History and Development of Biomedical Investigations in the Soviet Manned Space Program

Abstract

Introduction

One of the principal goals of the Soviet Union's space program is the permanent presence of humans in low Earth orbit, a capability they now possess. To help realize this objective, the Soviet Union has developed an active space life sciences program whose major goals are to understand the adaptations to space flight conditions and to make human habitation in space and readaptation to Earth feasible.

The Soviet space life sciences program can be functionally divided into three interrelated components (Gazenko 1987). First is the program associated with the manned space flight effort. In recent years, this effort has concentrated on long-duration flights of cosmonauts aboard the Mir space station complex. Crewmembers serve as subjects for numerous biomedical investigations preflight, inflight and postflight. In addition, an operational medicine program provides health prevention and maintenance measures, as well as specific countermeasures against potentially deleterious adaptations to space flight conditions.

Second, ground-based experiments are conducted using space flight analog environments such as long-term bedrest, antiorthostatic hypokinesia, parabolic aircraft flights, and immersions. Long-term bed-rest studies often precede space flights of comparable duration, serving both to gather useful data and to validate the analog environment.

The third part of the space life sciences program concerns animal investigations. This effort began with the flight of animals as precursors to human space flights. More recently, it has evolved into regular flights of animals as part of the Biokosmos program. Ground-based animal investigations support the space flight effort.

The relevant scientific literature has been reviewed to gain an overall view of the scope of the Soviet space life sciences effort. This review is limited to include only the human space flight-related aspects of the program. Its main purpose is to compile a summary of the goals, accomplishments and capabilities of this program and to place it in a proper historical perspective. No attempt is made to review or interpret the results of the numerous experiments that have been conducted as part of this program. Also, one of the limitations of this review is that, having access only to openly-published information about Soviet space life sciences, it is probable that certain aspects of that program remain unknown or incompletely understood.

Manned Flight Summary and Cosmonaut Population

The Soviet Union has carried out 68 manned space flights, the longest lasting 366 days. Eighty-two persons have flown Soviet spacecraft, accumulating more than 18 crewmember-years of flight time during 145 space flight exposures. Sixteen individuals have accumulated more than 200 days of space flight time, four individuals have spent more than one year in space with one cosmonaut accumulating 430 days during three missions.

These statistics underscore one of the current goals of the Soviet manned space program, namely long-duration flights with the aim of a permanent human presence in low Earth orbit. To successfully achieve that goal, the Soviets have invested substantial resources in the biomedical monitoring of their cosmonauts, as well as in a research program aimed at understanding human adaptation to space flight.

The Soviet space flight medicine program evolved as a branch of aviation medicine (Lavnikov 1977). One of its first tasks was to establish criteria for cosmonaut selection and training. In 1960, the first group of 20 cosmonauts were chosen from several hundred candidates. The twenty were mostly young (24-38 years old) military pilots. Subsequent cosmonaut selections have included military pilots, military and civilian engineers, as well as researchers with minimal training prior to space flight. The third category includes a small cadre of physicians, who work at their professional positions until shortly (6 months to one year) before their flights. The current active cosmonaut population is divided roughly equally between pilots and engineers (Hooper 1986).

The Early Years

Biomedical monitoring of cosmonauts in the early Vostok flights concentrated on the cardiopulmonary system (Kas'yan et al. 1968). During Vostok 1, the first manned flight, Yu. A. Gagarin's heart and respiratory rates were monitored by electrocardiography (EKG) and pneumography, respectively. The short-duration of the mission (108 minutes) precluded more extensive inflight studies. Inflight seismocardiograms (SCG) and kinetocardiograms (KCG) were added on the second flight which lasted about one day. It was also on this flight that space motion sickness (SMS) was first reported (Gurovskiy et al. 1975). Presumably in an effort to document any changes that might occur during

SMS, inflight electrooculography (EOG), electroencephalography (EEG) and studies of galvanic skin resistance were added on the next four flights (Akulinichev _et al._ 1963). No consistent changes in eye movements were seen in these four cosmonauts, including in one who complained of mild illusory sensations (Gurovskiy _et al._ 1975).

