large number of specific concepts of "performance capacity." Each of these concepts correctly reflects different aspects, characterizing the work of complex technical or ergonomic systems.

Not dwelling on evaluation of the correctness and completeness of these definitions, we only point out that it apparently is most advisable to take simultaneous account of both the results of the activity itself ("production criteria") and the functional state of the body of the astronaut during this activity (the "physiological value" of the activity), for evaluation of the performance capacity of a man on a space flight.

It seems appropriate to us to limit the occupational activity of an astronaut to that of an operator, servicing the basic systems of the spacecraft, ensuring flight safety, and to that of an investigator, i.e., creative, cognitive. Evaluation of the investigative activity of an astronaut can only be made some time after the /327 flight, allowing for the fact that the "revaluation of the value" may take place, with reception of new information. The operator activity can be evaluated sufficiently accurately inflight.

Evaluation of operator capabilities of astronauts by some investigators, based on simulation of one aspect or another of their activities, under flight conditions, in our opinion, requires a very cautious approach to interpretation of the results obtained.

It must be considered that the social and vital importance of a model experiment is immeasurably less than the actual operator activity in control of a spacecraft. Of course, the emotional background and "responsibility" in these two types of activity will differ significantly. In connection with this, in interpretation and analysis of data obtained, the functioning of the astronauts in the control circuit of an actual system, i.e., a spacecraft, must be taken into consideration without fail.

The flights of the Soyuz series spacecraft, in conformance with the Soviet space research program, were undertaken, for the purpose of solving difficult problems, connected with creation of long-term orbital stations. They have permitted manual and automatic docking operations and crew transfer and exchange operations to be worked out, testing of spacecraft control systems and crew life support systems to be tested and scientific equipment and communications facilities to be tested.

The work of an astronaut aboard a spacecraft is reduced to the following, in the most general form (A. I. Men'shov, 1971);

-- monitoring and control of the operation of onboard systems;

-- control of spacecraft movement in performance of various dynamic operations (orientation, stabilization, approach, docking, orbital correction, descent from orbit, landing);

-- conduct of radiocommunication and television reporting;

-- conduct of visual observations, conduct of scientific experiments and investigations;

-- assembly and disassembly of individual units of the craft, performance of various operations outside the spacecraft;

-- operation of special gear;

-- carrying out onboard documentation.

The clearly expressed and natural tendency towards complication of flight missions must be noted. This is explained by the objective course of development of astronautics, the continually increasing instrumentation of spacecraft and the procedural readiness of astronauts to conduct various studies.

This great loading of the flight program with research work makes an astronaut a wide-profile investigator.

The flight of the Soyuz 9 crew is of considerable interest, in connection with the problem we are examining, because it can, although provisionally, be considered to be a sufficiently academic experiment.

Actually, at the moment of launch of Soyuz 9, some manned craft of this series had flown.

The Soyuz craft were improved from flight to flight; therefore, the technical reliability of Soyuz 9 was quite high, and all systems functioned normally in flight, providing an appropriate baseline /328 of the emotional stress of the astronauts, performing a quite saturated program of activity during the 18 days.

During the flight of Soyuz 9, a large volume of scientific-technical studies and observations was carried out, for analysis of the operation of the spacecraft systems and solution of a number of scientific and national economy problems. Multiple testing of the onboard systems of the craft and its equipment and experiments were conducted, to work out methods and means of autonomous navigation. Various measurements were made in solving navigational problems, using a number of highly accurate instruments. The results of these measurements were used to determine elements of the spacecraft orbit and calculation of the necessary corrections to it.

To provide for navigational measurements, regulation of the heat and energy conditions, as well as to conduct a number of scientific experiments during a flight, several dozen dynamic operations were performed. These operations included orientation of the craft on the sun, earth, or stars, with subsequent stabilization of it, using gyroscopes or torsion. Orbital corrections were accomplished three times during the flight. All dynamic operations were performed, using the manual orientation system and semiautomatic and automatic modes. Several new instruments, used in spacecraft orientation and movement control systems, were tested during the flight. A number of experiments was conducted, to determine and precisely define the structural and inertial characteristics of the craft. Scientific experiments, in the interests of study of circumterrestrial space and study of the optical properties and characteristics of the atmosphere of the earth, occupied considerable space in the flight program. For this purpose, observation, photography and spectrography of the day and twilight horizons of the earth, etc., were carried out.

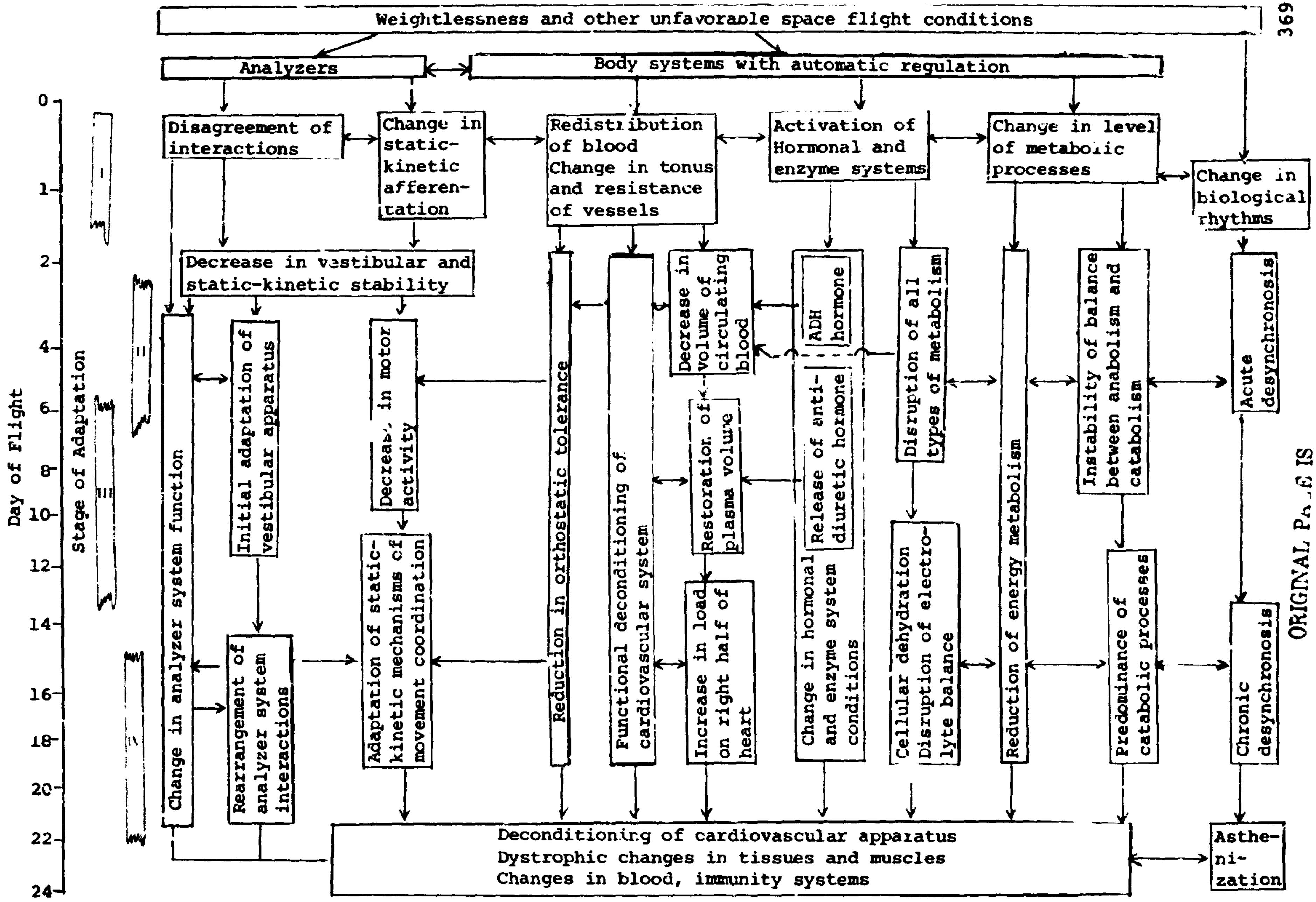
In the interests of meteorology, observation and photography of the cloud cover was carried out, the limits of snow cover were determined, the points of appearance of storms, gales, tropic typhoons and cyclones were recorded, and geological objects on the surface of the earth in the territory of the USSR were photographed, for the purpose of precisely defining the sites of occurrence of minerals. The astronauts also carried out a large set of biomedical experiments.

Even a very brief and general list of the work performed by /329 the crew members indicates the broad range of their activities and the complexity of evaluation of its quality and efficiency and evaluation of the performance capacity of the astronauts.

The performance capacity of the astronauts is not stable, and this instability depends on a great many factors. The basic causes of reduction in it are the effects of external environmental factors, having an unfavorable effect on the functional systems of the body, developing as a result of work fatigue and change in emotional state. However, under actual space flight conditions, the complex actions of these factors and their complex dialectic interrelationships have to be taken into consideration.

In analyzing the functioning of the crew in the control circuits of various spacecraft systems, ensuring flight safety, it must be noted that, through fault of the crew, not one reason developed for creation of an emergency situation aboard during the entire flight. Analysis of the work of the crew consisted of estimating the correctness of issuing commands, in accordance with the onboard documentation, timely control of the condition of systems before dynamic operations and during them, and deviations from the official flight program. As is clear from Fig. 91, the greatest number of erroneous acts was committed by the crew, in the first two days and on the 12th day of the flight. In our opinion, this is explained by the irregular distribution of dynamic operations by day of the flight (the greater portion of them was carried out in the first half) and by changes

Diagram 10: Diagram of adaptation to space flight conditions



in the functional condition of the astronauts, during adaptation to the effect of prolonged weightlessness.

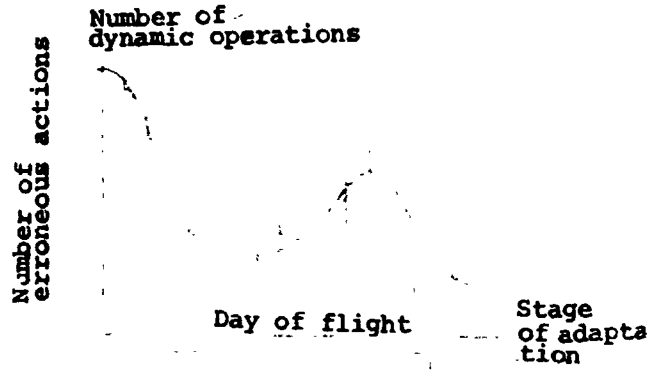


Fig. 91. Erroneous actions of crew in flight, during conduct of planned dynamic operations: 1, number of operations; 2, averaged curve of number of errors; 3, actual number of errors by day.

Adaptive Reactions and Performance Capacity of Man in Space Flight

The capacity for adapting and adjusting to the changing conditions of the surroundings is a positive sign of manifestation of the activity of any stable biological system. Man also is such a system: He continuously and delicately adjusts to external conditions. This adjustment takes place in some cases, only at the level of dynamic adjustment of the functional state of the systems and analyzers, within the limits of their physiological capabilities and in others, it involves the entire coordination structure of the system, which leads to morphological changes in the organs and tissues. However, in any case, during adaptive adjustment, deep-seated, unfavorable changes in function can be observed, which unfavorably affectthe performance capacity of man.

Possible pathogenetic mechanisms of the unfavorable effect of prolonged weightlessness on the human body were examined in detail in the first section of the preceding chapter. We approach this problem, from the point of view of possible processes of adaptation, developing in the body of the astronaut in flight.

Possible processes of adaptation of the body to weightlessness and other space flight conditions, permitting discussion and understanding of the diversity of known and hypothetical changes in the functional state of the body which ultimately determine, not only /331 the state of health, but the performance capacity of a man, are presented in simplified form in Diagram 10.

The basic conditions of space flight are shown in Diagram 10: weightlessness, high neuro-psychic stress, change in activity conditions, change in light conditions and other trigger mechanisms of "biological clocks" (biological rhythms), as well as hygienic living conditions. The conditions listed act on the human body continually, during the entire period of a space flight, and any of them may be a stressor for the body, which is capable of causing, not only deep-seated physiological shifts, but pathological changes, which were discussed in detail in the first section of the preceding chapter. It is evident that weightlessness should be considered the most specific condition of space flight.

Sufficient data have now been accumulated, to follow the dynamics of adaptive changes developing in spacecraft crews during a flight. Analysis of these data has resulted in distinguishing several stages in a single process of adaptation of man to conditions of living and activity in space, which are new to him. Of course, division of the adaptation process into stages is quite arbitrary, since these stages do not have distinct boundaries in time or nature of the physiological (or pathological) changes. Some changes, which are specific to individual stages, are observed, when the corresponding stages either still are not developed or have already ended. However, in our opinion, separation into stages is advisable; it makes possible, not only understanding of the pathogenesis of the so-called "weightlessness sickness," but development of a number of measures for optimization of the activity of man under these conditions, and preventing the unfavorable adaptive shifts, which border on pathology or which change into pathology.

Together with changes in function of the analyzer systems, changes in certain metabolic indices, peripheral blood and other systems, principally indices of the cardiovascular system dynamics were used for the adaptation scheme.

Under normal conditions, the vessels of the heart are subject to extracardiac nerve influences. However, metabolism in the myocardium, i.e., the consumption of oxygen and energy resources at each given moment by the heart, emerges as the basic regulator of coronary circulation. Consequently, the oxygen content of the heart muscles emerges as the driving link in self-regulation of cardiac activity, together with the extracardiac influences.

Data of ground experiments, under conditions of many-day hypodynamia in the horizontal position, immersion, etc., show that the most serious and quickly developed changes are observed, first and foremost, precisely in the cardiovascular system. In connection with this, onboard medical monitoring resources in spacecraft provide for obtaining telemetry information principally on the state of the circulatory system: EKG, seismocardiograms, kinetocardiograms, radial and femoral artery pulses, and the arterial pressure. It is not accidental that development of the stages of adaptation of the body to weightless conditions is based mainly on the results of analysis of the functional condition of the cardiovascular system.

Four stages of adaptation can now be distinguished, based on space flight experience:

-- sta of acute reaction (1st-2nd days of effect of weightlessn s); /332

-- stage of unstable compensation or initial adaptation (approximately days 2-8 of weightlessness);

-- stage of relative stabilization of reactions (days 4-15 of weightlessness);

-- stage of unstable equilibrium of homeostasis (beginning with day 14 of weightlessness).

The stage of acute compensatory reactions begins at the moment of development of g-forces and subsequent weightlessness during injection of the craft into orbit. During this period, the body, after a comparatively brief action of g-forces, enters conditions of practically complete weightlessness. Since, in the process of phylogenesis and ontogenesis, the human body has adapted well to functioning under conditions of constant gravitation and the g-forces of orbital injection are relatively small and short-term, a healthy and well-trained astronaut tolerates their effects comparatively easily. However, it must be noted that, according to some data (Yu. D. Pometov, 1972), aftereffects of these g-forces may show up over a period of several hours or even days, i.e., precisely in the first phase of adaptation to weightlessness.

The initial effect of weightlessness is characterized by symptoms of discomfort, and it begins primarily with changes in the cardiovascular system, which is connected to the greatest extent with provision of homeostasis.

The absence of weight leads to disappearance of the hydrostatic pressure of the blood and to redistribution of it in the region of the head and chest. All astronauts note a rush of blood to the head in the first minutes after the craft enters orbit. As many of them have reported, their faces become puffy. The unpleasant sensation of overfilling of the head creates some interference with occupational activity (A. G. Nikolayev, 1970).

In response to the redistribution of the fluids, primarily the blood in the circulatory system, which is unusual for the body, regional protective reflexes are triggered. With overfilling of the upper half of the body with blood, an increase in the central volume and venous return to the right side of the heart, adaptation to the new condition begins, by means of elimination of the "excess" fluid, to the level, at which signals from the volume receptors are adequate to the normal earth background. Evidence of this is the well-known fact of considerable loss of weight (mass) (2-3 kg and more), after one- or two-day space flight, in which no symptoms indicating the appearance of congestion in the lungs is observed. Normal pulmonary blood circulation apparently is provided by spasm of the pulmonary artery, with partial shunting of the blood to the left side of the heart, through arterial-venous anastomoses, with relative hypertension of the region of the pulmonary artery.

The consequence of the disappearance of hydrostatic pressure and of redistribution of the blood also is deposition of the blood, change in tonus of the veins, extinction of the vasomotor reflexes, etc. All this decreases the tolerance of the body for terrestrial gravitation, especially to the orthostatic position.

As it well known, in studies conducted in the hours and days immediately after landing on earth, there was a sharp reduction in orthostatic tolerance of American and Soviet astronauts (Berry, et al., 1966; Berry, 1967, 1969; V. V. Kalinichenko, V. A. Gornago, et al., 1970).

The small number of observations does not yet permit speaking of a correlation between flight length and orthostatic tolerance level. The difficulty consists, not only of a large difference in individual reactions of the astronauts, but in the nonuniform flight conditions: varying saturation of occupational activity, the presence or absence of special equipment and means for prophylaxis (special trainers, negative pressure, pharmacotherapy), nonuniform living conditions, etc. However, existing material provides a basis for assuming that there is such a correlation, beyond a doubt, for durations achievable at the present time and with the existing level of medical provision for space flight. /333

In the first minutes of a space flight, especially after injection into orbit, i.e., under weightlessness conditions, the flow of afferent information to the higher regulation centers, to the brain, changes. This concerns mainly the afferent pulses from the proprio- and interoceptors, as well as from the peripheral part of the vestibular analyzer, which leads to disagreement in the normal reactions of the analyzers and to disruption of the functional system of the analyzers constituted under earth conditions (G. L. Komendantov, B. I. Kopanev, 1965).

As is well known, such disruptions can lead to the development of illusory sensations and, sometimes, to persistent illusions, unfavorably reflecting on the general state of health and performance capacity.

Various authors present controversial data on change in the visual analyzer function. For example, A. L. Kitayev-Smyk (1964), in brief weightlessness, found changes in shape and color perception, deterioration of visual acuity, etc. B. B. Yegorov (1964), during a one-day space flight, did not notice this in himself or in his comrades. Only the negative fusion reserves of the ocular muscles increased somewhat. Together with this, Monti and Richard (1963) demonstrated that, in longer weightlessness, the qualitative component of vision (accuracy of readings of instrument scales) decreases noticeably. The examples presented again confirmed the opinion of many investigators that the data obtained in parabolic aircraft must be very cautiously transferred and, more than that, extrapolated to space flight, since the study conditions differ significantly. In the first case, there are the alternating effects of brief g-forces and brief (up to 20-30 sec) weightlessness, when the aftereffects are significant and many reactions cannot develop, and in the second case, the effect of g-forces lasts for minutes, but weightlessness lasts many hours and days. Ye. A. Ivanov, V. A. Popov and L. S. Khachatur'yants (1968), using test methods of study of the functional state of the visual analyzer, noted that perception of the brightness range of colors presented, especially purple, blue, green and red, of P. I. Belyayev and A. A. Leonov, during the flight of the Voskhod 2, decreased noticeably. These authors observed a significant reduction in visual performance capacity (from 20 to 40% and more) and a negligible reduction in visual acuity of various operators, under prolonged weightlessness, beginning with the first days of the flight. According to their hypothesis, the cause of these changes may consist of discoordination of the muscular apparatus of the eyes.

The presence of significant "distortion" of information coming from the static-kinetic analyzer, especially the vestibular part of it, leads to a still greater load on the visual analyzer and the necessity for constantly, actively correcting the amount of move- /334 ment and the magnitude of the muscle forces. Actually, in the initial period of a space flight, a definite discoordination of movement, a certain sweeping nature of them, disruption of precision of reproduction of assigned muscle forces, a reduction in the maximum force, disruption of fine coordinated movements, etc., are observed (I. I. Kas'yan, et al., 1964).

The establishment of new coordination relationships, of a new stereotype of motor activity, when moving and when secured in the ship, in particular, in performing occupational and domestic operations in weightlessness, quite rapidly causes a sense of fatigue (B. B. Yegorov, 1964; K. P. Feoktistov, 1964).

If it is considered that, in connection with the changes in functioning of the vestibular analyzers of some persons, especially during sharp movements of the head, the so-called space form of motionsickness can develop, and the general nervous-emotional background in the initial period of a space flight is considerably elevated, it becomes clear that, in the first stage of adaptation, the performance capacity of an astronaut decreases significantly. It is completely obvious that, the more expressed the disruptions and changes in the sensory, motor, vegetative and other components of the overall reactions of the body in the initial stage of its adaptation to weightlessness, the more this is reflected in performance capacity.

Subsequent adaptation to space flight takes place through a stage of unstable compensation. Obviously, terminology should be dwelt on here, once again, because the presence of compensation implies the falling or absence of some normal functions, i.e., the presence of a pathology.

Many investigators consider it necessary to use the term "adaptation" only for the designation "expedient" (by earth standards) changes, taking place in the body, in coming into equilibrium with the external environment, not going beyond the bounds of normal (with respect to earth conditions) physiological shifts and practically not impairing the functioning of the body, upon return to normal conditions of existence.

In those cases when changes in the body cross these limits close to a pathology, under the influence of the external environment, so that in changing to normal conditions requires conduct of special recuperative or even therapeutic measures, so as to ensure normal functioning, these authors propose to call it a pathology.

In our opinion, introduction of the term "disease" requires additional (and very complex) discussions on the limits and relationships of normal and pathology; therefore, it is right to abandon the term "adaptation," adopted by a number of authors, understanding that, in specific situations, as in normal life, adaptation diseases can develop (and actually do develop) (V. M. Dil'man, 1972). It then is completely understandable that, under the new and very unusual conditions of space flight, some "normal" physiological mechanisms of regulation become incompetent, and individual functions actually "drop out" or are considerably transformed.

In connection with this, in the process of adaptation to the new living conditions, in the process of adaptation to weightlessness, the body must compensate for them. Does this mean that a "breakdown" has occurred, that there is a pathology? Obviously, an unambiguous answer to this question is impossible: in the /335
initial stage of adaptation, there is not yet a pathology, but there are prerequisites for it, a prepathology.

<u>In the stage of unstable compensation</u> (stage II), changes in tissue metabolism, changes in the blood and, as a consequence of this, further changes in the cardiodynamics and hemodynamics and respiration, are observed. At this stage of adaptation, as the observations and studies conducted immediately after completion of orbital flights lasting up to five days have shown, a pronounced leukocytosis and a moderate decrease in erythrocyte mass and percent of hemoglobin, and an increase in all globulins and residual nitrogen are noted in the blood (V. I. Legen'kov, et al., 1971). Since it is well known (B. F. Korovkin, 1965) that α_1- and α_2-globulins are bound to "cardiac" transaminase (GCT), and β-globulins to the "liver" transaminase (GLT), an increase in globulin level may indicate an increase in enzyme activity, which is characteristic of the state of stress or disease, in cases of predominance of catabolic processes over anabolic ones, especially in the cardiac muscle and skeletal

muscle. The increase in residual nitrogen confirms this. It apparently is precisely the unusual state of the "weightlessness sickness," which leads to leukocytosis. The decrease in number of erythrocytes may be connected, on the one hand, with an increase in breakdown of them in the spleen, where part of the blood is deposited and, on the other, with the initial phenomena of suppression of hemopoiesis. In all likelihood, the latter is connected, not only with decrease in hemoglobin synthesis, because of the reduction in energy consumption (P. A. Korzhuyev, 1971), but with change in the physical load on the skeletomuscular apparatus, which can unfavorably affect the hemopoietic function of the bone marrow. Possible suppression of hemopoiesis by products of tissue, especially muscle, catabolism also cannot be excluded. The decrease in number of erythrocytes and amount of hemoglobin leads to further decrease in the oxygen capacity of the blood and to development of hypoxic phenomena in the myocardium. At this stage of adaptation, a phased occurrence of water-electrolyte metabolism (exchange of hypoosmolar dehydration, characteristic of days 1-3 of a flight, for hyperosmolar dehydration) also is noted, owing to release of antidiuretic mechanisms and reabsorption of potassium in the kidneys.

Further change takes place in the hypodynamic regime, with increase in load on the right side of the heart, in which the astronauts objectively tolerate the rush of blood to the head more easily, as well as the initial readjustment of the analyzer systems, primarily of the static-kinetic analyzer. As the result of formation of a new system of analyzer activity, the astronauts become accustomed to the new type of spatial orientation and movement in sections of the craft, and coordination of movement improves. An increase in performance capacity is a consequence. However, readjustment and adaptation to the new conditions still has not finished; therefore, good immobilization in the seat, work with fixed instruments or performance of work on a hard, "solid" support are necessary to improve the quality of the activities.

Moreover, the reduction in visual acuity, the marked reduction in contrast sensitivity and the subjectively perceived brightness of all colors (mainly orange-red and green-blue spectra) and, as was pointed out above, a reduction in working visual performance capacity continue. Besides, symptoms of acute desynchronosis, which apparently is one of the basic causes of development of fatigue and reduction in performance capacity, appear in adaptation stage II.

Adaptation stage III, the stage of relative stabilization of /336
reactions, is characterized by further adjustment of the static-kinetic mechanisms and by an improvement in coordination of movement, with some decrease in motor activity and energy metabolism. The decrease in motor activity takes place primarily because of efficiency in movements, in which the astronauts begin to use, not only their hands, as was observed during the first week of stay in weightlessness, but the legs, which "automatically" work as "braces," to secure

the body while working, moving and resting (A. G. Nikolayev, 1970). Progress of deterioration of the visual analyzer function is not observed in this period. Further adaptation of the vestibular analyzer is noted. Moreover, even for persons with quite high vestibular stability, adequate stimuli are not neutral: in the descriptive expression of V. I. Sevast'yanov, a feeling, reminiscent of movement of an inertial machine developed with sharp tilts of the head or trunk. In connection with this, in performing physical exercises or some other operation, the astronauts attempted to avoid such movements.

It should be noted that the feeling of blood rushing to the head, as in the preceding stage, still is noted, but it "does not interfere with work," and it becomes customary. However, together with stabilization of the basic indices of the cardiovascular system, respiratory system and metabolism, a distinctly expressed loss of mineral salts from the skeletal bones, with preservation of their mass, is observed (Berry, 1971), as well as a progressive decrease in the circumference of the calves, which evidently is an indicator of loss of body weight, not due to dehydration, but due to the tissue mass.

The basic cause of desynchronosis is insufficient efficiency in constituting the work and rest conditions, caused by the necessity for tying the waking period to the passage of the craft into the radio visibility zone of the ground tracking stations. In this case, a unidirectional shift takes place in the start of sleep, over specific periods of time, which leads to disruption of normal rest. Sleep become restless and interrupted; the astronauts do not feel rested upon waking up. The use of soporifics will not always be effective; therefore, by the end of the second week, fatigue phenomena increase in the astronauts, which reduces their efficiency and, especially, reliability in performance of occupational activities. An example of this is the increase in the number of remarks and erroneous actions in performing dynamic servicing and control operations on the spacecraft systems (see Fig. 91).

The physiological essence of stage IV, the stage of unstable homeostasis, consists, on the one hand, of reinforcement of the new structure of analyzer interactions and, on the other, of phenomena of deconditioning of a number of systems of analyzers and, as a consequence of this, development of fatigue phenomena and a reduction in efficiency. It still is difficult to completely explain the causes and mechanisms of change in functioning of the basic systems of the body at the present time, since data obtained during the flight of Soyuz 9 and Salyut are too scanty.

A definite stress of the circulatory apparatus can be noted, especially in performance of the functional tests. Apparently, with increase in space flight duration, deconditioning of the cardiovascular apparatus progresses, and the orthostatic tolerance /337 naturally decreases. The causes of this, as has already been pointed out, are the absence of hydrostatic pressure of the blood and hypodynamia under weightless conditions.

It must be noted that all these disruptions develop, despite use of various prophylactic means by the astronauts, which were developed on the basis of results of ground experiments with simulation of weightlessness. We apparently also are faced here with the dialectic struggle of opposites: the use of prophylactic means is directed towards preservation of the "ground" level of functioning of the body, which leads to considerable mismatch of the regulatory functions of the body which are adapted to weightlessness. Work should still be done in this area, in order to find the optimum methods and times for intervention in the adaptation processes. Shifts in metabolism are followed quite clearly during this period. Thus, after the 18-day flight of A. G. Nikolayev and V. I. Sevast'yanov, a tendency toward increase in loss of potassium and sodium by the body, an increase in elimination of phosphorus and residual nitrogen and also an increase in protein globulin fractions in the blood were observed (V. I. Legen'kov, 1971, 1972). Similar changes permit the thought that there is the phenomenon of considerable activation of protein breakdown in the body tissues. The majority of investigators are inclined to explain the tissue catabolism by the reduction in motor activity in weightlessness (hypodynamia), with which we have to agree. American investigators propose using corrective nutrition, to decrease catabolism, in which an adequate amount of potassium is introduced into the body. Owing to use of the potassium diet and the prescription of potassium preparations, the incipient disturbance of cardiac conductivity of the Apollo 16 crew members was successfully removed.

In adaptation period IV, no unfavorable shifts in the analyzer systems or progress in them were noted. However, they cannot be excluded, which is indicated by certain results of simulated weightlessness experiments on earth.

The fact of a marked reduction in intraocular pressure, a decrease in pressure in the central artery of the retina and certain changes in accommodation merit attention and require further study.

On the whole, this stage of adaptation is characterized by development of subcompensated general fatigue and asthenization of the body, development of which is favored to a great extent by the progress of symptoms of chronic desynchronosis (B. S. Alyakrinskiy, 1972).

Division of the adaptation process into stages, of course, does not reflect the completeness of adaptation of the entire body to weightlessness and other conditions of space flight. This scheme of adaptation of the body to changes in external conditions does not pretend to be complete, without error or conclusive, since much is still unclear in the data used to construct the theory of adaptation, in connection with which, a number of explanations and discussions are based on hypothetical situations. It still is difficult at present to even tentatively suggest, with a sufficient degree of probability, what will take place upon a considerable increase in duration of space flights (4-6 months and more), since the possibility is not excluded, on the one hand, of development of the subsequent adaptation stage V, the stage of stable homeostasis and, on the other hand, aggravation of the adaptive changes, as a result of prolongation of adaptation stage IV, the stage of unstable homeostasis. Only time and experience of future space flights will answer all the questions, as to the nature and peculiarities of adaptation of the body to weightlessness. /338

However, on the experience of already existing data, it can be stated confidently that adaptation of the body to weightlessness is inescapably accompanied by the development of "adaptation sickness." The cause of this disease is disruption of the biological rhythm in weightlessness. The symptoms and course, even with insufficient study of them, have characteristic peculiarities. A radical measure of prophylaxis and treatment apparently is creation of artificial gravitation in the spacecraft.

In our opinion, the basic internal contradiction in development of adaptation is the permanent conflicting parameters of regulation of the ultimate adaptive effect. In all stages of adaptation examined, the adaptive reactions can be both useful and harmful for the body, in a specific sense, since they disrupt its normal (accustomed) functioning. The catabolic processes in the tissue, in particular, are among such pathological reactions.

Atrophic and degenerative processes not only lead to morphological changes, but can promote an unusual intoxication. The latter can aggravate the functional changes, unfavorably affecting the performance capacity of a man.

It would appear that space flight experience indicates the opposite: as a rule, the astronauts speak of retention of adequate performance capacity for the duration of the entire flight. In any case, in brief flights, they did not note a decrease in it (N. M. Sisakyan, V. I. Yazdovskiy, 1962, 1965, and others). However, this contradiction is only apparent. Even with the absence of noticeable deviations in general, the performance capacity can be disrupted, because of that sense of unusual stress and fatigue, which many mention, including astronauts B. B. Yegorov (1964) and K. P. Feoktistov (1964). On long flights, by the end of the second week of weightlessness, even with special recreation days set aside for the astronauts, they developed fatigue phenomena and, upon return to earth gravitation, a reduced tolerance of previously accustomed loads: a decrease in orthostatic tolerance, right up to loss of consciousness, a sense of increased gravitation of approximately

2 g, even in the prone position, etc. Fatigue sets in still more rapidly when working in spacesuits. Of course, the degree of change in performance capacity will depend on the degree of expression of the disruptions discussed above.

It should be noted that the motor component of the operating activity of the astronauts is quite simple and, with development of space technology, it is being simplified more and more. However, the natural efforts of spacecraft designers to simplify information display systems and actuator systems, unfortunately, leads to complication of the logic of the control system. The latter, of course, complicates the mental activity of an astronaut, connected with analysis of the situation and making a decision, since the astronaut is deprived of direct subject-object perception of the state of the control system, and he has to do only with an information model of it. This circumstance places high requirements on operating thinking of the astronaut, since it is the most labile link in the analytical-synthetic activity and, under flight conditions, it is "broken" /339 easiest of all, with development of fatigue.

At the same time, the results of the flights performed indicate quite complete execution of the flight program by the astronauts. One of the favorable conditions, making it possible for the astronauts to cope well with assignments, is the performance of all operations, as a rule, in quite short intervals of time and in a definite sequence.

With further complication of the activities of astronauts (increase in number of work operations, the time for carrying them out, the necessity for simultaneously performing several operations in a definite time limitation on accomplishment of them, etc.), especially when working in the unsupported position or in a significant increase of autonomy (duration) of flights, when planned and urgent prophylaxis and repair of technical systems and equipment is unavoidable, it should be expected that shifts in the functional state of the body may show up on the efficiency and reliability of activities more strongly than up to now. This must be taken into account in organizing future long space expeditions.

Preservation of Performance Capacity of Astronauts

Natural biological adaptation to weightlessness, as was pointed out above, owing to its duality and the possibility of development of "adaptation sickness," cannot ensure preservation of homeostasis in a man, both under flight conditions and, especially, upon his return to earth conditions. The unfavorable consequences of weightlessness were displayed particularly clearly after the 18-day flight of A. G. Nikolayev and V. I. Sevast'yanov; therefore, on the threshold of still longer flights, the problem of the necessity of improving the means and principles used, and development of new ones, for prophylaxis of the unfavorable effects of flight conditions became still more urgent.

