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# PECULIARITIES OF HUMAN BLOOD CIRCULATION CAUSED BY SPACEFLIGHTS

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The data from medical examinations which we have available today, after /1*
a number of manned spaceflight programs have been completed in the USSR and the U.S.A., convince us of the correctness of the concept of the maximum reactivity of the cardiovascular system under spaceflight conditions, which goes back some time. It plays the principal role in maintaining working capacities since, in contrast to other physiological systems of the organism, the function of the heart and vessels reaches the limit of its capacity earlier than other systems.

In the course of the last ten years or so efforts have been directed at ascertaining the most important trends for research in the area of space medicine. They can be easily seen in the programs of the "Vostok" and "Salyut" as well as the "Mercury" and "Skylab" (O. G. Gazenko, 1962; O. G. Gazenko, V. I. Yazdovskiy, V. N. Chernigovskiy, 1962; O. G. Gazenko, 1964; O. G. Gazenko, V. N. Chernigovskiy, V. I. Yazdovskiy, 1963; N. N. Gurovskiy, M. A. Cherepakhin, 1967; N. N. Gurovskiy, 1966; S. P. Winograd, 1964; C. Berry et al., 1966).

My associates and American colleagues have changed their attitude toward problems of radiobiology, biorhythmology, group and engineering psychology, hematology and so forth as areas of knowledge which are related to the theory and practice of space medicine. In addition, our conviction of the particular importance of studying these functions of circulation has grown from year to year.

Any manned spaceflight potentially involves extreme influences. Some are /2
caused by the influence of so-called dynamic factors — weightlessness, hypokinesia, accelerations, and others that are linked to excessive emotional stress, sometimes with considerable physical stresses, as well as temperature

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

discomfort. Each of these factors individually (and especially when combined) has an important influence on the functioning of the cardiovascular system. For this reason, it is specifically the parameters of circulation which we use as the most important guideline for evaluating the general condition of the crew during flight. For this purpose, we use direct methods of investigation of hemodynamics at rest and during functional stresses.

Moreover, using the prism of metabolic and harmonal studies of the internal medium of the organism, we are trying in particular to determine the nature of the physiological mechanisms for regulation of circulation, and to evaluate the reserve capacities of the cardiovascular system.

## Role of Gravitational and Muscular Factors

In the USSR and in the U.S.A., there is agreement on the fact that during the next ten years gravitational biology will be one of the most important aspects of research in cosmonautics.

At the present time, we have no specific information regarding the mechanisms by which gravitational forces are perceived and no gravitational receptors have been found, despite the extensive studies that have been conducted at the 1 G gravitation level, during weightlessness or under Lunar gravitation.

The study of the action of gravitation up to 1 G on higher animals, including man, is of practical significance for carrying out prolonged flights /3
and can make an important contribution to fundamental knowledge

It would be very fruitful to study circulation because under the influence of gravitational forces the organism is subjected to purely physical phenomena based on the "stimulus and reaction" process. In this respect, weightlessness may be viewed as an integral stimulus which acts continuously at a given unattenuated level. The response to this stimulus, as we know, is a redistribution of the blood which is not normal for terrestrial conditions, with an increased flow of this fluid to the organs and parts of the body which are located above the level of the heart, so that compensatory processes must develop with participation of neuroreflex, metabolic and harmonal physiological mechanisms (L. I. Kakurin, 1968; C. Berry, 1971).

Hence, we can conclude that the etiology of the modification of human homeostasis during weightlessness contains a physical phenomenon — the absence of weight.

It is also important to note that the state of relative lack of stress on the muscle apparatus during weightlessness as an unfavorable factor has not lost its significance at the present time. We can disregard this very important problem at the present time since orbital stations have very large inhabited areas and means are provided on board for carrying out muscular training. Nevertheless, the organization of muscular activity in flight remains a very important problem.

After flights lasting 18 and 24 days, we have observed a decrease in the perimeters and tone of the muscles of the shin and hip. A very similar picture was seen in the American astronauts. Indirect studies (metabolic) indicated a decrease in muscle mass. Changes in the muscle system, such as those we are /4
discussing here, are usually interpreted as a functional disturbance, and more rarely they have been referred to as atrophy, without giving this concept the sense of pathology, mainly because the researcher did not have morphological data at his disposal.

The atrophy which is observed after an 18 day flight was produced in experiments involving 30 days bed-rest by volunteers. The principle problem consisted in studying the microstructure and the chemism of the muscle tissue. Before the beginning of the experiment, a sample of muscle tissue was taken from the soleus muscle of the right leg of each subject; this was done by biopsy for morphological and histochemical studies. 30 days after the start of the experiment, a sample of the muscle tissue from the same muscle in the left leg was taken from the same volunteers and in addition samples of the soleus muscle were taken from 4 men who had served as controls and had not been exposed to any kind of special effects.

At the end of the experiment, all of the subjects showed a decrease in muscle tone of the shin and hip and the perimeters had decreased. The tone of the anterior tibial muscle had decreased on the average by 21.2% and the perimeter of the shin had decreased 13%.

