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The Mortality of Space Explorers

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Abstract

Outer space exploration poses unique risks to human survival. Here, we review the current literature on United States astronauts and Soviet and Russian cosmonauts and provide updated and original research findings. As in previous research, both astronauts and cosmonauts are shown to have reduced risk of death by natural causes, particularly from chronic diseases such as cardiovascular disease and cancer, compared with appropriately matched general populations. Simultaneously, space explorers are at increased risk of death by external forces, particularly accidents such as plane crashes and spacecraft accidents. In total, both astronauts and cosmonauts are at reduced risk of all-cause mortality in comparison to the general populations of the United States and Russia. However, in comparison to astronauts, cosmonauts have been at equal risk of accidental death, but increased risk of death by chronic disease. We conjecture that the lack of risk from chronic disease may be due to the excellent health and medical monitoring of space explorers coupled with the deliberate attempts to limit their radiation exposure levels below those that would be detrimental. The differences in the astronaut and cosmonaut mortality experiences are likely due to lifestyle factors and the background rates of mortality in the two nations.

Keywords: astronauts, cosmonauts, mortality, cancer, cardiovascular

1. Introduction

For nearly 60 years, space exploration has captured our imagination and advanced human knowledge. Yet, in many ways, our understanding of space exploration is in its infancy. This is particularly true regarding possible long-term health consequences of living and working in space. For example, it is unknown whether humans will be able to safely explore deep space, colonize other planets, or live indefinitely on space stations even within Earth's orbit.

Data that will shed light on such questions have been, and continue to be, collected, and ongoing epidemiological analyses of those data will be required to determine the long-term hazards of space travel and to test whether countermeasures designed to mitigate those hazards are effective [1].

Measures of injury and morbidity, including incidence rates of acute physiological side effects or injuries related to space travel, and incidence rates or prevalence of chronic disease are important indicators of the relative safety of space exploration. Measures of mortality provide one kind of summary measure of such injury and morbidity outcomes that can potentially answer a fundamental question: is space exploration altering the lifespan of those who participate in it?

Exposures accrued during space exploration may elevate the risk of some causes of death, including those related to equipment failures or other accidents and cancers that may be related to exposure to radiation in space. Such elevated risks may be counterbalanced by the rigorous physical fitness and other health requirements of programs that have traditionally provided humans the opportunity for space travel, which may protect against some causes of death. In this chapter, we carefully examine the current evidence on mortality rates of space explorers, including cause-specific rates, and how they compare to those of age-, calendar year-, geography- and sex-matched general populations. We discuss the implications of this evidence and consider future steps in ongoing surveillance of the mortality and longevity of space explorers. Because space exploration to date has been largely confined to government-sponsored corps of astronauts from the United States and cosmonauts from Russia (via the former Soviet Union and current Russian Federation), our review will focus on these cohorts. As we shall see, evidence compiled and analyzed to date, as well as updated data and current analyses reported here for the first time, demonstrate that mortality rates for astronauts and cosmonauts differ in important ways from those of the general population and from each other.

2. Astronaut and cosmonaut cohorts

2.1. Demographic characteristics

The United States and Soviet manned space programs started at roughly the same time, with the selection of the first National Aeronautics and Space Administration (NASA) astronaut class in April 1959, the first group of United States Air Force (USAF) astronauts in June 1959, and the first Soviet cosmonauts in March 1960. The USAF eventually relinquished all astronaut training and manned space activities to NASA in 1969. The Soviet Space Agency is considered to have operated from 1957 to its official dissolution in 1991, after which its successor Roscosmos has continued space exploration for Russia. For purposes of analysis, we consider the “Soviet era” to be from the selection of the first Soviet cosmonaut class (March 15, 1960) until approximately the time of the fall of the Berlin Wall, which marked the beginning of the dissolution of the Soviet Union (December 31, 1989). The demographics of astronauts and cosmonauts are displayed in **Table 1**.

Characteristic	Astronauts, n (%)				Cosmonauts, n (%)				ALL	
	NASA		USAF		USSR		Russia			
<i>Total cohort size</i>	338	(100)	22	(100)	194	(100)	68	(100)	622	(100)
<i>Sex</i>										
Female	50	(14.8)	0	(0)	14	(7.2)	4	(5.9)	68	(10.9)
Male	288	(85.2)	22	(100)	180	(92.8)	64	(94.1)	554	(89.1)
<i>Race/ethnicity</i>										
Asian/E. Indian	4	(1.2)	0	(0)	0	(0)	4	(5.9)	8	(1.3)
Black	17	(5)	2	(9.1)	0	(0)	0	(0)	19	(3.1)
Hispanic	12	(3.6)	0	(0)	0	(0)	0	(0)	12	(1.9)
White	304	(90.0)	20	(90.9)	194	(100)	64	(94.1)	581	(93.4)
Other	1	(0.0)	0	(0.0)	0	(0.0)	0	(0.0)	1	(0.0)
<i>Military</i>										
Yes	237	(70.1)	22	(100)	127	(65.5)	36	(52.9)	422	(67.8)
No	101	(29.9)	0	(0)	67	(34.5)	32	(47.1)	200	(32.2)
<i>Education</i>										
High School	0	(0)	2	(9.1)	0	(0)	0	(0)	2	(0.3)
Bachelor	55	(16.3)	10	(45.5)	130	(67)	51	(75)	246	(39.5)
Master	173	(51.2)	9	(40.9)	6	(3.1)	6	(8.8)	194	(31.2)
Doctoral	110	(32.5)	1	(4.5)	58	(29.9)	11	(16.2)	180	(28.9)

Table 1. Demographic characteristics of astronauts and cosmonauts, 1959–2017.