In this work, it must be considered that the physiological defense-adaptive processes at a definite phase of development may be transformed into pathological processes, which also are adaptive-adjusting, but stop being protective. The essence of the problem is whether the body should be assisted in adapting to weightlessness more rapidly and more completely, or must an arsenal of resources be developed and used, which would regulate the adaptation process, interfering with its completion.

At the present time, particular attention is given to problems of selection and training in the training of crews. As previously, the requirement of preservation of the level of performance under space flight conditions, first and foremost, under weightless conditions, remains decisive in selection of candidates for flights. This is achieved by familiarization of astronauts with the effects of flight conditions, increasing their functional capabilities, by means of special medical training, and also working out the necessary work skills in brief weightlessness or simulation of it. As experience has shown, these measures are quite sufficient for successful execution of the programs of brief space flights.

In our opinion, changed requirements should be expected in /340 the immediate future, in the selection and some training of crew members. Requirements for selection of flight candidates should be more individual. With inclusion of narrow specialists in expeditions, the "semiuniversalism" of the astronauts, creating additional difficulties in their professional training, will disappear. In this case, the qualifications of the astronauts will become narrower and their reliability, as links in the spacecraft control system will obviously increase.

In a long space flight, a whole set of prophylactic measures may be used, and are being used, directed toward preservation of the health and maintenance of the performance ability of a man. This set includes common measures (selection of the optimum work and rest schedule, execution of hygienic procedures and special physical exercises), the use of pharmacological agents, conditioning of the cardiovascular apparatus, etc. In the period of preparation for a flight and in the initial stages of adaptation, a specially selected set of hormone and pharmacological preparations should, in all likelihood, be used. Subsequently, especially in the stage of unstable equilibrium of homeostasis, when predominance of catabolism over anabolism is observed, the use of amino acids and means of stimulating hemopoiesis apparently is necessary. At this time, as a consequence of considerable loss of trace elements by the body, compensation for these losses, using corrective nutrition, is advisable.

In connection with phenomena of deconditioning of the support-muscle apparatus and cardiovascular system, the use of the physical workloads and negative pressure on the lower half of the body is completely valid and lawful; these may assist in preparation of the human body for return to earth gravity conditions, to some extent, in particular, in retention of orthostatic tolerance. However, all these prophylactic measures (undoubtedly necessary at this stage of development of astronautics) may be, if you please, one of the main causes of the onset of development of the unstable homeostasis stage. Evidently, with increase in flight duration, the unstable homeostasis stage will begin and will depend on the duration of that period, during which this type of prophylactic load will be used, and the expression of the body reactions here will be determined by the intensity of these loads.

Considering that a loss of mass of the skelet [illegible] isculature, especially that of the lower limbs, is observed in [illegible] e flight, electrical stimulation of these muscles, in all lik [illegible] ood, will be useful.

It should be noted that the arsenal of prophylactic means listed, which already are used or will be used, may change and be supplemented significantly in the future. This is connected with the fact that many ecological factors of living, such as noise and vibration, the ionic composition of the air environment, ionizing radiation, etc., still have been studied insufficiently, and they are not given the necessary importance.

As space flight experience has shown, particular attention should be given to the work and rest schedules of the astronauts. For example, in the opinion of A. G. Nikolayev (1970), the primary reason for appearance of fatigue, reducing performance ability, in the 18-day flight was the "inverted" activity schedule of the crew (work at night, sleep by day). Of course, in planning space flight programs, the use of "inverted" or "migrating" schedules should /341 be avoided, since the disruption of biological rhythms in the body systems will be more deep-seated, in this case.

Since the capabilities of the human body have limits, together with improvement in the diverse means of prophylaxis, expanding the functional capabilities of the body, no less attention must be given to technical improvements of the work places in spacecraft.

The materials presented on the staging of the changes in the functional state of the primary systems and the phasing of some indices of operating efficiency in space flight taking place in the body show that the dynamics of the overall state and performance level described have special features, which are specific to the new profession, the profession of astronaut.

The uniqueness of the phasing of changes in operating efficiency of an astronaut is that, beside the normal daily phases (the ability to work in, optimum performance capability, subcompensation, etc.), similar "second order" phases are manifested, extending over the entire duration of the flight and definitely connected with the stages of adaptation to weightlessness and the set of other unfavorable flight conditions. Since a quite clear tie-in of the stages to flight duration is traced, the "second order" phases also are tied to flight time. Depending on the duration of a space flight, some phases may not appear. The phenomena of desynchronosis, and also the fact that the refreshing effect of sleep is weakened under spacecraft conditions, are of definite importance for development of these phases and stages. The effect of nervous-emotional stress, and the effect of livability of the spacecraft are superimposed on this. In connection with this, by the end of the flight, a gradual accumulation of fatigue sets in, which also shows up in performance capacity.

In the near future, apparently, as at the present time, the search should go in two main directions:

-- technical improvements of space flight vehicles (improvement of livability, dynamic characteristics of the spacecraft, efficiency of the workplaces, optimization of the display and control systems, etc.);

-- optimization of the schedules and conditions of work and rest of the crews, as well as development and improvement of the system of means and methods of prevention of the development of the unfavorable changes in the body and expanding its functional capabilities.

Successful solution of the numerous tasks of the general problem of "man and space" is impossible, without accumulation of data on the changes taking place in the body, during a long stay in space, without creation of a strict, scientifically valid theory of human adaptation to space flight conditions.

3. Astronaut Activity in Weightlessness and Unsupported Space

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The first research on performance ability of a man began in brief weightlessness, which was created by aircraft flights along a parabolic trajectory, and which lasted about 25-30 sec. The majority of these studies were of a test nature (L. A. Kitayev-Smyk, 1963, 1965; I. I. Kas'yan, 1963; Gerathewohl, 1957; Gerathewohl, Ward, 1960; Geser, 1961, and others). The work of L. A. Kitayev-Smyk (1965) is also of interest, from the fact that elements of the occupational activity of a man were analyzed in it: putting on and removal of the parachute shroud system. These studies showed that, under weightless conditions, movement coordination is /342 disrupted, the time for performance of some component motor acts is shortened and the motor reaction time increases. The authors connect these changes with disruption of the functions of the visual and motor analyzers, as well as with the effect of the so-called central integration. A study of sensorimotor coordination in prolonged weightlessness was carried out in the flights of Vostok 3 and Vostok 4 (V. I. Yazdovskiy, et al., 1963); however, the tests used were not precisely proportioned and, therefore, the results obtained were, to a certain extent, of a subjective nature. This dictated the necessity for more extensively developing studies of performance ability of an astronaut in a long space flight and extravehicular activity of a man, in which weightlessness emerges in a quality new to it, the "effect of unsupported space."

For the purpose of study of the performance ability of a human operator in prolonged weightless conditions, the following methods were used:

-- psychophysiological analysis of certain operations;

-- study of the dynamic characteristics of a man, included in a model control system, with direct and delayed feedback;[6]

-- evaluation of the singularities of analysis and quality of the working memory, in working with outlines of patterned and random lines;

-- biomechanical analysis of spatial orientation and motor activity in unsupported space.

The group of questions involved appears, at first glance, to be very extensive and many-sided; however, in the work, it was limited to the problem of performance of a reasonable occupational activity by the astronaut, under conditions of prolonged weightlessness. Despite the considerable abstractness of some methods, their generality consists of the fact that they assume examination of the condition of the body of the astronaut included in the control system.

The results of studies in brief weightlessness providing for performance of both individual "activity elements" (Atzler, 1927) and of some operations, demonstrated the great compensatory capabilities of man in coordination of elementary motor acts. It also was noted that the handwriting of the astronauts improved from orbit to orbit (O. G. Gazenko, 1961; A. I. Mantsvetova, 1965; /343
N. M. Sisakyan, 1965).

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[6]The work was conducted jointly with P. I. Belyayev, A. A. Leonov and V. K. Filosofov (1966).

The crew members of Voskhod and Voskhod 2 did not encounter particular difficulties in performing the program of working manipulations assigned to them. However, in analysis of the time spent in performing a number of operations (spacecraft control work, execution of medical manipulations, etc.), as well as in logical tests, it turned out that, at the start of the flight, this time increased somewhat over the results of ground studies or the time, which an astronaut used to perform the same manipulations in subsequent stages of the flight. Thus, for example, in the second orbit, V. M. Komarov used approximately twice the time, connected with orientation of the craft, as in succeeding orbits or on earth (in the training spacecraft) (Fig. 92). The same was noted of B. B. Yegorov, in performing almost all medical manipulations. It is possible that, together with the effect of weightlessness, this is explained by the effect of external inhibition, as a consequence of the novelty of the situation. Thus, P. R. Popovich emphasized that the novely of the feeling in weightlessness causes some stress in performance of work.

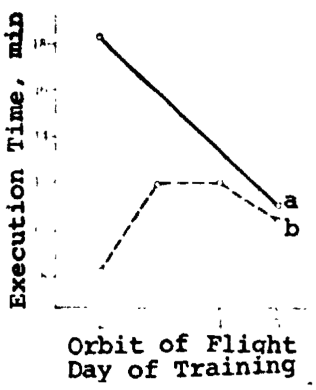

Fig. 92. Time of execution of spacecraft orientation by V. M. Komarov in space flight (a) and in training exercise on earth (b).

The change in structure of the skills, which were observed in analysis of radiocommunications carried out by P. I. Belyayev and A. A. Leonov, are interesting. The crew of Vostok 2 primarily used radiotelephone communications for transmission and reception of information. Only at individual stages of the work did they use transmission of short radiotelegraph messages, using the regular telegraph key.

The psychophysiological characteristics of the skill of carrying out communications was based on data of analysis of the magnetic tape recording of radio exchanges between the crew and earth. As a control, recordings of conversations carried out in the heat and pressure chamber, while working out the airlock operations and exit of the second pilot to open space, performed on a real time scale, were used. The organization of communications meant working out a clear stereotype of a report, which, as usually is done, included the call letters of the correspondents, his call letters, Moscow time and the text. While performing operations in the heat and pressure chamber, this report stereotype was not violated. In the actual flight, this stereotype was maintained, with respect to earth conditions, in only 35% of the cases. This is explained, not only by the effect of weightlessness, but by the combined effect of all the other space flight conditions on the condition of the astronauts.

The qualitative and structural changes in the skill of radiotelegraph communications, which is a more delicate form of coordinated motor activity, is more indicative, with respect to the problem being discussed. The instructor usually obtains the even "handwriting" of the radio operator from a student, in teaching radiotelegraphy. This "handwriting" is characterized by a standard dimension between the individual elements of the Morse code symbols. This phenomenon was reached, in its stable form, by the astronauts, by means of training exercises on earth. Nevertheless, the first study in flight showed that the disproportion of the work of the hand in transmitting Morse code by the key leads to disorganization of the skill: the break between elements of a symbol doubled, and the dash was somewhat drawn out.

The second study of this skill was conducted after 6-7 hours of stable weightlessness. Under these conditions, the average time of the dots and the intervals between elements of a symbol were identical, and the entire symbol was transmitted in somewhat compressed form. It should be noted that a more complex action than the dot stroke on the key, sending a dash, is drawn out, nevertheless. /344
This study confirms the necessity for use of occupational trainers in long space flights.

The work of the astronauts in more complicated algorithms was somewhat subject to change during activities in prolonged weightlessness. The most interesting fine changes in this respect are found in a psychophysiological analysis of the work of both crew members of Voskhod 2, during the period of going through the airlock and the extravehicular activity of the second pilot.

Performance Capacity in Unsupported Space

In accordance with the flight program for accomplishing operations, connected with ensuring the extravehicular activity of the second pilot, 120 min of operational time were set aside. In this period, movement through the airlock had to be accomplished along the route: spacecraft, airlock chamber, space and return. Moreover, in unsupported space, the astronaut had to execute free floating and assembly-disassembly work on the motion-picture unit. Even an approximate calculation of the so-called elements of work (Atzler, 1927) results in evaluating the activity of the astronauts during this entire period as very saturated and intense. Thus, P. I. Belyayev had to perform more than 50 purposeful motor acts, connected with a single finite purpose, and carry out 15 monitoring operations; correspondingly, A. A. Leonov had to perform 41 acts and 9 operations. It should be added that, during the same interval of time, the crew conducted 460 radio conversations.

An analysis of performance of the work algorithm in flight was accomplished, by means of a qualitative comparison of it with the same algorithm, but accomplished on earth, under heat and pressure chamber conditions. The results obtained showed that the crew of Voskhod 2 coped successfully with the assigned tasks, on the whole. However, at individual stages of the flight, some stress was observed, which was manifested as various psychophysiological disruptions. These disruptions were caused, not only by the novelty and uniqueness of the task performed under weightless conditions, but, in some respect, to coincidence of the start of the set of operations, preparing for the extravehicular activity, with the first minutes of flight of the craft in orbit, i.e., on a background of traces of the preceding emotional and physiological stress of the first encounter with weightlessness.

The quite marked state of stress of the astronauts was reflected in features of the emotional coloring of the radio traffic. While, in training exercises in the heat and pressure chamber, the astronauts carried on the necessary conversations in strict conformance with the program, without using joking expressions, jokes and colorful comparisons appear in the conversations in the actual flight.

The state of stress of the astronauts can also be judged by changes in their basic physiological functions (Fig. 93). Data on the pulse rate and respiratory cycle dynamics are presented, on a background of similar data obtained during training exercises in the barochamber. The graphs encompass the flight time betwee 11 hours 15 min and 11 hours 57 min, i.e., 17 min before opening the hatch /345 of the airlock chamber and 8 min after closing it. In the upper part of the figure, during the actual stay of A. A. Leonov in space, the main landmarks of the radiotelephone conversations of P. I. Belyayev and A. A. Leonov are shown, time-synchronized, which gives a representation of the crew activities in this segment of time. A total of 135 radioconversations was carried on in this period.

At 7 min before opening the airlock chamber hatch and the first acquaintance of A. A. Leonov with open space ("The hatch is open, I see light!") his pulse varied from 87 to 90 per minute, not exceeding the values recorded at this stage in the heat and pressure chamber.

Thus, the work of going through the airlock and movement of the astronaut from the spacecraft into the airlock chamber, involving physical work under weightless conditions, did not cause specific changes in his condition. However, immediately after opening the hatch, the pulse rate of A. A. Leonov begins to increase, and it increases by 60 beats in 6 min, reaching 147-162. Tone III appears on the seismocardiogram of A. A. Leonov during this period, which also indicates an abrupt emotional stress. The spacecraft commander behaves reasonably at this moment. Despite the quiet reports of A. A. Leonov, he attempts to calm him: "Things are good, pulse, respiration good . . . be calm, everything is in order here. The

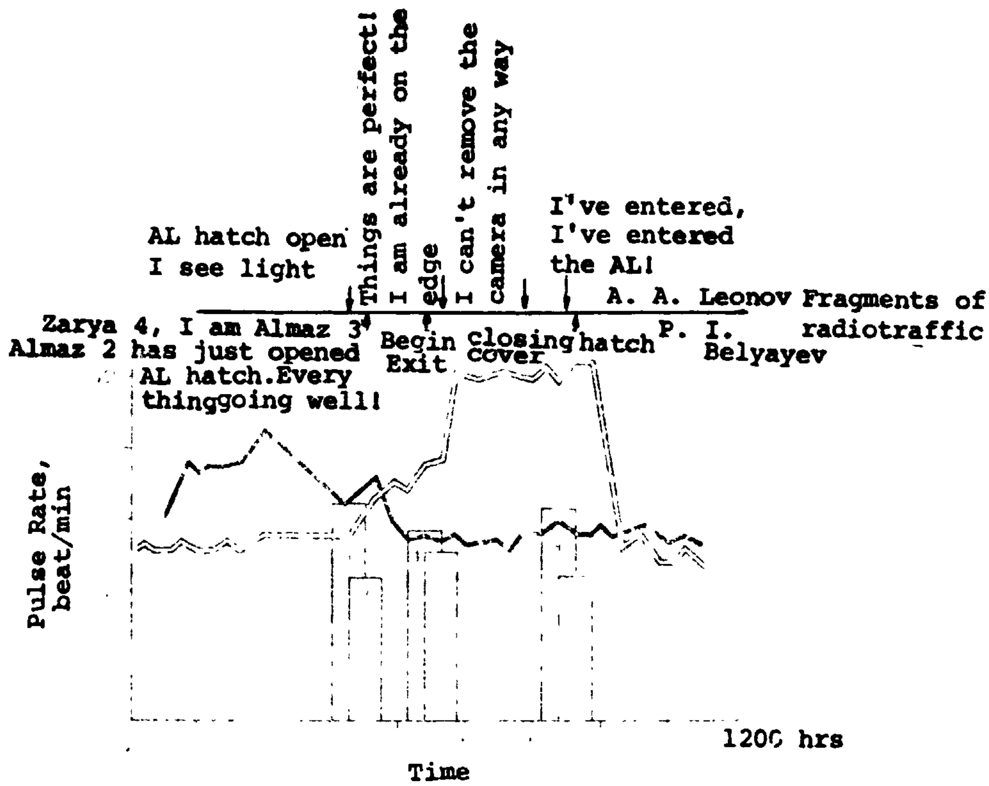

Fig. 93. Heart rate of astronauts P. I. Belyayev and A. A. Leonov during extravehicular activity of A. A. Leonov in flight: 1. A. A. Leonov in flight; 2. P. I. Belyayev in flight; 3. 4, P. I. Belyayev and A. A. Leonov in heat and pressure chamber

pressure in the cylinder is good, pulse, respiration excellent."

Immediately after closing the airlock chamber hatch cover, the pulse rate of A. A. Leonov decreases from 160 to 138 beats in a minute, to 117 beats after 2 min, to 91 beats after 4 min, i.e., 4 min after entering the airlock, the pulse rate became normal. The respiration rate during this period correlated completely with the heart rate. The correlation coefficient was 0.85. As A. A. Leonov reported, entering the airlock, he had to make several turns in it, he turned his head, he moved energetically. These actions are of extreme interest, from the point of view of tolerance of multiplane turns in weightlessness. Performance of this operation by A. A. Leonov permits elimination, with sufficient objectivity, of the presence of any unpleasant subjective feelings of vestibular origin.

In an analysis of the graph of the physiological functions of P. I. Belyayev in this same period of the flight, a different picture is noted. His highest heartrate was observed 7 min before opening the hatch. This moment exactly coincides with the most intense part of the work of the spacecraft commander. Thus, 20 min before opening the hatch, P. I. Belyayev carried on 30 radiotelephone conversations, transmitted two long radiotelephonograms to earth, asked about the state of health of A. A. Leonov 5 times, verified the pressure in the systems, determined the flight location on the globe. More than that, he carried out a series of critical operations (filling the airlock chamber with oxygen, opening the valve in it, unsealing the hatch, etc.). Together with this, the commander checked performance of both his actions (by a special indicator device) and the actions of the second pilot, giving him the command to plug in the backpack, etc.

After opening the hatch, the pulse rate of P. I. Belyayev began to decrease and, after five minutes, it reached the level noted in the heat and pressure chamber, in performing similar operations (94 per minute). Subsequently, during the entire time of the stay of the second pilot outside the craft, the pulse rate of P. I. Belyayev was not over 98 per minute. The correlation between the respiration /346 and heart rates of P. I. Belyayev was not recorded in this part of the flight (correlation coefficient 0.109). The highest respiration rate was noted 10 min before opening the hatch (32 cycles per minute). The sharp drop then began, and these figures held at the same level, with very insignificant scatter (±1 cycle per minute) until the moment the hatch was opened, not exceeding the figures obtained in working out the task in the heat and pressure chamber in the identical section (23 cycles per minute). After unsealing, the average respiration rate did not increase; however, the scatter of the data obtained increased sharply.

The activity of an astronaut upon leaving the craft should have taken place on a background of the effects of a number of unusual factors, which it is impossible to reproduce in the set on earth and during preceding space flights. First and foremost, this concerns the effect of the so-called unsupported space. Moreover, a number of specialists were inclined to consider that the moment when the astronaut had to leave the airlock would be accompanied by phemonena of extremely marked stress, in connection with the necessity for overcoming the "psychological barrier," in attempts to take a step into infinity.

An absolute originality must distinguish the process of spatial orientation of an astronaut, under conditions of weightlessness in free space flight. In the preceding space flights, spatial orientation of the astronauts was based on the accustomed coordinate axes ("up-down") and in the familiar interior of the cabin. It can be assumed that support in these coordinates assisted the astronauts in enduring weightlessness, to a considerable extent. Upon going out of the craft, a multiplicity of variants of the coordinates /347 can be assumed, for selection of the "up-down" axis; therefore, in preparing for this flight, the longitudinal and transverse axes of the craft were selected and recommended to A. A. Leonov as the reference coordinates.

The research program included performance of the following exercises: departures (floating) from the craft, pushing away from the exit airlock with the hands; approaches (floating) to the craft, pulling on the tether; turns of the body around the center of mass to angles of 90°, with the support of the flexible tether; performance of a number of operations (assembly and disassembly of the motion-picture apparatus, etc.).

The in-flight experiment was preceded by a large volume of ground training exercises. They included both the set of physical exercises on special equipment, and working out the motor activities, in conformance with the plan of the forthcoming studies in space, conducted in special test stands and in weightlessness in the laboratory-aircraft, with a mock-up of the spacecraft installed in it. The training exercises in the aircraft were necessary, for working out movement coordination and that work activity, which the astronaut was faced with performing in weightlessness. They made it possible to evaluate the degree of readiness of the astronauts for flight, and, besides, the results of the training exercises were necessary background material.

The motor activity of A. A. Leonov and his body orientation in space upon entering space were analyzed, on a basis of special processing of materials of motion-picture photography, conducted by the on-board motion-picture camera (24 frames per second). Additional information was obtained by interpreting the tape recordings of radio traffic between A. A. Leonov and spacecraft commander P. I. Belyayev.

In performing the first two exercises in space, A. A. Leonov accomplished three movements away from the craft and three approaches to it. In view of the fact that, in a number of cases, the astronaut went out of the frame, only two movements away from the craft and one approach were subject to complete analysis. For these cases, a number of parameters were calculated, giving a quantitative description of the movements. The data obtained were compared with the parameters during performance of these same exercises in the concluding flights in the laboratory-aircraft.

Determination of the rate of movement of the astronaut, in view of coincidence of the direction of the optical axis of the motion-picture camera lens and the direction of forward motion, was made, on the basis of scale changes of the size of the images of the helmet, backpack and other elements of the spacesuit, the actual dimensions of which are known. Errors, arising as a result of turning the body around the center of mass, were eliminated from these data to the extent possible. The correction $\pm\Delta l$ was calculated from the relationship:

$$\Delta l \quad \Delta\alpha r \cdot \cos\alpha$$

where r is the distance from the center of mass of the astronaut to the element of the spacesuit; α and $\Delta\alpha$ are the angle of turn of the astronaut's body around the center of mass in the plane perpendicular to the plane of the frame, and the increment of this angle in one frame, respectively.

The parameters of movement of the astronaut indicated above, for accomplishment of movement away from the craft in space and in the aircraft are presented in Fig. 94. Individual frames of the motion-picture record of the movement of A. A. Leonov away from the craft and approach to it, on the basis of which the calculations mentioned above were made, are shown in Fig. 95. Analysis of the data presented shows that the characteristics of movement, in accomplishing movements away from the craft in space differ /348 little from the same characteristics in training exercises in the aircraft. In both cases, the time for execution of the movements away is 4 sec away. The same can be said of the time for execution of the approach to the craft, which was about 10 sec in both cases. The average movement rates differ somewhat more. This difference is 20-30% of the rate in the aircraft flight, on the average, and the maximum differences reach 50%.

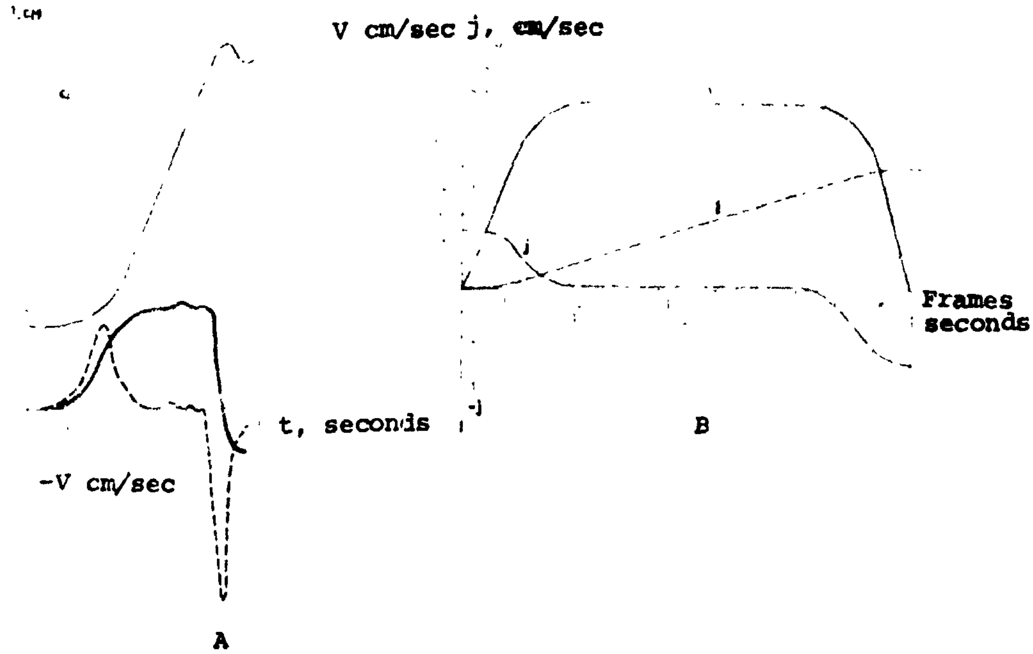

Fig. 94. Change in path traveled (l), rates (v) and accelerations (q) of body of A. A. Leonov in third movement away from the craft during extravehicular activity (A) and during aircraft flights in weightlessness (B).

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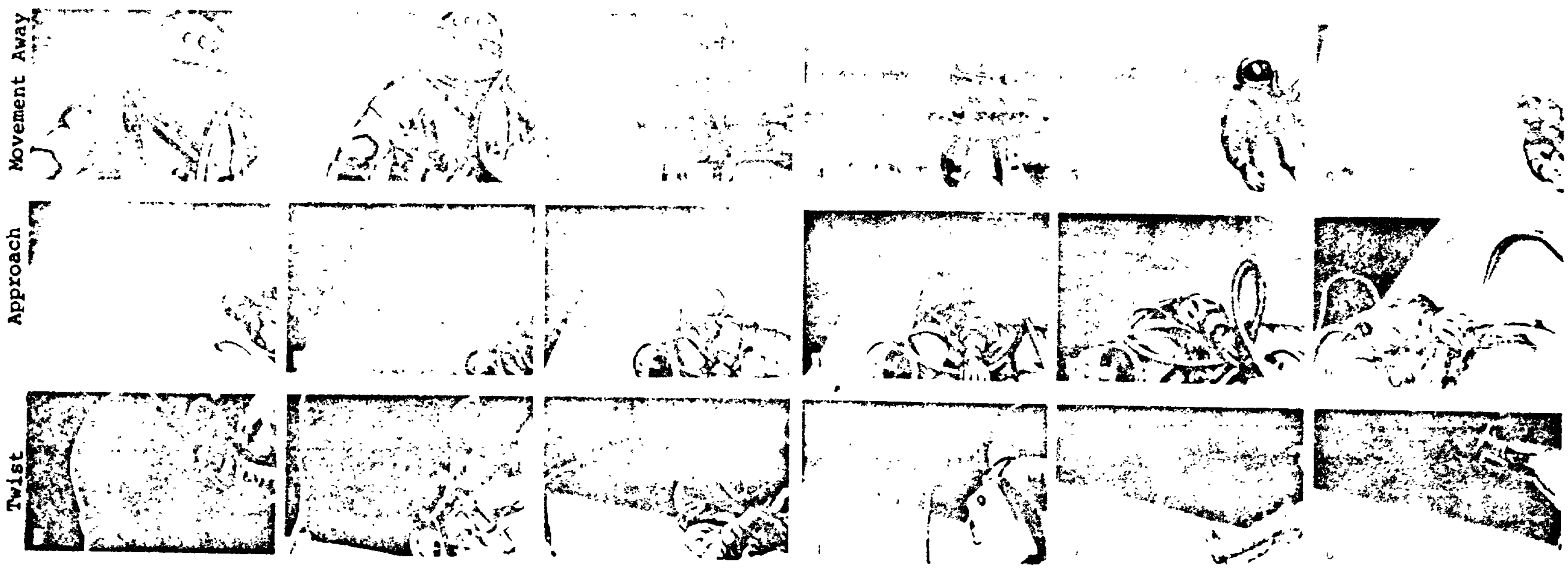

Fig. 95. Motion-picture record of movement away and twisting during extravehicular activity of astronaut A. A. Leonov (sequential phases of movement).

An estimate of the extent of preservation of the motor skills and movement coordination worked out on earth during extravehicular activity can be made, on a basis of a comparison of the maximum rates and accelerations of movement, as well as of the physical forces generated here.

In our opinion, impacts of the astronaut on the craft during an approach may be dangerous. If, for example, it is assumed that the astronaut acquired torsion in approaching the craft and was deprived of the capability of softening the impact with the hands or legs, depending on how and with what he struck, the force of the impact may be quite significant. In an unfavorable case, an approach to the craft, even at a rate of 100 cm/sec, may cause an impact, with a force of 100-150 kg and more. These considerations were taken into account, in developing the exercises which the astronauts had to perform in weightlessness. These same considerations determined the number of ground and aircraft training exercises, which would give definite guarantees of the absence of unforeseen movements in flight.

For a combined estimate of the quality of performance of the proposed exercises by the astronauts in flight, and for a comparison of their quality with the quality of performance of these exercises during training, a generalized quality criterion K_{gen} was proposed, which can be determined from the equality:

$$K_{gen} = \frac{100}{N} \left| \sum_{i=1}^{N} \left(\frac{P_{Ti}}{P_i} \right) \right| \%, \qquad (4)$$

where P_{Ti} is the required value of each of the parameters, P_i is the actual value of the parameters, and N is the number of parameters considered, which characterize the quality of performance of the exercise.

With an expedient choice of the required parameter values, the quantity K_{gen} will equal 100%, only if the assigned requirements are completely satisfied and, on the other hand, it will always be less than 100%, if the requirements are partially satisfied. For example, to characterize the quality of performance of the approach to the craft, the following parameters were taken into consideration:

-- duration $\Delta\tau$ and the deviation $\Delta\alpha$ of body position of the operator, from the position characteristic of the required body movement in performing the exercise;

-- total time for performance of exercise t_p;

-- time used in approaching the craft t_a;

-- total number of exercises performed n_{total};

-- number of exercises correctly performed n_c;

-- number of gross errors committed in performing exercises n_e.

In this case, the generalized quality criterion of performance of the exercise K_{gen} is determined, in accordance with expression (4), from the relationship:

$$K_{gen} = 20\left(\frac{\Delta\alpha_r}{\Delta\alpha} + \frac{\Delta\tau_r}{\Delta\tau} + \frac{t_{pt}}{t_p} + f\frac{t_{at}}{t_a} + \frac{n_c}{n_{total}}\right) \quad (5)$$

where

$$f = \frac{1}{n_e+1}.$$

Values, equal to the actual ones or a little less than them, in the final training exercises in the laboratory-aircraft, were used as the required parameters.

During the approach of the astronaut to the craft being considered, the quantities have the following values: $\Delta\alpha = 3.34°$, $\Delta\tau = 2.17$, $t_a = 7.5$ sec; $t_p = 11$ sec; $n_e = 0$, $n_{total} = 1$, $n_c = 1$. In this case, the generalized performance quality criterion of the approach was 39.7%.

In a comparison of the values obtained of quality of performance of the exercise in space with the quality of performance of the same exercise in the laboratory aircraft, during its flight along a Kepler trajectory, it could be noted that it is below the quality of A. A. Leonov in the last training exercises (K_{gen} = 57-60%), but higher than he had in his first training exercises (K_{gen} = 27-28%). It can be stated, from these results, that the training exercises carried out in weightless flights, as well as in the test stands simulating unsupported space, had a significant favorable effect on formation of the skills of controlling orientation and movement of the body in open space. The exercise performance quality in space, compared with its performance in the last training exercises, if it is taken as 100%, as is evident, turned out to be lower by only 30-35%.

90° turns around the vertical axis of the body were performed very well by A. A. Leonov. The time for each turn was not over 2 sec. In these turns, attention is drawn to the skill of controlling his movement, developed during training exercises on earth and in aircraft flights, holding the tether with his hand close to the center of mass of his body. This is a necessary condition for correct performance of the movement, and failure to observe it can lead to "torsion," i.e., to uncontrolled rotation of the body, which is a very undesirable phenomenon under weightless conditions. The turns per- /350 formed by A. A. Leonov also indicate good spatial orientation of the astronaut, permitting them to be carried out to precisely the assigned angle. Nevertheless, a somewhat similar "torsion" occurred in flight, when the angular velocities of body turns around the sagittal axis reached tens of angular degrees per second, and the angular accelerations, hundreds of degrees per second per second. The changes in angle of turn of the body, angular velocities and angular accelerations of this turn over time, in the plane parallel to the focal plane of the motion-picture camera, are represented graphically in Fig. 96, and they are illustrated by a series of frames from the motion-picture record of "torsion" (see Fig. 95). In analyzing the graphs, it can be concluded that, during this period, A. A. Leonov applied torques to the body of up to 10 kgm. This is possible, only when the astronaut removed his hand and the tether to a significant distance from the center of mass of his body, and which apparently led to the observed torsion.