A biometric study (measurement of the area of the cross-section of the muscle fibers by a planimeter) showed that all 4 subjects who were in a state of hypokinesia showed a statistically reliable decrease in the volume of the red muscle fibers in the soleus muscle and 2 of them showed a reliable decrease in the volume of the white muscle fibers, while 2 other subjects showed no changes in the white muscle fibers. Histochemical studies of the oxidative enzymes (succinate dehydrogenase, activity of $\alpha$-glycerophosphate dehydrog- /5
enase, $\beta$-oxybutyrate dehydrogenase, adenosine triphosphatase) of the muscle tissue made it possible to ascertain any changes that occurred in oxidative metabolism. However, in each subject the changes in the activity of the oxidative enzymes as a rule have their own distinctive character.

Electron-microscopic data have indicated that pronounced structural changes in the contractile apparatus occur in muscle fibers during hypokinesia; these changes take the form of separation of the myofibrils, local lysis of the latter, thickening and destruction of the Z band.

These data have indicated that muscle atrophy occurs in man following restriction of mobility for 30 days.

Interesting data have been obtained in experiments with hypokinesia of animals (V. V. Portugalov, K. D. Rokhlenko, 1969; V. V. Portugalov, O. G. Gazenko et al., 1967).

In an inactive muscle or in one which has its function limited, there is initially a development of dystrophic and atrophic changes in the muscle and neuronal elements which in turn causes a productive reaction of the connective tissue which constitutes the secondary effect. The decrease in the muscle activity is accompanied by stimulation of the growth of connective tissue. In addition to the sclerotic changes in the muscles during prolonged hypokinesia, there is also a development of perivascular sclerosis. In turn, the changes in the vessels in the late stages of hypokinesia can constitute one of the most important mechanisms that form the basis of the disruption of nutrition of muscle tissue and further pathological processes in the muscles.

Hence, during hypokinesia the interruption of the blood supply to the muscle tissue occurs not only in conjunction with the change in hemodynamics which has already been mentioned but also because of the restructuring of the vascular wall. We have reason to believe that the decrease in the tone of the vascular wall of blood vessels in man, when the latter is kept under conditions of bed rest for a long period of time, is associated with the development of "sleeves" of collagen fibers around the vessels of muscular type and the capillaries. /6

Under the influence of intensive muscular activity there is an increase in the general energy potential (phosphocreatinine, glycogen), an increase in the activity of the fermentative systems, there is an increase in the mechanisms responsible for the transportation of oxygen to the tissues and the maximum oxygen consumption rises.

It is still not clear what muscle stress can be recommended for cosmonauts during flight. It would hardly be possible to achieve this goal if we used as the criterion the adequate work in terms of energetics. It is necessary to consider the stereotype of motion in unsupported space which is specific for weightlessness, and which does not impose great loads on the gravitational musculature.

On the basis of laboratory experiments involving two months continuous rest by healthy men in bed, we concluded that daily work on a bicycle ergometer with energy expenditure of 900-1,100 kg makes it possible to retain the original resistance of the cardiovascular and respiratory systems to maximum physical stress (M. A. Cherepakhin, 1968). Such training, performed in a horizontal position, did not prevent hypohydration of the organism, but the negative fluid balance turned out to be more pronounced in the controls, where no training was carried out.

Similar results were obtained by American researchers who feel that /7
applying a physical load of 1,700-900 kcal during bed rest for no longer than 3 weeks is an effective means of maintaining the resistance of the cardiovascular system (K. H. Cooper et al., 1966). I do not know how this training affected retention of stato-kinetic reactions. In our experiments, despite the high level of physical working capacity, the subjects experienced difficulty during the first days following the end of the experiment in maintaining a vertical posture while walking and standing.

## Characteristics of Human Blood Circulation During Flights Lasting up to 24 Days

When we speak of the characteristics of human circulation during spaceflight, there are at least 3 firmly established facts that we must keep in mind which provide no basis for a pessimistic prognosis:

- retention of individual reactions of the organism;
- high mobilization of the mechanisms for compensation of the circulation;
- smooth, gentle changes in circulation in those cases when no great demands are made on the organism during flight.

I have before me the data that were obtained during the study of circulation in the course of the flight of the "Salyut" orbiting station. Against a background of high working capacity and good general condition, the parameters of hemodynamics at rest in the case of the cosmonauts G. T. Dobrovol'skiy, V. N. Volkov and V. I. Patsayev did not go beyond the limits of normal values during the entire flight. Table 1 shows the maximum deviations in the /8 parameters of circulation for the group of cosmonauts, not taking into account the values that were recorded during several orbits prior to the landing of the craft, since changes occurred during this period which were the result of emotional stress.

