A Cohort Mortality Study Among Soviet and Russian Cosmonauts, 1961–2014

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INTRODUCTION: Over 500 people from different countries have been to space since the first manned spaceflight in 1961. Factors of space and spaceflights might cause functional and somatic disorders, leading to increased mortality. Our research goal was to assess cause-specific risk of death among Soviet and Russian cosmonauts who had at least one spaceflight.

METHODS: The epidemiological cohort study included 115 male cosmonauts. The observation period was 54 yr (January 1, 1961–December 31, 2014) and 2707 person-years of follow-up were obtained. By the end of the period, 84 cosmonauts were still alive and 31 were deceased. The reference groups were the male population of Russia and of the Moscow Region, where Zvezdny City (Star City) is located. Mortality risk was assessed by standardized mortality ratio (SMR) with 95% confidence intervals (95% CI).

RESULTS: Death risk in the cohort was significantly lower than that in both reference groups: for all causes (A00–Y98; SMR = 40), for diseases of the circulatory system (I00–I99; SMR = 37 and 35 compared to Russia and the Moscow Region, respectively), and for other causes, i.e., all causes except circulatory diseases, cancer, and accidents, (SMR = 8). Death risk for accidents (V01–Y98) in the cohort was 1.8–1.9 times lower than that in both reference groups: SMR = 52 (95% CI 19–139) and 56 (21–151), but was not statistically significant. SMR for cancer (C00–C97) was also below 100 (71 and 66), but insignificant.

DISCUSSION: Our findings mainly characterize mortality among the first cosmonauts who have flown to space from 1961 through the 1970s, which indicates the necessity of continuing research.

KEYWORDS: standardized mortality ratio, causes of death.

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Long-term development of manned spacecraft is related to the exploration of the stellar bodies of the solar system, and consequently has led to increased spaceflight durations. These in turn have led to developments in science and technology, especially space medicine and biology.[27]

With an ever-increasing duration of flights, it is important to consider human performance. The habitat of cosmonauts on orbital stations is determined by a set of factors, such as weightlessness and cosmic radiation, factors arising as a result of operation of the station, as well as factors associated with the vital and professional activities of the cosmonauts themselves.[15] In their professional activities, cosmonauts need to maintain the viability and control of the station in order to support their own health and high performance efficiency and to perform engineering research, including that in outer space.[8]

All these factors could lead to functional and somatic disorders, especially during long-duration flights.[6,17] The negative effects of spaceflight and space could develop both in flight or during the postflight period, as well as in the distant future, which might increase cause-specific mortality rates. Therefore, the goal of our research was to assess cause-specific risk of death of Soviet and Russian cosmonauts who have flown in space at least once. By examining the characteristics of cosmonauts' health in terms of death-rate, we may be able to evaluate the degree of protection needed from extreme factors of the

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space environment and spaceflight, and provide some information in dealing with health care in this professional activity.

METHODS

Study Population

Since 1960, when the first Russian team of 20 cosmonauts called VVS No. 1 (Airforce Team No. 1) was formed, 57 yr have passed. The subject of this study is mortality among those Soviet and Russian cosmonauts for the period from 1961 to 2014. A total of 283 candidates were screened for the team. As of December 31, 2014, when the study was closed, 119 cosmonauts, including 4 women, had flown in space at least once. Women were excluded from the study due to drastic differences between male and female mortality rates and death causes. This issue requires sex-specific analysis of health indicators.

The cohort included 115 male cosmonauts who contributed 2707 person-years through the end of the observation period. There were 31 deaths. The follow-up lasted 54 yr, from January 1, 1961, through December 31, 2014. The observation period for each cosmonaut was from the date of the first flight until either December 31, 2014, or death. Those cosmonauts who started their first spaceflight after December 31, 2014, were not included in the cohort.

Information about Russian and Soviet cosmonauts was obtained from websites of the Federal Space Agency (http://www.federalspace.ru), the Federal State Organization "Gagarin Research and Test Cosmonaut Training Center" (http://www.gctc.ru/), and the "Space ASTROnote Encyclopedia" (http://astronaut.ru/). The personal data of the cosmonauts were coded. The authors obeyed ethical principles of research involving human subjects. In accordance with federal regulations concerning the protection of human subjects in research, this study was exempt from institutional review, as the authors made no contact with the cosmonauts under study and the data used in this research were obtained from open sources.