In spite of the Soviets sending the first female to space in 1963, the U.S. Astronaut Corps has selected a larger percentage of females (14% vs. 7%) over the entirety of the follow-up period. The NASA group is also more ethnically diverse, with about 10% of the astronauts selected having non-White race/ethnicity.

Table 2 shows the average ages for the cohorts, including age at selection, average age at death for those who died, and average age of survivors as of 31 October 2017. Cosmonauts were slightly younger at the time of selection, on average, at 31.3 years versus 34.4 years for astronauts. There were no significant differences in the age at death or the mean age at the end of the study; thus, the cosmonauts were followed for 2.6 years longer, on average.

2.2. Actuarial characteristics

Table 3 lists selected actuarial characteristics of the astronaut and cosmonaut cohorts as of 31 October 2017, including counts of astronauts and cosmonauts, total amount of follow-up time

Event	Astronauts		Cosmonauts		p > t
	Mean	(sd)	Mean	(sd)	
Age (year)					
Selection	34.4	(3.6)	31.3	(5.4)	<0.0001
Death	59.6	(17.8)	61.4	(14.2)	0.4762
End of study	64.0	(11.7)	63.2	(14.7)	0.5523
Follow-up (year)	28.6	(14.1)	31.2	(14.8)	0.0269

Table 2. Average ages and follow-up time for astronauts and cosmonauts, 1959–2017.

(in person-years), and counts of deaths. Crude death rates, being in each case the ratio of total deaths to total person-years lived by a respective group, are also reported. Crude rates are highly dependent on the age structure of each cohort, and differences in crude rates may be due to differences in one or more cause-specific rates, or due to age differences in the cohorts, or both. To better understand whether and to what extent the rates in the various cohorts may differ, a more careful examination of these issues is required.

There have been 622 individuals selected and trained as astronauts or cosmonauts between April 1959 and October 2017. These men and women have contributed a total of 18462.8 person-years of observation time and 176 deaths, for an overall crude mortality rate of 9.53 deaths per 1000 person-years of observation.

The United States space programs account for 360 astronauts, contributing 10,291.8 person-years of follow-up and 80 deaths, yielding a crude mortality rate of 7.77 deaths per 1000

Source	Count	Exposure*	Deaths	Crude rate†
All astronauts and cosmonauts	622	18462.9	176	9.53
U.S. astronauts-all sources	360	10291.8	80	7.77
NASA Astronaut Corps	338	9565.7	62	6.48
USAF programs	22	726.1	18	24.79
X-15	7	230.7	7	30.34
X-20	5	160.6	5	31.13
MOL	10	334.7	6	17.93
Cosmonauts-all sources	262	8171.1	96	11.75
Soviet (1960–1989)	194	7089.2	91	12.84
Russian (1990–2017)	68	1081.9	5	4.62

*Pooled observation time since selection, expressed as person-years.

†Crude death rate, expressed as deaths per 1000 person-years.

Table 3. Actuarial characteristics of astronauts and cosmonauts, 1959–2017.

person-years. The vast majority of astronauts have been selected by NASA: 338 versus just 22 from the USAF. The last of the USAF astronauts were selected in 1967, while NASA astronauts have been periodically selected across the follow-up period. This makes the USAF astronauts some of the oldest in the overall cohort; this is reflected in their large crude mortality rate in comparison to that of NASA astronauts.

Data on cosmonauts are shown stratified by era of selection: the era of the Soviet Space Program (1960–1989) and the post-Soviet era of the Russian Space Program under the Russian Space Agency, Roscosmos. The 262 Soviet and Russian cosmonauts have accrued 8171.1 person-years of follow-up and 96 deaths, yielding a crude mortality rate of 11.75 deaths per 1000 person-years (**Table 3**).

3. Causes of death and comparative mortality for United States astronauts

We focus here and throughout this chapter on underlying cause of death as reported in official NASA astronaut biographies and in the news media. In this way, astronaut and cosmonaut deaths are categorized according to a single underlying cause of death.

Though there are many ways to quantify the mortality experience of groups such as astronauts and cosmonauts, here, we will focus on the Standardized Mortality Ratio (SMR). SMR is a risk ratio; it is computed by dividing the observed number of deaths in a group by the number of deaths that would be counterfactually “expected” were the group subject to a set of death rates from a reference population. (By convention, the resulting ratio is multiplied by 100.) Thus, SMRs of 100 represent equal risk between the group under study and the reference population, SMRs above 100 represent increased risk for the group under study, and SMRs below 100 represent decreased risk for the same.

3.1. Numbers and causes of death

Figure 1 shows the distribution by cause of the 80 astronaut deaths recorded through 31 October 2017. More than half of all deaths (46/80) were due to natural causes. Among natural causes, most deaths have been due to cancer (41.3%), followed by cardiovascular disease (CVD) (23.9%).

The 34 deaths from external (i.e., not natural) causes are dominated by 33 accidental deaths. Plane crashes and space craft accidents account for 29 of these deaths, with vehicular accidents accounting for the other 4. The only nonaccidental externally caused death was attributed to suicide (**Figure 1**).