TABLE 1. MAXIMUM DEVIATIONS IN CIRCULATORY PARAMETERS IN COSMONAUTS DOBROVOL'SKIY (D), VOLKOV (V) AND PATSAYEV (P) DURING THE FLIGHT. (NUMERATOR - IN FLIGHT; DENOMINATOR - PRIOR TO THE FLIGHT)

| Cosmonauts | Pulse Frequency | Stroke Volume | Minute Volume | Main Arterial Pressure |
|---|---|---|---|---|
| D | $\frac{68}{67}$ | $\frac{90}{125}$ | $\frac{5.8}{5.5}$ | $\frac{115}{95}$ |
| V | $\frac{72}{79}$ | $\frac{130}{130}$ | $\frac{7.9}{7.8}$ | $\frac{110}{105}$ |
| P | $\frac{78}{75}$ | $\frac{85}{105}$ | $\frac{6.5}{6.5}$ | $\frac{120}{115}$ |

During the flight, Dobrovol'skiy's electrocardiogram showed individual ventricular extrasystoles, which were also seen in him during preparation for the flight, and were not interpreted as a symptom of pathological processes in the myocardium. Performance of functional tests involving physical stress (40 deep knee-bends per minute) with the body immobilized toward the end of the flight revealed a slight increase in the reactivity of the cardiovascular system. This was evidenced to a greater extent than at the beginning of the flight by the increase in the frequency of cardiac contractions during stress. Restoration of the frequency of cardiac contractions did not occur during the first minute following the stress.

As an example, the following is the reaction of the circulation of Volkov and Dobrovol'skiy (Table 2).

TABLE 2. CHANGE IN RHYTHM OF CARDIAC CONTRACTIONS DURING STANDARD STRESS AT VARIOUS TIMES DURING THE FLIGHT ABOARD THE "SALYUT" STATION

| Periods | Prior to Stress | Immediately After Stress | After One Minute |
|---|---|---|---|
| In Dobrovol'skiy: | | | |
| 2.5 Months Prior to the Flight | 60 | 94 | 62 |
| 4 | 60 | 96 | 88 |
| 16 | 68 | 108 | 72 |
| 21 | 72 | 110 | 90 |
| In Volkov: | | | |
| 2.5 Months Prior to the Flight | 64 | 90 | 64 |
| 4 | 58 | 92 | 70 |
| 9 | 54 | 85 | 54 |
| 15 | 60 | 118 | 90 |
| 21 | 58 | 104 | 76 |

The reaction of the cosmonauts to the test involving negative pressure, /9
performed by Dobrovol'skiy and Patsayev on the thirteenth day of the flight, is instructive. Within the container, a rarefaction of 27 mm of mercury was created for 2 minutes, and 36 mm of mercury for the next 3 minutes. Prior to the flight, in the case of Dobrovol'skiy, this action was accompanied by

practically no change in the frequency of cardiac contractions; the increase in this parameter on the ground was 4-5 beats, while in flight it was 24 beats per minute. The mean arterial pressure fell from 98 to 86 mm mercury. During the preflight examination, it was equal to the original level or rose to 8-10 mm mercury. The minute blood volume fell by 1.7 l and the systolic volume fell by 37 ml. On the ground, their maximum decrease was 1.1 l and 22 ml. In /10
comparison with the preflight data, there was a significant rise in the rate of propagation of the pulse wave along the ascending aorta, the subclavicular and upper half of the brachial artery. The test with negative pressure in Patseyev was not accompanied by a pronounced reaction. The increase in the pulse frequency, the change in the average pressure and minute volume were close to the parameters observed when the same effect was produced prior to the flight. In both cosmonauts, when the test was performed in flight, the phase of expulsion of the blood by the left ventricle was much shorter. In comparison with the preflight data, this parameter in Dobrovol'skiy was decreased by 28% and in Patsayev by 19%.

The decrease in the orthostatic stability, which was observed following the flight in practically all cosmonauts, as well as the decrease in resistance to physical stress of a high degree of intensity was indicative of a slight lack of training of the cardiovascular system.

On the basis of data from medical examinations performed in the course of the flight programs of the "Soyuz", "Gemini", "Apollo" and "Salyut" spacecraft, we can conclude that on flights lasting up to 24 days there were no critical disturbances in circulation. Weightlessness and other spaceflight factors, acting on the human organism within this space of time, cannot be viewed as excessive stimuli from the physiological standpoint.

The most important conclusion that was reached following the completion of the "Soyuz" program was that flight (L. I. Kakurin, 1971) by man aboard an orbiting station for a period of one month is possible. Moreover, we can predict with considerable accuracy the duration of the period of readaptation during which restoration of functions can be anticipated.

In December 1971, American researchers concluded that it was possible to /11
carry out a 45-60 day spaceflight from the medical-biological standpoint

(S. White, 1971). This view was amply confirmed by the flights of the two crews aboard the Skylab station. These flights will unquestionably have an honored place in the history of cosmonautics. We view them as an outstanding event in science, culture and civilization.

Our countries clearly will be expanding the limits of space research, emphasizing the solution of two fundamental problems: exobiology for purposes of finding extraterrestrial life forms and terrestrial ecology for understanding the processes occurring in the biosphere, for discovering and correctly utilizing natural resources, and so forth. These problems, enormous in terms of importance and scale), will not be solved by unmanned automatic spacecraft alone. Many specialists and administrators, including those who have nothing whatsoever to do with medicine, are convinced of the extent to which the research program carried out by men aboard a spacecraft will be of value.