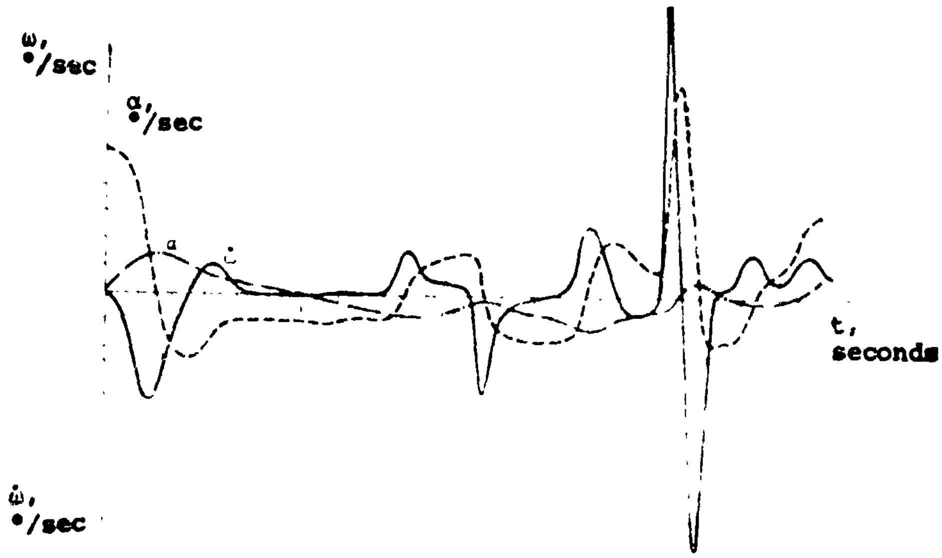

Fig. 96. Time change of angles, angular velocities and angular accelerations of rotation of body of A. A. Leonov during extravehicular activity

As has already been pointed out, in unsupported and little-oriented space, the "subjective coordinate system" of a man disappears (Klix, 1962), and the conceptions of "down" and "up" horizontal and vertical, which always are felt graphically in normal life, are completely terminated. In connection with this, the danger has been expressed of the possibility of loss of spatial orientation by the second pilot during the extravehicular activity in flight. However, in the entire time of his stay in open space, A. A. Leonov did not /351 lose spatial orientation, because he adhered to the conditions of orientation worked out on earth, determined by the coordinate axes of the craft.

The astronaut completely and correctly performed all specified work during the extravehicular activity. He assembled and disassembled the motion-picture unit, carried out radio reporting, made an interesting proposal on the effect of his movement on the movement of the spacecraft and carried out a series of observations. On the whole, it can be noted that the intense work of orientation and movement of A. A. Leonov in space was not significantly reflected on the remaining types of his activity in this period.

Study of Working Memory

From year to year, the activity of an astronaut controlling a modern spacecraft becomes more and more complicated. First and foremost, this is the complexity of control of the spacecraft in the accustomed coordinate system under weightless conditions. In the flight of Voskhod 2, it became difficult for investigators to evaluate all the characteristics of activity of an astronaut, by analysis of the actual performance of control operations; therefore, in the physiology of spacework, the procedure and methods of /352
scientific perception, widespread in the general physiology of work, in particular, the modeling method, is beginning to be used more and more.

It appears that just this method assists in revealing the structure of the functioning of an astronaut, included in a control system, in an unadapted situation unknown to him, with loss of the accustomed gravitation. In this connection, an attempt was made to model, true, very roughly, the activity of a man, in which the working memory becomes of primary importance. These studies were carried out in the flight of Voskhod, and they were continued in the flight of P. I. Belyayev and A. A. Leonov, as well as by the crews of the Soyuz spacecraft.

In connection with the inadequate study of the working memory of a man, materials frequently are proposed for characterizing it, which characterize the direct memory. Similar elements of these two types of memory are their briefness. However, according to the definition of P. I. Zinchenko and G. V. Repkina (1964), that briefness of memory which is included in any concrete activity and constitutes the conditions of its success is combined under the concept of "working memory."

In modern and, what is more, in prospective automatic devices, a tendency has been projected to change the requirements on the motor activities of man. The motor tasks are being simplified significantly: pressing buttons, switching toggle switches, etc. At the same time, the information presentation picture has been complicated sharply. Combined signals are appearing, including light, sound and other elements, and the rhythm of their succession is being quickened. All this significantly changes the requirements, as to the amount and lability of the working memory and its resistance to interference. In connection with this, it seemed advisable to conduct a study of the characteristics of the dynamics of the working memory of an astronaut, he being included in the working cycle, with analysis and reproduction of the finite result. /353

To produce equally informative tests of remembering, an abstract, but strictly proportioned volume of activity was proposed. The astronaut was given a series of cards for the work, on which curves were plotted, consisting of two identical outlines. The cards were exposed for a period of 1 minute. The time characteristics of the activity and the number of errors made, both in analysis and in reproduction of the outlines, were recorded in the test. Control studies (102 men) showed that the correlated value (derivative of the performance time and work quality) satisfies the requirements of the following expression:

$$K_{gen} = \frac{1}{\frac{t_1 + t_2}{k} + n_1 + n_2}, \qquad (6)$$

where K_{gen} is the generalized quality coefficient, t_1 is the analysis time in seconds, t_2 is the reproduction time in seconds, k is a weighting factor (k = 10 in the present studies), n_1 is the number of errors in analysis and n_2 is the number of errors in reproduction.

While preparing for performance of the scientific research program in flight, each astronaut carried out 12-16 training exercises, during which he was presented up to 70 test cards. In all cases, a stable plateau of this type of activity was reached, which served as the primary control data base.

Studies by this procedure were carried out with astronauts B. B. Yegorov, P. I. Belyayev and A. A. Leonov. The results obtained are presented in Fig. 97.

As is evident from the data presented, the results of the generalized quality coefficient of all astronauts, beginning with the 5th and 6th training exercises, are established at a single level, and they do not undergo significant change subsequently. The higher coefficient, the better working memory, was found in B. B. Yegorov. The coefficients obtained in space flight (the average data of the entire flight were used) was lower in all astronauts. The greatest reduction in flight (compared with the control data base) was observed in B. B. Yegorov, in which, judging by this result, he has

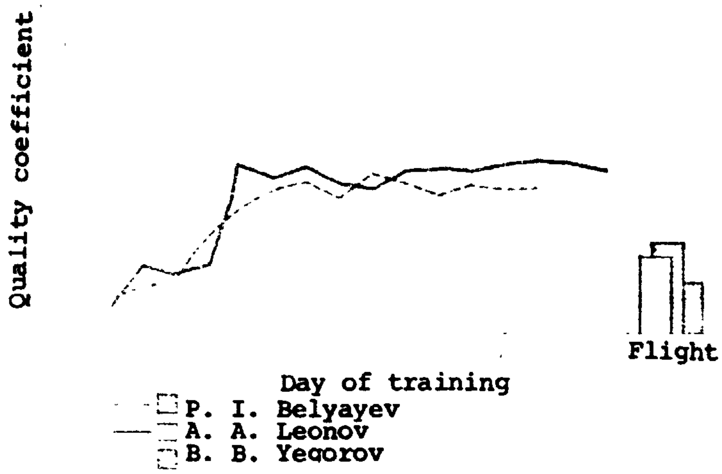

Fig. 97. Comparative characteristics of working memories under earth and space flight conditions

elements of an adaptive nature to the prolonged effect of weightlessness (Fig. 98). Thus, while, in the first 10 hours of the flight, the working memory lability decreased regularly (the generalized quality coefficient reached a value of 0.02 by the 10th hour), there was a break after this, the same regular improvement. Unfortunately, a similar dynamic study was not conducted in subsequent flights, in which only momentary measurements were made.

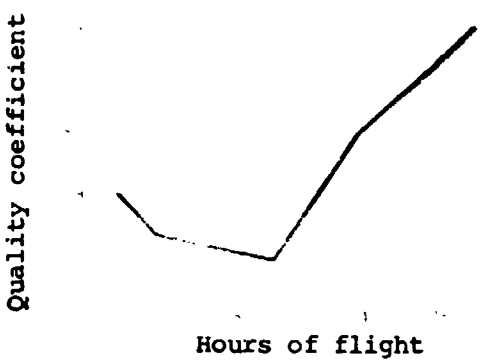

Fig. 98. Dynamics of working memory of B. B. Yegorov during space flight

Thus, the results obtained show that space flight conditions, prolonged weightlessness in particular, decrease the lability of the memory, which can provisionally be ascribed to the working memory, by all its characteristics. Moreover, on the basis of the results of the study of B. B. Yegorov, it can be proposed that there is a period of adaptation to weightlessness.

Study of Dynamic Motor Characteristics

In the flight of Voskhod 2 and the 18-day flight of Soyuz 9, together with study of the working memory of the astronauts, a study was conducted of the effect of prolonged weightlessness on the dynamic motor characteristics of the operator. This problem /354 arose in connection with certain tasks faced by engineering psychology in the developing space technology. Especially important in this respect is accumulation of material on the dynamic characteristics of man, for optimization of the control systems of prospective maneuvering spacecraft, accomplishment of soft landings of them on other planets, docking, etc. In connection with this, a model control system was first installed aboard a spacecraft, and the object of study was the previously indicated function of the human operator, included in a model control system (tracking), with the effects on him of space flight conditions, first and foremost, the prolonged weightlessness.

There have been particularly widespread presentations of studies of the behavior of man in tracking systems, with various loads on the regulating devices (Welford, 1953; Bahrick, 1957), different input signal characteristics (Hartmann, 1957, and others), damping of the regulating devices (Weiss, 1954; Conklin, 1957) and with individu- /355 al noises (Briggs, 1956); however, the effects of prolonged weightlessness on the tracking processes still has not been examined.

In attempting to give a description of tracking systems with man included in them, many authors have turned to the theory of communications in closed servo systems, considering them to be a model of a "man-machine" tracking system. Using the methods of mathematical analysis developed in automatic control theory and studying the nature of the changes taking place in the input signal, as a result of its passage through the system being studied, psychology has obtained the ability to objectively describe the dynamic properties of the human operator. Moreover, a positive aspect of this method is the fact that the form of the description is most suitable for quantitative characterization of the "man-machine" system as a whole, since all the rich arsenal of resources of automatic control theory are fully used, in this case.

Usually, in study of a tracking process, visual indicators are used (Melton, 1947; Adams, 1961, and others) and, more rarely, aural indicators (Forbes, 1946). A quantitative measure of tracking quality is considered to be the difference between the input and output signals, expressed by various methods, and the task of the operator is to reduce this difference to a minimum. A characteristic of the work of the operator usually is one function or another of this error, in a specific segment of time.

To create an autonomous tracking system in this experiment, the visual indication method was used, with graphic recording of the output signal. The input signals were plotted on the tape of a tape-winding mechanism, in the form of curves. The output signals were recorded with the same sight-pen recorder, which was rigidly connected to the control stick.

It was possible to study the operator reaction, by direct and delayed feedback, i.e., an inertial control system was simulated. In both cases, the task of the operators was to minimize the mismatch between the input and output signals. The contrast of the curve was about 0.85. The shapes of the curves, their tracking sequence and exposure time were the same at all stages of the test. The tape feedrate was stable, 5 mm/sec. This made it possible, to a certain extent, to estimate the latent reaction periods of the man, under various training conditions and in carrying out a space flight.

At all stages of the study, with the exception of the studies conducted in flight, measurements of the reaction were made three or four times. Before this, the operator became familiar with the apparatus and trained in a given type of activity, both under normal conditions and under some space flight conditions, reproduced under ground conditions. In flight, the study was performed twice. Each reaction measurement included 50 sinusoidal signals and 22 square pulses, set up in changing sequence, i.e., there was sufficient numerical material for statistical processing by computer.

The study of the dynamic characteristics of the operator in this test permits determination of the amplitude-frequency characteristic ($A[\omega]$), the phase-frequency characteristic (ϕ/ω), autocorrelation function (R), the mutual correlation coefficient (r), the transfer function and some other characteristics.

Signals, in the form of single functions of time, were used as the input signals:

$$x_{in}(t) = A \cdot 1(t) \text{ at } A = \text{const.},$$

in the form of a linear function of time: /357

$$x_{in}(t) = A \cdot t \text{ at } A = \text{const.},$$

in the form of a sinusoidal time function:

$$x_{in}(t) = A \sin \omega t \text{ at } A = \text{const.},$$

and nonmultiple frequencies between 0 and 1 Hz.

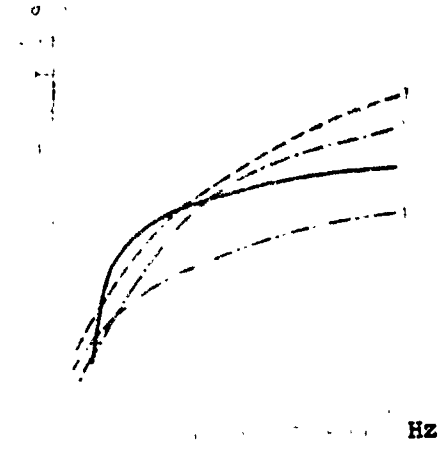

Fig. 99. Root mean error (δ) in tracking of A. A. Leonov at various stages: 1, space flight; 2, prelaunch period; 3, training spacecraft; 4, ground training exercises

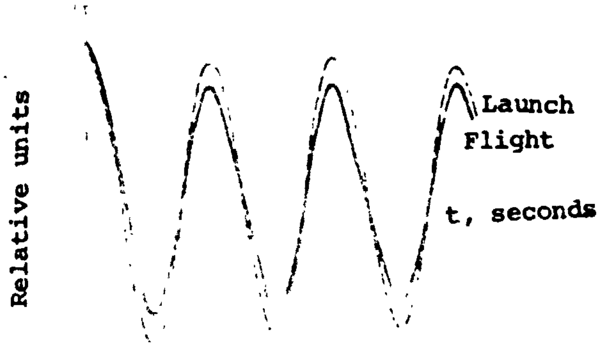

Fig. 100. Autocorrelation function (R[r]) of tracking parameters of P. I. Belyayev

In the first stage of analysis of the material, the root mean errors of the operator in various sinusoidal signals was determined (Fig. 99). These data show that, under various test conditions, the quality of the control activity of the man changes. External conditions (the effect of space flight conditions, mainly weightlessness, since the experiment was carried out in orbits 7-8) show up more in control, with signals of frequencies above 0.5 Hz. The scatter of the errors was increased in the prelaunch period.

Data obtained in the work of both astronauts were identical in nature. This gives some basis for considering that the extravehicular activity of A. A. Leonov did not have a significant effect on the quality of subsequent control activity.

The dynamic characteristics of the astronaut-operator can be illustrated most graphically, by means of the autocorrelation function. Correspondingly, the curves of the function, obtained on both astronauts two hours before launch and in flight, are presented in Figs. 100 and 101. Analysis of these curves (dying sinusoids) shows, first, that the relative tracking quality of A. A. Leonov in flight was somewhat better than that of P. I. Belyayev and, second, that this type of activity of both astronauts deteriorated in flight, from that in the launch period.

In subsequent analysis of the materials obtained, using the Fourier transform, the spectral densities of the signals mentioned above can be obtained, which permits determination of the type of transfer function for a given type of activity. This function can be determined by various methods, for example, using an integrating matrix by computer, on the assumption that the structure of the differential equation of the operator, as a dynamic control link, is known.

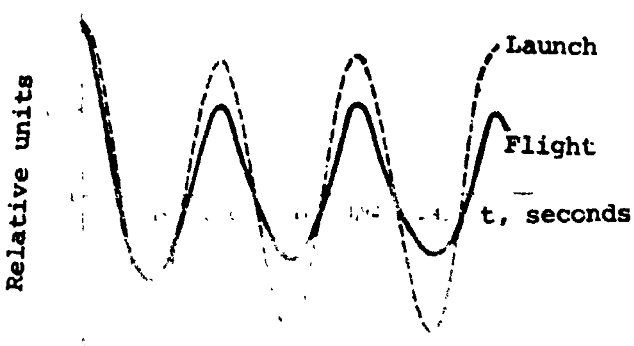

Fig. 101. Autocorrelation function of tracking parameters of A. A. Leonov

The analysis conducted of all materials obtained, as well as analysis of the frequency characteristics, in almost all cases, leads to a description of the dynamic properties of the operator performing tracking, by means of the following expression:

$$W_p = \frac{k e^{-p\tau}(a T_1 P + 1)}{(T_1 P + 1)(T_2 P + 1)}, \qquad (7)$$

where W_p is the operator transfer function, τ is the operator reaction time, T_1 is a time constant, a is a coefficient, T_2 is the operator delay time constant, k is the gain, P is the Laplace transformation argument, if $\tau > 0$ at $T_1 > 0$, $T_2 \geq 0$, $a \geq 0$.

It was found from analysis of the transfer function that the damping coefficient changes from 0.5 on earth to 0.1-1 in flight. Its optimum value is 0.7. The amplitude-frequency and phase frequency characteristics of the operator, as a dynamic link in the control system are shown in Figs. 102 and 103. By comparison of these /358
curves, it can be noted that the tracking quality of the higher sinusoidal signals deteriorates, especially in flight. Thus, for example, noticeable changes in the amplitude-frequency characteristics in flight set in, in work with a signal, having a frequency of 3-4 rad/sec. By analysis of the phase-frequency characteristics, the changes begin to be detected, with an input signal frequency on the order of 1-2 rad/sec, in which the magnitude of the change is more pronounced, in this case.

In study of the characteristics of reaction of the operator to a graded input signal, a specific range of change in the latent period of motor reaction can be determined. Thus, for P. I. Belyayev, in the training period in the training craft and at launch, the /359
latent period of motor reactions varied within 175-185 sigma. This value was 300-320 sigma in flight. There were no such sharp variations for A. A. Leonov: the results obtained in the training craft, at launch and in flight, were monotypic, and they varied from 180 to 185 sigma.

To all appearances, these numbers obtained in flight are a general estimate of the astronaut reaction. Thus, positively, the sensory component of the reaction had a greater delay, but it was leveled by the motor feature of the reaction, when some acceleration should have been expected, owing to the absence of gravitational

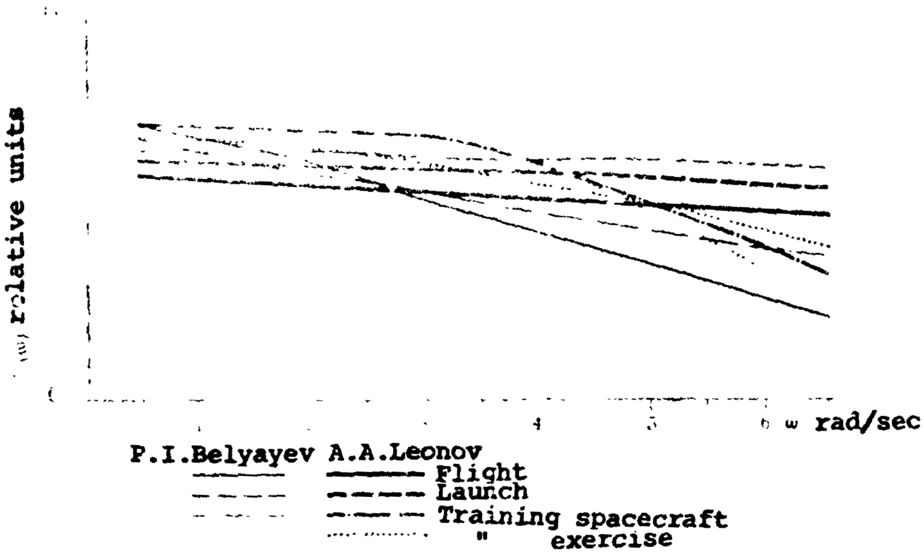

Fig. 102. Amplitude-frequency characteristic of operator tracking work

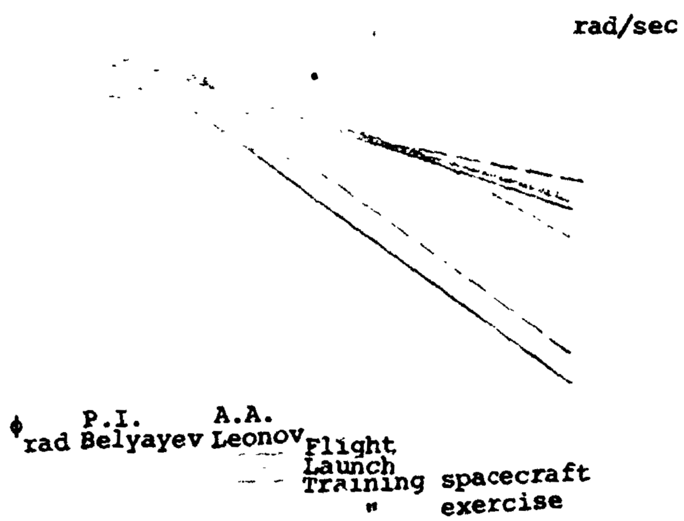

Fig. 103. Phase-frequency characteristic of operator tracking work

factors. In connection with this, the overall characteristics are not subject to significant changes.

A complex study of the dynamic characteristics of an astronaut was carried out, for the case of delayed feedback, with an input signal frequency of 0.06 Hz. In the opinion of V. P. Zinchenko and colleagues (1964), this method of investigation implies the necessity of the operator predicting the content of the problem being solved. For this, there usually is a window, through which the operator follows the input signal and sight (writer), the course of the tape is partially covered with a curtain, as a consequence of which the operator must extrapolate the input signal. The mutual correlation coefficients for these conditions are presented in Table 83.

TABLE 83

MUTUAL CORRELATION COEFFICIENT FOR CONDITION WITH DELAYED FEEDBACK (signal 0.06 Hz)

Operator	Stage of Study	Correlation Coefficient
P. I. Belyayev	In training craft	0.70
	Before launch	0.74
	Inflight	0.83
A. A. Leonov	In training craft	0.58
	Before launch	0.87
	Inflight	0.88

As is evident from Table 83, the flight data are better than the ground.

The opposite tendencies of change in the operator work characteristics inflight, with delayed feedback, attract attention. At the present time, no clear judgment can be made on the reasons for this, in our opinion, very interesting fact. However, it certainly merits study.

A detailed study of the psychophysiological characteristics and dynamic parameters of astronauts, included in a model control system, was conducted in the Soyuz 9 spacecraft.

The results of study of the operator activity of A. G. Nikolayev and V. I. Sevast'yanov, obtained during the 18-day flight, are presented in Tables 84 and 85. The average values of the parameters, characterizing the work quality of the operators, in compensating for a single mismatch, are given in them. These data reveal a number of interesting features. First, the value of the dispersion of the time of the transfer process turned out to be the most critical to space flight conditions. For A. G. Nikolayev, it was, in flight, four times, and, for V. I. Sevast'yanov, almost three times greater than on earth. Second, the time constant $M(T_0)$ of both astronauts turned out to be greater in flight: that of the spacecraft commander by 2.7 times and that of the flight engineer, 1.28times. At first glance, it may seem that, both by this value and by the remaining parameters, there are significant individual differences between the astronauts. Actually, in the average of 5 of the parameters listed, the work quality of A. G. Nikolayev in flight deteriorated 1.9 times more than that of V. I. Sevast'yanov. However, this is most likely explained by the fact that the work quality of V. I. Sevast'yanov is lower in absolute value than that of A. G. Nikolayev, 2.62 times for the baseline data and 2.7 times in flight, i.e., on earth and in flight, V. I. Sevast'yanov worked more poorly than A. G. Nikolayev, by approximately the same number of times (2.62 and 2.7) and, consequently, their reactions to space flight conditions were practically identical. The differences between them is that, evidently, A. G. Nikolayev is a more highly qualified operator than V. I. Sevant'yanov, the work quality of whom, even before the flight, reached the maximum level and could only be subject to changes in flight, because of the action of unfavorable factors. The work quality of V. I. Sevast'yanov in space could change, both from flight factors and as a result of continuing training (work with the instrument). /360

Considering what has been stated, it can be concluded that, on the basis of the experiment carried out with two operators on a long space flight, the operator reaction time constant to a single disturbance increases by 2.7 times.

The delayed nature of the process of tracking a single function by the astronauts 40 min after landing is understandable (Fig. 104). The delay in the process can be explained here by two factors: first, by partial discoordination of movement and, second, the weakness of the arms, out of practice of use of "earth" forces, which certainly must lead to slower and less abrupt movements. /361

The results of tracking of sinusoidal signals of various frequencies by the astronauts are presented in Figs. 105 and 106 and, in Figs. 107 and 108, of random signals with various characteristics, as a function of flight time. The data presented demonstrate definite individual differences in the operators. While the average tracking error level of A. G. Nikolayev, after a day of flight (orbit 20-21) approximately doubled, for both the random and the sinusoidal signal, the error level of V. I. Sevans'yanov in this period scarcely differed from the data base. But then, by the end of the second day of the flight (orbit 37), the tracking quality of A. G. Nikolayev improved and reached the data base level, which was maintained to the end of the flight (orbit 256). A tendency towards deterioration of tracking quality of V. I. Sevast'yanov was noted on /362

TABLE 84

REACTION PARAMETERS OF A. G. NIKOLAYEV TO A SINGLE MISMATCH

Parameter	Base-line	Orbit			Avg. for Flight	Flight/Base-line Ratio
		21	37	250		
$M\ [t_n]$, sec	0.29	0.37	0.595	0.85	0.605	2.09
$D\ [t_n]$, sec^2	0.104	0.348	0.232	0.66	0.413	3.98
$M\ [T_0]$ sec	0.045	0.078	0.121	0.17	0.1213	2.7
$t_{n_{max}}$, sec	0.5	1.2	1.35	3.5	2.01	4.02
$t_{n_{min}}$, sec	0.15	0.05	0.05	0.05	0.05	0.33
$\Delta\ t_n = t_{n_{max}} - t_{n_{min}}$	0.35	1.15	1.3	3.45	1.77	5.06

TABLE 85

REACTION PARAMETERS OF V. I. SEVAST'YANOV TO SINGLE MISMATCH

Parameter	Base-line	Orbit				Avg. for Flight	Flight-Base-line Ratio
		21	37	115	255		
$M\ [t_n]$ sec	0.92	1.0	1.19	0.935	0.91	1.01	1.1
$D\ [t_n]$, sec^2	0.108	0 375	0.216	0.25	0.365	0.3015	78
$M\ [T_0]$, sec	0.153	0.2	0.238	0.187	0.17	0 1965	1.28
$t_{n_{max}}$, sec	0.88	1.25	2.25	2.25	1 88	1.907	1.01
$t_{n_{min}}$ sec	0.25	0.75	0.375	0 35	0.25	0.431	1.72
$\Delta\ t_n = t_{n_{max}} = t_{n_{min}}$	1.62	0.5	1.88	1.9	1.62	1.475	0.91

on the second day (orbit 49), which appeared particularly clearly in the middle of the flight (orbit 115) and at the end of the flight (orbit 250 for the random signal). It can be stated in this /363 connection, that, on the whole, the control skills of A. G. Nikolayev in flight turned out to be more stable than those of V. I. Sevast'yanov. The possibility is not excluded that this is, on the one hand, a reflection of the professional qualities of A. G. Nikolayev-pilot and, on the other a better grounded physical and psychic readiness of A. G. Nikolayev-astronaut, accomplishing a space flight for the second time (Vostok 3 and Soyuz 9). The spread of the tracking errors of A. G. Nikolayev in flight increased by 26% on the average and that of V. I. Sevast'yanov, by 69%, with an overall higher tracking quality of A. G. Nikolayev (by 1.33 times) than by V. I. Sevast'yanov.

Concerning the dependence of quality of tracking the sinusoidal signal on its frequency, practically no differences between the

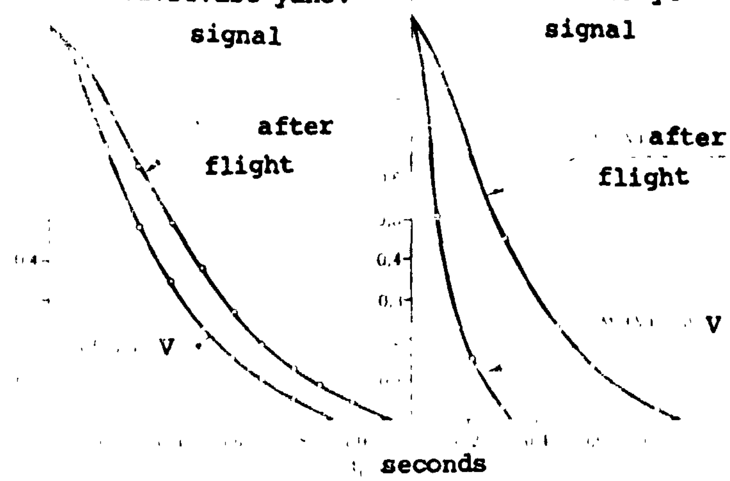

Fig. 104. Graphs of transfer processes describing operator reactions to a single signal in flight (for V. I. Sevast'yanov in orbit 49, for A. G. Nikolayev in orbit 250) and after the flight

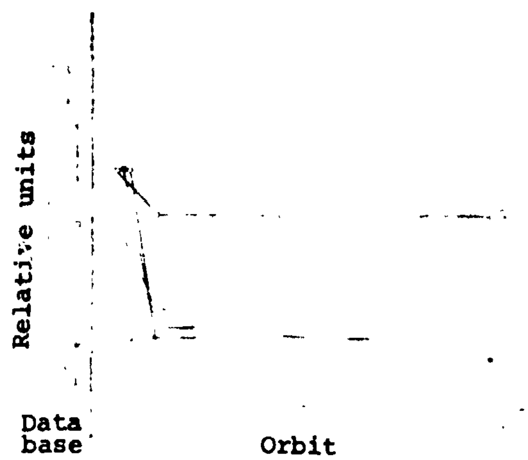

Fig. 105. Standard error of tracking sinusoidal signals of various frequencies by A. G. Nikolayev in space flight: 1, 0.12 Hz; 2, 0.16 Hz; 3, 0.2 Hz; 4, 0.5 Hz; 5, 1 Hz; 6, average of 5 studies

operators was noted (Figs. 109 and 110). With both operators, the effect of signal frequency on quality of tracking it was clearly expressed for both operators. It is characteristic that the highest tracking quality is observed at frequencies below 0.5 Hz, i.e., in the range, which was noted in the work of the crew of Voskhod 2. In our opinion, these results are a sufficient basis for taking them into consideration, in developing specific semi-automatic control systems of a spacecraft and its systems. The different degree of expression of these functions of the astronauts attracts attention. As should have been expected, the minimum of the $\sigma = \sigma(\omega)$ curve of A. G. Nikolayev is more depressed than that of V. I. Sevast'yanov, since

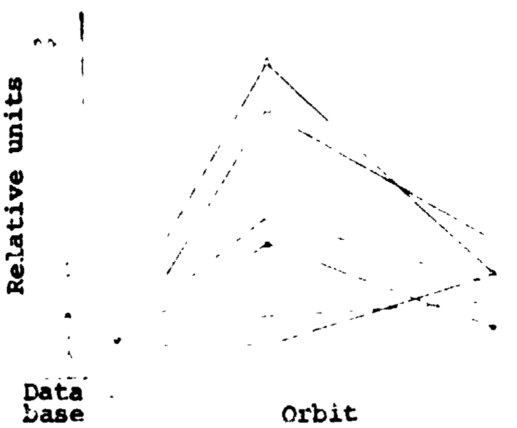

Fig. 106. Standard error of tracking sinusoidal signals of various frequencies by V. I. Sevast'yanov in space flight: designations same as in Fig. 105

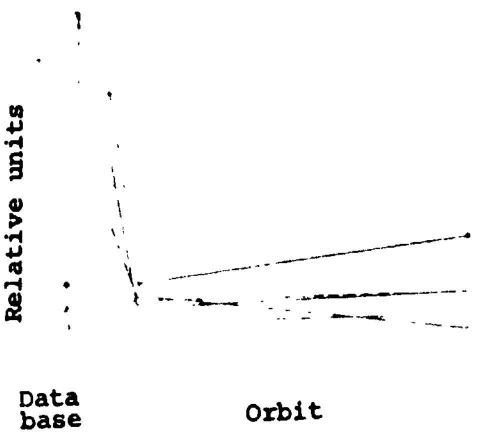

Fig. 107. Standard error of tracking random signals with various characteristics by A. G. Nikolayev in space flight: 1, random nonstationary signal; 2, random stationary; 3, random stationary; 4, quasi-stationary; 5, average of 4 studies

control skills of A. G. Nikolayev are more stable and the quality is higher. It can be assumed that the quantity $d\sigma/d\omega$ max can be one of the criteria of evaluation of the degree of stability of the control habits and of an adequate level of training of the operator. This circumstance confirms the regularity, and not the random nature of the changes recorded in flight and, moreover, it indicates, first, the sufficient universality of the sinusoidal signal as a standard and, second, adequate linearity of the human operator as a link in the dynamic system, because, with a clearly expressed nonlinearity, the nature of these functions would be different, in the general case. Here, as previously, a greater spread of the data in flight, compared with the background is noted for V. I. Sevast'yanov and a smaller spread for A. G. Nikolayev, which we are inclined to explain by the greater readiness of A. G. Nikolayev as an operator and an astronaut. The nature of tracking of various types of random signals by the operator assists in revealing features of activity of various functional systems of the body of the astronaut during a flight.

The data of study of some dynamic characteristics and reactions of the astronaut-operator in many-day flights are presented in Fig. 111.

The studies showed that the simple motor reaction time of an astronaut-operator, including the reactions of selecting from three, do not undergo significant changes. By analysis of a more complicated associative extrapolation reactions, adaptive changes were defined: A sharp increase in reaction time in the first days of the flight and the same sharp decrease by the third day.