For comparisons, all-cause United States general population mortality rates were taken from the Human Mortality Database for years 1960 through 2015 [2] and cause-specific rates from the CDC WONDER database for 1970 to 2015 [3–5]. The 2015 rates were used as the comparison rates for astronaut data from 2016 and 2017.

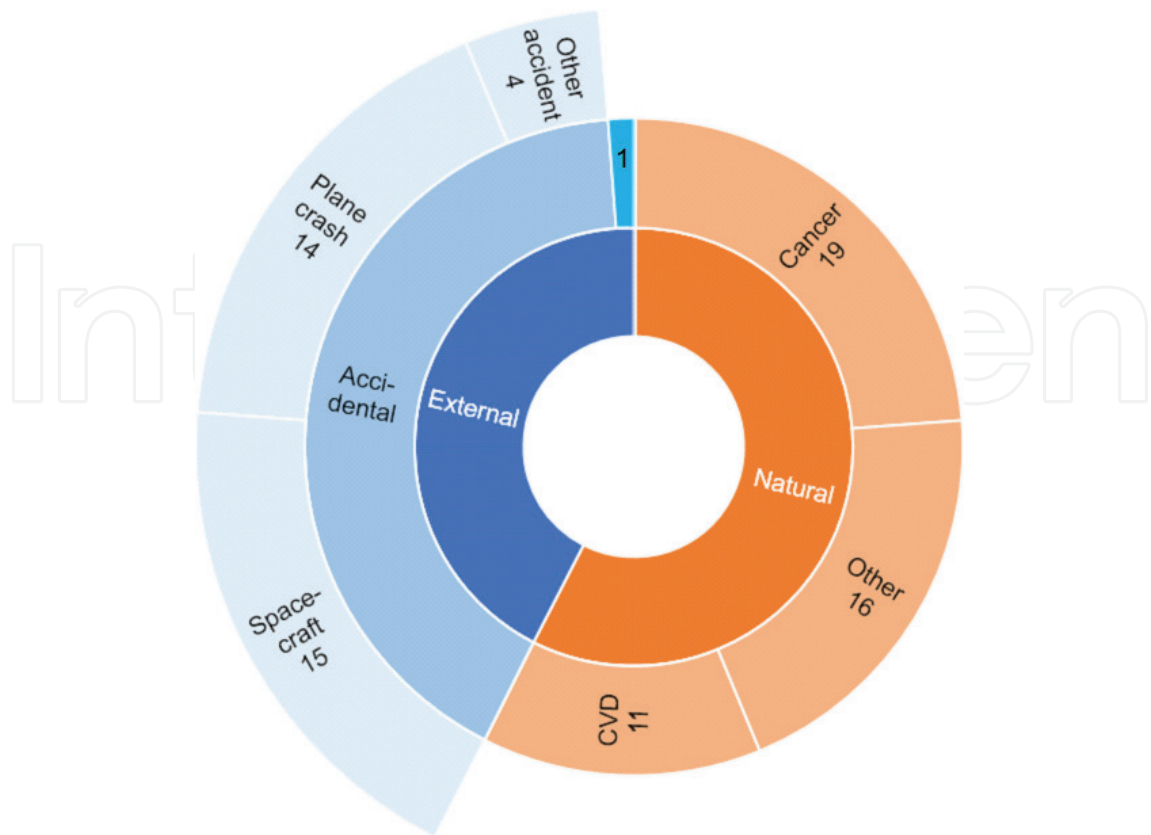


Figure 1. Causes of death among United States astronauts, 1960–2017.

3.2. All-cause mortality

In perhaps the first systematic analysis of astronaut mortality, based on data from 15 April 1959 to 30 September 1991, a nearly two-fold increased risk of death was reported compared to age- and gender-matched general population rates (SMR = 181, 95% CI = 110–279) [6]. The result was surprising, as it was expected that astronauts might experience lower all-cause mortality rates than the general population, thanks to their high levels of physical fitness, socio-economic status, and free access to presumably top-quality healthcare (a phenomenon often referred to as the healthy worker effect (HWE)) [7]. Another analysis of the same data compared astronauts with ground-based employees of the Johnson Space Center (JSC) in Houston, TX and found astronauts to be at more than 5 times the risk of death from all causes (hazard ratio = 5.07; 95% CI = 2.46–10.41), adjusting for sex, education, marital status at selection, and smoking history [8]. Comparing astronauts to a similar occupational cohort seemed to suggest that astronauts really were at greater risk of death by virtue of their status as space travelers. But if so, why?

By 2009, the picture had become clearer. After 1980, all-cause SMRs began declining: from a statistically insignificant 115 (95% CI = 53–219) in the 1980s, to 61 (95% CI = 29–112) in the 1990s, to finally a statistically significant 43 (95% CI = 23–74) in the first decade of the 2000s [9]. The overall SMR for 1980–2009 was also significant, at 59 (95% CI = 40–83) [9]. It appeared, then, that astronauts were at lower overall risk of death than the general population as a whole.

As it turned out, external causes-accidental deaths in particular-were the main drivers of the observed increased mortality risk in the early years, mainly due to deaths that occurred in the 1960s. A drop in the accidental death rate over time lowered SMRs from the year 1980 onward, though astronauts were still at a significantly higher risk of accidental death than the general population throughout the study period. Eventually, as the cohort of astronauts aged, the near absence of death by chronic diseases reduced astronaut all-cause mortality rates to levels significantly below those in the general population.