We may justifiably ask ourselves just how long man can stay in space. In this connection, a great deal will depend upon the life support system and this is a problem for technology. Physicians will have to say what the life support systems will have to be like, including means of prevention, and evaluate the reserve, auxiliary capacities of the human organism with respect to gravitational factors of two types: weightlessness and planetary gravitation. There is much work to be done in this area.

This promises to be a fruitful and fragmentary path which we have chosen today, setting ourselves the task of evaluating the circulatory system and the vestibular functions of man during spaceflights lasting up to two months.

It is important to understand the nature of the gravitational disturbances /12 in circulation and to reach some conclusions regarding a number of syndromes and symptoms which are widely known at the present time in conjunction with their frequent development in flight or during the rehabilitation period. These include:

- disturbance of the rhythm of cardiac activity;
- change in the contractility of the myocardium;
- disturbance of the regulation of circulation of the blood under orthostatic influences;

- change in the gas-energy exchange and hemodynamics under physical stresses of high intensity.

At the present time, considerable data have been accumulated which indicate that there are many systemic changes which directly or indirectly exert an influence on the function of the circulation of the blood. The most important are:

- hemodynamic;
- metabolic;
- hormonal;
- neuroreflex.

The significance of each of these types of changes can be followed by monitoring the state of circulation in man under weightless conditions and in experiments simulating the latter. In this connection, we would like to present some data and their treatment according to the following two questions:

1. Possibility of cardiovascular systems during hypohydration of tissues.

2. The function of the myocardium.

Capacities of Cardiovascular System During Hypohydration of Tissue /13

We know how popular the opinion is in literature dealing with space medicine that dehydration and decalcification of the organism as the result of disruption of water-salt metabolism may be a serious obstacle to the prolonged manned flights. It is important to summarize these studies and formulate our own opinion regarding a number of the specific questions of water-salt metabolism which touch on circulation. First of all, it should be pointed out that the data which we have do not indicate a development of such a serious condition as dehydration of the organism during weightlessness or during simulation of the latter. The nature of the changes in water metabolism rather indicates that the term hypohydration should be used which characterizes a moderate loss of fluid as the result of active physiological regulation of the level of hydration of the organism.

As the result of the postflight examination of cosmonauts who had made flights lasting 2-5 days aboard the "Soyuz" spacecraft, significant symptoms of hypohydration of the organism were found. A weight loss of 2-4 kg was observed in the cosmonauts and was due primarily to increased excretion of fluid.

The increase in flight duration to 18 days did not cause a progressive rise in moisture losses; in Nikolayev the body weight dropped 2.7 kg while in Sevast'yanov it fell 4.0 kg, which meant that the moisture losses were 52.0 and 42.5% respectively of the total loss of body weight. The figures given by Dr. Berry and Dr. Leach (C. Berry, 1970; C. S. Leach et al., 1972; C. S. Leach et al., 1973; C. S. Leach et al., 1973) also failed to indicate a critical drop in the volume of body fluids in the cosmonauts aboard the "Apollo" spacecraft (Table 3).

TABLE 3. CHANGE IN BODY FLUID VOLUME IN THE "APOLLO" 14, 15, 16 AND 17 ASTRONAUTS. /14

| Parameters | Average Change in Volume Immediately After the Flight, % | |
|---|---|---|
| | "Apollo" 17 | "Apollo" 14, 15 and 16 |
| Volume of erythrocyte mass | -11.2 | -9.7 ± 1.6 |
| Plasma volume | - 8.1 | -3.2 ± 1.8 |
| Total water in the organism | - 2.3 | -2.7 ± 0.4 |
| Extracellular fluid | - 5.1 | -1.7 ± 0.9 |
| Intracellular fluid | + 1.6 | -3.1 ± 0.5 |
| Interstitial fluid | - 4.3 | -1.4 ± 1.0 |

We followed the changes in water-salt exchange under conditions of hypokinesia during 120 days continuous stay by young men in a horizontal position. During the previous 20 days of background time, 4 subjects were kept on a food ration that consisted of natural products with a caloric content of 3,100 kcal. The contents were as follows: potassium - 52.4, sodium - 221, chlorine - 230, calcium - 50 meq/day.

In view of the relatively stable level of extrarenal losses with constant microclimatic conditions during hypokinesia, we evaluated the state of water balance on the basis of the ratio of the fluid consumed to the urine excreted which was strictly monitored (Table 4).

The maximum body weight loss was observed on the eighty-third day of the experiment and amounted to 2.3 kg. During this period, we observed the maximum negative water balance. In studying the reasons for the increase in diuresis at various stages of the experiment, it was found that during the period from the first to the forty-fifth days, parallel with the water diuresis, there was an increase in the renal excretion of sodium, from 249.7 to 289.7 meq/day, /15
which was considerably in excess of the amount taken in with the food. At the same time, there was an increase in the rate of glomerular filtration by 5% and in the renal blood flow by 10-11%. During this same period of time, osmotic diuresis predominated, which led to hypohydration of the organism, which is indicated by the decrease in the blood plasma volume by 11% and a rise in its concentration by 4%. We know that the increase in the osmolarity of the blood by more than 1.5% and the concentration of sodium by more than 2.5% increases the tone of the osmoregulatory system which is directed toward retention of water-salt balance (A. G. Ginetsinskiy, 1964). On the fifty-third day, fluid retention was observed, then (64-96th days) another increase in excretion. By the end of the experiment, we were again seeing a decrease in renal excretion of fluid and osmotically active substances. At the same time, there was a slow-down in the rate of glomerular filtration. At the end of the experiment, it only required 10-20 days for all these parameters to return practically to their original levels.