All six cosmonauts who flew Vostok missions ejected from their spacecraft approximately 20 minutes before touchdown and landed separately by parachute (Clark 1988). All seem to have tolerated this mode of landing even after flights of up to 5 days duration although published postflight data have been limited to body weight and hemoglobin (Balakhovskiy and Natochin 1973) and blood (serum proteins, mucoids, and cholinesterase activity) and urine (urinalysis, DNAase activity, mineralocorticoids) analyses (Fedorova _et al._ 1964). Anecdotal reports of reduced postflight exercise tolerance and decreased vital capacity have also been published (Kakurin 1977). All subsequent flights ended with the cosmonauts remaining with their spacecraft for soft landings.

The next flight program (Voskhod, 1964-5) included the addition of several new inflight investigations. Voskhod-1 was the first flight of a 3-person crew, including the first physician (B. B. Yegorov) to fly in space. He measured the crew's arterial pressure by Korotkov method, vital capacity and pulmonary ventilation using a hand-held spirometer, and hand grip strength with a dynamometer. He also performed writing and eyes closed pointing tests combined with galvanic vestibular stimulation (Yuganov et al. 1968). Capillary blood was drawn by finger stick and stored for postflight analysis of glucose, urea and chloride, as well as leucocyte count. Postflight renal function was assessed by a fluid load of 1.5 liters (Balakhovskii et al. 1968).

Voskhod-2 included the first extravehicular activity (EVA), during which heart rate, respiration rate and temperature were monitored (Kas'yan et al. 1968). A hand-held spirometer was used to measure lung volumes after the EVA (Kas'yan et al. 1975). Neurologic investigations included sensory and stereognostic testing, eye-hand coordination, reaction time, and eye movements recorded by EOG (Kas'yan et al. 1975).

Initially designed in the early 1960's, the Soyuz spacecraft and its derivatives have been the vehicles that cosmonauts have flown since 1967. Soyuz was originally intended as a multipurpose vehicle, to be used as a ferry to Earth orbiting space stations and as an integral element of a manned lunar program. The first flight of the program ended in tragedy when the pilot died of massive crush injuries incurred when his spacecraft crashed on landing following failure of the main parachute (Riabchikov 1971).

The next six flights recertified the Soyuz spacecraft and were possibly connected with the manned lunar effort. Inflight biomedical monitoring was limited to EKG, SCG, pneumography, sphygmomanometry, vital capacity (Gurovskiy et al. 1975) and sleep monitoring (Litsov 1972). During EVA, rectal temperature was also monitored. Inflight urine was collected on at least one of the flights for subsequent postflight analysis.

Pre and postflight cardiopulmonary investigations included bicycle ergometer stress tests, active and passive orthostatic and anti-orthostatic tests, during which heart rate and blood pressure were recorded by EKG and tachooscillography, respectively (Kakurin et al. 1977). Pulmonary volumes and gas exchange were also monitored. Cerebral blood flow was recorded by rheography. Blood and urine were analyzed for electrolytes (Grigor'yev et al. 1977). Renal function was assessed in most of the crewmembers by fluid loading (approx. 2% body weight), with pre and post load measurement of urine volume and electrolyte excretion (Balakhovskiy et al. 1971, Grigor'yev et al. 1977). Muscle tone, strength and EMG activity at rest and after exercise were investigated (Kakurin et al. 1971). Postflight mineral density of finger bones and calcaneous was evaluated radiologically in four crewmembers (Krasnykh 1975).

The First Space Stations

In 1969, a government-level decision redirected manned space flight efforts away from a lunar program and toward the development of Earth orbital space stations, to be called Salyut. These spacecraft were designed to house cosmonaut crews for extended durations. The 18-day flight of Soyuz-9 in 1970 was a test-bed for some of the hardware and procedures to be used on board future space stations. These included an air-regeneration system (Newkirk 1990), prototype "Penguin" suits and elastic chest expanders requiring 10-kg of force for exercise (Dmitriyev et al. 1973).