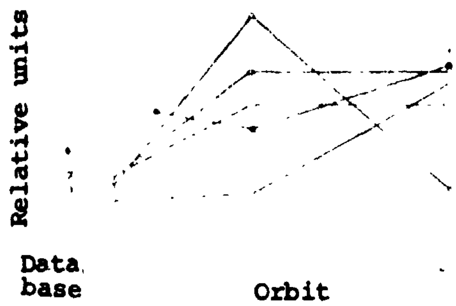

Fig. 108. Standard error of tracking random signals with various characteristics by V. I. Sevast'yanov in space flight: designations same as in Fig. 107

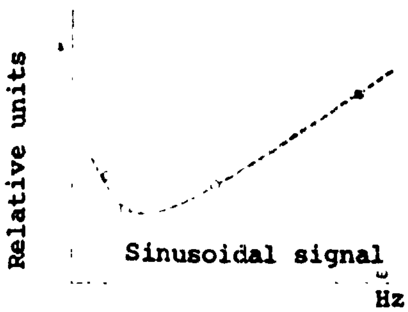

Fig. 109. Standard error of tracking sinusoidal signals of A. G. Nikolayev vs. their frequencies (in space flight)

Reflexographic observations were made of four astronauts. Despite the fact that each point of the corrected curve contains 30 measurements of reactions in flight, we are inclined to consider the data to be preliminary. However, the relationship of the flight data and their dynamics to the results obtained in long model experiments show that the basic complex /364 associative extrapolation reaction, which is the most subject to change during a flight, is the working memory, the mechanisms of functioning of which are phylogenetically young and, therefore, the least protected from the effects of unfavorable external factors. As was shown by the studies carried out in the Voskhod, Voskhod 2 and Soyuz 6 space flights, the dynamics of the working memory has approximately the same nature of change as the dynamics of the foresight reaction time (see Fig. 97). Consequently, it can be assumed that disruption of the normal course of motor acts is explained by complex central changes, which again emphasizes the general effect of weightlessness on various body functions. This is the cause of the disruptions, which were noted in /365 analysis of the more complicated integrative characteristics of motor activity of an astronaut in flight, such as the tracking reactions, finely coordinated control activities, transmission of radiotelegraph signals, etc.

For a deeper dissection of the mechanisms of disruption of motor coordination in weightlessness, of the inner structure of motion and of the mechanisms of its reorganization, the conduct of a series of biomechanical experiments was necessary. The first successful effort in this area was undertaken by L. V. Chkhaidze. However, he studied a limited group of kinematic chains, with a small number of links. Therefore, one of the authors, together with I. A. Kolosov and I. F. Chekidra, conducted a series of experiments in weightlessness, the purpose of which was to study the internal coordination structure of voluntary movements of the arms, under conditions of varying weight.

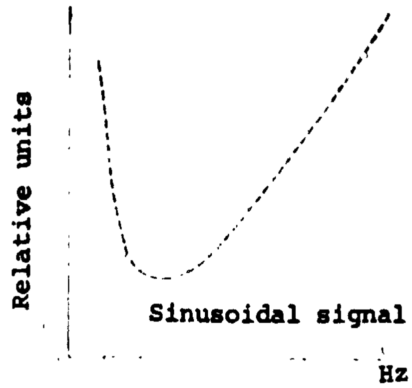

Fig. 110. Standard error of tracking sinusoidal signals of V. I. Sevast'yanov vs. their frequency

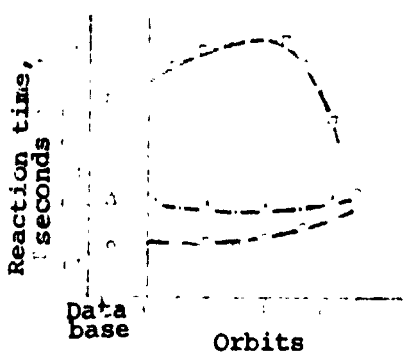

Fig. 111. Change in time of various types of sensorimotor reactions of the astronauts in space flight: 1, simple reaction; 2, reaction of choice from three; 3, reaction with simple association

It was determined in a series of studies that processing of actions by astronauts takes place, with simultaneous reorganization of the structure of the motor skills applicable to the conditions of absence of body weight. During the training process, the coordination structure of special purpose arm movements of the astronauts, of varying complexity, was studied photocyclogrammetrically. It was found that, in the first flights in weightlessness, the coordination structure of movement is complicated, compared with normal weight conditions: the muscle efforts and amplitude and number of correcting signals from the central nervous system sent to the periphery during movement increase. In the fourth or fifth flight in weightlessness, the structure of test movements proves to be almost the same as under normal gravity. Between the 20th and 30th flights in weightlessness, stabilization of the movement structure takes place; the muscle forces applied decrease, and, which is especially interesting, the magnitude and number of corrections of movement decrease, compared with those under normal weight conditions. Owing to recording of the biomechanical characteristics (speeds, accelerations, forces, muscular torques) in microintervals of time, objective criteria were successfully worked out for evaluation of the rapidity of reorganization of motor skills, in a parallel study of work activity as a whole, by means of analysis of motion-picture materials, time and motion charts, psychophysiological reactions, performance ability and quality of work performance. A mutiple evaluation of activity permits difficulties to be revealed, which arise in an astronaut in performing various elements of an assignment and the process of formation of a stable dynamic stereotype of occupational, work activity of an astronaut, worked out in mock-up sections of spacecraft under weightless conditions, to be controlled.

In this manner, a comparative analysis of the results of completion of time and motion tests, conducted under flight conditions and on earth, the results of model experiments and biomechanical calculations have shown that the disruptions noted under weightless conditions, to all appearances, are connected with control-coordination function mechanisms. In fact, if attention is directed to the scheme of the movement control apparatus of N. A. Bernshteyn, a series of elements can be found, which are very sensitive to the effects of weightlessness. The basic work units of this most simple scheme are: the effector, the work of which is subject to regulation; the assigning unit, introducing the required value of the parameter regulated into the system one way or another; the receptor, perceiving the actual current value of the parameter and signaling it to the comparison apparatus in some manner; the comparison mechanism, perceiving a divergence of the actual and required values, with its /366 magnitude and sign; a device, recoding the comparison apparatus data to correcting pulses; the regulator, controlling the functioning of the effector by a given parameter.

The central command post of this system, in the expression of N. A. Bernshteyn, is the assigning element. At the output of this element, an image or representation of the result of the action forms (final or by stages), to which this action is directed. The morphological structure, providing the function of the assigning element, is still unknown; however, to all appearances, it encompasses a number of cortical formations of the brain. Grandpierre (1967) demonstrated experimentally that the extrapolating activity of monkeys in weightlessness is significantly disrupted, simultaneously with a reduction in the bioelectric activity of the brain. The working memory suffers in this case, and the conceptual model of command actions is disrupted. Disturbances in the work of the peripheral apparatus leads to considerable changes in the function of the assigning element. The commands determined for the required action will continually direct signals known to be inaccurate to the "bottom instances of the assigning complex," which will delay switching of the command to the next microinterval of the program. According to the definition of P. K. Anokhin, the "sanctioning afferentation" is disrupted. In this case, the comparison apparatus will send correct information to the central units, on the disagreement between the assigned and actual picture, while correction of the activity will be based on the old "earth" representations of the magnitude of the pulse, which must be directed to the divergence effector, and which will be extreme. All this leads to disruption of the control-coordination function of the higher sections of the brain and to deterioration of task performance quality.

The first studies of performance capacity, conducted with simulation of the programs of flights of various lengths, demonstrated a deterioration in quality of the activity in the first orbits. Subsequently, the level of these changes decreased, in the majority of cases and duplicated the baseline results, in some experiments.

An analysis of this revealed that, despite the satisfactory condition of the astronauts in flight and, basically, execution of the flight programs, disturbances were noted, especially of the motor elements of occupational skills, in the first orbits of a flight. Thus, for example, the Gemini 3 spacecraft commander, W. Grissom, performed a maneuver of the craft in the first orbit, the purpose of which was to make it possible for the second pilot, D. Young to observe the second stage of the launch rocket, revolving in orbit. The experiment failed. In the flight of Gemini 4, in the first and at the start of the second orbit, astronaut J. McDivitt attempted to approach the second stage of the launch vehicle for a period of an hour. He wasted half the working time on this operation, without achieving the required result. Because of overconsumption of fuel, he was forbidden further approaches in a second approach and in maneuvering experiments, in the 30th and 45th orbits. As was established, besides errors in control (tracking), the astronaut incorrectly estimated the distance to the target (it actually was 600 m, but 120 m, by his determination).

The clearest example of the problem being considered can be introduced by analysis of the activity of the Gemini 10 spacecraft commander. To dock with the Agena-10 rocket, the spacecraft commander D. Young carried out a maneuver in the second orbit of the flight. The docking was accomplished with great difficulty, but it turned out that the astronaut used twice as much fuel as had been planned. The overconsumption of fuel took place in the final guidance stage, when small, finely coordinated movements of the hands predominate in the motor structure of the operation. In the same flight, but in the 30th orbit, the same astronaut carried out docking with the Agena-8 rocket, using only 87% of the fuel available for the maneuver. /367

The adaptation process of the Voskhod spacecraft crew members had a somewhat different nature. The astronauts did not encounter particular difficulties in performing the working manipulations assigned to them by the program. As was noted above, an analysis of the time spent in performance of a number of operations (spacecraft control work, medical manipulations, etc.), as well as in logic tests, showed that this time was considerably greater at the start of the flight than in subsequent orbits.

As is evident from the material presented, the adaptation fluctuations harmed the activities in which the motor analyzer plays an active part in the output. However, as a result of specially conducted studies, a similar picture was disclosed in other systems of the body.

All these materials permit it to be assumed that, in the first orbits of an orbital space flight, the capabilities of man to perform purposeful work, especially motor operations, are considerably restricted. In connection with this, after the flights of the Voskhod spacecraft, it was recommended that critical measures, connected with work activity, especially with performance of finely coordinated motor acts, be planned in the second half of a one-day flight.

A psychophysiological analysis of the condition and activity of the astronauts of the Soyuz 3, 4 and 5 spacecraft gave the most clearly expressed symptomatics of the process of adaptation in flight. Thus, for example, according to data of the dynamics of the physiological functions of G. T. Beregovoy, the most active adaptation process was observed in the 1st to 15th orbits. In this period, the heart rate increased to 104 beats per minute, with a subsequent decrease in pulse rate to 66 beats per minute. In the second phase of the flight, the pulse rate held at this value, typical of the astronaut, with a spread of ±5 beats per minute.

The personal record of G. T. Beregovoy is interesting. Despite the good general condition, affirmed by objective indicators and radio reports, the astronaut noted some pecularities in the first hours of the flight. Thus, in performing purposeful movements, he distinctly registered an involuntary, brief pause, between the "command" and "execution" elements of activity, which he perceived as a certain "standstill of time." This condition first arose immediately after injection of the spacecraft into orbit. During approximately the same hours, the astronaut noted some illusory perception of spatial position. It appeared with the eyes closed and in the position, when the head was on the support; in this case, it seemed that the craft began to rotate around the transverse axis and that he himself was thrown legs up. The illusions disappeared with muscle tension, with strong support of the legs on the wall of the craft, by means of tightening the binding straps. The expression of these peculiarities gradually decreased, and they completely disappeared by the 10th to 15th hour of the flight. In phase II of the space flight, despite active work involving abrupt movements of the head and turns of the body, G. T. Beregovoy did not note any discomfort.

The crews of Soyuz 4 and Soyuz 5 subjectively confirmed the /368
presence of an adaptation period, to one extent or another. Thus, in the words of A. S. Yeliseyev, "On the second day of the flight, it was simpler to work than on the first and, at the start of the third day, there was the impression that it was absolutely fully assimilated and that the present work situation had set in." B. V. Volynov wrote: "Operations which are complicated and delicate, from the point of view of movement coordination, must be planned, not earlier than after a day. During the first days, some singularity prevails over you." Other crew members hold to similar opinions.

The initial period of adaptation in orbital flight is accompanied by peculiarities in the subjective condition of the crew. Immediately after going into orbit, V. A. Shatalov began to experience a feeling of "bulging out in the head," similar to that which takes place on earth, when a man is in the head down position and the blood vessels are overfilled with blood. In the first days of the flight, this condition was pronounced, although it did not disrupt performance capacity, it weakened considerably on the second day and it almost on the third day. However, some very small manifestations of it remained until the end of the flight. This remark was made by V. A. Shatalov and A. S. Yeliseyev, after the second flight in Soyuz 8. The subjective feeling described has a certain relationship to singularities of motor activity and movement coordination. It seemed to the astronaut that his center of gravity was displaced upward, as a consequence of which, he had to float up in the state of weightlessness. This subjective feeling is certainly of "earth origin." The spatial orientation stereotype of man apparently includes pulses from the interoceptors of the vessels of the brain. Because of the increase in blood pressure in the brain vessels in the absence of the accustomed afferentation from the vestibular apparatus, a subjective feeling of the effect of the force of gravity in the direction of the head developed in the astronaut in phase I of the stay in orbit. This forced the astronaut to continually hold onto the arms of the chair with the hands in the initial period of the flight ("so as not to float up"). Of course, such a situation leads to unjustified muscle and psychic stress. The fact that the "sense of floating up" occurs in stabilized flight, when there are no centrifugal forces causing rotation of the craft, indicates that it is precisely the psychophysiological mechanism described of the "sense of floating up" which acts in weightlessness.

Facts confirming the presence of an adaptation period have been noted in study of coordination of movement of the oculomotor group of muscles, in study of the working visual performance capacity, in study of the ergonomic characteristics of the exiting astronaut and of certain other functions.

Thus, a psychophysiological analysis of the activity of investigators, in simulating the programs of long space flights, as the results of studies carried out jointly with the crews of Voskhod Voskhod 2, Soyuz 1 and Soyuz 9, and facts stated in American publications, permit it to be concluded that there are several phases in a space flight. The first phase of the initial adaptation is characterized by changes in the condition of many functions, especially the function of the static-kinetic analyzer, which frequently are accompanied by illusory perceptions of spatial position. In subsequent phases, some stabilization of operator performance capacity is noted, at a level approximating the baseline data.

Thus, the first experiments give a basis for thinking that /369 the dynamic characteristics of man, acted on by the conditions of a one-day space flight, do not undergo sufficiently serious changes. More than that, a 10-minute stay of the operator in open space also did not show up in the characteristics. However, it should also be emphasized that the activity of a man, with input signals having a frequency of over 0.5 Hz, is the most subject to the effect of space flight conditions.

Further many-day flights will also permit an answer to the question of changes in stability of the astronaut, as a dynamic link in the control system, as a function of flight time, the nature of a task performed and the conditions in which he finds himself.

Condition of Working Visual Performance Capacity

A characteristic feature of man in a space flight is the fact that the basic input of information on operation of the spacecraft systems and on the external situation is almost only through the visual analyzer channel. The monitoring-measuring instrument system, by means of which astronauts monitor the operation of all spacecraft systems and control it and its systems, belongs here, first and foremost. The design of the control systems of prospective spacecraft, intended for maneuvering flights, approaching and docking of space stations, as well as for accomplishing landings on other planets, also is based on the ability of man to detect light signals on one background or another, recognize various types of visual images and a number of other properties of the visual analyzer, for example, depth perception, visual memory, visual estimation, etc. In this connection, the importance of the level of functional capabilities of the vision of an astronaut for successful performance of the bulk of the flight tasks is understandable.

The vision of the astronauts has an important role in their performance of planned tasks, during a flight along the earth-moon-earth course, especially in landing on the moon. Special light conditions of the work of vision in these cases are capable of affecting the nature of visual perception. These conditions are characterized by a great absolute brightness of observed objects with large angular dimensions. For example, the earth and the moon, illuminated by the sun appear to an astronaut, at a distance of several thousand kilometers, as very bright disks on a black background. In this case, as we shall see below, the ability of astronauts to find and recognize given formations on the surface of these planets is strongly reduced. The contrast between the illuminated part of the object and its shadow part, which becomes practically invisible, reach very high levels, and there are practically no half tones. In order to understand the characteristics of vision under these conditions, to predict the level of the visual capabilities of the astronauts, and this means, to make a judgment of the reliability of execution of the entire flight program, again, a precise study of vision is necessary.

The great role of vision in a space flight is determining the importance, which is given to study of this problem at the present time by specialists of various professions. These data are of interest to designers of various space systems, physicians and engineering psychologists.

Before carrying out a space flight, it can be assumed that the reduction in visual efficiency observed in pilots during aircraft flights is greatly increased in orbital space flight, when the effect of various unfavorable factors is immeasurably larger. /370

Determination of the extent of the effect of space flight on the basic characteristics of vision (visual acuity, light sensitivity, color vision, etc.) was the first important task of space medicine, since this is important for perception of instrument signals and the capability of control of the craft.

Before flights in space, it could be assumed that the absence of the effect of gravity in orbital flight would cause deformation of the shape of the eyeball, to one extent or another, and that this, in turn, would be reflected in some way on the functional capabilities of the eyes. It could also be expected that, in the state of weightlessness, the oculomotor apparatus would lose the coordination of movement, worked out in the process of living on earth, to a greater or lesser extent, and that this would lead to definite disruptions of the perception of visual images, deterioration in depth perception and the capacity for accommodation and other functions of the eyes.

It was not clear how the liquid and semiliquid media of the eye behave in weightlessness and whether or not the nature of the occurrence of the biochemical processes in the eye remain unchanged and what effect all this has on vision. These questions waited for solution.

The start of these studies involved experiments in flights along the Kepler trajectory. The briefness of these studies and the instability of weightlessness led to the appearance of artefacts in the first periods (and, unfortunately, lead to them at the present time). The results obtained frequently were very inconsistent. Thus, for example, according to the data of American authors, visual acuity decreased under these conditions, by 6% on the average. A. A. Volkov, Ye. S. Zav'yalov (1965) and L. A. Kitayev-Smyk (1963) also noted a reduction in visual activity in the period of onset of weightlessness, in which, according to their observations, during a subsequent stay in weightlessness, it is restored or even exceeds the established level in some persons (such changes take place in 25-40 sec under weightlessness conditions). Subsequently, L. A. Kitayev-Smyk noted an increase in the subjective brightness of colors, especially yellow. According to his hypothesis, the visual reactions developing in weightlessness are caused by disruption of the integrative processes, in both the centers and the periphery of the visual analyzer, in particular, by a reduction in the tonus of individual eye muscles. Digressing ahead, it could be noted that the similar studies, conducted in actual space flight, during the prolonged action of weightlessness, does not make it possible for us to agree with these conclusions. Study of the functional indices in brief weightlessness should be taken as a tentative, orienting step.

In the very short time of action of action of weightlessness, the body does not succeed in adapting to the conditions of the experiment, and its indicators will characterize, not the settled, but some transitional (from g-forces) values of the function studied.

The functional state of visual performance capacity of the astronauts in an actual flight is judged by three basic documents: a) the reports of the astronauts (subjective evaluation of the visual function); b) the results of studies, using special tests and scientific apparatus; c) reports on execution of visual work during flight.

The reports of the astronauts on the capabilities of visual observation of the surface of the earth and objects in space are of great interest, from the point of view of, not only the effect of prolonged weightlessness on the resolving power and other functions of vision, but of the effect of weightlessness on the process of comprehension of the information obtained. /371

Data on the visual acuity of the astronauts, calculated on the basis of certain data of observation of the surface of the earth by the astronauts, are presented in Table 86.

TABLE 86

APPROXIMATE VISUAL ACUITY IN OBSERVATION OF OBJECTS OUTSIDE THE CABIN

Object Observed	Approximate Visual Resolution (angular minutes)	Visual Acuity
Rivers of the Amazon, Volga, Nile type	at least 10-20	over 0.1-0.05
Major Asphalt roads	0.2—0.5	5—2
Runways	0.5—1.0	2—1
Ships in the sea in roadsteads	0.3—1.5	3—0.7
" " " " underway	1—3	1—0.3
Aircraft contrails and their shadows on the earth	0.3—0.6	3—1.7
Beach zones (Caucasus)	0.3—0.5	5—2
Railroads	0.4—0.8	2.5—1.2

As is evident, visual acuity in orbital flight exceeds the average standard; however, this concerns linear, extended objects (roads, aircraft contrails, etc.), for which visual acuity under earth conditions also is increased to a greater extent than indicated in Table 86, in a number of cases (S. V. Kravkov, 1950). Moreover, the objects listed (roads, runways, beach zones, etc.) were observed by the astronauts, in the form of bright lines on a dark background. In this case, as a consequence of the phenomenon of irradiation, the visual angular size of objects is increased to some extent, and visual acuity, determined from the actual sizes of these objects, appears to be overstated. In connection with this, on the whole, on a basis of the data presented, specific quantitative conclusions cannot be drawn, as to changes in visual acuity under weightless conditions, in observation of objects outside the cabin; however, it can be said with great confidence that significant changes in the functional capabilities of vision in a space flight do not take place.

Soviet and American astronauts report that the color of the surface of the earth appears to be approximately the same as from high-altitude aircraft. They note a great diversity of azure and blue tones of the oceans and seas, the malachite color of the water in Lake Baykal and the delicate azure of the aerial haze close to the horizon of the earth. In the opinions of the astronauts, the richness of the tones of the water, from the blue-tinged black color to delicate azure, is determined by various altitudes and azimuths of the sun up above the portion of the surface of the earth being observed, as well as by different sun angles, i.e., the angle at which the sun and the spacecraft are seen from the terrestrial object observed.

The astronauts describe space dawns identically; they are distinguished by a diversity of warm tones, from carmine red through red, cinnabar red, orange and yellow, to greenish, with a transition to the dark blue tone of the shining atmosphere at great angular distances from the horizon of the earth. The astronauts dis- /372 tinguish well the tones of the conifer and leaved forests, young green shoots of plantings, green forest protection belts, etc., and the easily distinguished soils by color: sandy, podzol, rocky plateaus in mountain regions, and the Bordeaux-tinged color of the rocky and sandy regions of Africa. The American astronauts have noted the color characteristics of lunar rocks and soils on the moon, which, in some positions of the astronaut, relative to the direction of the sunlight, took on a slightly warmish-brown tone and, sometimes, appeared to be neutral grays.

All these results of observation of the colors of objects in space permit it to be considered that appreciable changes in the subjective color senses of the astronauts do not take place in flight; the color-vision function remains practically unchanged.

It also is known from the reports of the astronauts that they could observe such phenomena as the faint glow of the cloud cover on the nightside of the earth, under which illuminated cities are located, aircraft contrail shadows on the surface of the earth, smoky strips along the primary wind rose direction from industrial enterprises, darkening of the snow along main railroad lines, storms and typhoons in the ocean, and smoke trails from forest fires. Different depths of the seas and oceans in the coastal zones are seen well from space, by means of the different intensities of color of the water and differing brightness of separate sections of the water areas.

These results of observations by the astronauts indicate that the contrast sensitivity of their vision or, in other words, its discriminating power, also does not undergo noticeable changes.

It has long been known that, during a flight, the astronauts saw stars on the nightside of the earth and city lights well and distinguished networks of streets. The astronauts repeatedly observed storms; as they note, lightning is a very frequent phenomenon on our earth.

There are some disagreements among the astronauts, relative to the visibility of stars above the dayside of the earth (without the earth in the field of vision). However, these disagreements are produced by none other than insufficient allowance for the rate of dark adaptation of vision and the speed of light adaptation. Frequently, in discussions of the question of visibility of the stars by day, it is forgotten that complete dark adaptation sets in only after 50-60 minutes. Thus, even when an astronaut looked at the bright surface of the earth in the last orbit, in the next exit from the shadow of the earth, his eyes still do not acquire complete light sensitivity, and a portion of the stars (for example, 5th and 6th magnitudes) will not be seen by him. If the astronaut looks at the bright surface of the earth in a given passage over the dayside of the earth (and this most frequently will be by virtue of well-known psychological reasons, determining movement of the gaze toward the brightest object in the field of view), the light sensitivity of vision may be decreased by a factor of 3-3.5. In this case, one or two stars will be seen, and the brightness of the rest of the stars will be below the threshold of light sensitivity. This is actually the case. The unanimous reports are that, only the stars Sirius and Canopus (-1.6 and -0.9 magnitudes, respectively) are visible on the dayside of the earth. However, it is natural to assume that such a deep-seated disadaptation of vision most often will not occur, and, then, the astronauts see stars of zero, 1st and, very rarely, stars of 2nd and 3rd magnitudes. Moreover, it is a random matter to /373
notice a weak star, since the sensitivity of the retina differs in different places in it. It changes up to 1-1/2 - 2 times. Accommodation of the dark-adapted eye in an unoriented field, which the starless sky of space is, is characterized by a myopia of from 0.6 to 1 diopter. The latter circumstance leads to the situation that the scattering circle of star images on the retina will have a diameter of about 0.05 mm, instead of a size of 0.01 mm, due only to diffraction of light by the edge of the pupil, and illumination of the retina will be reduced by 20-25 times, on the average, which may prove to be completely adequate, for the illumination of the retina by the star to be subthreshold. Increased mobility of the eye may play a large part in this matter, by decreasing the effective illumination of the retina, as the consequence of a certain inertia of vision (A. V. Luizov, 1961).

As is clear, the disagreements of the astronauts on the question of visibility of the stars above the dayside of the earth are due to a large number of factors, which sometimes have a decisive effect on it. Since the effect of various factors differs in each individual case, the results of star observations are different. It should also be added that all the astronauts note the tremendous number of stars in the sky above the nightside of the earth. In the opinions of some astronauts, it is even capable of significantly hampering the finding of the required stars and constellations in the sky.

Analysis of subjective evaluations of the visual function, on the basis of the reports of the astronauts, leads to the conclusion that no significant changes in the light sensitivity of the vision of the astronauts in flight take place. The light sensitivity remains practically unchanged. However, to solve practical problems, the use of the visual communications channel of man, when he is included in the control system, more complete and objective data are necessary. Tasks to study individual visual functions were set up for this purpose, beginning with the second space flight.

The most purposeful, objective studies of the effect of prolonged weightlessness were carried out in the flight of the Voskhod spacecraft, and they were continued by the crew of Voskhod 2. Methods of objective study of the resolving power of the visual analyzer, the dynamics of visual operating performance capacity and characteristics of perception of various object colors by man were included in the program of these studies.

A man with good vision is capable of distinguishing two separate points, if the angular distance between them is equal to or greater than 1 min. In connection with this, the resolving power of vision in a space flight was determined, by means of a set of lined globes, pasted in the log of the astronaut and examined from a fixed distance of 300 mm. The set included 25 globes with various line frequencies, permitting visual acuity to be tested from 0.3 to 2.2 units. Moreover, as a control, the visual acuity of the Vostok spacecraft crew commander V. M. Komarov in flight was tested, by means of a Landolt ring. To eliminate the effect of astigmatism of the eyes on visual acuity, each globe included four groups of lines, the directions of which differed. The astronaut had to find the globe, on which he could barely, but completely confidently, distinguish the direction of the lines in all four groups.

To calculate visual acuity, using the lined globes and to express it in normal units as the initial data, the distance from the top of the cornea of the eye of the observer to the surface of the globe (l in millimeters) and the number of lines of the globe per mm of its length (N) were used. In this case, the width of the white interval will be $1/2\,N$. The radial measure of the angle, at which the observer sees the white interval α, is determined by the quantity

$$= \frac{1}{2lN},$$

On this basis, the expression for calculation of visual acuity is written in the form $Vis = C\,N \cdot 10^{-4}$.

To develop the connection between visual acuity, determined by the normal method from Civtsev tables and calculated by the method indicated above, a series of correlation tests was conducted, in which 51 subjects (102 studies) participated. The visual acuity of these persons was initially determined from the Civtsev tables (Landolt ring) and, then, from the lined globes. To do this, the lined globes were glued to test tables in order of increasing complexity, and they were exposed together with the Landolt rings, with the same illumination, but at the standard distance of 300 mm.

Only the data of those persons who correctly determined the direction of the lines in a selected globe and had a visual acuity of 1.0 in each eye, according to the Civtsev tables, were subjected to statistical processing and correlation. 17 men turned out to be such subjects. The results obtained almost corresponded to the visual acuity determined by the two methods indicated; the visual acuity, found from the Civtsev table, and equal to 1.0 for each eye, corresponded to visual acuity, determined from the lined globe, of 1.0 ±0.03. The conduct of careful correlation studies before the primary tests made it necessary to obtain objective results, not causing doubt inflight (a unique and costly experiment).

Besides weightlessness, a number of other factors affect the human body under space flight conditions. To differentiate the effects of weightlessness, studies also were carried out with spacecraft crews in the training spacecraft, in which all space flight conditions, with the exception of weightlessness, were simulated. On this basis, it was determined that those additional changes, which were noted in flight, are basically the result of the effect of prolonged weightlessness on the human body.

In an analysis of the resolving power of the vision of the astronauts, sharp deviations were obtained during studies in the training spacecraft, compared with optical laboratory conditions. These changes are easily explained by the adaptation processes of the human body, under conditions which are new to it.

Astronauts V. M. Komarov, P. I. Belyayev, A. A. Leonov, B. B. Yegorov, G. T. Beregovoy, V. A. Shatalov, B. V. Volynov, Ye. V. Khrunov, A. S. Yeliseyev, G. S. Shonin, V. N. Kubasov, A. V. Filipchenko, V. N. Volkov, V. V. Gorbatko, V. I. Sevast'yanov and A. G. Nikolayev worked with the procedures developed for study of vision inflight, at various stages of it. They carried out a large number of studies of the resolving power of the visual analyzer. Analysis of the results obtained gives a basis for agreeing with the authors, who deny a sharp effect of prolonged weightlessness on visual acuity of astronauts, but only with the stipulation that these changes do not develop in the course of a one-day space flight.

The level of the working visual performance capacity was determined, by means of a set of the same lined globes.

In this case, the task of the subject was determination of the element of the globe, in which he not only saw the direction of the lines, but could count up the number of them. The quality of the working visual performance capacity was determined from the number of globes with which the astronaut worked, the number of errors made and the working time on the test. These parameters also were worked out initially with healthy people, having normal visual acuity (102 studies). In this investigation, a voluntary choice of globe size eliminated the effect of visual acuity on the test results, since, in any case, the subjects, according to the conditions of the experiment, worked with quantities, which were /375 above their thresholds. To exclude memorization, the order of placing the globes on the tables was varied. The results of this group were used as the baseline data for the data obtained in flight

The reduction in reliability of work of the astronauts inflight was determined from the ratio of the number of errors to the actual number of lines counted. The working time on the test, as well as the dimensions of the lines selected for counting, with respect to the resolution threshold of the eye in this period, played a large part in the correlated characteristics of the visual operating activity.

The results obtained inflight, for one of the groups of astronauts, are presented as an example in Fig. 112. As is evident from the data presented, the greatest reduction in reliability in work was that of physician-astronaut B. B. Yegorov (by 43%). The reason for this evidently is the accelerated training course of B. B. Yegorov as an astronaut; his body was still little conditioned to the unusual conditions of weightlessness. Among the other astronauts completing the full training course, these changes were much less, amounting to 19-26%.

The effect of special training exercises on this visual function is indicated by the data presented in Fig. 113. In the Voskhod flight, the astronauts determined visual acuity by the lined globes twice, with a time break of about 9 hours. The stability of the indices of V. M. Komarov and deterioration of this function in B. B. Yegorov are evident. A similar conclusion can be reached by analysis of the multiplicity factors of the superthreshold increases in counting the lines. Thus, B. B. Yegorov took a globe for counting the lines, the resolution of which exceeded the threshold of his visual acuity by 45%, while this value varied from 15 to 25% for the remaining astronauts.

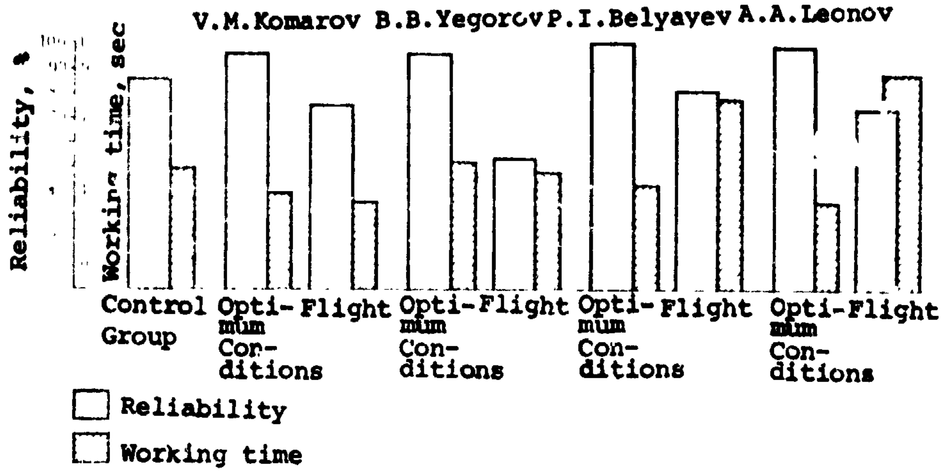

Fig. 112. Reliability and time of operating visual activity of astronauts

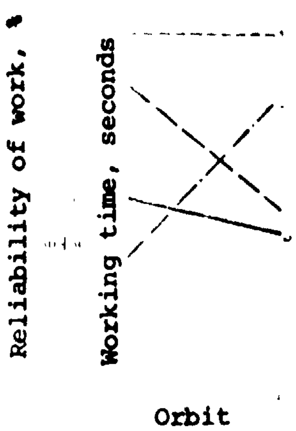

Fig. 113. Visual operating performance capacity during space flight: 1, reliability of work of V. M. Komorov; 2, reliability of work of B. B. Yegorov; 3, working time of V. M. Komorov; 4, working time of B. B. Yegorov

Why does this type of activity deteriorate, with the visual resolving power unchanged under weightless conditions? It is known that, in counting fixed linear objects, the eye must move, i.e., quickly change the point of fixation. According to the data of H. Hartridge (1952), this change in fixation takes place very quickly, in approximately 1/60 sec, in which the duration of the shift of fixation point depends on the angle, at which the point is seen by the observer. If a point located at an angle of 1° (which is approximately observed in the globe count) is considered, this time is approximately 0.01 sec, 0.02 sec at an angle of 2° (A. L. Yarbus, 1954). In sighting two similar lines of the globe, the astronaut fixes his look at a minimum of four points, in changing the the next line, four more points, etc. In this manner, a previously programmed series of pulses reaches the eye muscles, with a repetition rate on the order of one pulse per 0.01 sec. Under weightless conditions, together with the general discoordination of movement, the oculomotor group of muscles loses coordination to some extent, but the mass of the eye and its moment of inertia remain unchanged; however, because of loss of weight, the friction in the moving tissues of the eyes decreases and, therefore, the force of the muscle group, which should change the fixation point ot the gaze, becomes excessive. As a consequence

of thi -, the look "jumps over" the required point. A new adjustment of the eyes is necessary, but it is difficult to do this in the assigned segment of time, since the following pulse takes place after 0.01 sec; it enters during the refractory phase and, consequenty, it is omitted. Thus, it seems that the primary cause of reduction in reliability of visual operations under weightlessness conditions is discoordination of the oculomotor apparatus. This does not set in, in counting larger details, since the repetition period of pulses increases sharply with increase in angle of resolution. Data from long flights, carried out in a sealed spacecraft cabin /376
simulator, when the visual operating performance capacity decreases only in the first hours, but is restored subsequently and remains at the same level, are in favor of this hypothesis. Consequently, it can be assumed that the effect of weightlessness is the basis of disruption of the visual operating performance capacity in flight.