TABLE 4. RELATIONSHIP BETWEEN WATER CONSUMPTION AND DIURESIS (ml/day)

| Parameters | Days | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 6 | 19 | 26 | 36 | 53 | 64 | 83 | 96 | 120 |
| Water consumption | 990 | 1095 | 1070 | 1135 | 1147 | 1050 | 1060 | 1117 | 1085 |
| Diuresis | 1190 | 1330 | 1350 | 1450 | 1240 | 1400 | 1615 | 1490 | 1165 |
| Difference between fluid consumed and diuresis | -200 | -235 | -280 | -315 | -93 | -350 | -555 | -373 | -80 |

Results of the studies indicate that 120 days spent by a human being with reduced muscular activity in a horizontal position does not lead to so-called /16
dehydration of the organism. During this time, the physiological mechanisms

for regulating water-salt balance are functioning actively. As the result, the tissues of the organism remain sufficiently hydrated. We found that in such experiments there was a relatively high effectiveness of muscular training. Work involving energy expenditures of 900-1,000 kg, performed in a horizontal position, made it possible to reduce the symptoms of hypohydration and to keep resistance to maximum stress on the bicycle ergometer at the original level. The same effect was observed in a seven-week experiment when in addition to the daily exercise on the bicycle ergometer in a supine position (500 kcal/day) electrical stimulation of muscles was carried out. In the control group (hypokinesia) the decrease in the volume of circulating blood was 9.4%, while in the subjects with physical training and electrical stimulation this parameter was decreased 5.7%; the volume of circulating plasma in the groups was decreased by 11.8% and 15.4%, respectively; the erythrocyte mass in the controls was decreased 1.8% while in the group with training this parameter increased 1.5%.

On the basis of these data, we can conclude that active muscular work has a favorable effect on the hydration of the organism. The high resistance of the cardio-respiratory system during stress close to the limit is correlated with the hydration level of the organism.

The dependence of circulation and hydration was the subject of special studies. It was found that during the first days of bed rest the subject showed a decrease in the hydration coefficient from from 1.80 to 1.40 due to a decrease /17 in the intake of fluid into the organism and an increase in diuresis (B. S. Katkovskiy et al., 1970; G. I. Kozyrevskaya, 1967).

During this period, the stroke and minute volumes of blood remained practically constant: the minute blood volume was 4.3 l/min. By the sixth day of bed rest there was an increase in hydration due to the rise in fluid consumption and decreased diuresis. This was accompanied by an increase in the stroke and minute volumes to 98.2 ml and 5.77 l/min, respectively.

For three days prior to the end of bed rest, there was increased diuresis against a background of practically constant fluid consumption. The magnitude of cardiac output during this period showed a tendency toward a decline. Hence, increasing the hydration of the organism is accompanied by an increase in the minute volume of circulation primarily due to systolic output. A reduced cardiac output corresponds to a lower hydration level.

The close relationship between the course of diuretic processes and the functioning of the cardiovascular system must be taken into account each time when a question arises of the advisability and selection of preventive measures. Preventive effects in this case can be achieved by a direct method — increasing the level of hydration or indirectly by muscular training, as was shown in experiments on the ground.

We wanted to direct your attention to the very important physiological phenomenon which we observed in many experiments. In persons with prolonged limitation of motor activity during bed rest, beginning approximately on the sixth day, with high values for the minute volume, we observed a decrease in /18
oxygen consumption and consequently in energy exchange. This difference between the dynamics of oxygen consumption and cardiac output is explained by the redistribution of the blood, when there is an increase in its flow to the heart and a disruption of the processes of tissue restoration. Changes in the oxidative metabolism were observed in muscle tissue which was taken by means of biopsy from the subjects who spent 30 days under bed rest conditions. They showed up in the form of a significant change in the activity of the oxidative enzymes and, according to data from electron-microscopic studies, were accompanied by structural changes in the contractile apparatus: separation of myofibriles, local lysis and destruction, changes in shape and size of mitochondria.

Similar disturbances (but more clearly pronounced) were seen in experiments involving strict limitation of mobility of animals. We observed a decrease in the protein content in the muscles due to inhibition of its synthesis, a change in the activity of oxidative enzymes, a decline in the correlation between respiration and phosphorilization. In other words, the mitochondrial apparatus, which is viewed at the present time as a "energy generator", functioned inadequately during hypokinesia. Similar phenomena can be seen only in hereditary and endocrinal forms of myopathy.

Unfortunately, we have no detailed information obtained during flight that could indicate a decrease in the ability of the organism of the cosmonaut to absorb oxygen.