Figure 2 displays all-cause decade-specific SMRs for astronauts for 1960 to 2017, as well as a summary SMR for the entire 1960 to 2017 period, based on the latest available data. It is immediately apparent in **Figure 2** that 1960–1969 was a period of high risk for astronauts, as they were more than 8 times as likely to die during this period as were age- and gender-matched members of the United States general population. The pattern across the decades is consistent

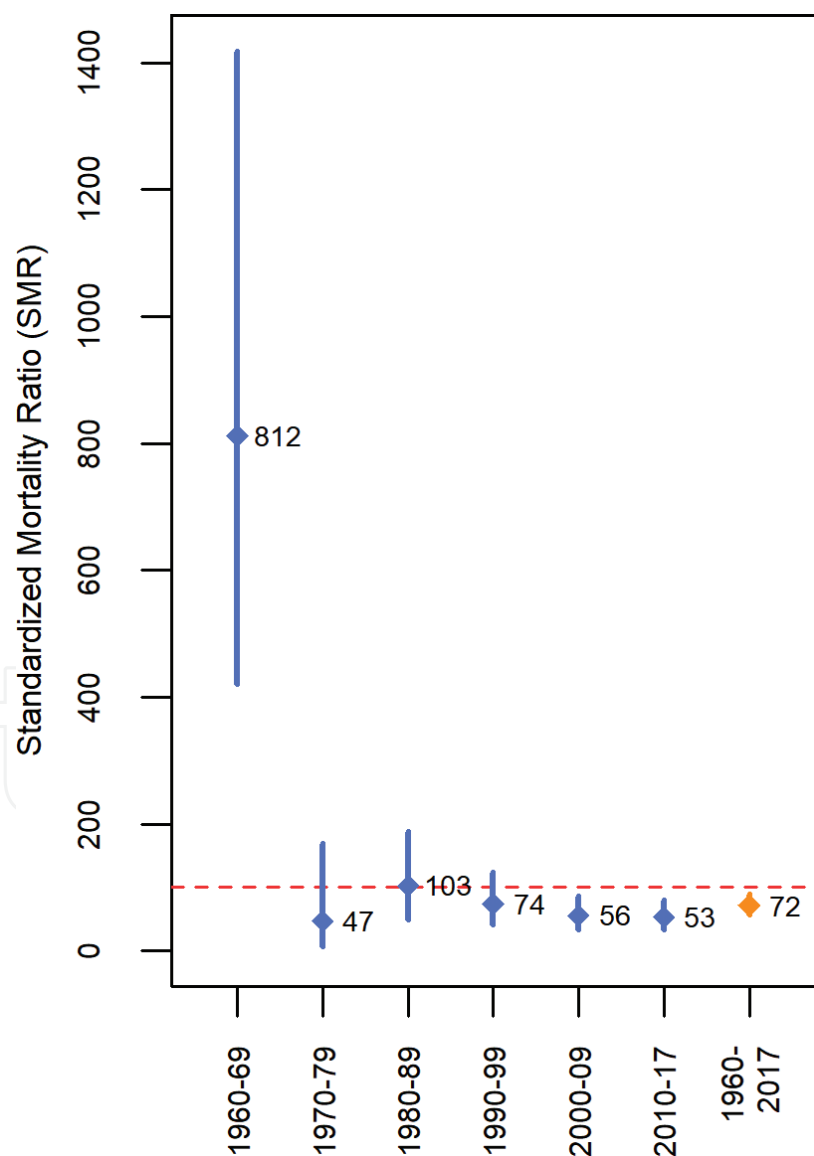


Figure 2. SMRs for all causes of death among United States astronauts, 1960–2017.

with previously published results, with higher astronaut mortality in the 1960s, then falling rates up to the current decade, and an overall lower than expected rate of mortality for astronauts from 1960 to 2017.

SMR of 53 (95% CI = 34–80) for 2010–2017 is reported here for the first time, based on all currently available data. This is broadly consistent with SMR from 2000 to 2009, suggesting a sustained reduction in risk for astronauts and a possible plateauing of the protective effect. If trends in specific causes of death continue as they have, this trend in all-cause SMR will continue as well.

3.3. External causes

Causes of death are subdivided at the most basic level into internal and external causes. Examples of external causes include drowning, electrocution, poisoning, burns, and trauma. For purposes of analysis, we consider external causes to be any death with primary cause code of E800–E899 in the International Classification of Diseases code set, Eighth Edition (ICD-8), E800–E899 in the ICD-9 code set, and V01–Y89 in the ICD-10 code set.

3.3.1. All external causes of death

As we have noted, accidental deaths accounted for all external deaths in the astronaut cohort for many years, and no published study bothered to report on nonaccidental external causes for this reason. Current data include a fair number of deaths due to external causes other than accidents, and we present in **Figure 3**, for the first time, SMRs for all external causes combined, as well as SMRs for accidental causes.

Across all decades, United States astronauts have been at approximately 250% risk of the general population of death due to external causes. This excess risk continues to be driven almost entirely by accidental deaths, some of which occurred in catastrophic accidents that many readers will recall, which took the lives of multiple astronauts in single events.