Reference Populations

The reference cohort included the male populations of the Russian Federation and the Moscow Region, the location of Zvezdny City (Star City), where cosmonauts live and train. The age structure of the male population and the number of case-specific deaths in each age group were obtained from the following sources:

- For 1960–1987, from the State Archive of the Russian Federation, the State Archive of the Moscow Region, the Russian Fertility and Mortality Database of the Center of Demographic Research of the Russian Economic School,[23] and based on the findings of the study of Modern Tendencies in Mortality by Causes of Death in Russia in 1965–1994.[14]
- For 1988–2014, from the Federal State Statistics Service (Rosstat) and the Moscow Regional Office of the Federal State Statistics Service.

Statistical Analysis

The composition of death causes was calculated as the number of deaths from specific causes divided by the number of deaths from all causes, multiplied by 100.[20] The standardized mortality ratio (SMR) was used to assess the cosmonauts' mortality risk. Age standardization was carried out indirectly. SMR was determined by dividing the actual number of deaths in the cohort by the expected number. The expected number of deaths was calculated using the following steps:

1. Age-specific death rates for the male population (reference population) were determined by dividing number of deaths by annual population for each 5-yr age group in each observation period (1961–1964, 1965–1969 …. 2005–2009, 2010–2014).
2. Person-years lived within each age group and observation period were determined and based on the cosmonaut's date of entry into the corps and the end of follow-up.
3. The expected number of deaths were determined as person-years lived (step 2) and multiplied by age-specific death rates (step 1).

Statistical significance was evaluated by the 95% confidence interval (95% CI).[5]

SMR in the cohort were estimated for the following causes of death according to the International Statistical Classification of Diseases and Related Health Problems 10th Revision: diseases of the circulatory system (I00–I99), cancer (C00–C97), accidents (V01–Y98), and all causes combined (A00–Y98). The group of "other causes" includes all causes except the three mentioned above.

The average age at death for the Russian male population ages 20+ was calculated by the survival table[20] for the period 1961–2014. Information for the survival table was obtained from Rosstat data on the average annual male population and number of deaths in each age group. The average age at death for cosmonauts was obtained from the cosmonaut database. Statistical processing and data analysis were carried out using Microsoft Excel 2010.

RESULTS

The cosmonaut cohort included 115 male cosmonauts who have flown to space at least once. By the end of the follow-up (December 31, 2014) 84 cosmonauts ages 37 to 87 were alive. During the 54-yr observation period, 31 cosmonauts died at the age of 34 to 83: some due to illness at the age of 44 to 83 yr, and some due to accidents from 34 to 62 yr.

Of the four causes of death, diseases of the circulatory system (I00–I99) formed a large part (45.2%; 14 cases), followed by cancers (C00–C97; 32.3%; 10 cases). Accidents (V01–Y98) contributed 19.3% (6 cases). One cosmonaut died of a disease of the digestive system, related to "other causes" (3.2%). Distribution of causes of death among the cosmonauts had certain differences from that in the reference groups (**Fig. 1**).

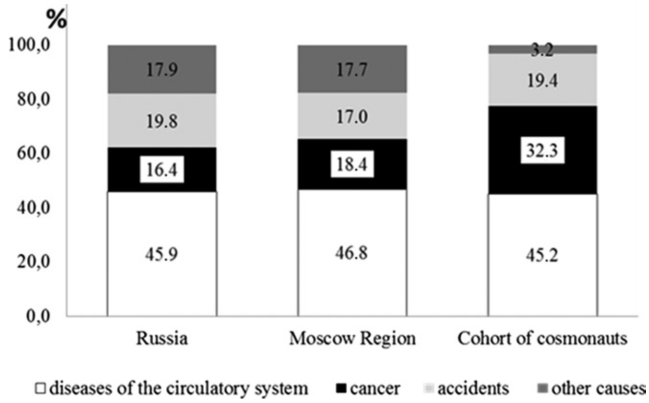

Fig. 1. Causes of death for the cohort of cosmonauts and the reference male population of Russia and the Moscow Region.

The percentage of cancer deaths in the cohort (35%) was higher than in the reference groups (16.4% and 18.4%); however, the percentage of "other causes" of death was lower. About 20% of deaths in Russia and in the Moscow Region related to these other causes, whereas only one cosmonaut died from a disease of the digestive system (purulent peritonitis) (3.2%). The mortality rate for diseases of the circulatory system in the cohort was slightly (4–5%) lower than those in the reference groups. The percentage of deaths from accidents was similar.