The tendency toward a decrease in this parameter was noted ( G. I. Voronin, A. M. Genin, A. G. Fomin, 1967) on the basis of a postflight analysis of the regenerative substance aboard the "Vostok" and "Voskhod" spacecraft. From data /19 in the literature we know that our colleagues in 1970-1971 considered the fact of a decrease in energy exchange by man in weightlessness to be established. Energy consumption of the crew aboard the "Apollo" 7, 10 and 14 was approximately 1,700 kcal and corresponded to the energy consumption of a 75 kg man in a state of rest (C. Berry, 1970).

In all forms of activity on the surface of the Moon the total energy consumption turned out to be less than that which was measured on Earth during simulation of the conditions of the flight (preliminary immersion, execution of tasks in a spacesuit on a stand with reduced weight). Thus, the energy exchange in the case of Armstrong rose by 250 kcal/hour instead of the calculated 340 kcal/hour while in the case of Aldrin it rose by 272 kcal/hour instead of 315 kcal/hour.

The decrease in oxygen consumption under conditions of hypokinesia (bed--rest, immersion) is mentioned by many authors (G. S. Katkovskiy, 1966; B. S. Katkovskiy et al., 1969 et al.).

The decrease in oxygen utilization by the tissues in the cosmonauts following the flights, which shows up particularly clearly in physical exercise, is a well-known fact.

In the case of the cosmonauts aboard the "Soyuz" spacecraft, even in those cases when the flight did not last any more than 4 days, during the maximum physical stress on the first day following landing, there were already symptoms of a decrease in oxygen consumption. A significant decrease in oxygen consumption under stress was observed in the American astronauts aboard the "Apollo" spacecraft (Table 5).

TABLE 5. RESULTS OF POSTFLIGHT TEST INVOLVING PHYSICAL STRESS; "APOLLO" 7-11 ASTRONAUTS. /20

| Pulse Rate Beats Per Minute | Oxygen Consumption, %* | Standard Deviations | Number of Astronauts |
|---|---|---|---|
| 120 | 68.6 | 15.2 | 15 |
| 140 | 74.5 | 11.6 | 15 |
| 160 | 77.8 | 10.8 | 15 |
| 180 | 73.8 | 8.1 | 3 |

*100% - average value of data from three preflight experiments.

During the first days of the flight, against a background of active processes of hypohydration, one could anticipate compensatory hyperfunctioning of the myocardium, caused primarily by redistribution of the blood. The basic symptom might be increased systolic and minute blood volume. On the basis of experimental and flight data, one could anticipate a lack of agreement between the high volume of cardiac output and the decrease in energy consumption on the periphery. As far as we know, the monkeys aboard the "Biosatellite-3" showed an increase in the venous pressure in the auricle and the large veins during the flight by 1.25 mm of mercury, remaining at this level during the entire flight (W. R. Adey et al., 1969). With a deficit of active muscle activity and an increase in hypohydration, when the total and circulating volumes of blood were decreased, the activity of the cardiovascular system (with the decline in cardiac output) became adapted to the reduced oxygen demand of the tissues. Such a development of events may be completed by the tenth to fifteenth day of the flight.

The decrease in the load on the heart due to small volumes of circulation /21 and correspondingly reduced minute volumes of blood on a long flight may have considerable consequences for the function of the myocardium.

I would like to express my own point of view and to explain the insufficient load of the volume of blood by a decrease in the area of the heart muscle in the majority of projections and also a definite decrease in the ratio of the sizes of the heart during diastole and systole, which our American colleagues observed during x-ray examinations of the "Apollo" crew members during the first few days after their flight. These changes were observed in 22 out of 27 astronauts (R. L. Johnson et al., 1972; R. L. Johnson, 1971).

Circulatory disturbances, disruption of water-salt exchange, deviations in the production and activity of hormones, particularly catecholamines, constitute interrelated processes. On long flights, there is a need for methods that will allow monitoring these processes.

Function of the Myocardium

The results of physiological studies, obtained during orbital flights and suitable ground experiments, indicate that one of the most important and frequent consequences of the action of unfavorable spaceflight factors on the human organism is disruption of myocardial activity. This is indicated both by the general decline in the functional capacities of the circulatory system in cosmonauts and the development of specific (alerting the physicians) symptoms of disturbance of cardiac activity.

Even during the first, relatively short spaceflights, it was observed that /22 exposure of man to conditions of weightlessness and hypodynamia can lead to a change in physiological parameters that characterize the functional state of the heart. Thus, for example, during orbital flight, some of the Soviet cosmonauts showed the following symptoms:

- decrease in the amplitude of the T peaks (Bykovskiy, Tereshkova, Titov);
- increase in length of electrical systole (Titov);
- relative increase in duration of mechanical systole (Bykovskiy, Tereshkova);
- slowing down of the auricular-ventricular conductivity (Bykovskiy, Nikolayev, Popovich);
- development of individual atrio-ventricular extrasystoles (Belyayev).