Extensive pre-, in- and postflight medical investigations were performed on the Soyuz-9 crew. Inflight studies of the cardiopulmonary system included: EKG, pneumogram, SCG, arterial pressure measurements by Korotkov method, and lung volumes. Inflight neurologic testing consisted of hand dynamometry, kinesthetic sensitivity reaction time and eye-hand tracking (Ivanov et al. 1975, Kas'yan et al. 1975). Renal function was assessed by measuring volumes and electrolytes in 24-hour urine samples (Balakhovskiy and Natochin 1973).

Pre- and postflight testing of the cardiopulmonary system consisted of active and passive orthostatic tests, during which cardiac function was evaluated by EKG and phonocardiography (PCG), arterial pressure by tachooscillography, regional blood flow by rheography, and pulmonary gas exchange by gas analyzers (Kalinichenko et al. 1970). Neurologic testing included EEG, sleep monitoring, and studies of posture, locomotion (Chekirda et al. 1970) and muscle tone, strength and electrical activity (Cherepakhin and Pervushin 1970). Changes in the radiologic density of fingers and calcaneous and urinary calcium excretion were evaluated (Biryukov and Krasnykh 1970). Blood (Legen'kov et al. 1973) and urine analyses were performed. Studies of intestinal and skin microflora and immune status of the crew were performed.

After their record-setting 18-day flight, the Soyuz-9 crew experienced significant orthostatic intolerance, muscle weakness especially in the legs, and mild vestibular disturbances (Beregovkin et al. 1977). To maintain stabilization during flight, their spacecraft was spun in the yaw axis at three deg/sec (Gurovskiy et al. 1975), and the resulting Coriolis effects combined with the lack of appropriate countermeasures probably contributed to the crew's prolonged readaptation period. To prevent infections, the crew was maintained in isolation for 2 weeks following the flight, at a facility originally designed as a quarantine site for cosmonauts returning from the moon.

The first Salyut space station was launched in 1971, and represented a quantum leap for Soviet space life sciences. Not only would cosmonauts be able to spend extended periods of time in space, but their health status could be closely monitored using onboard equipment. In addition, facilities for providing countermeasures against certain deleterious adaptations to weightlessness would be available.

Several new countermeasure devices were introduced on Salyut-1. The Penguin suit is a one-piece garment worn for 8-10 hours a day while the crewmember is working (Gazenko 1987). Adjustable elasticized straps within the suit provide an axial load on the musculature of the trunk and legs (see figure). The cosmonauts must exert muscular force to overcome the suit's tendency to flex. Modification of this suit have been worn by all long-duration cosmonauts.

A lower body negative device called Chibis was first used on Salyut-1 (Vasil'yev et al. 1974). The crewmember dons the suit by placing both legs inside the device, with a pressure seal at the iliac crest level. A microcompressor creates a partial vacuum on the lower half of the body. Rarefaction to -35 mmHg was achieved on early missions, and increased to -45 mmHg on later flights. Although it was used only once aboard Salyut-1 to test the crew's orthostatic tolerance (Degtyarev <u>et al.</u> 1973), the Chibis unit has been used during subsequent long-duration flights as both a diagnostic device and as a pre-landing countermeasure to stress the cardiovascular system.

Salyut-1 also carried the first treadmill in space (Vasil'yev <u>et al.</u> 1974). Although little has been published about this original version, later models measured cm x cm. Both powered and unpowered modes were available on later versions (Gurovskiy <u>et al.</u> 1975). A harness system providing 50 kg downward force was worn by the crewmember during walking or jogging. On Salyut-1, the treadmill and harness was used to perform deep knee bends. Additional exercise equipment consisted of expanders, mainly for working the arms and torso.

The Polinom apparatus was first introduced aboard Salyut-1 (Vasil'yev <u>et al.</u> 1974). A variant of it has been in use aboard every Soviet space station. Polinom can record 22 different physiological parameters (EKG, SCG, arterial pressure, body temperature, etc.) with a maximum recording capability of five simultaneous parameters. Data can be stored onboard magnetically or downlinked to ground stations. Using this apparatus, the crew's health especially the cardiovascular system, could be monitored at rest, during exercise on the treadmill and during lower body negative pressure (LBNP).