In the 1980s and 2000s, astronauts were at significantly increased risk of death from external causes, and this is unsurprising. These two decades each saw the destruction of a space shuttle, with the death of multiple astronauts in each: the space shuttle Challenger explosion in January 1986, which claimed the lives of five astronauts, and the Space Shuttle Columbia reentry disintegration in February 2003, which killed 6 astronauts.¹ These deaths pushed SMRs significantly high, even as deaths from other external causes-particularly other accidental sources-were on the decline. These deaths are largely responsible for the overall 2.5-fold increased risk of death due to external causes for the entire follow-up period. Indeed, without these deaths, overall SMR in the 1980s would be approximately 160, and not statistically significant. Likewise, SMR for the 2000s would be approximately 115, and not statistically significant.

¹Three additional people were killed in these two disasters, all of whom were Payload Specialists, i.e., civilians trained for single missions only. As they are not considered a part of the NASA Astronaut Corps, those individuals were not included in either prior research or the updated analyses presented here.

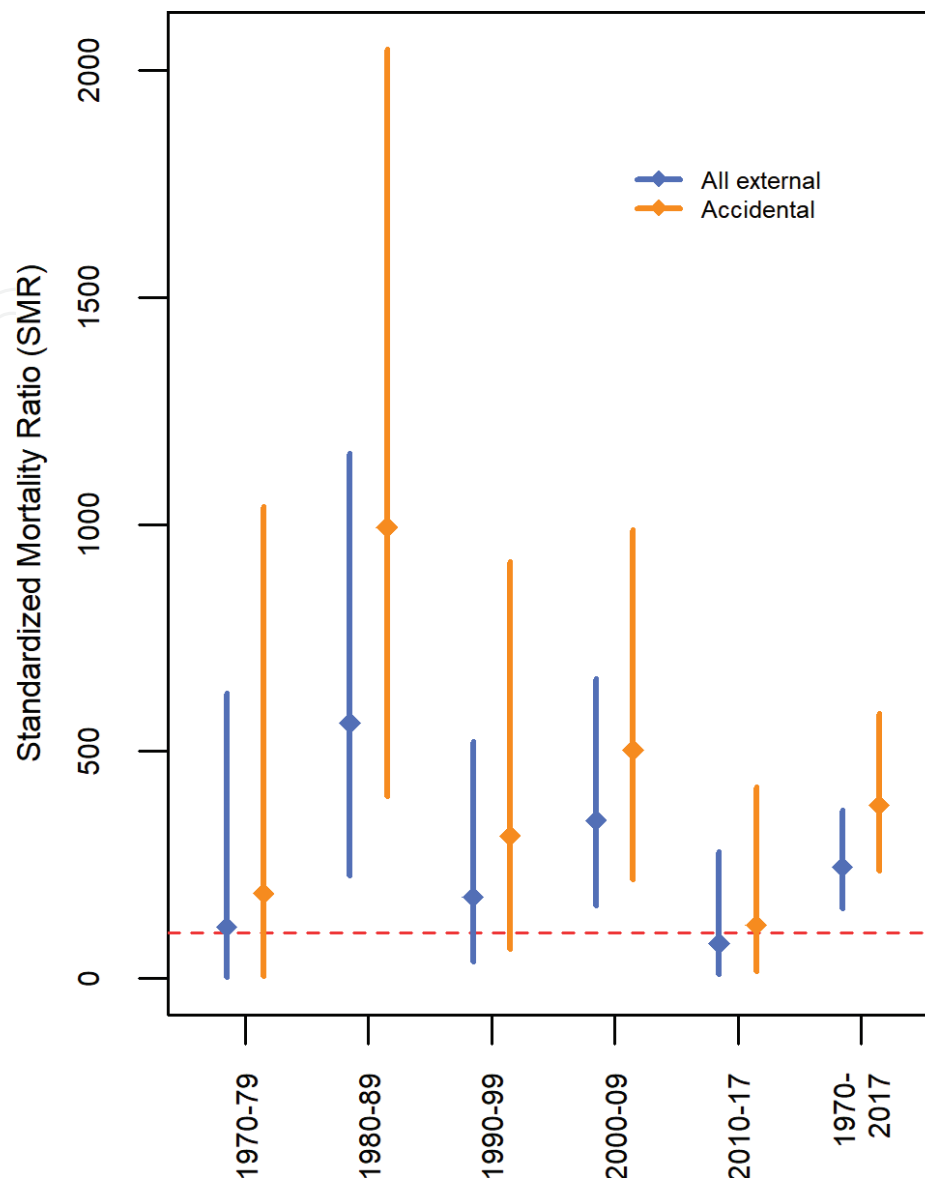


Figure 3. SMRs for all external causes and accidental causes of death among United States astronauts, 1970–2017.

3.3.2. Accidental death

The high risk of accidental death was anticipated from the beginning of the United States space program, when then U.S. President Dwight Eisenhower called for astronauts to be selected from the ranks of military test pilots, because, among other reasons, they were accustomed to high-risk vocational activities [10]. This proved to be prescient: by the end of 1991, 16 of the 20 recorded astronaut deaths were accidental, with half due to space craft accidents, and several of which were duty-related plane crashes. As we have noted, the rate of accidental deaths for this cohort is significantly greater than expected in an age- and sex-matched cohort from the general population.

Accidental death SMRs for all astronauts based on data through 2017 are also given in **Figure 3** as the orange points and lines. The progression of risk for accidental death is the main driver

of the risk for death by all external causes. As such, SMRs follow much the same pattern as those from all external causes. The main difference is that SMRs for accidental death are higher than those for all external causes due to the smaller number of expected deaths in the general population from this causal subset.