More pronounced changes in the bioelectrical activity of the heart in cosmonauts were observed during the active stages of the flights. Thus, in the case of cosmonaut Yegorov during landing, there was a brief sharp flattening of the T and P peaks, such that they completely disappeared. These changes were not observed under the influence of corresponding G-forces in a centrifuge prior to the flight. In the final stage of the flight, the decrease in the amplitude of the T peaks was observed in cosmonauts Komarov and Feoktistov. Thus, in the case of cosmonaut Feoktistov when the parachute opened there was also a significant change in the duration of the R - R intervals with a subsequent 20-second bradycardia and symptoms of disruption of the regulation of cardiac activity with development of sino-auricular block. In this connection, one is struck by the fact that the degree of decline in the amplitude of the T peaks during the action of the G-forces on landing the spacecraft was /23 relatively great while the normalization of the T peaks to original levels occurred more slowly than during similar G-forces on a centrifuge prior to the flight.

During the postflight examination, there were also some symptoms of a negative influence of weightlessness on the cardiac activity of the cosmonauts. For example, in the case of cosmonauts Belyayev and Bykovskiy, there was a slight slowing down of intraventricular conductivity, while in Yegorov, Komarov and Feoktistov there was a decrease in the voltage of the EKG peaks. The decrease in the functional capacity of the myocardium was observed when the cosmonauts were carrying out tests involving stress. Thus, during work on the bicycle ergometer, Bykovskiy and Tereshkova recorded changes in the EKG and in the phase structure of the cardiac contractions, characteristic of a decline in the contractile capacity of the myocardium.

In evaluating the changes in cardiac activity in the cosmonauts following relatively short flights, it is necessary to point out the fact that on the whole they were not of a pathological nature and return to normal in a short time following the end of the flight.

On subsequent flights, the length of time spent by man in space was increased, and the working and physical stresses on the crew members of the spacecraft was sharply increased. The cosmonauts were faced with the problem of working actively in space, partly under extreme physical and emotional stresses. All of this meant a considerable increase in the stress imposed on their organisms as a whole and on the cardiovascular system in particular. It may be that this has something to do with the fact that during the last spaceflights there was a development of more significant disturbances in the cardiac activity of the cosmonauts. A clear example of the disturbance of cardiac activity in cosmonauts can be seen from the data obtained during the flight of the "Apollo" 15 spacecraft. The crew members of this spacecraft, during various stages of the flight (work on the Moon, after docking, and so forth) showed a significant slowing down of the pulse frequency at rest (especially during sleep — to 28 beats/minute) and the development of arrhythmia of cardiac contractions, going far beyond the normal limits. In the case of astronauts Irwin and Scott, a great many auricular or ventricular extrasystoles were observed, as well as bigeminy which changed to auricular arrhythmia. Extrasystolia (lasting up to one hour) was observed in these cosmonauts at rest and (primarily) during considerable physical and emotional stresses. It should be pointed out, however, that the normalization of the functional capacities of the cardiovascular system in the crew members of the "Apollo" 15 spacecraft after the flight took place much more slowly than in the case of the other cosmonauts. This was clearly evident during the performance of the functional tests. At the same time, as in the case of the other cosmonauts, normalization of physical working capacity took place as a rule in the course of 24-48 hours; in the case of the "Apollo" 15 crew it occurred at much later times: for the pilot of the spacecraft 3-5 days, for the pilot of the Lunar module, on the ninth day and for the spacecraft commander only on the thirteenth day after landing. A similar "delay in normalization" was observed in the performance of a test involving the action of NPLB (negative pressure on the lower half of the body). While in the case of other astronauts the normalization of the reaction to NPLB took place 2-3 days after landing, in the case of the "Apollo" commander it took place on the fifth day, for the commander of the Lunar module on the ninth day and the pilot of the command module — on the sixth-seventh day, although an absolutely normal result was obtained only on the thirteenth day. /24

In the opinion of American scientists, the changes in cardiac activity that are observed in the crew members of the "Apollo" 15 were a symptom of general fatigue and a developing potassium deficit. There is reason to believe that the disturbance in the function of the myocardium may be due to other physiological mechanisms of regulation. /25

The possibility of a negative influence of spaceflight factors (weightlessness, G-forces and hypokinesia) was considered in the performance of corresponding model experiments. Basically, these were experiments in which the subjects were kept under conditions of strict bed rest with various angles of inclination of the body or were submerged in immersion media. In the course of these experiments, the "hypokinetic syndrome" was observed and described; one of its particular symptoms is the disruption of cardiac activity — a decrease in the functional capacities of the heart and the development of characteristics that indicate a change in bioenergetics and trophics of the myocardium.

An analysis of the electrocardiographic tests which were conducted during and after the subjects' stay under hypokinetic conditions revealed the following most frequently encountered changes in the bioelectrical activity of the myocardium:

- sinus arrhythmia;
- relative slowing of atrioventricular conductivity;
- decrease in the amplitude of the T peaks;
- formation of the $T_1 > T_6$ syndrome, and so forth.

Similar EKG changes were observed during experiments involving immersion of the subjects in water. Thus, according to the data of L. A. Ioffe, the first /26 24 hours of immersion showed a significant decrease in the amplitude of the T peak with standard leads; after $5^x$ days the right chest leads showed an increase in the T peaks while those on the left showed a pronounced drop, with formation of the $T_1 > T_6$ syndrome in 9 out of 13 subjects.