The structure of causes of death characterizes mortality only by its percentage composition. To compare the frequency of death in the cohort with that of the reference groups, we used SMR. **Table I** provides actual and expected numbers of deaths, SMR, and confidence intervals for each cause.

The SMR shows that cosmonauts are at lower risk of all-cause mortality, circulatory diseases, and other cause mortality than the general population of Russia and the Moscow Region. For cancer and accidents, SMR was insignificant.

All-cause mortality (SMR = 40 compared to the Russian Federation and the Moscow Region, respectively) and mortality from diseases of the circulatory system (SMR = 37 and SMR = 35, respectively) were almost 2.5 times lower in the cohort compared to the population. SMR for other causes in the cohort was 13 times lower compared to the population. There was a tendency for a lower risk of accidental deaths (SMR = 52) and cancer (SMR = 71), but SMR were statistically insignificant.

Table I. Actual and Expected Numbers of Deaths and SMR in the Cohort of Soviet and Russian Male Cosmonauts Who Have Made at Least One Spaceflight (1961–2014).

CAUSE	ACTUAL	EXPECTED	SMR (95%CI)
Reference Population: Russian Federation			
All causes	31	76.8	40 (27–61)
Circulatory	14	38.3	37 (20–67)
Cancer	10	14.0	71 (32–160)
Accidents	6	11.5	52 (19–139)
Other causes	1	12.9	8 (1–6)
Reference Population: Moscow Region			
All causes	31	78.0	40 (26–60)
Circulatory	14	40.0	35 (19–64)
Cancer	10	15.1	66 (30–147)
Accidents	6	10.7	56 (21–151)
Other causes	1	12.6	8 (1–6)

During the 56 yr since the first manned spaceflight, more than 500 people from all over the world have flown in space, among them more than 100 Soviet and Russian cosmonauts. Of scientific interest is the analysis of distribution of deaths among cosmonauts by the years of joining the corps, since it determines the stage of space exploration to which the obtained mortality data can be related. All deceased cosmonauts were enrolled in 1960–1970s. Of 31 deceased cosmonauts, 5 joined the team in the 1970s, and the rest in the 1960s (**Table II**).

Of the cosmonauts, 12 who had participated in at least one spaceflight joined the first team formed in 1960. As of December 31, 2014, four cosmonauts were still alive, and their average age was 80 yr. Eight cosmonauts died (66.7%), five cosmonauts from circulatory diseases and two from accidents, including one death at the end of the spaceflight. One more cosmonaut died of peritonitis at the age of 44. There were 28 cosmonauts who enrolled in the Corps in the 1960s and the average age of the 10 survivors was 78.5 yr. Of these 28, 18 (64.3%) have died; the average age at death was 64.1 yr. In the 1970s, the team was joined by 24 more cosmonauts; the average age of the 19 survivors was 69.8 yr. Among deceased cosmonauts (20.8%), two deaths were from diseases of the circulatory system and three deaths from cancer, including one death from astrocytoma at the age of 47 associated with prior traumatic brain injury resulting from a hard landing of the spacecraft. No death cases were registered among the rest of the 51 cosmonauts who had been to space and who joined the team in the 1980s or later. As of December 31, 2014, the average age of the cosmonauts who had joined the team in 1980–1989, 1990–1999, and 2000–2014 was 58.8, 52.0, and 42.8 yr, respectively.

The analysis of the average death age of the male population of Russia during the observation period showed that the lowest average age of death was for accidents. In 1960–2014 it was 45.9 yr for 20-yr-old and older men. The average age of death from accidents among the cosmonauts was lower (42.0 yr).

To the present day, it is impossible to calculate the life expectancy in the current cohort because most of cosmonauts included are alive. However, according to the data on current deaths, we can say that the life expectancy of cosmonauts will be significantly greater than that of the Russian male population, which ranged from 57.6 to 65.3 yr during 1960–2014.

DISCUSSION

Previously, American epidemiologists conducted cohort studies of mortality among American astronauts.[18,22] The follow-up of the first study was from 1959 to 1991, with less than 3000 person-years.[18] SMR for accidents, mostly professional, was very high. SMR for all causes of astronauts was 1.8 times higher compared to the general population, while SMR for circulatory diseases was lower, but not significantly.

The observation period of the second study lasted 30 yr (1980–2009) and the number of person-years exceeded 6000.[22] The cohort included both men and women who had been and

Table II. The Average Age at Death from Different Causes for Cosmonauts and Russian Male Population Ages 20 yr and Older for 1960–2014.