3.4. Natural causes

Natural causes of death are causes originating within the body (albeit possibly as a result of an unseen and perhaps unfelt external force, such as cancer precipitated by radiation exposure), rather than a cause related to an obvious external force or object. In the universe of all possible causes, natural causes are the complement of external causes, and thus, in terms of ICD-8, -9, and -10 codes, these would include all codes other than those noted above for external causes in Section 3.3. Natural causes are also a major concern for astronauts in relation to space travel: does time in space equate to a higher mortality risk due to disease?

Natural causes of death include cancer, cardiovascular disease (CVD), and myriad other less common diseases. Testing hypotheses related to large numbers of potential causes as a group can boost statistical power, which can be helpful when analyzing rare events that may have long latency periods (e.g., cancers related to radiation exposure). However, studying natural causes as a single group has its drawbacks, too. The rigorous physical fitness requirements, high-quality health care and careful follow-up of health, and relative high socio-economic status of astronauts may all be protective of some diseases. Thus, there may be two forces at work, each of which may mask the effects of the other relative to all natural-cause mortality: exposure to space on the one hand, which may elevate the risk of death due to some causes, and a healthy lifestyle on the other hand, which may mitigate the risk of other (or even some of the same) causes. We will explore these issues in some depth now.

3.4.1. Any natural cause of death

As far as we are aware, analysis of natural-cause mortality of astronauts has only previously been reported in the context of a dissertation project [11]. In that project, the authors fit a Poisson regression model to explore possible differences in natural-cause mortality rates of astronauts above and below the median in estimated space radiation exposure. Unfortunately, the risk of misclassification of exposure and demonstrably low statistical power made the results inconclusive [11]. We present SMRs for death by natural causes, CVD, and cancer in **Figure 4**.

The darker blue points in **Figure 4** suggest that astronauts have been at a consistently reduced mortality risk due to natural causes and significantly so since the year 2000. For the entire 1970 to 2017 period, astronauts were at less than half the risk of death from natural causes as the general population. As with SMRs for external causes, SMRs in **Figure 4** are based on only a few deaths through the end of the 1990s and thus do not reach statistical significance. From the year 2000 onward, the aging astronaut cohort resulted in dramatic increases in the number of expected deaths, and observed astronaut deaths did not keep up, resulting in SMRs statistically significantly less than 100 for the latest two periods.

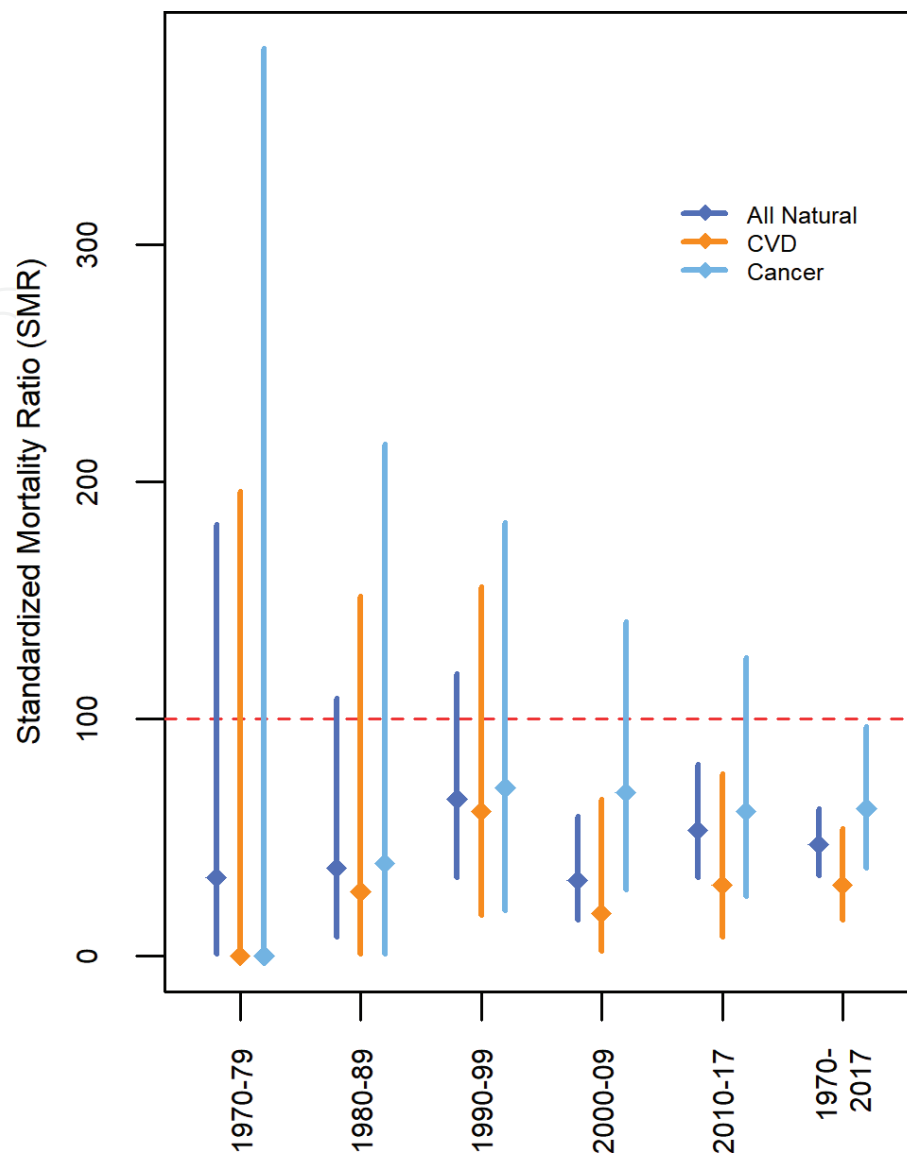


Figure 4. SMRs for natural-cause, CVD, and cancer mortality among United States astronauts, 1970–2017.