Measurement of the contrast sensitivity of vision was carried out, by means of a special tabular test.

The visual contrast sensitivity measurements in space flight were carried out by the Soyuz 3, Soyuz 4, Soyuz 5 and Soyuz 9 crew members.

It was a table containing 70 circles, divided in two and having contrast between halves. The task of the astronaut included recording of the direction of the interface of the halves of the circles. The working time of the astronauts on the circles having different contrast was recorded simultaneously with the results of work on this test. Calculation of the threshold visual contrast value was carried out, on the basis of errors committed and cor- /377
rect answers, as to the direction of the dividing line of the halves of the circles. The average value of the contrast of the circles, falling in the range in which the astronauts simultaneously committed errors and solved problems correctly, was used as the threshold value. With selected characteristics of this test, 5-7 circles fell in this range, as a rule. With uniform distribution of the number of circles by contrast values within the working limits of the measurements (from 0.01 to 0.1), which was provided in fabrication of the tables, the standard error of one measurement of contrast sensitivity was obtained (because of the limited number of circles used in the calculation of K_{thr} it equals ±12-13.5%). The total error of the method, allowing for all factors affecting measurement error, is estimated at ±19.6%.

The statistically processed measurement results indicate that the visual contrast sensitivity decreases during a space flight. While the reduction was 10% of the ground baseline data, on the average, in the initial phase of the flight, right up to orbits 20-30, the reduction subsequently continued to be augmented, and it reached 20% by the 50th orbit. Measurements carried out by A. G. Nikolayev during the flight of Soyuz 9 in the 93rd orbit, show, however, that stabilization of this function can be expected subsequently. Study of the visual contrast sensitivity in flight is of great theoretical and practical interest. Its results are capable of explaining many visual phenomena, which are observed in space flight.

A study of color perception of objects was carried out, using special tables.

A table contained six paper strips of different colors, located beside a black-white graded wedge. It is known that all colors approach black with decrease in their brightness; therefore, it was considered that a comparison of the brightness of one color or another with brightness of the black-white wedge scale serves as an indicator of its brightness. The color table contains six strips of different colors. The three primary colors -- red (λ_{max} = 615 nm), green (λ_{max} = 545 nm) and blue (λ_{max} = 478 nm) and the three complementory colors -- blue, purple and yellow, were selected as the color tones. All the colors used had high saturation and brightness (for example, red $P = 0.75$, ρ = 30%; yellow $P = 0.87$, ρ = 88%, etc.). During the study, the astronaut had to find the field of the black-white wedge for each color, which had brightness identical to it.

The black-white wedge parameter selected permitted measurement of the brightness of the objective colors, i.e., the colors of colored objects, within a tenfold change in them. The average error value of each single color brightness determination from the table described was on the order of 15-20%. As a result of statistical processing of the data of repeated measurements carried out in flight, the color brightness error was reduced to 5-6%. Taking the applied purposes of such studies into consideration, this error value was acknowledged to be satisfactory. Both the baseline and the flight results were obtained under illumination of the same nature. This permitted determination of the differential changes in the nature of perception of object colors.

It is well known that a number of conditions, such as the color adaptation conditions, simultaneous and sequential contrast, the features of the comparison process, etc., significantly affect the level of the functional stability of chromatic vision. In this connection, to obtain the pure effect of weightlessness on the function being studied, the root mean error of a single comparison of the color and black-white field brightnesses was determined. The measurements, carried out at different times and with different color tables, disclosed that this error is ±7.8% for the colors used, on the average.

With allowance for this error, the measurements made during space flights showed a noticeable reduction in subjective bright- /378 ness of the colors being examined, for all astronauts participating in these experiments. The average reduction in brightness of all the colors exposed by P. I. Belyayev, for example, was 26% and 25% for A. A. Leonov, in which the greatest reduction in brightness was observed for both astronauts indetermination of the colors purple, azure, green and red. The reduction in brightness of the remaining object colors was not over 10%. An increase in brightness was not observed in a single case. The reason for this significant difference in the differentiated decrease in brightness of individual colors under weightless conditions is not clear now, and it requires additional study.

The great amount of study of visual acuity, visual contrast sensitivity and visual operating performance capacity in space flight provides a basis for speaking of the dynamics of these functions as the flight evolves (Fig. 114). For example, it turned out that visual acuity remains practically unchanged during a flight lasting up to 7 days, and is decreased by 5-10% from the baseline values.

The visual operating performance capacity of the astronauts in the 2nd orbit of the flight turns out to be decreased by 20% from the baseline values. The reduction reaches a maximim (26%) by orbits 8-10, after which a monotonic increase in quality of this function takes place, and the visual operating performance capacity turns out to be only 10% below the baseline by the 50th-60th orbit.

The nature of the change in visual contrast sensitivity is different. After this value decreases by approximately 10% at the very start of the flight, the decrease subsequently is augmented, as is shown by the results of the flight studies in Soyuz 9, right up to the 60th or 70th orbit. However, according to the measurements of A. G. Nikolayev, which he made in the 93rd orbit, the contrast sensitivity was reduced by 10%. This single experiment (70 presentations were made) does not now give a sufficient basis for final conclusions on the return to normal of the contrast sensitivity level by the 93rd orbit, after it had dropped to 25% in the 50th-60th orbits, but a tendency towards this can be assumed. Actually, if a continuation of this rate of reduction in contrast sensitivity, obtained between the 30th and 60th orbits, is assumed to continue after the 60th orbit, one would have to deal with a significant reduction of this function, while the astronauts did not subjectively note such a reduction in the flight of Soyuz 9 and during the flights of American astronauts over the earth-moon-earth course.

An analysis of the psychophysiological mechanisms causing the changes being discussed in visual functions of the astronauts and the dynamics of them during the flight is extremely interesting. It might be thought that dissection of these mechanisms would permit understanding many phenomena of our vision, which are not now completely clear, for example, color, contrast sensitivity level, etc., and that measures and recommendations, directed towards blocking the undesirable disruptions in flight, would be successfully worked out on this basis. The tempting aspect of analysis of these mechanisms is the theoretical aspects of the physiology and psychology of visual perception. Efforts at such generalizations have been undertaken; however, the material obtained up to now is insufficient for /379

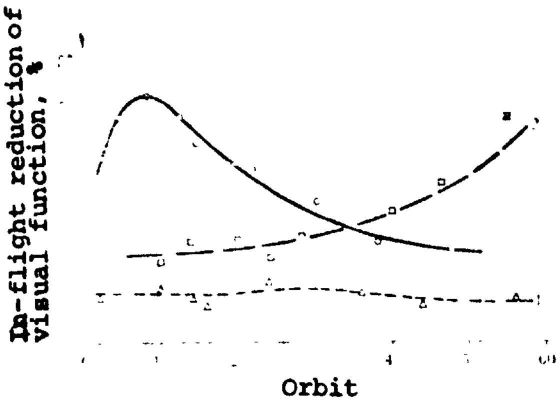

Fig. 114. Decrease in visual function of astronauts during space flight (18 astronauts took part in the work) (the level of the visual function in ground experiments was adopted as 100%): 1, visual acuity; 2, contrast sensitivity; 3, visual operating performance capacity.

completely validated and reliable conclusions.

On the whole, the observation results show that, in prolonged weightlessness, the functional capabilities of the visual analyzer undergoes changes, in a number of cases. To a great extent, these changes are inherent in the visual operating performance capacity, which decreased between 20 and 40% and more, for different operators, under weightless conditions. Allowing for small changes in visual acuity in this case, the cause of this phenomenon should apparently be sought in motor discoordination of the work of the muscular apparatus of the eyes. Definite changes have been noted in the nature of perception of the colors of objects by operators, under conditions of prolonged weightlessness.

* * *

We have presented the results of studies of the performance capacity of astronauts in flight (primarily, the functions of vision and the motor analyzer). The working conditions of astronaut-investigators, astronaut-testers and methods, including specific ones for space psychophysiology, and regularities, which have been worked out and revealed by the authors, in study of the emotional stress of an astronaut in flight, have been examined.

On the whole, a psychophysiological analysis of spacecraft crew activities in flight have shown that the human operator, the astronaut, is a reliable link in the control system, even under such complicated conditions as those of space flight, including the complicating failure of individual links of automatic devices. Man can be entrusted with execution of operations of varying complexity, of both a motor and sensory nature. However, the analysis carried out also showed that the transition to functioning under these conditions assumes an adaptation period, when a number of symptoms, reducing the reliability of the human link of the control system, can be observed in the performance capacity of an astronaut.

For quantitative characterization of the performance capacity of an astronaut and the entire "spacecraft-astronaut" system, well-known evaluations and characteristics, developed for technical

devices and closed automatic control systems, are not fully suitable. The reason is that the human operator, in particular, the astronaut is distinguished by an incomparably broader diversity of all his qualities, properties and characteristics. They can change rapidly and within considerable limits, depending on external working conditions of the astronaut, his internal psychological mood, physical condition, the motivation of his activities and many other things. Therefore, a basic feature of quantitative estimates of the level of efficiency of an astronaut is their probabilistic nature. This leads to the situation that the experimental data obtained each time characterizes only the specific condition of the astronaut or /380
system, at a given moment of time, under given conditions, with him in a given mood, etc., but it is not suitable for any generalized estimates. In this connection, a very urgent task is development of methods of setting up and conducting experimental research on the performance capacity of astronauts in flight, which would give the maximum of useful information on the phenomenon being studied, with a high level of confidence, with procedures, which are limited in time, place and weight. The data reported above, on research on the basic visual functions of astronauts in flight give a basis for considering that changes in these functions under space conditions are comparatively small. The quantities, changes in functions, varying between 5 and 30-40%, turn out to be insufficient to be noticed by the astronauts themselves.

It can be stated that the vision of astronauts in flight is almost as reliable as on earth, and that utilization of vision in space gives unlimited possibilities for the conduct of scientific and applied work.

It seems to us that further evolution of research on the "man-machine" system, applicable to space flights, will involve a series of significant features.

1. By extrapolating present scientific programs, it can be considered that the role of the national economic yield of a space flight will increase significantly in the future. Complicated apparatus is appearing for this aboard manned spacecraft (MSC). Man will have to service it and carry out preventive inspections and repair.

2. The role of the human operator in control of MSC in powered stages of flight apparently will increase, which implies the creation of special protective means and special methods of training astronauts in control operations under g-forces.

3. The problem of prolonged interplanetary flight must become the subject of deep and many-sided research. Together with solutions of a number of life support problems, including prophylactic measures against the prolonged action of weightlessness, difficulties are arising in solution of a number of control problems.

CHAPTER 7 N75 23133

SOME RESULTS OF BIOMEDICAL STUDIES CARRIED OUT IN THE GEMINI AND APOLLO PROGRAMS

Quite a lot of data have been accumulated recently, on the effect of space flight on the human body. Suffice it to point out the successful completion of the Soyuz space program in the USSR and the Apollo program in the USA. However, there is not very much correlated information on the results of the flights, especially those of American astronauts, in our literature. There are the works of I. I. Kas'yan and colleagues (1967), O. G. Gazenko and colleagues (1968), P. V. Vasil'ev and colleagues (1969) and some others. However, they were published comparatively long ago, at the end of the 1960's, and some material requires refinement and new interpretations, in the light of modern theoretical concepts of the physiological mechanisms of the effect of space flight on the human body.

We have made an effort to correlate data in the literature,[7] on the results of biomedical studies performed in the Gemini and Apollo programs, which is all the more necessary, in connection with the program of joint work of Soviet and American investigators in the conquest of space.

As is well known, ten manned space experiments were accomplished in the Gemini program and eleven experiments in the Apollo program in the USA, in 1965-172. In a period of seven years, 31 men visited space, 13 of them repeatedly: 8 men twice, 4 men three times /386
(C. Conrad, T. Stafford, D. Scott, E. Cernan) and 2 men four times (J. Young and J. Lovell). Some data on the flights of the American astronauts are presented in Table 87.

It is apparent from the data presented in Table 87 that the Gemini program provided for study of the possibility of a many-day stay of man in space; working out of the technique of docking under weightless conditions, with an unmanned satellite-target; conduct of extravehicular activity experiments and performance of work by an

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[7]Translations made by Yu. D. Gol'dovskiy, Yu. B. Yeliseyenkov, L. L. Zhurnya, Ye. P. Kostrub, A. Z. Mnatsikan'yan, S. B. Murav'yeva, E. M. Panova and G. Ya. Tverskaya, were used in the work.

TABLE 87

SOME DATA ON THE FLIGHTS OF ASTRONAUTS IN THE GEMINI AND APOLLO PROGRAMS

Spacecraft	Astronauts	Flight Date	Flight Duration days	hrs	min	Primary flight tasks and their execution
		Gemini Program				
Gemini 3	V. Grissom SC E. White, P	23 Mar 1965	--	4	53	Tasks: Study of prolonged stay of man in space; check-out of on-board equipment; maneuvering in orbit. Tasks completed.
" 4	J. McDivitt SC E. White, P	3 Jun 1965	4	0	56	Tasks: Rendezvous with object in orbit; extravehicular activity. First task partially completed. Approach to second stage of launch vehicle accomplished, to distance of about 600 m. Astronaut E. White stayed in space 20 min, moving by means of tether and jet device.
" 5	G. Cooper SC C. Conrad, P	21 Aug 1965	7	22	55	Tasks: Check-out of on-board equipment; rendezvous with object in orbit. Latter task not completed.
" 7	F. Borman SC J. Lovell, P	4 Dec 1965	13	18	35	Tasks: Rendezvous with object in orbit, group flight. Tasks completed. Craft approached each other to within 1-30 m and flew together 5-1/2 hrs
" 6	W. Schirra SC T. Stafford P	15 Dec 1965	2	1	51	Same
" 8	N. Armstrong SC D. Scott	16 Mar 1966	--	10	42	Tasks: Rendezvous with object in orbit. Task completed. First dock-

Notes: 1. The problems faced by the Gemini 3 crew were solved in all succeeding flights of the Gemini and Apollo craft.

2. In this table and subsequently, these designations are adopted: SC -- spacecraft commander; P -- second pilot; CMP -- command module pilot; LMP -- lunar module pilot.

3. The Apollo 1-6 and Gemini 1 and 2 spacecraft were technical and were launched without astronauts.

TABLE 87 -- continued

Spacecraft	Astronauts	Flight Date	Flight Duration			Primary flight tasks and their execution
			days	hrs	min	
						ing with Agena rocket.
Gemini 9	T. Stafford SC E. Cernan, P	1 Jun 1966	2	0	21	Tasks: Rendezvous with object in orbit, docking; extravehicular activity. Docking not accomplished. E. Cernan stayed in space 2 hrs 5 min
" 10	J. Young, SC M. Collins, P	18 Jul 1966	2	22	46	Tasks: Rendezvous with object in orbit; docking with it; use of Agena rocket engine in transfer to higher orbit; extravehicular activity. Tasks completed. M. Collins stayed 38 min in space (instead of planned 2 hrs).
" 11	C. Conrad SC R. Gordon, P	12 Sep 1966	2	23	17	Tasks: Same as in flight of Gemini 10, plus stabilization of satellite and rocket, connected by cable. Task completed. R. Gordon stayed 44 min in space instead of 107 min.
" 12	J. Lovell SC E. Aldrin, P	11 Nov 1966	3	22	35	Tasks: Same as in flight of Gemini 11. Agena rocket engine not used for transfer of craft to higher orbit. E. Aldrin stayed 2 hrs 10 min in space.
		Apollo Program				
Apollo 7	W. Schirra SC W. Cunningham CMP D. Eisele LMP	11 Oct 1968	10	20	9	Tasks: Flight in earth orbit with man aboard; testing of command and service module; approach to last stage of launch vehicle; maneuvering. Tasks completed.

TABLE 87 -- continued

Spacecraft	Astronauts	Flight Date	Flight Duration days	hrs	min	Primary flight tasks and their execution
Apollo 8	F. Borman SC J. Lovell CMP W. Anders LMP	21 Dec 1968	6	3	0	Tasks: Test of command and service module, with insertion into seleno-centric orbit. Tasks completed.
" 9	J. McDivitt SC D. Scott CMP R. Schweick-art, LMP	3 Mar 1969	10	1	0	Tasks: Testing of craft in low geocentric orbit; rearrangement of modules; transfer of LMP from lunar module to command and service module and return through space; independent flight of lunar module with 2 astronauts aboard. Task completed, except transfer through space, due to illness of LMP
" 10	T. Stafford SC J. Young CMP E. Cernan LMP	18 May 1969	8	0	3	Tasks: Test of regular craft with insertion into selenocentric orbit; independent flight of lunar module around moon at altitude of 15 km. Tasks completed.
" 11	N. Armstrong SC M. Collins CMP E. Aldrin LMP	16 Jul 1969	8	3	18	Tasks: Landing on moon; extravehicular activity to install instruments and take soil samples. Tasks completed. Returned approximately 20 kg of lunar soil samples. N. Armstrong and E. Aldrin accomplished lunar EVA.[8] Total stay time on moon 21 hrs 36 min, on surface 2 hrs 10 min
" 12	C. Conrad SC R. Gordon CMP A. Bean LMP	14 Nov 1969	10	4	36	Tasks: Landing on moon; 2 lunar EVA to install instruments, sample lunar soil, remove part of Surveyor 3 equipment, organization of impact

[8] [Translator's note: EVA -- extra-vehicular activity.]

TABLE 87 -- continued

Spacecraft	Astronauts	Flight Date	Flight Duration days	hrs	min	Primary flight tasks and their execution
						of spent ascent stage of lunar module on moon. Task completed. Astronauts C. Conrad and A. Bean completed lunar walk. Total stay time on moon 31 hrs 31 min, on surface 7 hrs 55 min. Returned approximately 36 kg of soil.
Apollo 13	J. Lovell SC J. Swigart CMP F. Haise LMP	11 Jun 1970	5	22	54	Tasks: Same as in flight of Apollo 12. Tasks not completed (except organization of impact on moon of last stage of launch vehicle), because of explosion of oxygen tank on earth-moon course. Emergency return to earth.
" 14	A. Shepard SC S. Roosa CMP E. Mitchell LMP	31 Jan 1971	9	0	2	Tasks: Same as in flight of Apollo 12. All tasks completed. A. Shepard and E. Mitchell landed on moon. Total stay time 33 hrs 30 min, on surface of moon 9 hrs 14 min. Returned approximately 43 kg of soil.
" 15	D. Scott SC A. Worden CMP J. Irwin LMP	26 Jul 1971	12	7	12	Tasks: Landing on moon, 3 EVA; testing of lunar rover; soil sampling; conduct of series of scientific-technical experiments. Tasks completed. D. Scott and J. Irwin landed on the moon, tested lunar rover, collected approximately 77 kg of rock. Total stay time on moon 66 hrs 55 min, on surface 18 hrs 36 min.

TABLE 87 -- continued

Spacecraft	Astronauts	Flight Date	Flight Duration			Primary flight tasks and their execution
			days	hrs	min	
Apollo 16	J. Young SC T. Mattingly CMP C. Duke LMP	16 Apr 1972	11	1	51	Tasks: Same as in flight of Apollo 15. Tasks completed. J. Young and C. Duke landed on moon, tested lunar rover (traveled 27.1 km). Collected 95 kg of soil. Total stay time on moon 71 hrs 2 min, on surface 20 hrs 14 min.
" 17	E. Cernan SC R. Evans CMP H. Schmitt LMP	7 Dec 1972	12	16	31	Tasks: Same as in flight of Apollo 15. Tasks completed. Astronauts E. Cernan and H. Schmitt accomplished 3 lunar EVA, traveled in lunar rover (36.2 km). Collected lunar soil. Total stay time on moon 75 hrs, on surface 22 hrs 5 min.

astronaut under these conditions; performing various scientific-technical (including biomedical) experiments; and testing of the onboard equipment and life support system. The Apollo program planned a landing on the moon by astronauts, performance of scientific-technical experiments, collection of lunar soil samples and return of the spacecraft crew to earth. The Gemini and Apollo programs were closely connected. The tasks of the Apollo program could be successfully solved, only in the case of completion of all tasks facing those executing the Gemini program, since, in order to land on /387 the surface of the moon, problems connected with approach and docking of spacecraft had to be solved, the amount of possible work of a man in open space revealed, the degree of harm of the long effect of space flight on the human body established, first and foremost, that of weightlessness, and onboard life support systems tested.

There are some very important general features in the plan of evaluation of the effect of space flight conditions on the bodies of the astronauts, in accomplishing these programs: 1) duration of the effect of weightlessness did not differ significantly in one case or another (approximately 0.4-14 days in the Gemini program and 5-13 days in the Apollo program); 2) participation in the flight of, not one, but two or three astronauts, i.e., crews flew in all cases, which certainly was very important; 3) adherence to approximately the same schedule of work, rest and eating by the flight crew, in the majority of flights; 4) a definite generality in performance of individual operations: rendezvous with an object, docking with it, extravehicular activity, etc. All this permitted us to consider the biomedical changes of the astronauts in Gemini and Apollo program flights from the unified positions, as reactions of the body to unusual external conditions of approximately the same biological importance. Of course, in analysis of the materials, we did not forget certain singularities, which were inherent in the flights of each specific program. Thus, in distinction from the Gemini program flights, beginning with the flight of Apollo 11, the astronauts were subject to the effect of lunar gravitation 1/6 g, for a period of 27-71 hours, during the flight (Berry, 1969; Slater, 1971, and others). The gaseous atmosphere in the Gemini spacecraft cabins consisted of pure oxygen, of oxygen (60%) and nitrogen (40%) in the cabins of some Apollo spacecraft in the launch stage and, in all succeeding stages of flight, of oxygen, with a small amount of nitrogen (1-3%) (Berry, 1969, 1970, 1971; Lomonaco, 1969, 1970, and others). The Gemini cabins were of small volume, and the astronauts had limited capabilities for movement, while the Apollo cabins were larger, and the astronauts moved a great deal and performed physical exercises. There were definite differences in the scientific-technical experiment programs: in the Gemini program, for example, biomedical experiments were specified and they were almost completely excluded during Apollo program flights (Berry, 1970, 1971).

The experience of medical support for space experiments in both the USSR and the USA indicates that physiological shifts in the majority of organs and systems of the body are observed in space flight. However, the most significant of them are changes of: a) body weight; b) cardiovascular system; c) blood; d) mineral and electrolyte metabolism; e) performance capacity (N. M. Sisakyan, V. I. Yazdovskiy, 1962, 1964; O. G. Gazenko, et al., 1965, 1967; V. I. Yazdovskiy, 1966; N. M. Sisakyan, 1965; Yu. M. Volykin,et al.,1967; V. V. Parin, et al., 1967, 1968; I. M. Khazen, 1971; Berry, 1967, 1969, 1970, 1971; Dessaucy, 1970; Graybiel, 1971; McCally, 1971; Nickolson, 1971; Wagner, 1971; White, et al., 1971, and others).

Change in Body Weight

One of the important indices of the condition of the astronauts in flight was body weight. It turned out that, after each space flight, it decreased (Berry, 1970, 1971; Davis, 1970). Thus, during the /388 Gemini program flights, the astronauts lost approximately 3-8% (2-5 kg) of their weight, recorded before launch. After brief flights, these losses were recovered in the first 12-24 hours after splashdown[9] In the 14-day flight of Gemini 7, the weight loss of the crew members was retained for more than a day after the flight (Table 88).

TABLE 88

CHANGE IN BODY WEIGHT OF CREW MEMBERS OF APOLLO SPACECRAFT, COMPARED WITH PREFLIGHT DATA

Spacecraft	Crew Member	Weight Change: Immed. after flt. kg	Weight Change: Immed. after flt. %	Weight Change: 24 hrs after flt kg	Weight Change: 24 hrs after flt %
Apollo 7	SC	−2.5	−3.2	+1.0	+1.3
	CMP	−4.0	−6.4	+1.4	+2.2
	LMP	−3.2	−5.1	+2.2	+3.5
" 8	SC	−3.5	−5.1	+1.1	+1.6
	CMP	−3.1	−4.5	+0.3	+0.4
	LMP	−1.6	−2.8	−0.2	−0.3
" 9	SC	−2.1	−3.3	+1.1	+1.7
	CMP	−3.3	−3.2	+3.4	+4.8
	LMP	−2.4	−3.8	+1.7	+2.6
" 10	SC	−0.8	−1.1	+0.8	+1.1
	CMP	−2.0	−3.0	+0.4	+0.6
	LMP	−4.0	−5.8	+0.8	+1.2
" 11	SC	−3.2	−4.7	+2.4	+3.7
	CMP	−2.8	−4.2	0.0	0.0
	LMP	−0.4	−0.6	+1.6	+2.4
" 12	SC	−1.7	−2.8	+0.8	+1.4
	CMP	−2.9	−4.7	+1.6	+2.7
	LMP	−5.0	−8.2	+1.2	+2.1
" 13	SC	−5.6	−8.1	—	—
	CMP	−4.4	−5.6	—	—
	LMP	−2.6	−4.2	—	—
" 14	SC	+0.4	+0.5	+0.4	+0.6
	CMP	−4.8	−7.2	+2.8	+4.8
	LMP	+0.4	+0.5	+0.4	+0.6
" 15	SC	−0.5	−0.7	+0.4	+0.5
	CMP	−1.2	−1.9	+0.8	+1.3
	LMP	−2.2	−3.4	+2.0	+3.2
" 16	SC	−3.0	−4.3	+1.4	+2.0
	LMP	−2.6	−4.0	+1.2	1.9
	CMP	−2.2	−4.1	+1.0	+1.8

As is evident, the weight of all the astronauts was recovered in the first days on earth. This apparently indicates that the weight reduction was primarily caused by loss of fluids and the favorable water balance in the initial hours after completing the flight. Before the flight of Apollo 14, it was assumed that extracellular losses of fluids constitute the larger part of the total moisture deficit in the body. The opinion was expressed that the water loss occurred mainly on the part of interstitial fluids.

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[9]The American spacecraft descended into ocean waters (they splash down), but they descended to the surface of the earth; therefore, it is more nearly correct to speak of landing.

However, the results of evaluation of the water metabolism obtained after the flight of Apollo 14 showed (Berry, 1971) that the water deficit was caused by a decrease in intracellular fluid. The data of Table 89 indicate that the amount of extracellular fluid is practically unchanged. It follows from this that the total water deficit in the body was caused by a decrease in volume of intracellular fluid. Berry (1971), analyzing these data, expressed some doubt. In his opinion, this conclusion still needs further refinement. It is absolutely not excluded that the reduction of weight in flight is connected with loss of the solid mass of the body. This should be completely agreed with, considering the nature of change in the blood indices and mineral and electrolyte metabolism. Soviet investigators also are inclined to connect the decrease in weight of the astronauts with dehydration of the body in flight (N. M. Sisakyan, V. I. Yazdovskiy, 1962, 1964; V. V. Parin, et al., 1967; Ye. I. Vorob'ev, et al., 1969, 1970; Yu. G. Nefedov, 1969, 1972; I. S. Balakhovskiy, et al., 1971; G. I. Kozyrevskaya, et al., 1972). According to their data, a 2-4 kg decrease in body weight, a decrease in kidney excretion of electrolytes, as well as of osmotically active substances, by all Soviet astronauts was noted. Weight recovery after flights lasting up to five days took place in a period of 2-3 days; the times increased during longer flights. A change in kidney function, manifested by the high elimination of sodium, potassium, chlorine and calcium after water-loading, was common to flights lasting over three days. The investigators noticed one curious phenomenon, the absence of thirst of the astronauts during the flight, which is characteristic of exsiccoses. I. G. Popov and colleagues (1972) explained this from the point of view of development of a process of adaptation to weightless conditions. In their opinion, dehydration is a normal reaction to change in gravitational effects; consequently, by suppression of the feeling of thirst, the homeostatic conditions in the body are not disrupted by additional introduction of water from outside. /389

TABLE 89

CHANGE OF FLUID VOLUME IN BODIES OF APOLLO 14 CREW MEMBERS 24 HOURS AFTER COMPLETING FLIGHT (in % of indices recorded directly after flight)

Index	Measurement Method	SC	CMP	LMP	Control Tests		
					1	2	3
Erythrocyte mass	Cr^{51}	[illegible]	[illegible]	4.0	-4.4	[illegible]	[illegible]
Plasma volume	I^{125}-albumin	1.2	[illegible]	0.1	[illegible]	[illegible]	[illegible]
Extracellular fluid	SO_4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Intracellular fluid	by calculation	[illegible]	[illegible]	[illegible]	0.0	[illegible]	[illegible]
Total Water	H_2^2O	1.9	[illegible]	1.8	[illegible]	[illegible]	[illegible]

The physiological mechanisms of dehydration of the body in weightlessness have been studied sufficiently at present. The trigger mechanisms are reduction in hydrostatic pressure of the blood, redistribution of it and disruption of the volumetric constancy of the blood. As a result, an inflow of blood takes place to the large vessels of the chest cavity, excitation of the receptor formations of the large veins and development of compensatory reactions (Gauer, et al., 1967; Gauer, 1971). Plasma loss develops, the total volume of circulating blood decreases, the action of the antidiuretic /390 hormone weakens, reabsorption of water and sodium in the kidneys decreases and diuresis increases. A definite importance in regulation of water-salt metabolism is attributed to osmoreception and output of aldosterone, which increases sodium reabsorption. Together with dehydration of the body, as was pointed out above, thirst decreases. As a result, the water-salt metabolism is restored at a new level; the body adapts to the changed conditions. The experiments, which were carried out on a monkey, during the flight of Biosatellite 3, are a brilliant confirmation of some of the conclusions expressed above (Adey, et al., 1971; Meehan, et al., 1971). By catheterization of the arterial and venous circuits, it was demonstrated that an increase in central venous pressure is observed in weightlessness. It increased by 2[illegible] mm H_2O in the right auricle, which is sufficient for onset of compensatory loss of fluid from the body. Having analyzed the results of the flight of Gemini 7, the authors of the work spoke their minds on the pathways of adaptation to weightlessness. The venous tonus apparently decreases gradually, the elasticity of the venous system increases and the blood returns to the peripheral parts of the body, as a result of which the pressure decreases in the central veins and the water-salt metabolism regulatory mechanisms are restored.

Changes of Cardiovascular System

In carrying out the Gemini and Apollo programs, much attention was given to study of the effect of space flight on the cardiovascular system. In this case, the study was carried out, both during the flight and after it. During the Gemini flight program, the electrocardiogram in two leads and the arterial pressure were recorded (by the method of Krotkov, using a phonocardiographic sensor) and, in Apollo program flights, the EKG. In both cases, a large number of studies was accomplished before and after the flights, to determine the orthostatic tolerance, for the purpose of revealing deconditioning of the cardiovascular system. The /391 passive standing method or decompression of the lower part of the body, created by gradual reduction in pressure (NPLB-negative pressure on lower part of body), was used as a test. One of the reasons for using the NPLB test is that it was used to evaluate the orthostatic mechanisms and their conditioning in the flights carried out in Skylab. Despite the differences in the tests, the physiological reactions to them were approximately the same (Johnson, 1971; Musgrave, 1971, and others). Data of the examination of astronaut

F. Borman, before and after the flights in Gemini 7 and Apollo 8, might be introduced as an illustration (Fig. 115).

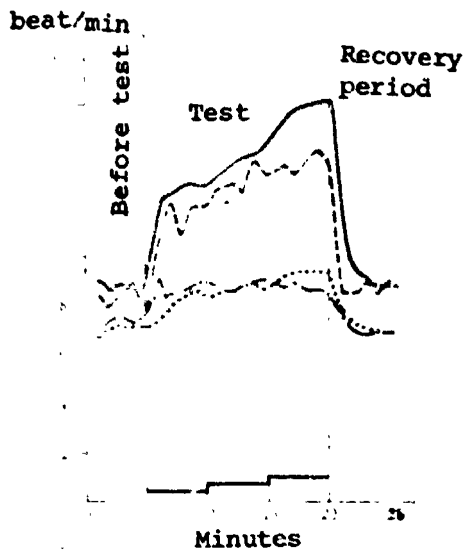

Fig. 115. Pulse rate of astronaut F. Borman during passive standing test on rotary table at angle of 70° before (1) and after (2) 14 day flight in Gemini 7 and with negative pressure on the lower part of the body of 30, 40 and 50 mm Hg before (3) and after (4) 6-day flight in Apollo 8.