	ALL CAUSES		CIRCULATORY DISEASES		CANCER		ACCIDENTS		OTHER CAUSES	
	COUNT	AVERAGE AGE	COUNT	AVERAGE AGE	COUNT	AVERAGE AGE	COUNT	AVERAGE AGE	COUNT	AVERAGE AGE
1960 – First enrollment (12)	8	57.8	5	68.8	0	0	2	37.0	1	44.0
1961– 1969 (28)	18	64.1	7	70.0	7	69.4	4	44.5	0	0
1970 – 1979 (24)	5	60.2	2	70.5	3	53.3	0	0	0	0
1980 – 1989 (19)	0	0	0	0	0	0	0	0	0	0
1990 – 1999 (23)	0	0	0	0	0	0	0	0	0	0
2000 – 2014 (9)	0	0	0	0	0	0	0	0	0	0
Total: 115	31	61.8	14	69.6	10	64.6	6	42.0	1	44.0
Average age at death for men ages 20 yr and older in Russia 1960–2014 (calculated with tables of survival)		64.7		70.7		65.3		45.9		63.2

never been to space. The percentage of the latter was negligible. The total number of astronauts was 321. For the majority of astronauts, flight duration was from several days to 2–3 mo, but for some, total flight duration was about 1 yr.

Astronauts were at much lower risk of all-cause mortality, cardiovascular diseases, and cancer compared to the U.S. population. Despite drastic differences in approaches to the cohort formation in the American study of astronauts and the Russian study of cosmonauts, the findings are similar. Cosmonauts were at lower risk of all-cause mortality and cardiovascular disease mortality as well. The differences were in the tendency of lower mortality rates for cancer and accidents among cosmonauts, while astronauts were at larger risk of accidents compared to the U.S. population.

Another study presents the mortality trends among Soviet and Russian cosmonauts.[21] The authors studied mortality among all candidates who began cosmonaut training in Star City. The cohort included men and women, regardless of their spaceflight experience. The authors concluded that cosmonauts were at lower risk of all-cause mortality compared to the population of Russia and Ukraine. Due to the lack of data on cause-specific mortality rates in Russia, the authors compared mortality among cosmonauts and astronauts. Cosmonauts were at greater risk of death from circulatory diseases and cancer compared to astronauts.

One hypothesis offered by the authors was that cosmonauts were at greater risk of cancer mortality because of longer duration missions on stations Salyut, Mir, and the ISS in low Earth orbit with higher background radiation.[21] Analysis of residence time on orbit shows that among 10 deaths from cancer, 6 cosmonauts were in space from 2 to 17 d, 2 for 64 and 80 d, and only 2 of them had missions for 268 and 374 d. In our opinion, the causal relationship between spaceflight duration and mortality from cancer needs to be researched in a future study. However, it is unlikely that this relationship will be identified in the coming years due to the small size of the cohort, its young-age composition, and the relatively small number of deaths.

More plausible seems another position advanced by the authors, that higher mortality rates from cancer, circulatory, and other forms of chronic disease among cosmonauts compared with astronauts may be due to the higher background mortality in Russia compared with the United States.[21] These differences in background mortality are caused by lower living standards in Russia, which have repeatedly been shown in our studies.[9] It can be expected that factors of conditions and lifestyle reflect on mortality rates for all professional and social groups without limitation of cosmonauts and astronauts.

To summarize, cosmonauts and astronauts are at reduced risk of chronic diseases compared to the general population (Russia and the United States). Similarity in mortality trends might be explained by selection to the corps of the healthiest, most mentally stable, and physically trained candidates, who are exposed to effects of the same occupational factors.

It is important to note that the methodical approach of cohort forming used by our American colleagues may allow an isolating role of the selection of the healthiest individuals to the corps. Comparing mortality in the cohorts of the general population, the healthiest individuals included in the corps, and cosmonauts and astronauts who have flown to space allows us to estimate the health effects of spaceflights and the space environment.