3.4.2. Cardiovascular disease

Cardiovascular disease includes ischemic heart disease, heart failure, stroke, and any other circulatory disease captured by ICD-8 codes 390–458, ICD-9 codes 390–459, and ICD-10 codes I00–I99.

Death from CVD is an outcome that has been tracked since the first published research on astronaut mortality in 1993. Even though CVD has been one of the most common causes of death for astronauts, SMR for CVD through 1991 was reported to be a statistically insignificant 47 (95% CI = 5–168), suggesting (inconclusively) that astronauts may be at less than half the risk of death from CVD in the general population [6]. An analysis comparing the same astronaut mortality rates to those of ground-based controls from the JSC found astronauts to have an insignificant elevation in risk (HR = 1.20; 95% CI = 0.27–5.28) [8]. Considering the

wide range of possible effect sizes those two studies suggested were possible (and the lack of statistical significance in both of them), no solid conclusions could be drawn about CVD mortality from the 1991 data set.

The 2010 study of astronaut mortality by Reynolds and Day [9] reexamined CVD mortality and found that, in comparison to the general population for the 1980 to 2009 period, CVD SMR was a statistically significant 27 (95% CI = 9–63), validating the findings from Peterson et al. [6].

Again, it has been speculated that HWE is responsible for the reduction in risk of CVD mortality even in the face of potentially heavy smoking by the earliest groups of (mostly military) astronauts [9, 12]. Prior reports of astronaut biometric measurements have shown astronauts to be at or below suggested normal limits for blood pressure, cholesterol, and body mass index, all important risk factors for cardiovascular disease [8, 13].

Figure 4 shows updated SMRs for CVD among astronauts (orange points and lines), once again adding in the USAF astronauts and extending follow-up to the end of 2017. Thin data in the early decades give statistically insignificant SMRs through 1999. However, in the last two periods, SMRs show significant reductions in CVD mortality rates for astronauts, as does the overall 1970–2017 SMR. For the overall period, astronauts are at less than one third the risk of death from CVD as is the general population of the United States (SMR = 30; 95% CI = 15–54).

In total, the evidence thus far suggests that astronauts are at a greatly reduced risk of death from CVD in comparison to the general population.

3.4.3. Lunar astronaut mortality from CVD

In 2016, a published study investigated the risk of CVD mortality for astronauts who had either walked on the moon or who completed circumlunar flights as part of the Apollo missions (so-called lunar astronauts) [14]. The study compared lunar astronauts to astronauts who only completed missions on low Earth orbit (LEO), or to astronauts who had not flown to space at all (“nonflight” astronauts). Dividing the lunar astronaut percentage by the percentage of deaths from CVD in the comparison groups (up to the end of 2015), the authors computed proportionate mortality ratios (PMRs). PMRs attempt to look for differences in the proportion of deaths by a specific cause between two groups. In this case, PMRs demonstrated that a higher proportion of lunar astronauts died of CVD than either of the comparison groups, leading the authors to conclude that lunar astronauts were at greater risk of death by CVD than astronauts who had never left low Earth orbit or never flown into space at all. Conflating these findings with a model of how radiation may damage vascular endothelial tissue in rats, the authors proposed a potential biological mechanism to match their purported epidemiologic findings [14].

Other authors were quick to point out flaws in the study. Questions arose regarding the data set used, the analytic method, and the potential imprecision of the disease outcome definition [15]. Several comments on the online version of the paper pointed to methodological flaws in the PMR analysis, particularly the potential biases related to competing risks or confounding by age when the age structure is markedly different between groups [16]. As it turns out, these two issues were, in fact, driving the PMRs to be misleading.

A reanalysis of the astronaut data set used by Delp et al. [14] revealed that lunar astronauts were significantly older than the nonflight and LEO-only astronauts at the start and end of the study, making the potential for age confounding in the PMR high [17]. Using SMRs instead of PMRs demonstrated that when the age structure was taken into account (and all the available information, including follow-up time, used), there were no significant differences between any of the astronaut groups in risk of death from CVD [17].

In comparison to nonflight astronauts, lunar astronauts had no significant increase in risk, with an SMR of 117 (95% CI = 24–343) for the 1968–2015 period. In comparison to LEO astronauts in the same period, SMR was 67 (95% CI = 14–197), and, in comparison to the combined group of LEO and nonflight astronauts (nonlunar astronauts) in the same period, the SMR was 77 (95% CI = 17–237) [17]. These results offered no plausible evidence of an increase in risk of death from CVD for Apollo lunar astronauts and showed that prior research on the topic was still entirely tenable: there is simply no evidence to support the hypothesis that lunar astronauts are at elevated risk of CVD mortality compared to nonlunar astronauts [17].