Indirect data on the state of the cardiovascular system was also obtained during the measurements of the calf perimeter and heart dimensions (by radiography) of the astronauts in the preflight and postflight periods. It was determined by analysis of the in-flight material that the cardiovascular system indices (pulse rate and EKG parameters) of all astronauts change quite regularly: initially (still before the flight), the pulse quickens, this increase becomes still more significant during insertion of the craft into orbit, then, the pulse slows down under weightless conditions and again increases, on entry into the dense layers of the atmosphere while landing (Table 90). The changes of the Soviet astronauts were of a similar nature (R. M. Bayevskiy, et al., 1964; I. I. Kas'yan, et al., 1966; Ye. I. Vorob'ev, 1969, 170, and others). Since the pulse rate of narcotized /392
animals does not increase under weightless conditions (A. M. Galkin, et al., 1958), the tachycardia noted in the first hours of flight, in the opinion of the majority of investigators, is not the result of the specific effect of weightlessness on the cardiovascular system. It is dependent on the acceleration in the powered section and the descent period and on the nervous-emotional stress in both the prelaunch period and over the duration of the entire flight. The change in physical conditions -- removal of hydrostatic pressure of the blood, as a result of which the weight of the blood disappeared, the work of the heart was eased, the pulse distinctly slowed down -- apparently it does not play the least role under weightless conditions.

In an analysis of the data of Table 90, the moderate nature of the increase in pulse rate in the powered section during the Apollo flights, compared with the Gemini flights, attracts attention. This apparently is explained by lower accelerations and greater confidence of the crews in the reliability of the technology and the safety of the flights. Repeated participation of the astronauts in

TABLE 90

MAXIMUM PULSE RATE OF SOME ASTRONAUTS DURING SPACE FLIGHT

Spacecraft	Astronaut	Powered Section	Period of Weightlessness	Entry into dense layers of atmosphere during descent
Gemini 3	[illegible]. Grissom	[illegible]	The heart rate of all astronauts decreased in the weightless period: to 60-80 beat/min after 3-5 hrs, and it stabilized between 40 and 80 beat/min after 36-48 hrs; it was at a minimum in the sleep period. In performing individual operations inside the craft or switching on the sustainer engines, the pulse briefly quickened to 100-120 beat/min.	165
	J. Young	120		130
" 4	J. McDivitt	148		140
	E. White	128		125
" 5	G. Cooper	148		170
	C. Conrad	155		178
" 6	W. Schirra	125		195
	T. Stafford	150		140
" 7	F. Borman	152		130
	D. Lovell	125		134
" 8	N. Armstrong	138		130
	D. Scott	120		90
" 9	T. Stafford	142		160
	E. Cernan	120		126
" 10	J. Young	120		110
	M. Collins	125		90
" 11	C. Conrad	166		120
	R. Gordon	154		117
" 12	J. Lovell	136		142
	E. Aldrin	110		137
Apollo 8	W. Anders	118		92
	J. McDivitt	145		110
" 9	D. Scott	135		82
	R. Schweickart	95		82
" 11	N. Armstrong	10		
	M. Collins	99		
	E. Aldrin	88		

space experiments also is of great value. This is seen especially graphically, in analysis of the data of examination of the Apollo 11 crew members. The quickening of the pulse was more significant in all astronauts during the Gemini flights. The question of change in pulse rate of the astronauts at rest, in proportion to the stay under weightless conditions, was of interest. Dietlein (1970) compared the pulse rate (in percent of the preflight data) during Gemini flights of differing durations. It turned out that an almost linear increase of the indices is observed, up to the 8th day and a decrease to the 14th. The authors explained this by improvements in the work, rest and eating schedule of the Gemini 7 crew members and, mainly, by the fact that the astronauts did not wear the spacesuits during a large part of the flight (Fig. 116).

Vallbona, Dietlein and colleagues (1970) thoroughly studied the effect of space flight conditions on the bioelectric activity of the heart. Studying the EKGs recorded in the Gemini 4-Gemini [illegible] flights, they found considerable variability of the cardiac cycle parameters in all the astronauts. A direct correlation was noted, of the nature of the change in EKG indices and heart rate. It was shown by /393

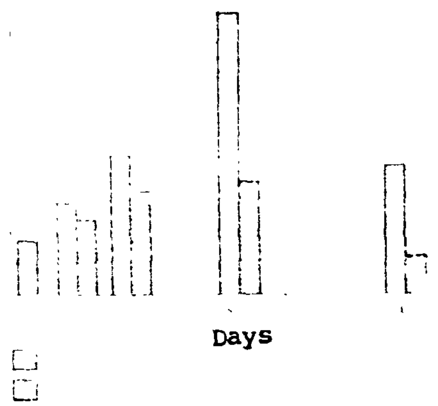

Fig. 116. Change in pulse rate at rest (in percent of control examination data; average values) of Gemini crew members and subjects in bed rest vs. length of experiments: 1, bed rest; 2, space flights; Roman numerals are spacecraft numbers

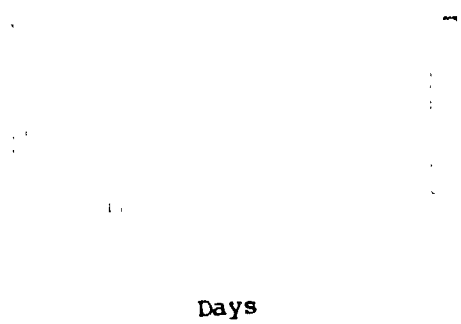

Fig. 117. Change in pulse pressure at rest (in percent of control examination data; average values) of Gemini crew members and subjects in bed rest vs. length of experiments: designations same as in Fig. 116

statistical processing (regression method and others) that the deviations observed do not go beyond normal limits. Several extrasystoles were recorded in flight, primarily during the acceleration in launch and descent. Arhythmic contractions of the cardiac muscle in flight also were pointed out in a brief report of the results of the flight of astronauts D. Scott and J. Irwin in Apollo 15.

In the opinion of Berry and colleagues (1966), study of the arterial pressure revealed no regularities. With quickening of the pulse, it also increased. During the flight of Gemini 7, over a period of 14 days, the maximum arterial pressure of the astronauts was within 110-145 mm Hg, the minimum, 50-80 mm Hg and the pulse, 50-90 mm Hg. In proportion to the stay under weightless conditions, a change was noted in the pulse pressure, which is evidence of hemodynamic shifts (Fig. 117).

Study of the cardiovascular system was carried out in flight, not only with the astronauts in a state of rest, but while they performed work: during extravehicular activity and while on the surface of the moon. As is well known, five astronauts performed extravehicular activity in the Gemini space flight program. They were there and worked about 6 hours overall. The first extravehicular activity took place during the flight of Gemini 4. The pulse and respiration of E. White, who went out into space, were recorded (Fig. 118). As is evident, the pulse rate was considerable. At individual moments (while closing the hatch), it reached 176 beat/min. Approximately the same data were recorded for E. Cernan. At the moment of opening the hatch, the pulse of E. Cernan reached 155 beat/min, it decreased to 125 beat/min after 30 min and, then, it remained between 130 and 170 beat/min. The highest rate also was noted upon closing the hatch (180 beat/min). Such significant physiological shifts, as it turned out, were dependent

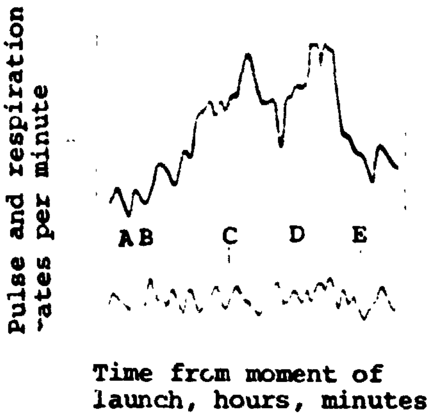

Fig. 118. Pulse (1) and respiration (2) rates of astronaut E. White during extravehicular activity: A, hatch opening; B, receipt of command to leave cabin; C, exit from cabin; D, return to cabin; E, hatch closing

mainly on external causes: inadequacies in the spacesuit life support systems, inefficient fastening systems, disruptions in organization of the work and rest schedules of the astronauts. All this was taken into account in succeeding extravehicular activities, when somewhat different data were obtained. The physiological shifts were quite moderate (Fig. 119). Similar results were obtained in the extravehicular activities of R. Schweickart, T. Mattingly and other astronauts in the Apollo program.

American astronauts landed repeatedly on the surface of the moon. They were on it for more than 70 hours overall. A definite moderation of changes in pulse rate attracts attention here. It quickened, but the shifts were not significant in the majority of cases. Thus, the pulse rates of the first travelers to the moon were 90-100 beat/min on the average during the extravehicular activity; N. T. Armstrong had the maximum value of 160

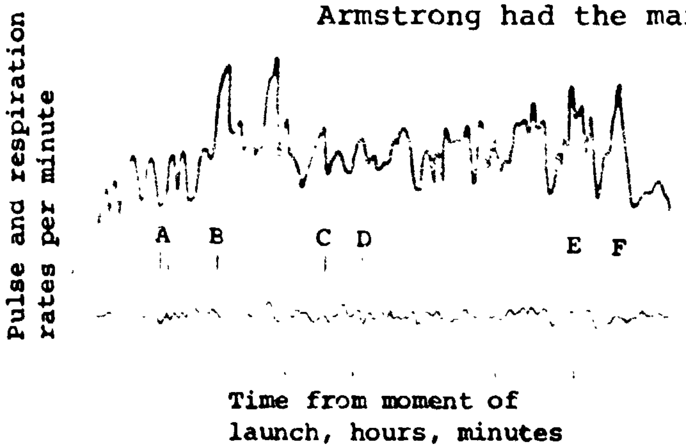

Fig. 119. Pulse (1) and respiration (2) rates of astronaut E. Aldrin during extravehicular activity: A, hatch opening; B, attachment of cable to satellite hull; C and D, actions in space; E, return to cabin; F, hatch closing

beat/min and E. Aldrin, 125 beat/min (Fig. 120).

During the first extravehicular activities of astronauts C. Conrad and A. Bean, the average pulse rate of the former was 105 (80-150) beat/min, and that of A. Bean, 121 (82-151) beat/min. Their state of

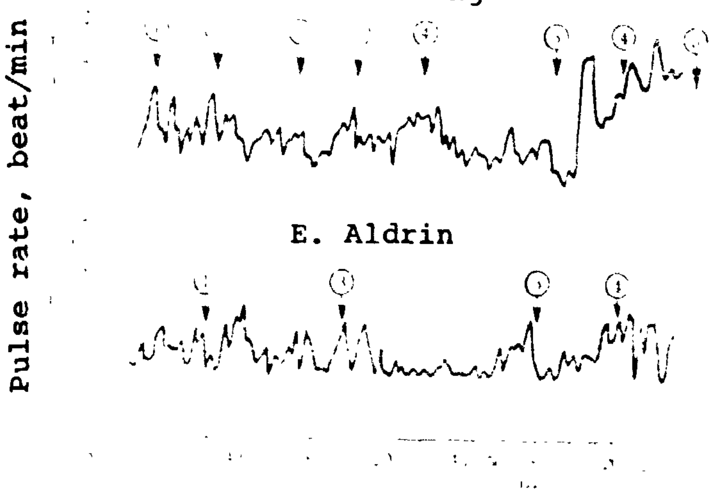

Fig. 120. Change in pulse rate of astronauts N. Armstrong and E. Aldrin during first lunar extravehicular activity: 1, arrival on surface of moon; 2, collection of emergency samples of lunar soil; 3, installation of apparatus; 4, collection of main sample of lunar soil; 5, completion of work in space

health was excellent. True, during the second extravehicular activity, the shifts were more significant. The pulse fluctuated between 165 and 170 beat/min. Fatigue apparently showed up. The pulse changes of A. Shepard and E. Mitchell also were moderate during the lunar extravehicular activity from Apollo 14. That of the first varied between 90 and 100 beat/min and, the second, 100-120 beat/min. /395

In this respect, the results of the work of V. S. Georgiyevskiy and colleagues (1972), studying the effect of a 5-day orbital flight on blood circulation during physical work of moderate intensity, 100 W (612 kgm/min), are of definite interest. It turned out that, after the flight, the reaction of the cardiovascular system deteriorated (more rapid pulse, delay in return to normal of its rhythm after the test, etc.). However, the hemodynamic shifts did not go beyond normal limits. The functional reserves were completely preserved.

Speaking of the physiological mechanisms of such changes, American investigators connect them primarily with physical work, which was performed in flight by the astronauts. This apparently is true. However, the claim of Berry (1970) deserves attention. Analyzing the results of the lunar experiments, he pointed out that, in a number of cases, quickening of the pulse was not caused by work. In the opinion of the author, there are some other, presently unknown causes of this phenomenon, which must be studied further.

Based on space experiment materials, R. M. Bayevskiy and O. G. Gazenko (1964) and V. V. Parin and colleagues (1967) distinguished several phases in the nature of change in the hemodynamic indices in weightlessness: transitional reactions, of the "unloading" type and stabilization reactions, reflecting predominance of parasympathetic effects. Without denying the presence of these phases, A. M. Genin and I. D. Pestov (1971) consider that, during a long stay under weightless conditions, the appearance of reactions of a sympathetic nature is likely. Thus, in the 18-day flight of Soyuz 9, during the last week of the flight, a tendency toward increase in pulse rate was noted (Ye. I. Vorob'ev, et al., 1970).

The first information that the transition from weightlessness to terrestrial gravitation is a quite difficult process appeared after the first orbital flights (Link, 1965). Pronounced signs of reduction in orthostatic tolerance, which were retained for a period of 19 hours after the flight, were observed in astronauts flying in the Mercury program (Berry, 1971). Taking this into consideration, special studies were included in the preflight and postflight study program, for determination of orthostatic tolerance. The fact is that, by a number of indicators, the direction of change in cardiovascular system indices was identical, under both orthostatic actions and under weightless conditions. From this, it is possible to predict, with a certain degree of probability, the development of orthostatic incompetence in astronauts under space flight conditions (P. V. Buyanov, N. V. Pisarenko, 1972, and others).

As a result of the systematic examination of the Gemini crew members, a postflight decrease in orthostatic tolerance was established, expressed by quickening of the heart beat, reduction in systolic and pulse pressure, and an increase in tendency towards development of fainting states while maintaining the vertical posture (Dietlein, 1970). It turned out that orthostatic tolerance after the 14-day orbital flight of Gemini 7 decreased no more than after flights of shorter duration (1-6 days). As an illustration, data on the change in pulse rate after space flights of various durations and the results of the examination of the Gemini 7 /396
commander F. Borman (Fig. 122) are presented in Figs. 121 and 122. In the latter figure, the noticeable increase in pulse rate in the first postflight examination attracts attention. Although the prefainting condition was not noted, the pulse pressure decreased. The leg volume increased, which indicated considerable filling with blood. Similar data were obtained in Apollo program examinations (Dietlein, 1970; Johnson, 1971; Berry, 1971). As a rule, during the first postflight examinations, creation of negative pressure on the lower part of the body or a standing test led to acceleration of the heart rate, which was greater than before the flight (Fig. 123).

The changes in arterial pressure during the orthostatic test were not regular. In a number of cases, the systolic and diastolic pressure decreased and, in others, they increased. However, the pulse pressure turned out to be reduced from the preflight data in all astronauts (Fig. 124). Variations in systolic and diastolic pressure were characteristic. In persons who were close to the fainting state during the test, a considerable decrease in pulse, systolic and, to a lesser extent, diastolic pressure and marked bradycardia were noted.

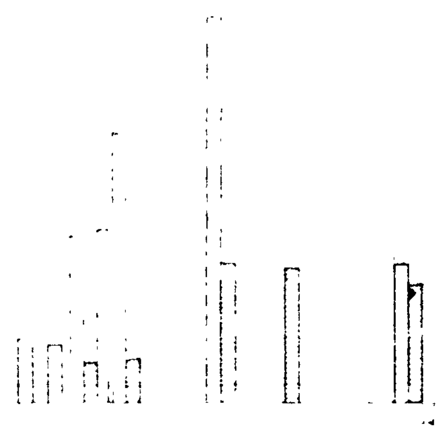

Fig. 121. Change in pulse rate (in % of control examination data; average values) in orthostatic test of astronauts after Gemini flights and of subjects after bed rest vs. length of experiments: designations same as in Fig. 116

In the flights of Apollo 11, Apollo 12, Apollo 14 and Apollo 15, some astronauts were in a state of weightlessness for a long time and others were partly under conditions of decreased gravitation (1/6 g), while performing specific types of work. In this connection, it was interesting to compare the estimates of their orthostatic tolerance. It turned out that, in astronauts performing lunar extravehicular /397 activity, it decreased, but to a lesser extent than in persons in weightlessness all the time. The latter is illustrated by the results of examination of the Apollo 14 crew members, where S. Roosa, the command module pilot, did not perform lunar extravehicular activity and the other crew members did (Table 91). As is evident, for astronauts A. Shepard and E. Mitchell, subject to lunar gravitation, almost no changes over the preflight reactions were found in the passive standing test. For S. Roosa, on the other hand, the pulse rate increased very noticeably and the arterial pressure decreased. Moreover, in the examinations immediately after the flight and 12 hours after it, a prefainting state was noted. Of course, it is still early to draw final conclusions on this question, the more so that this dependence did not appear in examination of the Apollo 15 astronauts. In the opinion of American investigators, refinement and additional studies are required.

As was pointed out above, the functional state of the cardiovascular system in the postflight period also was evaluated by dynamic measurements of certain indices of the astronauts in the state of rest, without functional tests. In particular, the pulse rate and arterial pressure were recorded, the leg volume was measured and heart radiography was performed. The most complete and interesting summary of the results of these measurements of the Apollo crew members is that of Johnson (1971). According to his data, in the postflight examinations, a decrease in perimeter of the calves of the astronauts regularaly appears during the examination immediately /399 after splashdown. The perimeter of the extremities of all the crew members of Apollo 7-11 and Apollo 15 decreased by one cm on the average (0.25-2 cm).

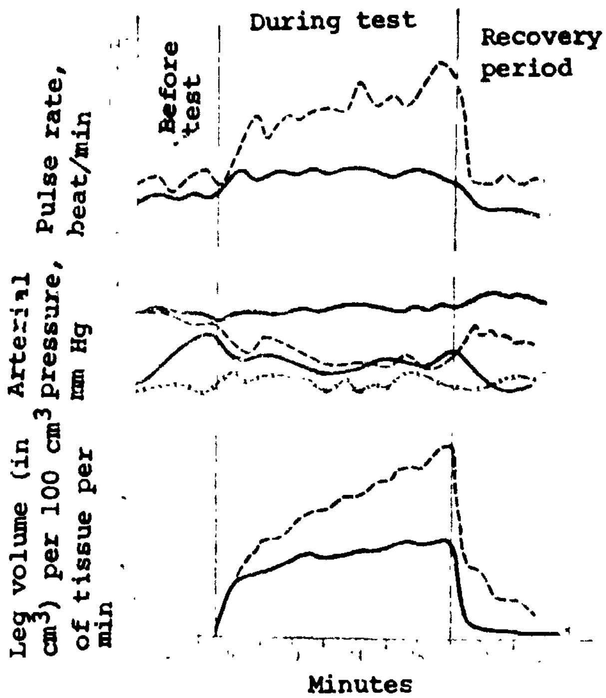

Fig. 122. Physiological reactions of Gemini 7 spacecraft commander to orthostatic tests before and after space flight: 1, preflight pulse rate; 2, postflight pulse rate; 3, maximim preflight arterial pressure; 4, maximum postflight arterial pressure; 5, minimum preflight arterial pressure; 6, minimum postflight arterial pressure; 7, preflight leg volume; 8, postflight leg volume

Radiography of the thoracic cage of 24 pilots in the Apollo program resulted in determining that the heart shadow size of 19 men decreased. The Gredel index (ratio of the lateral dimensions of the heart and lungs) decreased by 0.01 in five astronauts, by 0.02 in two, by 0.03 in three, by 0.04 in six, by 0.06 in one and by 0.01 also in one astronaut. This amounted to 0.5-3 cm lateral diameter of the heart shadow. Among the crew members performing lunar extravehicular activity, the changes were less. and that of N. Armstrong, the Apollo 11 spacecraft commander, there were none at all. Inspection of the preflight and postflight photos of the thoracic cage of the Gemini crew members disclosed the same regularity: a decrease in the Gredel index and a change in configuration of the heart shadow.

During the postflight examinations, in clinical electrocardiograms recorded in the prone position, a decrease in the T-spike and small, but noticeable shifts in the QRS complex frequently were noted. The Apollo 15 astronauts were the first for whom vector cardiograms were made before and after flights. There was an identical widening of the QRS-T angle of divergence for the spacecraft commander and the lunar module pilot. The T-spike was shifted 30° clockwise from its average lower and left direction. The QRS complex increased in all three planes. The vector was directed backwards; both the left side and the right side ones became appreciably larger. An exception was the data of the command module pilot. The final part of the QRS complex had a projection, more oriented to the right and rear, /400 and the lobe of the T-spike was directed slightly more to the rear and vertically than that recorded before the flight. Such vectorographic changes indicate a decrease in heart volume (Johnson, 1971).

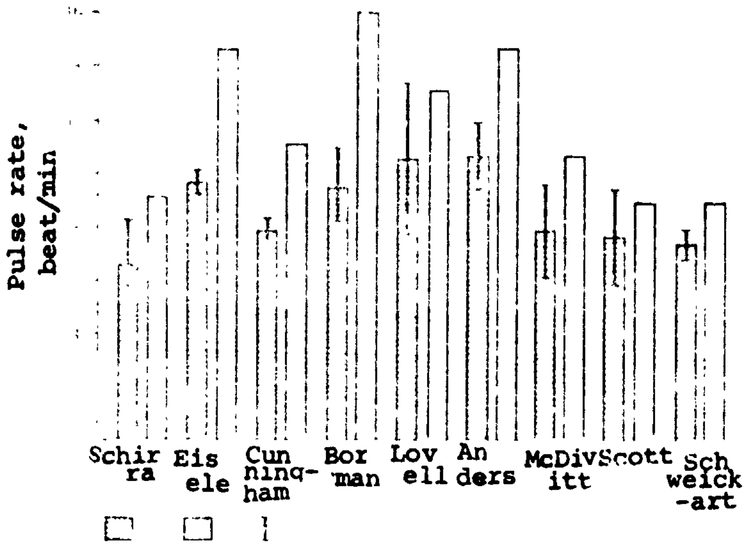

Fig. 123. Maximum pulse rate level of some astronauts after Apollo program flights with negative pressure on lower half of trunk: 1, preflight examination results; 2, postflight examination results; 3, limits of variation

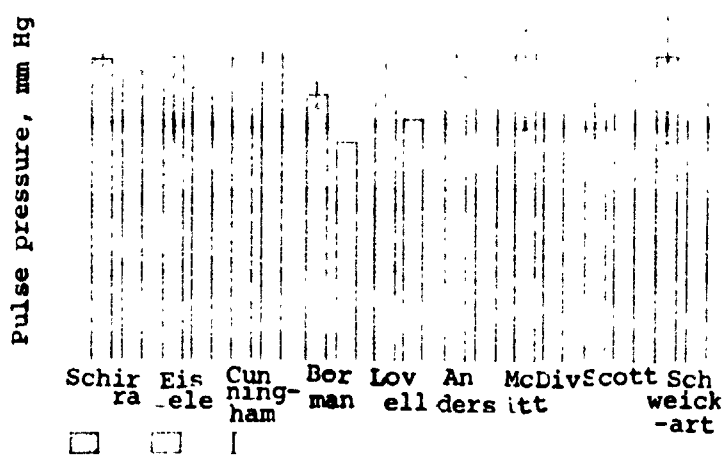

Fig. 124. Pulse pressure of some astronauts after Apollo program flights with negative pressure on the lower half of trunk: designations same as in Fig. 123

TABLE 91

CARDIOVASCULAR SYSTEM REACTION INDICES OF APOLLO 14 CREW MEMBERS IN PASSIVE ORTHOSTATIC TEST (average data)

Astronaut	Preflight Data		Postflight Data							
			Immediately after flight		After 12 hrs		After 24 hrs		After 36 hrs	
	Lying	Standing	Lying	Standing	Lying	Standing	Lying	Standing	Lying	Standing
	Pulse rate, beat/min									
A. Shepard, SC	56 ± 3.6	74 ± 7.0	54	69	53	67	58	71	60	75
S. Roosa, CMP	63 ± 7.0	73 ± 6.7	80	91	83	95	79	104	77	100
E. Mitchell, LMP	65 ± 1.5	79 ± 4.6	63	86	67	86	69	91	71	89
	Systolic arterial pressure, mm Hg									
A. Shepard, SC	101 ± 0.6	103 ± 7.2	100	98	108	116	108	116	111	115
S. Roosa, CMP	120 ± 16.0	126 ± 16.0	123	129	116	98	118	118	112	115
E. Mitchell, LMP	111 ± 4.7	106 ± 4.5	113	104	119	107	112	95	117	111
	Diastolic cerial pressure, mm Hg									
A. Shepard, SC	60 ± 8.1	70 ± 15.3	68	75	71	81	70	70	66	67
S. Roosa, CMP	72 ± 7.4	86 ± 12.4	89	93	77	75	73	88	68	80
E. Mitchell, LMP	60 ± 7.5	62 ± 10.1	76	74	72	73	55	66	56	52

The pulse rate and arterial pressure were not recorded at rest for all astronauts. There was a statistically significant increase in pulse over the preflight data for 12 of 21 astronauts and it was practically constant for 9.

It should be noted in conclusion that the changes observed in the cardiovascular system under weightless conditions are adaptive reactions to these unusual conditions. There was not a single case of deterioration in cardiac activity during the flights. Changes in the cardiovascular system became evident only after the return earth gravitation. In the postflight period, an increased accumulation of venous blood in the lower parts of the body, a quickening of heart rate in the othostatic test (up to 150-170 beat/min), a decrease in pulse pressure and a prefainting state were found. These changes should be closely connected with the disproportionately large capacity of the vessels, with respect to the volume of circulating blood and with imperfections of the regulatory mechanisms, which is confirmed by the considerable oscillations of arterial pressure during the postflight examination. The degree of change and length of the recovery period depended to a certain extent on flight duration. The recovery period did not exceed 72 hours. In the opinions of American authors (Berry, Dietlein and others), studies of this problem should be continued.

Changes in Blood Indices

American scientists paid much attention to hematological studies in the postflight examinations. They carried out general analyses of the blood, as well as special studies. In analysis of the results of examination of the Gemini crew members, it was determined that, after the flights, the erythrocyte mass decreased quite regularly (by 7-20% from the preflight examinations) and, to a considerably smaller extent, the blood and plasma volume. After a 14-day flight, the two latter indices of the astronauts even increased (Table 92). Dietlein explains these differences by the singularities of nutrition. In the flight of Gemini 7, the astronauts were allowed to eat and drink everything they wished. This apparently favorably affected plasma volume, and this index did not decrease. /401

TABLE 92

HEMATOLOGICAL INDICES OF GEMINI CREW MEMBERS AFTER LONG FLIGHTS (in % of preflight data)

Index	Gemini 4 4 days		Gemini 5 8 days		Gemini 7 14 days	
	Commander	Pilot	Commander	Pilot	Commander	Pilot
Blood volume	−7	−13	−14	−13	+1	−1
Plasma volume	−4	−13	−8	−4	+15	−4
Erythrocyte mass	−12	−13	−20	−20	−19	−7
Total hematocrit	—	—	−3	−5	−8	−2
Erythrocyte fragility	—	—	—	—	+	+
Average blood corpuscle vol.	—	—	+4	+1	+9	+13
" hemoglobin concentration in erythrocytes	—	—	—	—	−3	−5
Spleen and liver blood erythrocyte ratio	—	—	—	—	+30	+13
Reticulocyte content per 1000 erythrocytes	—	—	−1.2	−1.2	+0.05	−0.08
Erythrocyte-half-life, days	—	—	−6	9	−6.5	0

As follows from Table 92, after a flight, the erythrocyte lifetime decreases, increased fragility of them is noted, their volume increases, the total hematocrit decreases and the hemoglobin concentration in the erythrocytes decreases. The spleen and liver blood erythrocyte ratio increased significantly. No reticulocytosis was disclosed (Dietlein, 1970).

Approximately the same data were obtained in examinations of the Apollo astronauts. Leukocytosis was revealed, accompanied by absolute neutrophilia and lymphopenia. The deviations were brief. The number of leukocytes and the leukocyte formula returned to the initial level 24 hours after the flight. In the opinion of Berry

(1970), the changes developed, as a result of an increase in adrenalin and steroid concentrations in the blood, as a reaction to the stressor effects of the flight. Concerning the erythrocytes, differences were revealed in experiments in the Apollo spacecraft: for crew members of Apollo 7-10 and Apollo 14, the reduction in erythrocyte mass was negligible, but it was pronounced for the Apollo 9 crew members. (This index was not studied during the flights of Apollo 11 and Apollo 13.) A multitude of hypotheses has been proposed, as to the causes of this phenomenon. At the present time, the most widespread opinion is that it is a toxic effect of oxygen, as a result of staying in a 100% oxygen atmosphere and the inhibiting effect of nitrogen (Lomonaco, 1969; McCally, 1971, and others). The loss of erythrocyte mass was the least, during those flights, when a small addition of nitrogen (from 3 to 5%) was preserved in the cabin atmosphere. An atmosphere containing 100% oxygen was maintained in the Gemini and Apollo 9 spacecraft. In this case, a considerable decrease of erythrocyte mass of the crew members was disclosed. White, Berry and colleagues (1971) think that this hypothesis will subsequently be subject to experimental verification. There are other explanations. Thus, Jensen, referring to the research of Hyatt, considers that, in the state of rest (physiological deafferentation), the body decreases the ability to form erythrocytes. Lancaster, agreeing with this statement, also does not deny the toxic effect of oxygen. In our opinion, the hypothesis of the toxic effect of oxygen is more valid. This is confirmed by the results of the flights of Soviet astronauts, in which an atmosphere of air at normal barometric pressure was provided in the spacecraft cabins. As a rule, during the postflight examinations, no reduction in erythrocyte mass was noted in them (N. M. Sisakyan, V. I. Yazdovskiy, 1962, 1964; V. V. Parin, et al., 1967; Ye.I Vorob'yev et al,1967, 1970; Yu. C. Nefedov, et al., 1972). Of course, here too, the development of adaptive processes, connected with an increase in oxygen content in the environment, cannot be excluded. /402

Some additional biochemical studies of the plasma and erythrocytes were made after the flight of Apollo 14. A brief hyperglycemia was revealed, as a consequence of increased formation of catecholamines and steroids, as a result of neuroemotional stress, and a reduction in serum cholesterol and uric acid level, apparently, because of eating unusual food. No other biochemical changes were noted, indicating disruption of the function of the liver or other internal organs.

Concerning the physiological mechanisms of changes in certain other indices (acceleration of ESR, neutrophilic leukocytosis with lympho- and eosinopenia, etc.) which frequently are found in astronauts (N. M. Sisakyan, 1965; Berry, 1967, 1970, 1971; N. S. Molchanov and colleagues, 1970; Ye. N. Zhuravlev and colleagues, 1972), they are very complex. Some of them are considered (A. M. Genin, I. D. Pestov, 1971) to be manifestations of an inflammatory reaction to venous congestion, impairment of tissue metabolism, and traumatic myositis in the general biological stress reaction. The state of the hemodynamics under weightless conditions also predisposes to development of hemophilic reactions on the part of blood coagulability. A decrease in number of thrombocytes in the blood of some astronauts was noted after flights (N. S. Molchanov, et al., 1970, and others). All this indicates that, under weightless conditions, a definite directional nature of the change of one of the major fluids of the body, the blood, also is observed, which increases, when the astronaut is in a 100% oxygen environment.

Changes in Skeleton and Mineral Metabolism

The decrease in mechanical forces acting on the support- /403
motor and skeletomuscular apparatus under weightless conditions can lead to demineralization of the bones and reduction in strength and tonus of the muscles (Stubbs, 1970, and others) The effect of weightlessness on the bone tissue of the astronauts was studied during Gemini and Apollo program flights (Mack, et al., 1966; Hattner, McMillan, 1968; Chemin, 1969; Berry, 1970; Grandpierre, 1971, and others).

TABLE 93

CHANGE IN BONE DENSITY IN SPACE FLIGHTS, FROM RADIOGRAPHIC DATA (in % of preflight data)

Spacecraft	Flight duration, days	Anatomical Localization	Spacecraft Commander	Pilot
Gemini 4	4	Calcaneus (normal section)	7.8	-10.27
" 5	8		15.1	-8.9
" 7	14		2.91	2.84
" 4	4	Calcaneus (other sections)	6.82	9.25
" 5	8		10.31	8.9
" 7	14		-2.46	2.54
" 4	4	Phalange II finger V	-11.85	-6.24
" 5	8		-23.20	-16.97
" 7	14		-6.78	-7.83
" 5	8	Phalange II finger IV	-9.98	-11.37
7	14		-6.55	-3.82

During the flights of the Gemini 4, Gemini 5 and Gemini 7 spacecraft crews, the bone tissue density was studied, using a narrow beam of X-rays. The density of the wrist, finger and heel bones of six astronauts were measured for a period of several weeks before and after the flight (Table 93). As is evident, the bone tissue density of all astronauts decreased. Restoration of bone density to the initial value took place over approximately 10 days. Relatively small changes were noted in examination of the Gemini 7 crew members. The majority of the investigators explain this by execution of purposeful prophylactic measures: physical exercises in flight, increased consumption of calcium with the food (up to 921-945 mg per day), etc.