The Soyuz-11 crew were the first to board a space station. During their 23-day occupancy of Salyut-1, they used the Polinom apparatus to record their EKG, KCG, femoral sphygmogram, and arterial pressure using tachooscillometry at rest (Degtyarev et al. 1974), before and after squatting exercises (Degtyarev et al. 1978), and before, during and after a LBNP test in the Chibis suit (Degtyarev et al. 1974). They also used a spirometer to measure lung volumes, flow rates and gas exchange (Vasil'yev et al. 1974).

Neurologic testing consisted of hand grip strength measured with a dynamometer, kinesthetic sensitivity, and measurements of visual acuity, color and contrast sensitivity, convergence and accommodation. Mineral saturation of bones was also studied (Vasil'yev et al. 1974).

Capillary blood was drawn on three occasions inflight and stored on filter paper (Balakhovskiy et al. 1974). The samples were subsequently analyzed back on the ground for glucose, urea, and cholesterol. Blood smears were also prepared for blood cell counts (Legen'kov et al. 1973).

The record-breaking 24-day flight of Soyuz-11 ended tragically when all three crewmembers died due to a sudden depressurization of their descent module about 20 minutes before touchdown. A pressure equalization valve had jarred open during a separation sequence, the spacecraft losing pressurization within one minute. The crew were not wearing pressure suits. Examination of the crewmembers' bones at autopsy revealed inconclusive histologic changes after 24-days of weightlessness (Gazenko et al. 1977, Prokhonchukov et al. 1978, 1980, Prokhonchukov and Leont'yev 1980).

Between 1971 and 1977, the Soviet Union recertified the Soyuz spacecraft following the loss of the Soyuz-11 crew, successfully operated three Salyut space stations with five crew occupancies, and flew several non-space station-related missions including the Appolo-Soyuz Test Project, a joint flight with the United States. During this time period, they extended their flight duration record from 24 to 63 days. They also introduced several new critical biomedical hardware items and procedures, in addition to continuing the investigations developed during earlier flights.

Following the Soyuz-11 accident, all subsequent Soviet crews wore pressure suits during launch and entry. Beginning with the 8-day Soyuz-13 flight in 1973, cosmonauts wore inflatable anti-g suits during entry and post-landing

(Gurovskiy et al. 1975). These suits are similar to devices worn by Air Force pilots and are worn under the launch-and-entry pressure suits (Gazenko 1987). Postflight bicycle ergometer stress tests, LBNP tests, and passive and active orthostatic and anti-orthostatic tests became standard procedures with this mission (Anonymous 1974). Extensive biochemical analyses of crewmembers' blood and urine also became routine practice.

The Salyut-3 station was manned by the Soyuz-14 crew for 15 days in 1974. On board was a treadmill that could be operated in powered (for running) or unpowered (for walking) modes. A harness provided 50 kg load on the cosmonauts' vertical axis. The crew exercised on the treadmill for 1.5-2 hours per day and also wore Penguin suits during waking hours, probably contributing to their rapid readaptation to 1-g conditions (Gurovskiy et al. 1975). Extensive inflight EKG studies were performed by the Soyuz-14 crew (Korotayev et al. 1977). The Chibis LBNP unit, however, was not carried on Salyut-3.

Two successive crews (Soyuz-17 and 18) occupied the Salyut-4 station in 1975 for 29 and 62 days, respectively. In addition to the treadmill and Penguin suits flown on previous stations, Salyut-4 once again carried the Chibis LBNP device. In addition, a bicycle ergometer was for the first time in the Soviet program used both as an exercise countermeasure device and to perform inflight evaluations of the crews' exercise tolerance.

It was near the end of the Soyuz-18 flight that the Soviets first used a combination of fluid/salt loading and application of LBNP as a countermeasure against postflight orthostatic intolerance (Gazenko et al. 1979). First evaluated during long-duration bed rest studies (Grigoriev 1983), the countermeasure consisted of the ingestion of 9.0g sodium chloride and 1000-1200 ml water in three divided doses on the final mission day. LBNP training was carried out for the final four days of the flight with 30-minute daily sessions (Gazenko and Yegorov AD 1976). A modification of this protocol is still in use today.