Hence, even in a state of rest, the subjects showed a change in the amplitude and time factors of the EKG, which in a number of cases were characteristic of a disturbance of the extracardial regulation of cardiac activity and a deterioration of the trophics of the myocardium (L. A. Ioffe, 1970).

More pronounced disturbances of the function of the myocardium, caused by hypokinesia in the experiment or during weightlessness, showed up clearly during functional stresses — orthostatic testing and physical stress. During these tests, the following changes in the electrocardiogram were observed:

- significant (in some cases up to 150-160 beats/minute) tachycardia;
- different types of arrhythmia: sinus arrhythmia, auricular or ventricular extrasystole (single or group), migration of the rhythm with areas of transition of the normal sinus rhythm to nodal, dissociation of rhythms;
- slowing of the auriculo-ventricular conductivity;
- relative increase in the duration of electrical systole;
- a shift of the electrical axis of the heart to the right;
- formation of the $T_1 > T_6$ syndrome;
- increase in amplitude of P peaks;
- change in the amplitude and deformation of the final portion of the ventricular complex. Decrease (and in some cases, inversion) of the /27 T peaks, primarily in the II, III and left chest leads. In some cases, the decrease in the T peaks had a phasal nature, accompanied by a decrease in the ST interval below the isoelectrical level and did not correspond to the change in position of the heart in the chest.

These changes were a direct function of the magnitude of the influence and its duration. In individual cases, symptoms of functional insufficiency of the myocardium, evidenced by the EKG, were so pronounced that there was reason to designate the subject as one with a critical condition and in some instances to eliminate him from tests involving physical stresses.

It should be pointed out that the changes described above were reversible and as a rule recovery of the function was restored in the course of 3-5 days following the end of the experiments.

Hence, allowing man to stay under conditions of strict bed rest may be accompanied by the development of specific (and in some cases, very pronounced) symptoms of disturbance of bioenergetics and trophics of the myocardium, most clearly evidenced in the reaction of the heart to functional tests.

These data show that spaceflight conditions may have unpleasant effects on the functional status of the human heart, even causing development of arrhythmia of cardiac contractions which goes far beyond normal limits. The change in cardiac activity may be a factor which limits the activity of man in space.

"Physical overstressing" of cosmonauts perhaps should be viewed not so much as a cause of certain disturbances in the cardiac activity as an unfavorable background against which they develop.

Disturbance of cardiac activity during spaceflights may be caused by the following: /28

- a change in extracardioregulation of cardiac activity, as the symptom of a general restructuring of the neuroregulatory mechanisms of the cardiovascular system (particularly the change in the relationship of the activity of the centers of sympathetic and parasympathetic innervation);
- restructuring of intracardial hemodynamics in conjunction with the general reaction of the circulatory system to the change in physical conditions involved in the movement of blood;
- hormonal changes and readjustment of water-salt metabolism.

We cannot exclude the development of structural changes on the cellular level and a disturbance of metabolic processes in the myocardium.

These results show the necessity of carrying out further specific cardiological research whose final goal is the increasing of our knowledge concerning the origin of the disruption of cardiac activity in man under spaceflight conditions, as well as the development of appropriate preventive measures and principles for medical monitoring.

We understand that it is very difficult to apply to man those changes which researchers have observed in animal experiments. Nevertheless, this information may be useful in understanding the disturbances of myocardial functions. In rabbits subjected to a rigorous limitation of mobility, B. M. Fedorov and his associates observed the following:

- changes in the catecholamine and hormone metabolism;
- disruption of the ultrastructure of the myocardium;
- change in the content of electrolytes in the blood and muscle of the heart; /29
- a change in the functional state of the vegetative centers of the brain.

Some of the results of these studies, extending over many years, were presented at the Congress in Baku (B. M. Fedorov, 1973). The material was published in a generalized form in one of the recent issues of the journal "*Kosmicheskaya Biologiya i Meditsina*". The author concludes that one of the important reasons for the disruption of the function of the myocardium is the change in the nervous regulation of blood circulation. It is expressed primarily by a decrease in sympathetic influences on cardiac activity under resting conditions as well as an imbalance of the other systems of regulation of blood circulation, including the level of the higher vegetative centers.

In discussing the question of prolonging spaceflights, we will obviously be moving in the right direction if we proceed on the basis of the following postulate. Man can fly in space for two months, but this does not mean that the medical and biological problems of space have been solved. On the contrary, there are a great many problems still, and the problem of circulation remains one of the most important of them. It is impossible to overlook the serious disturbances in this function which the researchers of our two countries have found.

Our "preventive measures" thus far are limited only to one undisputed measure — compensation of the deficit of muscular activity which man undergoes during weightlessness. We have only scattered information concerning the experimental basis for medicinal prevention and therpay, although it is clearly understood that the disturbances of circulation of which we are speaking can be coped with successfully in clinical practice. The problem of prevention therefore is one of the most important ones we face today.

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