In subsequent reports of Soviet and American investigators, the fact of moderate decrease in density of the bone apparatus in weightlessness was predominantly confirmed. This was found by Mack (1969), Ye. N. Biryukov and I. G. Krasnykh (1970), Berry (1970) and others. By radiography, Mack (1969) examined the crews of Apollo 7/404 and Apollo 8. Seven anatomical sections of each of the astronauts was studied (Table 94). In the majority of cases, there were more significant changes in the bones of the arms than in the bones of the legs. Analysis of the material presented by the author established the cause of the difference. The decrease in bone tissue density of the Apollo 7 crew members was less significant, since they regularly engaged in physical training. The beneficial effect of physical exercises on the skeletal system under weightless conditions apparently consists of "tightening" the muscles attached to the bones, which, in turn, stimulates blood circulation in them. The examination data of the Apollo 14 crew members was a definite dissonance. The preflight and the postflight examinations of the left heel bone and distal part of the right radii and ulnae by means of adsorption of monoenergetic photons did not reveal leaching out of the mineral salts from the bone in a 10-day flight. The reason for the disagreement of these data is not clear (Berry, 1971). Possibly, they are connected with procedural peculiarities. In the opinion of Nordin, the radiographic method of determination of bone tissue density has some errors, because of the presence of a layer of soft tissue around each bone. Moreover, the structure of the bones themselves is irregular. In the trabeculae, for example, only 20% of the tissue actually consists of bone, and the remaining 80% consists of soft tissue, and this may not be reflected in densitometry results. Despite this, it seems to us that there is no basis for questioning the effectiveness of radiographic studies. A confirmation of this is the success of use of this method in both the USA and the USSR, as well as the results of study of mineral metabolism, especially calcium, which indicate definite changes in the body.

TABLE 94

CHANGES IN BONE TISSUE DENSITY (in % of data, obtained before flight on crew members of Apollo 7 and Apollo 8)

Anatomical Localization	Apollo 7			Apollo 8		
	SC	CMP	LMP	SC	CMP	LMP
Center of calcaneus	−5.32	+0.74	+2.27	−2.13	−6.95	−2.93
Various planes of calcaneus (avg. data)	−4.1	+1.19	+0.85	−7.08	−6.04	−6.50
Center of astragalus	−3.6	+1.75	+2.89	−2.62	−2.81	−3.18
Finger IV-II phalanges	−9.3	+2.04	−6.50	−2.19	−2.41	−4.81
Os magnum	−4.07	+3.31	−3.44	-9.6	−12.11	-6.65
Distal end of radius	−3.25	+3.34	−3.64	−8.76	−11.06	−11.39
" " " ulna	−3.02	+2.12	−3.41	−6.42	−12.41	−16.17

Conventional designations: SC spacecraft commander; CMP command module pilot; LMP lunar module pilot

Whedon, Lutwak and colleagues (1969) carried out a thorough study of metabolic processes of the Gemini 7 crew members in the 14-day orbital flight. Analysis of the fecal masses, perspiration and urine were carried out for a period of 10 days before the launch, during the flight and for a period of four days of the recovery period after it. With the astronauts on a strictly measured food /407 ration, they determined the expression of calcium, magnesium, phosphorus, nitrogen, sodium, potassium, and also of 17-oxycorticosteroids (17-OCS), aldosterone and catecholamines. The authors point out, however, that the procedure for collection of materials (especially urine) was not completely adhered to in orbital flight, in all cases. Because of the unusual situation, there were losses of material, as well as errors in addition of preservatives. This was allowed for by the investigators in calculation of all the indices. It turned out that the expression of calcium with the urine of all astronauts did not change significantly in the first seven days. However, beginning with the 8th day, the calcium content of the urine of F. Borman clearly increased and remained so subsequently (Table 95, Fig. 125).

The urine phosphate content increased in the first nine days, but it then decreased almost to the control values. The final balance of calcium was negative for both astronauts, which is connected with an increase in elimination of it with the feces of the pilot and with the urine of the commander. The content of nitrogen in the urine of both pilots decreased during the flight, reaching

TABLE 95

METABOLIC BALANCE OF ASTRONAUTS F. BORMAN (SC) AND J. LOVELL (P) DURING FLIGHT OF GEMINI 7

Period of Experiment	Duration of examination, days	Material	Calcium, g		Magnesium, g		Sodium, meq		Potassium, meq	
			SC	P	SC	P	SC	P	SC	P
Preflight	10	Food	1.103 ± 0.041	1.108 ± 0.48	0.338 ± 0.011	0.366 ± 0.018	151.7 ± 15.7	123.6 ± 9.6	128.9 ± 22.9	116.0 ± 15.5
		Urine	0.215 ± 0.021	0.159 ± 0.017	0.117 ± 0.014	0.101 ± 0.015	172.4 ± 16.8	143.7 ± 26.3	98.9 ± 17.0	74.[illegible] ± 7.6
		Feces	0.765	0.431	0.221	0.173	3.0	4.9	7.9	6.5
		Persp.	0.026	0.023	0.007	0.006	21.7	25.2	10.4	14.3
		Balance	−0.097	+0.495	+0.043	+0.086	−48.4	−50.2	+11.7	+2[illegible].1
Flight	14	Food	1.042 ± 0.251	1.042 ± 0.251	0.198 ± 0.04	0.198 ± 0.04	145.1 ± 28.4	145.1 ± 28.4	36.8 ± 8.9	[illegible] ± 8.9
		Urine	0.238 ± 0.032	0.162 ± 0.019	0.129 ± 0.033	0.097 ± 0.016	196.3 ± 41.1	181.8 ± 22.6	93.4 ± 41.6	50.1 ± 6.3
		Feces	0.796	0.766	0.115	0.109	26.3	10.3	1.1	7.2
		Persp.	0.014	0.016	0.006	0.007	18.6	2.9	6.9	1.6
		Balance	−0.06	+0.098	−0.052	−0.015	−72.1	−49.9	−64.6	−22.9
Postflight	4	Food	1.102 ± 0.111	1.090 ± 0.119	0.371 ± 0.052	0.359 ± 0.035	167.2 ± 29.3	125.3 ± 30.4	122.9 ± 20.9	117.1 ± 12.5
		Urine	0.286 ± 0.002	0.172 ± 0.014	0.093 ± 0.011	0.093 ± 0.006	140.1 ± 34.8	74.5 ± 21.8	90.3 ± 3.9	63.4 ± 14.7
		Feces	0.769	0.766	0.148	0.109	6.5	10.3	9.6	7.2
		Persp.	0.043	0.045	0.015	0.017	12.0	9.8	11.0	11.4
		Balance	+0.004	+0.107	+0.115	+0.140	+8.6	+30.7	+12.0	+35.6

Period of Experiment	Duration of examination, days	Material	Phosphates, g		Sulfates, g		Nitrogen, g		Chlorides, meq	
			SC	P	SC	P	SC	P	SC	P
Preflight	10	Food	2.548 ± 0.239	2.373 ± 0.150	2.737 ± 0.338	2.562 ± 0.304	24.78 ± 2.36	22.32 ± 1.44	—	—
		Urine	1.323 ± 0.091	1.259 ± 1.133	1.344 ± 0.292	1.077 ± 0.433	22.83 ± 2.65	20.36 ± 2.2	145.3 ± 10.9	129.3 ± 23.0
		Feces	0.557	0.407	0.182	0.09	1.78	1.22	18.4	16.1
		Persp.	0.00	0.00	0.004	0.005	0.19	0.36	0.1	0.5
		Balance	+0.668	+0.707	+1.207	+1.[illegible]9	0.02	+0.38	—	
Flight	14	Food	1.362 ± 0.161	1.362 ± 0.161	0.874 ± 0.163	0.874 ± 0.163	15.81 ± 2.85	15.81 ± 2.85	—	
		Urine	1.741 ± 0.442	1.577 ± 0.155	1.254 ± 0.21	1.019 ± 0.102	17.9 ± 2.27	16.24 ± 1.86	65.7 ± 42.5	116.4 ± 22.1
		Feces	0.311	1.289	0.127	0.096	1.31	0.87	1.4	0.2
		Persp.	0.00	0.00	0.063	0.002	0.003	0.04	0.2	2.2
		Balance	−0.690	−0.504	−0.51	−0.243	−3.43	−1.34	—	—
Postflight	4	Food	2.424 ± 0.292	2.376 ± 0.168	2.655 ± 0.276	2.588 ± 0.191	22.82 ± 3.36	22.02 ± 2.48	—	
		Urine	1.563 ± 0.286	1.296 ± 0.542	1.689 ± 0.453	1.529 ± 0.104	25.34 ± 3.97	19.92 ± 2.91	126.7 ± 48.6	65.7 ± 26.8
		Feces	0.503	0.289	0.121	0.096	1.21	0.97	0.3	0.2
		Persp.	0.00	0.00	0.004	0.010	0.26	0.29	15.1	17.[illegible]
		Balance	+0.358	+0.791	0.838	+0.953	−3.99	+0.84	—	

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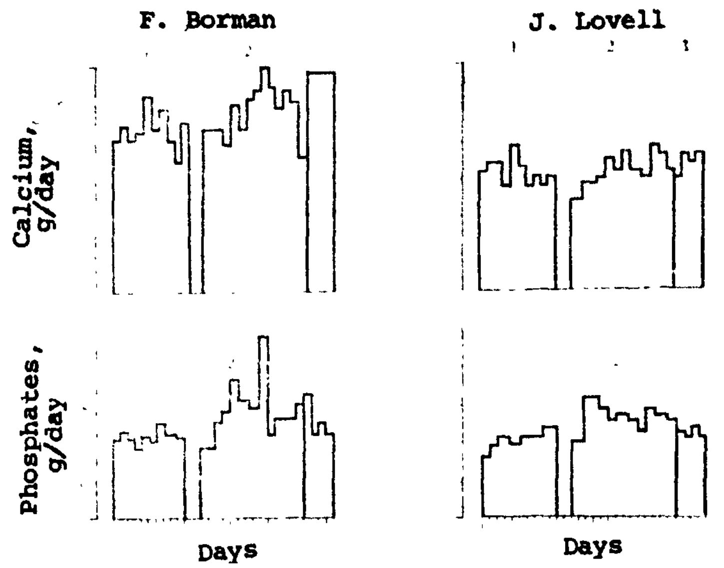

Fig. 125. Excretion of calcium and phosphates of Gemini 7 crew members: 1, preflight; 2, during flight; 3, postflight; time in days on abscissa

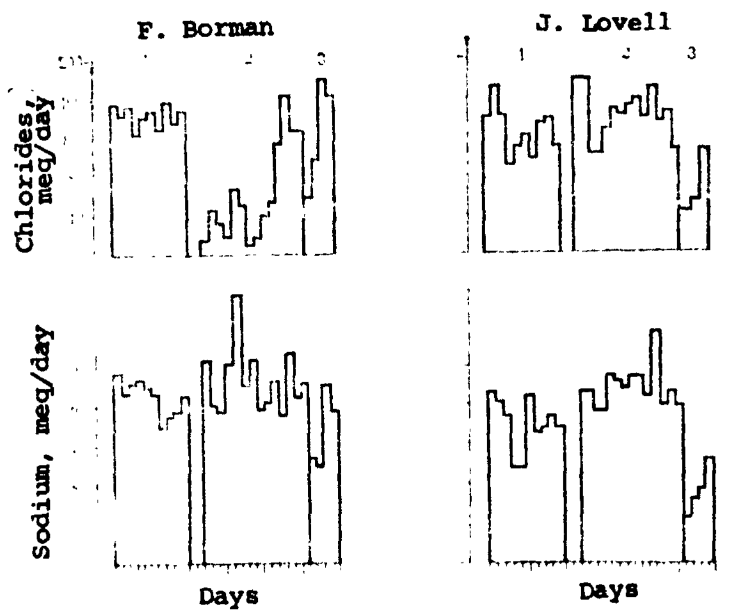

Fig. 126. Excretion of sodium and chlorides with urine of crew members of Gemini 7: designations same as in Fig. 125.

the preflight values by the end of it. Nitrogen consumption with the food decreased sharply, and this was the cause of the negative nitrogen balance. Elimination of magnesium and sulfates was similar to that of nitrogen. The nature of the potassium metabolism of the astronauts differed. Elimination of potassium with the urine of the commander decreased at the start of the flight, against a background of a noticeable decrease in entry of it with the food. In the second half of the flight, elimination of potassium with the urine increased. After the flight, potassium excretion decreased, and the intake of it with the food increased. Only a little decrease in elimination of potassium with the urine of the pilot was observed during the entire flight, as well as a return to normal after completion of it. Data on elimination of sodium and chlorides with the urine of the astronauts are presented in Fig. 126.

As is evident, elimination of sodium by F. Borman was considerable in the first half of the flight, and that of J. Lovell in the second half. In the postflight period, retention of sodium in the bodies of both astronauts was noted. The chloride level changed in conformance with this: that of F. Borman decreased in the first 10 days of the flight and that of J. Lovell, in the postflight period.

Data on hormone elimination is of great interest. J. Lovell had the highest level of adrenalin and noradrenalin on the launch and landing days, i.e., in the greatest "stressor" periods. Excretion of catecholamines by F. Borman was approximately the same. The level of elimination of 17-oxycorticosteroids was comparatively low during the entire orbital flight. That of both astronauts increased on the day of landing (Fig. 127). The aldosterone level in the urine increased during the flight and immediately after landing (Fig. 128). The work of Whedon, Lutwak, et al. (1969) was essentially the first fundamental research on this problem. The data they obtained was subsequently confirmed and refined. Thus, in the work of Brodzinski and colleagues (1971), materials on mineral metabolism of the Apollo 7-11 crew members was presented. Neutron activation analysis of the feces collected during the flight aboard the craft, as well as the urine, samples of which were taken before the flight and after it, and comparing them with data on consumption of the elements (from NASA[8] materials), the authors examined the extent of disagreement and possible consequences of /408 disruption of the mineral balance. The results are presented in Table 96.

[8]NASA -- National Aeronautics and Space Administration.

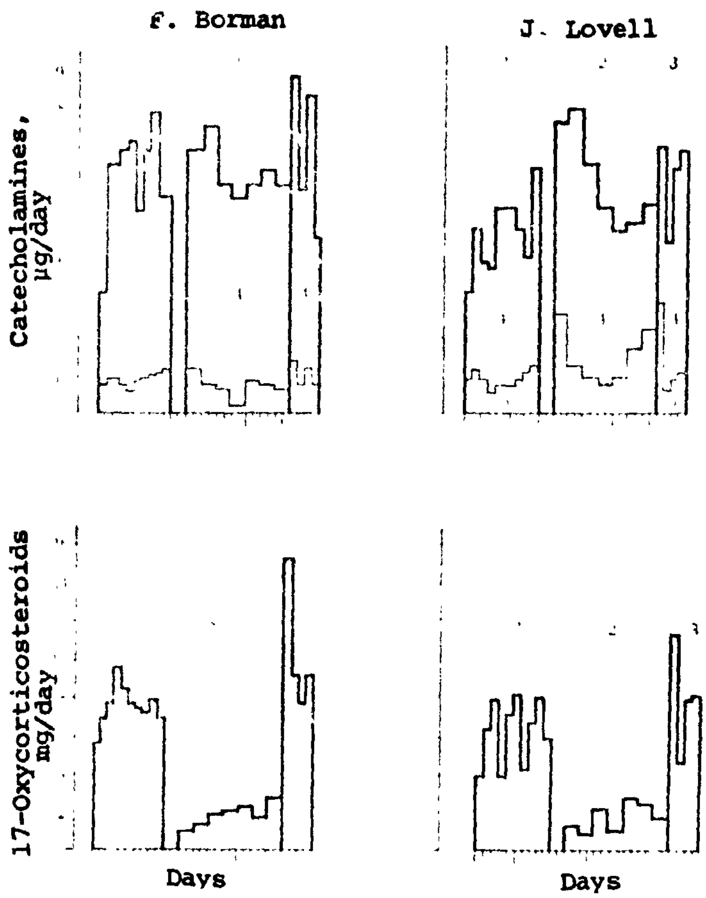

Fig. 127. Hormone excretion of Gemini 7 crew members: 1, preflight; 2, in flight; 3, postflight; 4, noradrenalin; 5, adrenalin; time in days on abscissa

As is evident, the calcium losses per day were 635 mg, which is 0.0605% of the total calcium content of the body, for a man weighing 70 kg. The fact that the elimination rate was greater (990 mg) in the first three flights than in the last two (220 mg) attracts attention. Elimination of potassium from the body also follows approximately the same pattern. On the average of all flights, the potassium losses were 296 mg (0.16% of the total potassium content of the body). It was higher (668 mg) in the first three flights and lower (48 mg) in the last two. Concerning iron, it was eliminated in approximately the same quantity in all flights (about 6.4 mg per day). These changes in mineral metabolism in weightlessness (elimination of calcium, sodium, potassium, iron and other elements) are compensated for by the body in the postflight period. Study of the electrolytes in the urine and plasma after the flights disclosed a tendency toward retention of them in the body. Thus, in the urine of the Gemini 7 /409

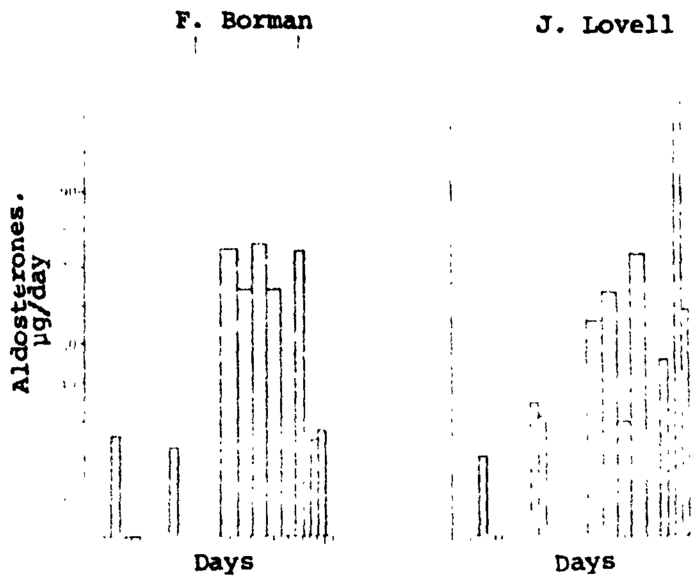

Fig. 128. Aldosterone excretion by Gemini 7 crew members: designations same as in Fig. 125

pilot, a decrease in excretion of potassium was noted in flight, and it was maintained for 24 hours after the flight. The correctness of the hypothesis of a decrease in total potassium content in the body was completely confirmed in ^{42}K studies in the Apollo 13 and Apollo 14 spacecraft. Gamma spectrometry demonstrated a considerable decrease in total potassium content in the body, and it was maintained by the Apollo 14 spacecraft crew for a period of 17 days after the flight (Berry, 1971). The same thing was disclosed in examination of the Apollo 15 crew. Apparently, sodium retention reflects a tendency towards return to normal of the water-salt equilibrium, and potassium retention is explained by muscle protein recovery processes.

The content of electrolytes in the urine is a typical consequence of the effect of space flight on the human body (Fig. 129). The same thing was confirmed by analysis of the chemical composition of the urine of other Apollo crew members.

Investigators are giving sufficient attention to analysis of the aftereffects, which can set in in the body, with extreme elimination of one substance or another. Thus, in the opinion of Dick (1966), and of Brodzinski and colleagues (1971), the loss of calcium in the quantities recorded during the flights of Apollo 10 and Apollo 11, as well as during weightlessness simulation experiments, may be permissible for a period of several years. Another point of view is held by L. I. Kakurin and Ye. N. Biryukov (1966). They think that the loss of calcium, which has a high physiological activity, may lead to a number of functional disorders of the cardiovascular system, the blood coagulability functions, etc. Elimination

TABLE 96

AVERAGE DAILY CALCIUM, POTASSIUM AND IRON BALANCE IN BODIES OF APOLLO ASTRONAUTS

Craft	Astronaut	Calcium, mg					Potassium, mg					Iron, mg				
		Intake with Food	Eliminated with Feces	Total Eliminated[1]	Discharge Intake Ratio	Mass Balance mg/da	Intake with Food	Eliminated with Feces	Total Eliminated[2]	Discharge Intake Ratio	Mass Balance mg/da	Intake with Food	Eliminated with Feces	Total Eliminated[3]	Discharge Intake Ratio	Mass Balance mg/da
Apollo 7	Avg. for crew	836	1140	1430	1.7	—590	—	—	—	—	—	8.1	15.7	15.7	1.9	[illegible]
" 8	Spacecraft Commander	[illegible] 2	1150	1440	3.36	—1010	1229	499	3020	2.46	—1795	5.0	13.3	13.3	2.7	—8.3
" 9	Command Module Pilot	[illegible] 5	1119	1490	2.64	—930	1677	273	1540	0.916	141	7.1	11.6	11.6	1.6	4.5
" 9	same	491.3	1100	1380	2.78	—880	1386	2.76	1670	1.21	—286	5.9	13.2	13.2	2.2	7.3
" 9	Lunar Module Pilot	489.0	2260	2830	5.78	—2340	1708	403	2140	1.43	—732	6.5	17.2	17.2	2.6	10.7
" 10	Avg. for crew	829.9	730	910	1.1	—80	1340	176	1070	0.797	+273	5.1	6.7	6.7	1.3	1.6
" 11	" " "	1009.3	1090	1360	1.36	—360	1751	350	2120	1.21	—3.67	8.0	10.4	10.4	2.1	8.4
Average Total		767.7	1120	1400	1.83	—635	1527	300	1820	1.19	—296	6.8	13.2	13.2	1.9	—6.4

[1]On condition that 80% of all calcium eliminated from the body is present in feces.
[2]On condition that 15.5% of all potassium eliminated from the body is present in the feces.
[3]On condition that 100% of the iron eliminated from the body is present in the feces.

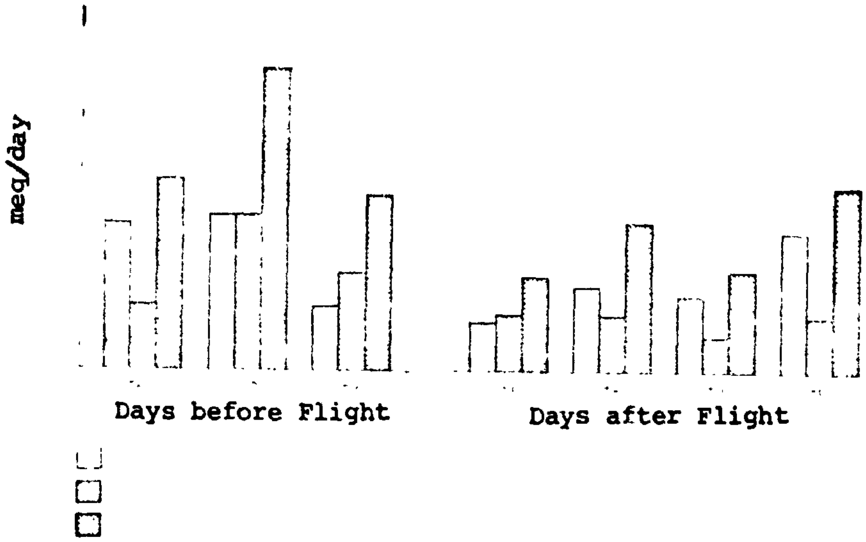

Fig. 129. Electrolyte content in urine of command module pilot of Apollo 14 before and after flight: 1, sodium content; 2, potassium content; 3, chloride content

of calcium from the body under weightless conditions, according to /410 the general opinion, is explained by an insufficient load on the skeletal muscles and removal of the weight load. Ye. N. Biryukov and I. G. Krasnykh (1970), in addition to these reasons, indicate certain other mechanisms of regulation of the calcium metabolism, hormonal in particular. Possibly, calcium ions are mobilized from the bone cation depot, to eliminate the electrolyte imbalance, arising under weightless conditions. Berry (1971), supporting Ye. N. Biryukov and I. G. Krasnykh, emphasizes the necessity for study of the parathyroid hormone and calcitonin content in subsequent flights, for the purpose of precisely defining the mechanisms of leaching out of mineral salts from the bones.

Much remains obscure about elimination of the electrolytes, sodium and potassium. From far from complete data of Whedon and Lutwak (1970) and Brodzinski and colleagues (1971), the losses of these elements are negligible. However, there obviously is no basis for reassurance in this case, especially if the role of these substances in normal functioning of the central nervous system, in regulation of the osmotic pressure and in transport of a number of major substances through the cell membrane is remembered. The iron balance is very important for preservation of the vital activities of the body. As is evident from what has been stated above, the rate of elimination of this substance does not depend on flight length, and it is quite significant. In the opinion of Brodzinski and colleagues (1971), development of an anemic condition in the astronauts is possible in long flights. The cause of the intensive elimination of iron is not clear. One possible cause is the oxygen-rich atmosphere of the spacecraft cabin. In this case, the iron of healthy and disintegrating erythrocytes is removed from the body. Moreover, it is not excluded that such a large loss is caused by hemorrhage, the possibility of which is created by administration of radioactive chromium to the astronauts in the preflight period (Brodzinski, et al., 1971).

As is evident, very many problems are still far from a final solution. Additional studies are necessary, both in flight experiments and under laboratory conditions. /411

Performance Capacity of Astronauts

In all space experiments, questions of performance capacity have been the subject of the steady attention of investigators. A set of indices has been studied here, which included: a) psychosensory reactions of the subjects; b) movement and orientation under conditions of changed effects of gravitation; c) specific analysis of performance of flight programs, first and foremost, during extravehicular activity in space and on the surface of the moon; d) change in performance capacity of astronauts in the postflight period, which have been studied, using various tests.

The most valuable information on the psychosensory reactions of astronauts has been obtained from their reports. It was noted, as early as the first space flights in the Mercury and Gemini programs, that a sense of "discomfort" developed in the state of weightlessness, connected with the absence of the pressure of the back and seat of the chair on the body of a man. Something like this was experienced by the crew members of Apollo 7-11. They felt the absence of the weight of various objects and clothing (Berry, 1970). The mechanisms of such phenomena apparently depend on change in the kinetic sensations, as a consequence of removal of the stimulation of the tactile mechanoreceptors, normal for earth conditions. In more pronounced cases, the astronauts complained of pain in the legs and lower part of the back (Berry, 1971). The causes of these pains still are not clear, but it can be suggested that they are due to the unusual posture, which the astronauts assumed while sleeping (the fetal position), as a consequence of which the kinetic sensations changed.

The majority of the American astronauts participating in the Gemini and Apollo flights, besides this, noted the feeling of heaviness of the head, during the transition from g-forces to the state of weightlessness, similar to that, which arises on earth in a man hanging head down. The phenomenon was temporary, and it had no effect on the spatial orientation of the astronauts (Berry, 1970, 1971). The explanations of these phenomena are quite contradictory. Some specialists consider them to be a consequence of redistribution of the blood, rushing to the head (Berry, 1971, and others) and others, by disruption of the systematic work of the analyzers reflecting space, as a consequence of changes in afferentation from all mechanoreceptors, primarily of the otolith portion of the vestibular apparatus (M. D. Yemyel'yanov, Ye. M. Yuganov, 1962; G. L. Komendantov, V. I. Kopanev, 1962; M. D. Yemyel'yanov, 1966; O. G. Gazenko, A. A. Gyurdzhian, 1967; Graybiel, 1968). Both points of view apparently are valid to a certain extent; however, the second has some advantages. In their reports, the astronauts noted that the illusions are intensified by rapid movements of the head and that they are analogous to the sensations arising during the action of Coriolis forces (N. M. Sisakyan, V. I. Yazdovskiy, 1962; N. S. Molchanov, et al., 1970).

In a number of cases, the astronauts who had the illusory sensations in flight developed the space form of motionsickness. Thus, during the flight of Apollo 8, F. Borman felt nausea and pain in the stomach. He began to have diarrhea. The other crew members experienced some poor health. The astronauts felt better after taking a motionsickness tablet. The majority of specialists have concluded that motionsickness is caused by manifestation of the side effects of soporfics, combined with reactions to too abrupt movements of the head and trunk, during the first hours of weightlessness. Astronaut R. Schweickart (Apollo 9) had motionsickness. While putting on the spacesuit before entering the lunar module, he had an attack of vomiting, which was repeated several hours later. According to the data of Berry (1971), of 27 astronauts in the Apollo program, 6 had unpleasant sensations in the stomach and 2, nausea and vomiting. Although there are no direct indications of motionsickness of other astronauts, the Gemini and Apollo crew members, there are indirect data that excitability of the vestibular centers was elevated: after the landing of the Gemini 3 crew, both astronauts experienced dizziness, and V. Grissom was nauseated; although the astronauts flying in Apollo 10 did not complain of motion sickness, for some reason, they took "Lomotil" tablets (diphenoxylate hydrochloride) to quiet stomach pains, and the contents of one of the feces bags was similar in odor to vomit, with pH equal 2 (Dietlein, 1970). Astronaut J. Irwin (Apollo 15) experienced discomfort in the first three days of the flight: heaviness of the head and stomach. It seemed to him that nausea and vomiting could develop with continuation of fast movements. In the words of J. Irwin, for a period of five days after the flight, the feeling of the head being thrown approximately 30° did not pass. /412

From what has been reported above, it is evident that the problem of motionsickness is urgent for specialists in the field of space medicine, both in the USA and in the Soviet Union (G. L. Komendantov, V. I. Kopanev, 1962; Ye. M. Yuganov, 1965; Graybiel, 1968, 1971; Johnson, 1971, and others). According to reports of Lawrence (1971), the underestimation of this problem, which occurred earlier among specialists and American astronauts, does not exist now. The causes of development of motionsickness have been revealed (great freedom of movement of the head and trunk in flight), and the astro- /413 nauts have understood the necessity for preflight vestibular training. The problem of motionsickness is becoming still more urgent, with the time when scientists, the static-kinetic stability of whom is lower, on the average, of course, than that of flight professionals, will participate in flights.

The physiological mechanisms of development of space sickness are quite complicated. There is an opinion that the reciprocal interactions between the receptor formations of the otoliths and semicircular canals change under weightless conditions (K. L. Khilov, 1969, and others). Deafferentation of the otolith apparatus promotes the release of reflexes from the semicircular canals and increases their sensitivity to angular accelerations. As Miller and colleagues (1969) and I. A. Kolosov, 1969) have determined, movement of the head in brief weightlessness leads more often development of vegetative syndromes, than under conditions of earth gravitation. Wonder (1965) introduced the hypothesis that nausea may be provoked by the unusual distribution of gases and fluids in different parts of the gastrointestinal tract. G. L. Komendantov and V. I. Kopanev (1962), V. V. Bara..ovskiy and colleagues (1962), I. D. Pestov (1965) and other investigators have developed a reflex theory, according to which disruptions of the afferent effects from the mechanoreceptors, providing for spatial analysis and perception of gravitational effects are the basis of space sickness.

Of interest also is a report of Berry (197), on the characteristics of the feeling of hunger under weightless conditions. There are analogous to the sensations arising under earth conditior but they have appeared more rarely, although the astronauts have e t less food. The Gemini 4 crew members having a deficit each day of essentially 500-700 kcal (normal 2500-2600 kcal), did not experience hunger in flight; they were very hungry after the flight. The members of one crew reported that the normal amount of food and drink hindered their use of a stomach "expander." Weightless conditions apparently had an effect on the receptor apparatus of the interoceptive analyzer, to a definite extent. /414

Much attention has been given by the astronauts to the function of vision. Subjectively, the astronauts have not noted significant changes. According to their data, visual acuity even increased, in a number of cases. They easily distinguished ground reference points: rivers, lakes, roads, cities, motor vehicles and groups of people, they detected rocket launches and they could detect the main streets at night; they saw the wakes of moving ships in the water, at a distance of 800-1000 km, and signal smoke, at a distance of 640 km (Cooper, 1963; O'Lone, 1965; Berry, 1970, 1971, and others).

A number of hypotheses have been expressed as to the psychophysiological mechanisms of this phenomenon. A. A. Leonov and V. I. Lebedev (1971) considered that an illusory sense of recognition developed in the astronauts, because of euphoria, following the decreased pulsations from the gravireceptors and proprioreceptors in weightlessness. In the opinion of W. White (1965), the increase in visual sensitivity in weightlessness is caused by quickening of the physiological tremor of the eyeballs. The suggestion of Yu. P. Petrov (1969) is most probable; it is that the high visual resolving power of the astronauts may be caused by an initial significant visual acuity and discrimination of objects by secondary signs, i.e., "conjecture" of the objects took place. For example, in distinguishing a wake of a ship in the open sea, in the form of an acute angle, the astronaut saw the ship.

In all their reports, the astronauts, as a rule, mentioned the wide range of colors, which they observed in examining ground objects and the sky. However, there are certain differences in the descriptions. Thus, the Apollo 10 crew members saw the surface of the moon as predominantly a brown color, and F. Borman, the Apollo 8 spacecraft commander, asserted that it was gray, etc. Thus, perception of color in space and on earth is an ambiguous process. Understanding the mechanisms of it requires further study and, in all likelihood, it is connected, not only with singularities of the physiology of vision, but with the objects themselves and the conditions of their illumination at the moment of observation.

The claim of the astronauts, that they observed flashes of light (bands, points) in flight, with a frequency of one flash in two minutes, both with the eyes opened and closed, is interesting. There are no data that the flashes are caused by the effect of weightlessness. The mechanism of this phenomenon is still not clear. However, investigators are more inclined to think that the flashes (photopsy) are caused by external sources of radiation, apparently of cosmic origin (White, Berry, et al., 1971).

During the Gemini and Apollo flights, data also were obtained on the quality of movement of the astronauts, under changed gravitational conditions. It turned out that movement in weightlessness is determined by external conditions, to a great extent. They are facilitated, if they are performed in a place of limited space, for example, in a spacecraft cabin. Great efforts are not required for such movements; frequently, they are similar to swimming motions. /415 Turns in any plane also are executed without difficulty. The possibility of an astronaut colliding with the walls of the cabin increases the precision of the motion. Berry (1971) spoke out on the necessity for taking these circumstances into consideration, in selection of the optimum spacecraft cabin dimensions. Movements became more difficult, when the astronauts performed extravehicular activity. After the extravehicular activities of the astronauts making the Gemini 9, Gemini 10 and Gemini 11 flights, it became clear that they used much energy in holding the body in a specific position. The thought arose of the necessity of some method of securing oneself and the tools to the workplace. This was taken into account subsequently, in preparing for the Gemini 12 and Apollo flights. As was pointed out above, the American astronauts also used hand jet devices, for movement under weightless conditions. Experience demonstrated that they are effective, but that they still need technical improvements.