The Salyut-5 station also housed two crews in 1976, for 48 and 17 days (Soyuz-21 and 24, respectively). The treadmill, Chibis device, and Penguin suits were flown, but the bicycle ergometer was not carried (Anonymous 1977). In its place, the Soviet Union's first inflight body mass measurement device was flown (Sarychev et al. 1980). Based on the principle that a body attached to a spring will, if perturbed, oscillate with a period depending on the spring's properties and the body's mass, this unit had an accuracy of less than 0.5%. Modifications of this mass measurement device were flown on subsequent space stations.

Space Marathons

In 1977, the Soviet Union launched Salyut-6, the first of its next generation space stations. These stations had an on-orbit refueling and a resupply capability enabling multiple long-duration flights. Between 1977 and 1981, the soviets carried out five such flights on Salyut-6 of 96, 140, 175, 185 and 75 days, significantly expanding their flight duration record. The follow-on Salyut-7 station supported 211, 150, 237, 166, 65, and 51 day occupancies between 1982 and 1986.

Biomedical monitoring of the prime crews, detailed biomedical investigations, and the development of effective countermeasures were integral parts of the long-duration missions. These relied heavily on the experience gained during previous space station operations and ground-based studies, but new hardware items and procedures were introduced on both Salyut-6 and 7. Both stations carried the previously-flown treadmill, Chibis LBNP unit, bicycle ergometer (Grigor'yev et al. 1986) and body mass measuring device (Talavrinov et al. 1988). For cardiovascular investigations, basic equipment consisted of EKG, KCG, rheogram, SCG, tachooscillogram, AV pulsogram, pneumogram. The Polinom-2M apparatus was used for recording the various parameters (Yegorev et al. 1986).

Ballistocardiography was first used in space in 1977 during the 96-day Soyuz-26 mission (Bayevskiy et al. 1987), and used on several subsequent flights. Beginning with the 140-day Soyuz-29 mission in 1978, inflight leg volumes were measured on all long-duration crews (Talavrinov et al. 1988). The technique of measuring leg volume, initially developed during bed rest studies, consisted of an elastic stocking-like device worn on the lower leg, with 8 measurements of circumference taken at 3-cm intervals. the volume was determined as the sum of the volume of the segments, estimated as truncated cones (Kas'yan et al. 1980). The late inflight LBNP and fluid/salt loading protocol developed on Salyut-4 was refined during Salyut-6 flights (Yegorov et al. 1986). Pre and post flight echocardiograms were first recorded for the Soyuz-26 crew in 1977 (At'kov et al. 1987). Inflight echocardiograms were recorded on the Soyuz-T5 crew in 1982, using the Soviet-build Argument device and subsequently using the French-made Echographic unit, in conjunction with the visiting Soviet-French Soyuz-T6 crew. During the 8-month Soyuz-T10 mission, echocardiograms were obtained at rest, during exercise on the bicycle ergometer, and during LBNP.

Many of the prime crews also performed extensive EVA activities, the two stations supporting 16 2-person EVAs totaling nearly 52 hours. The crew of L.D. Kizim and V.V. Solov'yov accounted for over 31 hours of this total during 8

EVAs on two flights, one of them performed on mission day 182. The EVA suits were semi-rigid, with a water-cooled undergarment. Nominal pressure in the suit was 270-300 mmHg, but could be lowered to 1982-210 mmHg for short-periods for work requiring greater suit mobility. EVA activities are preceded by 30-minute denitrogenation. During EVA, the crew's EKG, respiration and skin temperature (post-auricular) were recorded, along with suit pressure, oxygen utilization, CO_2 concentration and suit water coolant temperature (Abramov et al. 1982).

The Salyut-6 and 7 long-duration prime crews also hosted over a dozen short-duration (4-12 days) visiting crews, which usually included a non-soviet guest cosmonaut. During these support flights, the visiting crew performed specific, usually single-flight, biomedical experiments. A list of these investigations, along with similar studies performed by the prime crews is provided in Table 1.

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