The list of risks and hazards associated with the implementation of space missions has been expanded and standardized to date.[15] Direct and delayed effects developed by the space environment and spaceflights may result from G load during orbit insertion or recovery phase, microgravity factors, atmosphere deficiency, cosmic radiation, meteor danger, and other factors associated with being in the enclosed space of manned space vehicles and orbital bases. Cosmonauts experience many changes such as barometric pressure and gas composition; chemical, biological, and mechanical effects; ionizing radiation; ultraviolet irradiation; noise, temperature, and humidity parameters inconsistent with hygienic standards; inactivity; hypokinesia; constant stay in a confined environment; a whole set of psychological factors associated with strenuous operator activities in combination with monotony and working activity in a small autonomous team; and other stressful situations.[8,15]

Radiation safety of cosmonauts is one of the most acute problems of manned spaceflights. It is mainly related to the constant increased flight duration and, secondly, to the plans for exploration of other planets of the Solar System. Earth radiation belts, as well as solar and galactic cosmic rays, create high background radiation in low Earth orbits and so radiation exposure during a spaceflight has a complex composition.[3,10] If there are no special protective measures, radiation will increase health risks.[19,28] Many researchers believe that cosmic radiation and its associated health risks are the main limiting factor of spaceflight duration.[3] Risks of health disorders to be considered include cancer,[7] acute radiation syndrome,[2,10] central nervous system affliction,[16,26] and degenerative effects,[17] including cataracts,[4,8,12] heart diseases,[17] etc.

One of the most negative factors is weightlessness (microgravity), which is not just a decrease in gravity, but an active factor causing a wide range of functional and somatic disorders, especially in the cardiovascular system.[6] This is primarily due to displacement of fluids to the upper part of the body and the increase in the relative blood volume in the pulmonary circuit and in cerebral vessels. Under the influence of weightlessness, functional changes occur not only in the cardiovascular system, but also in the musculoskeletal system and connective tissue, such as intervertebral disc disorders and andosteoporosis.[25] After a long period of weightlessness lasting from 6 to 12.5 mo, while moving through dense atmosphere, the effect of overload can be extremely dangerous and can lead to sinus tachycardia, cardiac arrhythmias, and the risk of vision disorder, performance impairment, and orthostatic intolerance.[6,11]

The study of metabolism during long-duration spaceflights shows that physical inactivity, a reduced load on the musculoskeletal system, hypo-hydration, redistribution of body fluids, etc., lead to a decreased basal metabolic rate.[13] Sustainable functioning of the body with such a homeostatic level is achieved in 5–6 mo. On return to Earth conditions, the human body needs an abrupt adaptation associated with the resumed gravity load.

Another negative factor is impact acceleration that significantly increases the risk of severe injuries of the musculoskeletal system and penetrating wounds of the thoracic and abdominal cavities, and arterial and venous vessels.[1,24] These can occur during the landing of a spacecraft, a crash landing in particular, as well as during the docking of spacecrafts.[11]

In this regard, it is important to focus on such a significant factor of a spaceflight as an increased risk of accidents. During some spaceflights, emergency situations have occurred which directly threatened the crew or reduced flight safety. Several times technical problems have led to loss of life. For instance, in 1967 during a 27-h flight on Soyuz-1, the parachute landing system failed and the cosmonaut perished. In 1971, after a 23-d flight, a Soyuz-11 crew of three cosmonauts perished as a result of an accidental depressurization of the cabin when entering the atmosphere.

Since 1971, neither Soviet nor Russian cosmonauts have died in spaceflight-related accidents. However, some emergencies have taken place. In 1987, a rough landing occurred, the cosmonaut sustained a head injury, and died of astrocytoma in 1988. Two other cases of accidental deaths among cosmonauts were related not to spaceflights, but to a practice airplane flight and a household accident.

Our findings mainly characterize mortality causes and levels among the first cosmonauts who flew on spaceflights in the 1960s and 1970s. SMR in the cohort of cosmonauts are significantly lower compared to the male population of Russia and the Moscow Region.

Lower risk of mortality from chronic diseases in the cohort compared to the reference population may be attributed to professional candidate selection. Cosmonauts have high health indicators, levels of physical fitness, sufficiently reliable protection of crews from extreme factors related to spaceflights and outer space, and top-quality medical monitoring in the preflight and postflight periods. These advantages enable cosmonauts to preserve superior health status compared to the general male population.

The current study of mortality, i.e., the final characteristics of health status, has only slightly disclosed the health effects of long-duration spaceflights. It demonstrated that no direct lethal effects of long-term (from 6 mo to 2 yr or more) stays on orbital stations were observed. Long-term health effects estimation is limited by a young cohort and short observation period since prolonged space missions were introduced. Further research into the mortality of cosmonauts who have flown to space is necessary for the future development of manned cosmonautics, considering the increasingly long durations of staying at space stations and planning flights to other planets.

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