Data on movement on the surface of the moon are interesting. F. Aldrin (Apollo 14 spacecraft commander) tried various methods, in particular, the "kangaroo jump," with the legs pressed together. In this case, it was difficult for him to maintain equilibrium, so as not to fall forward. The most expedient method turned out to be normal walking. C. Conrad and A. Bean (Apollo 12) also moved easily over the surface, despite the dust, and they frequently resorted to jumps, up to 1.2 m long ("giraffe running," in slow motion). This method of movement was used most often by the Apollo 15-Apollo 17 crew members.

The opinion was expressed before the first space flights that there would be disorientation phenomena in weightlessness. According to the data of American investigators, the apprehension proved to be vain (Berry, 1971). They did not exist in the spacecraft cabins or in extravehicular activity in space or on the lunar surface. In evaluating this phenomenon, nevertheless, it should be kept in mind that three astronauts flying in the Apollo program had illusions of the upside-down position in space. It turned out that the Gemini 4 crew members noted that they made four- fivefold errors in visual estimation of distances, during approach to a target. The same thing was revealed on the surface of the moon. The absence of a reference point and the change in the relief image, depending on sun height, seriously hampered distance determination. From the data of the Apollo 7 crew members, it did not appear to be possible to use the horizon of the earth as a reference line during orientation in space. All this undoubtedly will hamper spatial orientation of man under unusual space flight conditions.

Thus, the astronauts experienced a number of inconveniences under weightless conditions, which showed up in their psychosensory sensations, on the nature of orientation in space and movement in it. All this certainly could not fail to be reflected on the performance level. This is clear from analysis of execution of the flight experiment program, especially during extravehicular activity of the astronauts, during the operation of approach and docking of satellites with space targets, in carrying out the program of scientific experiments and during the lunar surface extravehicular activities.

The data of Table 97 confirm that all Gemini crew members basically accomplished all tasks during extravehicular activity. The activities of the astronauts outside the craft were more and more complicated, and the stay time increased. They worked with motion-picture /417

TABLE 97

DATA ON EXTRAVEHICULAR ACTIVITY OF GEMINI CREW MEMBERS AND PERFORMANCE OF WORK UNDER THESE CONDITIONS

Space-craft	Astronaut Performing EVA	Length of stay in space, min	Primary operations performed during EVA	Some characteristics of activity and reasons for nonperformance of tasks
Gemini 4	E. White	20	Installation of motion-picture camera on hull of satellite, movement in space using hand jet device, photography	Did not lose orientation during stay outside satellite. Made recommendations on improvement in securing small objects needed in work to workplace
" 9	E. Cernan	125	Installation of motion-picture camera and mirror on hull, removal of holder from meteor particle traps, movement along hull, maneuvering with tether, test of jet unit for movement (35 individual operations) and its connection to spacesuit.	Experiment on movement in space using AMI unit not performed, because of misting of helmet window, deterioration of radiocommunications with craft and defect in unit. Movement along the hull of satellite in space assisted by facing of "velcro" adhesive material. In opinion of astronaut, execution of operation required 4-5 times greater force than on earth. Heat liberation (250-500 kcal/hr) considerably exceeded calculated data.
" 10	M. Collins	38	Maneuvering by means of jet device, photography, removal of holders with meteorparticles from Agena-D satellite rocket	Duration of EVA reduced, because of overconsumption of fuel in spacecraft stabilization system. It was difficult to move in space without handhold or other holders. Movement by

TABLE 97, cont :ed

Space-craft	Astronaut Perform-ing EVA	Length of stay in space, min	Primary operations performed during EVA	Some characteristics of activity and reasons for non-per-formance of tasks
				pulling on tether more difficult than by means of jet device.
Gemini 11	R. Gordon	44	Connected satellite and Agena-D rocket with 30 m cable, removal of contain-er with nuclear emulsion from hull.	Extravehicular activity shortened, because of heavy sweating.
" 12	E. Aldrin	130	Connection of satel-lite and rocket with cable, instal-lation of holder with traps, reload-ing of motion-picture camera, operations in "work areas": a) removal of tapes of various lengths, made of "velcro" adhesive material, from satellite hull and sticking it on again; b) casting cable on grapples of various sizes; c) disconnecting and connecting electrical plugs and pipes; d) cut-ting multiple-strand cable with scissors; e) un-screwing and tight-ening 2 bolts with wrench.	For securing astro-naut to workplace, used "blocks" for feet, as well as loops and hooks; for move-ment, special "trowels," glued to "velcro" on satellite hull.

cameras, meteorparticle traps, they maneuvered with the tether and the jet device, they connected the satellite to the Agena rocket with a cable, etc. In all these operations, there were no significant changes in the vitally important systems, although the pulse and respiration, as was discussed above, fluctuated within considerable limits. At individual stages, the quickening of the pulse, as well as the energy consumption, were significant (up to 860 kcal/hour). As a result, abundant perspiration, excessive accumulation of heat and fatigue phenomena were noted (Berry, 1969, 1970, 1971; Chatelier, et al., 1969, and others). It turned out that considerably more effort was required to perform various operations in space, than was assumed, on the basis of the results of ground experiments. In the opinion of Wagner (1971), twice the time under earth conditions is spent in performing test tasks in space. The main cause of the high energy losses is the necessity for holding the body in space.

A complication of the task of orbital flights, mainly, /418 approaching other craft or rockets, docking with them, transferring to other orbits, all considerably complicated the operator duties of the crew members. Nevertheless, the Gemini crew members handled these tasks, on the whole (Table 98). In analysis of the data, it is evident that the experiments were not performed in the Gemini 5-Gemini 9 spacecraft, for technical reasons.

A large number of scientific experiments was characteristic of the Gemini program: biomedical (9), physical-technical (64) and military-applied (16). A portion of the experiments was not performed by the astronauts, but, as the analysis showed, not because of decrease in performance capacity, but for other reasons (failure of procedure, inconvenience of laboratory equipment, deficiency in research program, etc.).

In analysis of the Apollo program, the fact that the astronauts performed all tasks, during their extravehicular activity and in transferring to the lunar module and back (with one exception), also attracts attention. Only in the flight of Apollo 9, R. Schweick- /419 art could not completely accomplish the extravehicular activity, because of symptoms of incipient motionsickness.

In evaluating performance capacity, the data on the activity of the astronauts on the surface of the moon is of special interest. As is well known, N. Armstrong, then E. Aldrin, first set foot on the surface of the moon, at 2 hours 56 min 20 sec, 21 July 1969. For a period of 2 hours 10 min, the astronauts performed a great amount of work, installing a television camera, reflectors, seismometers on the surface of the moon, deploying meteor traps, collecting lunar soil samples, testing various methods of moving on the moon and a number of other operations. As was pointed out above, the nature of change in the physiological indices was quite adequate to the unusual conditions. Beside this, during their stay on the moon, careful

TABLE 98

EXPERIMENTS IN APPROACH AND DOCKING OF GEMINI SPACECRAFT WITH TARGETS IN ORBIT AND QUALITY OF PERFORMANCE OF THEM

Target name	Spacecraft	Tasks and performance quality
2nd stage of Titan II launch vehicle	Gemini 4	Task: Approach rocket. Experiment failed: astronaut controlling satellite erred in visual estimation of distance, sometimes fivefold.
REP apparatus	" 5	Task: Approach to distance of 10 km, approach target to distance of 30 m. Experiment not performed, because of breakdown of fuel cells.
Previously launched Gemini 7 satellite	" 6	Task: Approach of satellites. Experiment performed. As a result of 9 maneuvers of craft, Gemini 6 approached Gemini 7 at a distance of 36 m. Group flight continued 5-1/2 hrs; the distance between them was from 1 to 30 m, in this case.
2nd stage of Titan II launch vehicle	" 7	Task: Approach rocket immediately after separation of satellite. Experiments performed. Flight took place with 2nd stage at distance of 15-18 m.
Agena-D rocket	" 8	Task: Approach and docking. Experiment performed. 9 maneuvers carried out; approach to 45 m, then docking.
ATDA apparatus	" 9	Task: Approach and docking. Experiment not performed. Docking failed because of failure of equipment.
Agena-D rocket	" 10	Task: Docking with rocket and, after this, change to new orbit. Experiment performed.
same	" 11	same
"	" 12	Task: Approach and docking. Experiment performed. Onboard radar failed here. Approach and docking (twice) was performed manually. Astronauts controlled satellite in turn.

monitoring of the metabolic indices was carried out, on the basis of analysis of pulse rate, oxygen consumption and differences in the water temperature at the inlet and outlet of the water-cooling system (Berry, 1970). The last two methods proved to be the most precise for the evaluations. They not only gave similar results, but they were a good reflection of the physical activity of the astronauts, recorded by telemetry.

On the average, the energy consumption of the Apollo 11 crew members varied from 226 to 300 kcal/hour, reaching maximum values (over 600 kcal/hour) at individual moments. The subsequent EVA of the Apollo 12, Apollo 14 and Apollo 16 astronauts were accompanied by an ever-increasing amount of research, stay time on the surface of the moon, and weight of lunar rock collected by the astronauts. Despite this, White, Berry, et al., (1971) noted that the energy consumption connected with the lunar EVA decreased. Thus, the energy consumption of astronaut A. Shepard was 210 kcal/hour and that of E. Mitchell, 220 kcal/hour. They explained this by the proper planning of work on the moon and training of the astronauts. The results of the Apollo 15 flight should be dwelt on particularly (Berry, 1971; J. Tiziou, 1971, and others). Just at the time of this flight, the specialists noted a slowing down of readaptation to earth conditions, because of overfatigue of the astronauts. As was pointed out above, interruptions of the cardiac rhythms of the astronauts D. Scott and J. Irwin and symptoms of motionsickness (of J. Irwin) were observed in flight. In the opinion of Berry, these symptoms were connected with overfatigue, because of the great workload. The author concludes that it is necessary to introduce certain changes in the work schedule of subsequent space flights (cited by Buldan, 1971).

The high performance ability of the astronauts was displayed most completely, during the dramatic flight of Apollo 13, when, on the way to the moon, an accident happened, an oxygen tank blew up. The astronauts had to use the quite limited oxygen supply of the lunar module, struggle with accumulation of excess carbon dioxide in the air and experience longitudinal and lateral vibrations, apparently because of escape of gas from the craft (Lomonaco, 1970). These vibrations, combined with weightlessness, promoted activation of the vestibular reactions, which impaired the psychophysiological condition of the astronauts. They felt severe fatigue by the 134th hour (and they had to take Dexedrine tablets, a stimulant). Despite this, they clearly performed the entire volume of operations specified in landing.

The performance capacity of the astronauts also was estimated /420 by the quality of performance of proportioned physical workloads before and after a flight. The bicycle ergometer was used for this, in the majority of cases; it can fix a constant workload, which gradually increased, until the pulse rate reached 120, 140, 160 and 180 per min. Beside the pulse, data on oxygen consumption, CO_2 formation, minute volume, arterial pressure and rate of respiratory processes were used as tolerance indices (Dietlein, 1970; White, Berry, et al,. 1971). As it turned out, after long space flights in the Gemini craft, the performance capacity of the crew deteriorated somewhat. The same relationship was found in examination of the Apollo crew members. Thus, at a heart rate of 120 beats per minute, during the bicycle ergometer studies of the astronauts of Apollo 7, Apollo 8 and Apollo 9, the amount of oxygen consumed decreased in 8 of 9 men. The extent of change was less at high heart rates.

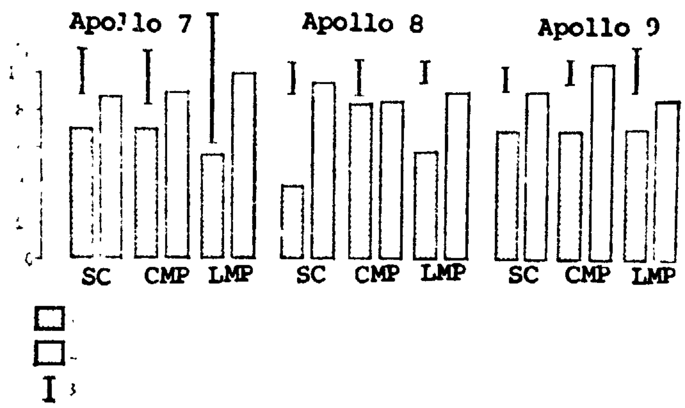

Fig. 130. Change in oxygen consumption level of some astronauts in Apollo program, at pulse rate of 120 beats per minute during postflight examinations (in % of preflight data): 1, results of examination immediately after flight; 2, results of examination a day after flight; 3, range of change in preflight examinations

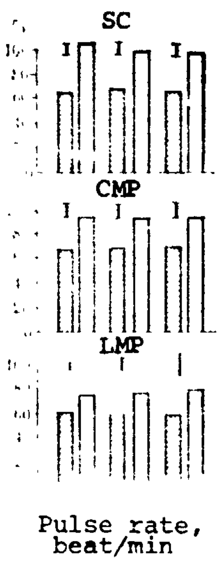

Fig. 131. Oxygen consumption during period of work on bicycle ergometer of Apollo 10 crew members at pulse rates of 120, 140 and 160 beats per minute (in % of prelight data): designations same as in Fig. 130.

The results of examination of the Apollo 7-Apollo 10 crew members are presented in Figs. 130 and 131. Usually, but not in all cases, recovery of the preflight values took place over a period of 36 hours of reaction, on the average (Johnson, 1971; Berry, 1971, and others). As was pointed out above, the results of examination of the Apollo 15 astronauts is an exception. Their recovery of performance capacity, at various levels of proportioned workloads, took place considerably /421 later than the 50-hour period, which was required for this purpose, for example, by the Apollo 14 crew members. According to the data of Soviet investigators (A. V. Yeremin, et al., 1970; A. S. Barer, et al., 1972), the energy consumption of a man in changed (reduced) gravity also decreases. This was convincingly demonstrated, in a series of experiments simulating these conditions.

Prophylaxis of Unfavorable Effects of Space Flight

In carrying out the Gemini and Apollo space programs, specific attention was also given to these questions. Work continued on further improvement of the atmosphere in which the astronauts found themselves, nutrition systems, work and rest schedules, etc. Thus, the use of a two-gas breathing mixture (oxygen and nitrogen), with a small nitrogen content, in the Apollo spacecraft, considerably attenuated the decrease in erythrocyte mass, previously noted in Gemini. Inclusion of calcium-containing substances in the food ration promoted improvement of the mineral metabolism of the astronauts on the whole (Berry, 1969, 1970, 1971; Dietlein, 1970, and others).

A favorable result was obtained by including potassium in the food ration of the Apollo 16 and Apollo 17 astronauts, in prevention of arhythmia of the heart. These measures, directed towards reduction of the harmful effect of flight, improved, not only the individual indices, but the overall state of health and performance capacity of the astronauts.

Organization of the work, rest and sleep schedule of the astronauts was of great importance in medical support of the Gemini and Apollo program of flights (Berry, 1969, 1970, 1971; Dietlein, 1970; Aschoff, 1971, and others). As is well known, the normal workday is adapted to a 24 hour cycle: 8 hours of work, 8 hours of rest, 8 hoursof sleep. It has been proved that this ratio is quite stable and is preserved under various space flight conditions. Foreign investigators (Berry, 1967, 1971; Strughold, 1969; Aschoff, 1971, and others), in organizing the work and rest of the astronauts for each flight, are attempting to make more complete allowance for this regularity and to attain the highest level of performance. While this question was given a little attention in the first flights, by the flight of Gemini 7, the order of the day was such, that the astronauts could sleep during hours, corresponding to nighttime on the earth. Serious attention also is given to the optimum alternation of work and rest periods of the astronauts, especially during work in space. An increase in number of astronauts in the Apollo spacecraft and the desire to continually have one waking time for the astronauts in them, led to the situation that the work-rest-sleep cycle in the flight of Apollo 7 was almost unregulated, and the order of day of the Apollo 8 crew was far from prefection. The astronauts interfered with each other, both in performing work and in getting ready for sleep. Change in the periods of work and rest was unregulated, and it differed significantly from the preflight schedule. The crew members reported feeling poorly in the first three days of the flight. Some astronauts slept during watches and others had to take stimulant tablets. The idea of a continuous watch had to be /422
rejected and, beginning with the flight of Apollo 9, all the astronauts worked and slept at the same time (Fig. 132). As a result, the rest periods became closer to earth conditions, complaints decreased and performance capacity increased.

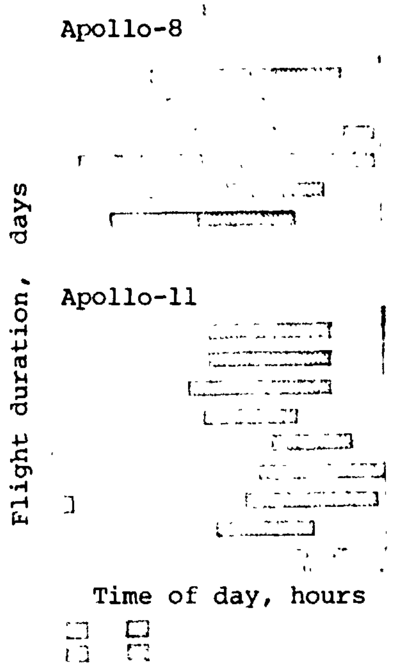

Fig. 132. Sleep schedule of Apollo 8 and Apollo 11 crew members: arrow, bedtime at Cape Kennedy; 1, sleeping time of spacecraft commander (SC); 2, sleeping time of command module pilot (CMP); 3, sleeping time of lunar modular pilot (LMP); 4, time of joint sleep of CMP and LMP in Apollo 8 and entire crew in Apollo 11

This view was held by certain Soviet investigators (V. A. Bodrov, A. Ye. Muzalevskiy, 1972, and others). The great physiological advantage of the "combined" schedule, by which the crew members sleep 8 hours continuously, during a period corresponding to nighttime on earth, was proved in laboratory experiments. Of course, such a solution of the problem obviously cannot be considered to be conclusive. It becomes particularly incompetent, if the possibility of emergence of an emergency situation during the sleeping period of the astronauts is presented, when clear and rapid actions are required of the crew members. Seminara and Shavelson (1969), attempted to evaluate the performance capacity of a spacecraft crew after sudden waking, in laboratory tests. As a result, they determined that the less time was spent on performance of a task, the more distinctly the effect of sleepiness showed up in it. For example, in turning on the alarm signal button, i.e., in a very brief action, 360% more time was used after sleeping than under waking conditions; the time increased by only 12.6% in a longer operation, putting on the clothes.

In an analysis of the American programs, it is evident that the investigators still have not finally solved the problem of work, sleep and rest, during the period of work on the moon. The lunar module is too noisy, and the climate inside the spacesuit is far from optimum. The Apollo 14 and Apollo 16 crew members complained of poor rest in the lunar module (Berry, 1971). American investigators consider that further work must be carried out to improve the living conditions of the astronauts, based on 12 hours for work, 8 hours for sleep and 4 hours for rest.

For prophylaxis of cardiovascular disorders in flight, special /423
pneumatic cuffs, which are put on the thighs of the astronauts, and an automatic device, providing for periodic blowing up of the cuff, to a pressure 80 mm Hg in 2 min, at 4 min intervals, have been tested.

Although this experiment, which was planned for the Gemini 5, Gemini 6 and Gemini 7 flights, was not completely performed in a single flight (because of technical failures), the American specialists rated the prophylactic importance of the cuff as low. In their opinion, they did not have a significant effect on blood circulation. In the opinion of many specialists, the most effective method of prophylaxis of the unfavorable reactions may be the building of spacecraft with artificial gravitation (Ye. M. Yuganov, et al., 1967, 1971; A. M. Genin, 1969; Gualtierotti, 1969; Green, et al., 1970; Nieto, 1970; Grohmann, 1971; Lange, et al., 1971; Young, 1971, and others).

TABLE 99

PREFLIGHT AND POSTFLIGHT DATA OF EXAMINATION OF APOLLO 14 CREW MEMBERS

Effect	Constant weightlessness	Stay under 1/6 g	
	CMP	SC	LMP
Weight loss, kg	−5.4	+0.45	−0.45
Decrease in orthostatic tolerance	Significant	Minimal	Minimal
Changes, %:			
Erythrocyte mass	−9	4	−2
Plasma volume	10	1	Unchanged
Total water volume	18	2	−2
Intracellular fluid	−27	−3	−3
Performance capacity (oxygen consumption, systolic arterial pressure)	Significant reduction	Unchanged	Small reduction

Very interesting materials were obtained in carrying out the Gemini and Apollo flight programs. First and foremost, by conducting the experiment which included connecting the Gemini spacecraft to the Agena-D rocket by a single cable, the possibility of creating an artificial force of gravity in such an apparatus was demonstrated. Additional and very important information was successfully obtained in the Apollo program flights, when the crew members experienced partial weight on the surface of the moon. In each flight, it was possible to compare the extent of the effect of this factor on the course of the psychophysiological reactions caused by the state of weightlessness. A tendency was revealed towards more moderate changes in persons experiencing the effect of lunar gravity, than in persons experiencing weightlessness all the time (Berry, 1970, 1971). The results of examination of the Apollo 14 crew can be presented as an illustration (Table 99). The results of the flight of Apollo 15 were an exception (Berry, 1971). A greater decrease in performance capacity was noted in the two crew members working on the moon than in the command module pilot, possibly as a result of overfatigue, caused by the great amount of work.

The problem of artificial weight is closely connected with /424 prophylaxis of motionsickness. Graybiel (1971) writes that, if artificial weight is reproduced by means of rotation of an individual part of the spacecraft, the rapid transition of man between the rotating and nonrotating parts is obviously a basis for development of serious problems of a vestibular nature. In simulation of these conditions, the author noted ways to overcome them: optimum training exercises and medicinal therapy.

The work of Gualtierotti (1969) deserves particular attention. The author maintains the firm opinion of the necessity of creating artificial gravity in long flights. Having noted that it can be obtained by rotating the spacecraft, he pointed out the undesirable side of things, the development of motionsickness, as a consequence of the effect of Coriolis acceleration. In his opinion, another way can be considered, the use of nonspecific stimulation of the static receptors of the inner ear. In tests on frogs, he studied the effect of vibrations on the static receptors. As a result, Gualtierotti concluded that vibrations at a constant rate and constant direction caused effects similar in their basis to problems observed with the effects of linear accelerations.

In this manner, the American investigators have determined that, as a result of the effect of space flight on the human body, a moderate reduction in body weight, deconditioning of the cardiovascular system manifested by a decrease in orthostatic tolerance and a number of other changes, a decrease in bone tissue density, small losses of calcium, iron, nitrogen and other elements by the muscles, some decrease in erythrocyte mass, a negligible reduction in performance capacity, greater energy consumption while working in space and moderate ones under lunar surface conditions and the development of motionsickness in weightlessness are noted.

Berry (1969, 1970, 1971) considers these changes to be separate links in the process of adaptation of the body to the stress factors of space flight (Diagrams 11 and 12).

As follows from this hypothesis, the immediate reaction of the /425 body in the transition to the weightless conditions is redistribution of the total mass of circulating blood. An increase in blood filling of the right auricle is accompanied by a reaction, directed towards decrease in the amount of circulating fluid in the body, by means of increased diuresis. This process is regulated by reduction in the antidiuretic hormone level and production of aldosterone. In this case, elimination of water, sodium, potassium from the body by the kidneys and a decrease in body weight are observed. The accompanying decrease in plasma volume leads to recovery of the initial aldosterone

Change to weightless conditions. Redistribution of volume of circulating blood → Reaction of body directed towards decrease in volume. Antidiuretic hormone level decreases and formation of aldosterone is reduced

↓

Losses of water, sodium, potassium (decrease in body weight) → Decrease in plasma volume. Increase in aldosterone production

↓

Increase in sodium retention. Elimination of potassium continues. Cellular acidosis and alkalosis of extracellular fluid develop → Intracellular exchange of potassium and hydrogen ions. Bone tissue density, muscle mass, muscle cell potassium content decrease

↓

Respiratory and kidney compensation. Stabilization of body weight → Stabilization of new volume of circulating blood and water-salt and electrolyte balances

Diagram 11: Diagram of process of adaptation of the body to weightlessness (from Berry)

WEIGHTLESSNESS

Redistribution of total circulating blood volume

Stress phase	Decrease in aldosterone content		Decrease in ADH (Gauer-Henry reflex)	
	→ Diuresis ←			
Adaptation phase	General water loss of body Tendency towards increase in aldosterone and ADH secretion	Losses through kidneys ↓ Cellular exchange of H ions for K ions	Decrease in plasma volume ↓ Decrease in erythrocyte mass, as a result of hyperoxia	
	Compensatory reabsorption of Na^+ in kidneys	Decrease in plasma CO_2 content result- from hyperventilation	Decrease in bone-muscle mass	
Adapted phase	Stop of water loss Weight stabilization	New introcellular fluid and electrolyte balances	Decrease in performance capacity	Deconditioning of cardiovascular system. New load on cardiovascular system

Diagram 12: Phases of process of adaptation of body to weightlessness (from Berry)

level. Disruption of the water-salt balance sets in in the body, against the background of which, retention of sodium is observed and elimination of potassium continues. Losses of intracellular fluid and elimination of potassium from the body cause cellular acidosis, with a weak (compensatory) hypocalcemic alkalosis of the extracellular fluid.

It is supposed that the reaction of the body to reduction in total potassium content is manifested by removal of potassium from the cells, and entry of hydrogen ions into them. The potassium deficiency is connected with the decrease in bone tissue density and muscle mass. Possibly, decrease of potassium content in the cells /426 of the cardiac muscle is accompanied by an increase in its excitability and a tendency towards arhythmia.

In the last phase of adaptation, the hyperacidity of the cells stimulates the activity of the respiratory system, as a result of which the carbon dioxide content of the plasma is decreased by increasing pulmonary ventilation. Kidney compensation begins at the moment when potassium reabsorption takes place in the kidney tubules. At just this moment, the body weight stabilizes. This part of the complex process of adaptation of the body is completed. The new state of equilibrium establishes the optimum total volume of circulating blood or a "new load" on the cardiovascular system, and a new level of the electrolyte and water-salt balances.

The author of the hypothesis (Berry) considers it to be far from completed. In his opinion, it will be supplemented and improved. The hypothesis makes it possible to follow the course of the changes taking place in the human body, under the influence of unfavorable environmental factors, in the period of surmounting which, the capabilities of the body are not exceeded.

Berry (1971) thinks that there is now a basis for carrying out flights of long duration. For this purpose, flights of the Skylab orbital station (OS) lasting 28, 56 and 84 days, were carried out in the USA in 1973. Scientists of the USA conducted very interesting studies during these flights.

As is evident, the principal attention of investigators will be given, as before, to those systems and functions of the human body which are subject most of all to changes under weightless conditions.

Study of the following medical problems are planned in the Skylab program (Diagram 13).

At the present time, we are witnesses of partial completion of the Skylab program. Three crews have completed space experiments. The first crew, consisting of C. Conrad (spacecraft commander), J. Kerwin (physician-astronaut) and P. Weitz (pilot-astronaut), spent 28 days in space flight, in the period from 25 May to 22 June 1973. The duration of the second experiment, in which A. Bean (spacecraft

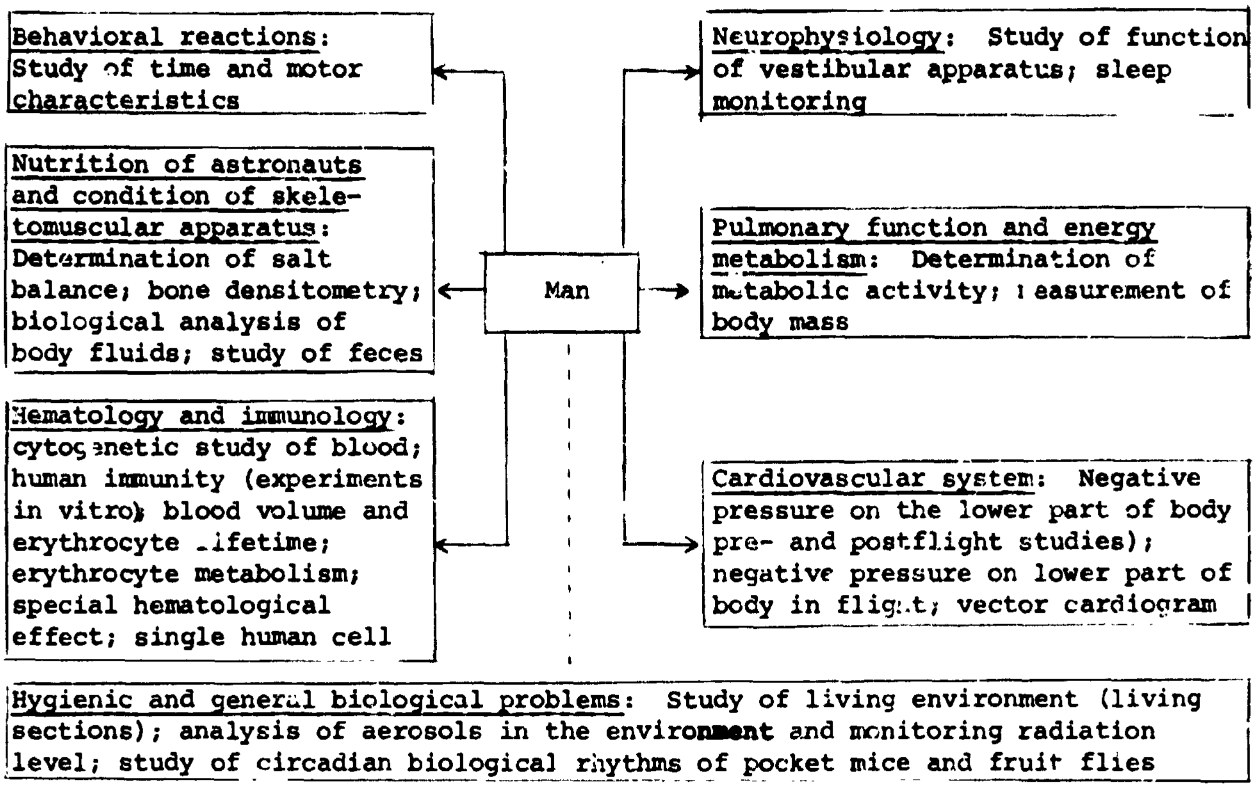

Diagram 13: Biomedical experiments in the Skylab orbital station

commander), O. Garriott (scientist-astronaut) and J. Lousma (pilot-astronaut) participated, was more significant, 59 days (from 28 July to 25 September 1973). The longest flight duration was that of the third crew, more than 84 days. The spacecraft commander was G. Carr and the crew members, W. Pogue (pilot-astronaut) and E. Gibson (scientist-astronaut).

The scientific results of the experiments have not yet been published. However, by analysis of the materials published in the periodical literature, it is evident that the astronauts completed the flight program, on the whole. The first crew of Skylab quickly adapted to weightlessness and earth gravity. C. Conrad explained the rapid adaptation to weightlessness by satisfactory living conditions and regular and prolonged physical exercises on the bicycle ergometer. In the opinion of C. Conrad, the first 6-7 days were the most difficult, because of the saturated nature of the program of experiments. The spacecraft commander emphasized the importance of the experience he had received during the preceding space flights in Gemini 5, Gemini 11 and Apollo 12. Weighing of the astronauts immediately after the flight showed that the weight of

C. Conrad decreased by 1.7 kg, of J. Kerwin by 2.9 kg and of P. Weitz, by 3.7 kg. The size of their calf muscles decreased by 2.5 cm on the average. The results of the first expeditio.. also indicate /427 high performance capability of the astronauts in flight, which they retained for the entire duration of the experiment. In particular, the amount of repair work which they performed on the craft, to eliminate a defect revealed after launch, as a result of jamming of the solar battery panels by aluminum fragments, is evidence of this.

The results of the second experiment turned out to be approximately the same as those of the first. True, one singularity was revealed. All the crew members experienced motionsickness, caused by the effect of weightlessness, in the first five days of the flight. The expression of motionsickness was considerable, as a result of which, performance of scientific research and experiments was delayed. However .he astronauts soon began to adapt to the flight conditions. The health of the astronauts was good during the entire flight. In a space interview, A. Bean stated: "We feel just as well as the first crew, perhaps even better, since we took its advice. We feel wonderful, we eat with a good appetite, sleep well and are happy." That this was so, is confirmed by their appeal to the flight director, with a request to increase the length of this experiment by another 10 days.

Roy Hawkins, the medical director of the flight, confirmed /428 that the astronauts "Are in outstanding shape," and he explained this by the fact that the duration of their physical exercises had been approximately tripled over that of their predecessors. The astronauts also carried out experiments on live organisms in the state of prolonged weightlessness, mice, mosquitoes, spiders, fish, and they obtained valuable material.

The astronauts of the third crew successfully conducted medical studies, studied the natural resources of earth and performed technical experiments of astronomical observations during the 84-day orbital flight.

All three astronauts experienced a slight headache, as well as "heaviness of the head, a sensation as though we were suspended legs up," in the first days of the flight.

Astronaut W. Pogue felt more poorly than the remaining crew members; he was nauseated; therefore, he could not perform his part of the work in full measure.

The symptoms of illness of all three crew members stopped after three days, they felt good, could perform various operations, both in the craft and during extravehicular activity.

According to the statements of the medical directors, the astronauts of the third crew felt quite well after the flight, despite such a long flight.

At the present time, the medical data obtained are being processed and analyzed.

It should be emphasized in conclusion that the Skylab program flights produced additional data, which will refine and extend our conceptions of the effect of weightlessness on the human body.

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