3.4.4. *Cancer mortality among astronauts*

Since the beginning of the space program in the United States, there has been concern that radiation exposure in space may lead to greater mortality from cancer, particularly from the unique radiation sources found in outer space [18, 19]. Because of this, cancer incidence has been under regular surveillance by NASA, and cancer mortality has been reported on repeatedly over the years [6, 8, 12].

Cancer deaths are those with a primary cause ICD-8 code of 140–239, ICD-9 code of 140–239, or ICD-10 code of C00–D48. The first study of astronaut mortality from 1993 did not report any mortality measures related to cancer and for good reason: at that point in time, there had only been one death due to cancer among astronauts. The first reported analysis of cancer mortality among astronauts was from the 1998 Longitudinal Study of Astronaut Health (LSAH) [12]. The study compared the three observed astronaut deaths from cancer to the number expected in two comparison groups: the general population of Public Health Region 6 of Texas and ground-based controls from Johnson Space Center (JSC) [12]. In comparison to the general population, astronauts were found to be at less than half the risk of dying from cancer (SMR = 47; 95% CI = 10–105). In comparison to the LSAH controls, however, astronauts were at almost three and a half times the risk of death from cancer (SMR = 345; 95% CI = 66–756) [12]. These results suggested three possibilities for astronauts: (1) they are at greater risk of cancer due to exposure to space travel, (2) the JSC ground-based controls are healthier than astronauts in ways that protect against cancer, or (3) these results represent a statistical anomaly of this relatively small sample of data. In any case, the small number of observed deaths provides for low statistical power, making results inconclusive.

The LSAH reexamined cancer mortality in a study published in 2000 [8]. In a proportional hazards model, again comparing astronauts to the LSAH controls, astronauts were found to have a hazard ratio of 3.19 (95% CI = 0.93–21.85), adjusted for sex, education, marital status at selection, and smoking history [8]. This similar result is not surprising, as the analysis was based on essentially the same data set as the prior study: there had been only one additional

cancer death among astronauts since the 1998 study. Once again, the small number of deaths plus lingering doubt about the suitability of the controls yielded an underpowered and, ultimately, inconclusive analysis.

In the 2010 study of astronaut mortality, cancer mortality was analyzed by decades between 1980 and 2009 [9]. By the end of 2009, the number of astronaut deaths from cancer had risen to a total of seven. For the three decades 1980–2009, SMRs for cancer in comparison to the general population were consistently below 100, but still, small numbers of cases made SMRs nonsignificant. Pooling the data from the entire 30 years led to SMR of 47 (95% CI = 19–97) [9]. This was the first time that the observed reduction in cancer mortality among astronauts reached statistical significance and was consistent with prior general population comparisons.

Updated findings through 2017 are displayed as the lighter blue points and lines in **Figure 4**. With the additional follow-up time and incorporation of USAF astronauts, we can see that astronauts are still estimated to be at about half the risk of cancer mortality as the general population between 2010 and 2017, though the results are again not significant (**Figure 4**). SMR for the period 1970 to 2017 is significant, however, with SMR of 62 (95% CI = 37–97).

3.4.5. *The effect of competing risks on rates of death by natural causes*

As we have seen, astronauts have at times been at elevated risk of death due to external causes (primarily accidents) and have been and continue to be at reduced risk of death due to natural causes. External and internal (or natural) causes are mutually exclusive, competing causes of death (at least in terms of an underlying cause of death). That this may explain the low natural-cause SMRs that have been observed has been suggested in recent literature [17, 20]. Given that a significant number of astronauts have died (some quite young) of external causes, this could alter natural-cause mortality rates at older ages.

Such altered natural-cause mortality rates would in turn affect SMRs for natural causes, and this could explain the low natural-cause SMRs that have been observed for astronauts. We can attempt to quantify the potential effect of this via sensitivity analyses, whereby we compute SMRs under extreme hypothetical alternative scenarios regarding the reassignment of observed deaths due to external causes. These alternative SMRs are shown in lighter blue (left-most SMR in each cluster) and darker blue (right-most SMR in each cluster) in **Figure 5**, along with the observed natural-cause SMRs in orange.

Specifically, the lighter blue and darker blue point estimates in each period form an upper and lower bound to our natural-cause SMRs under two differing counterfactual assumptions regarding the occurrence of deaths due to external causes: (1) assuming the external deaths did not happen at all and the astronauts are still alive as of the end of the follow-up period (lighter blue); (2) assuming all external deaths occurred at the observed times, but were due to natural causes instead (darker blue). The former is the most optimistic, biasing SMRs downward by inflating only the denominator of the natural-cause SMR. As a result, all of these point estimates are lower than their corresponding observed (orange) point estimates. The latter scenario is the most pessimistic possible scenario, biasing SMRs for natural causes upward by inflating the number of natural-cause deaths without changing the observation time. This

leads to all darker blue point estimates being higher than their corresponding orange point estimates. The true (unbiased) estimates, and estimates for all other potential scenarios, must be somewhere in between. Thus, the light blue zone surrounding these sets of SMRs show the total range of possibility for the true SMR (with 95% CI) in each period.

In the observed SMRs for natural causes (**Figure 5**), no SMRs are statistically significant until the 2000–2009 period. However, SMRs in the optimistic scenario (**Figure 5**) reach statistical significance in the 1980s and remain significant through the end of the observation period. This suggests that early deaths due to external causes may in fact be biasing SMRs for natural causes upward. Had those astronauts lived, SMRs for natural causes could be even lower than observed.

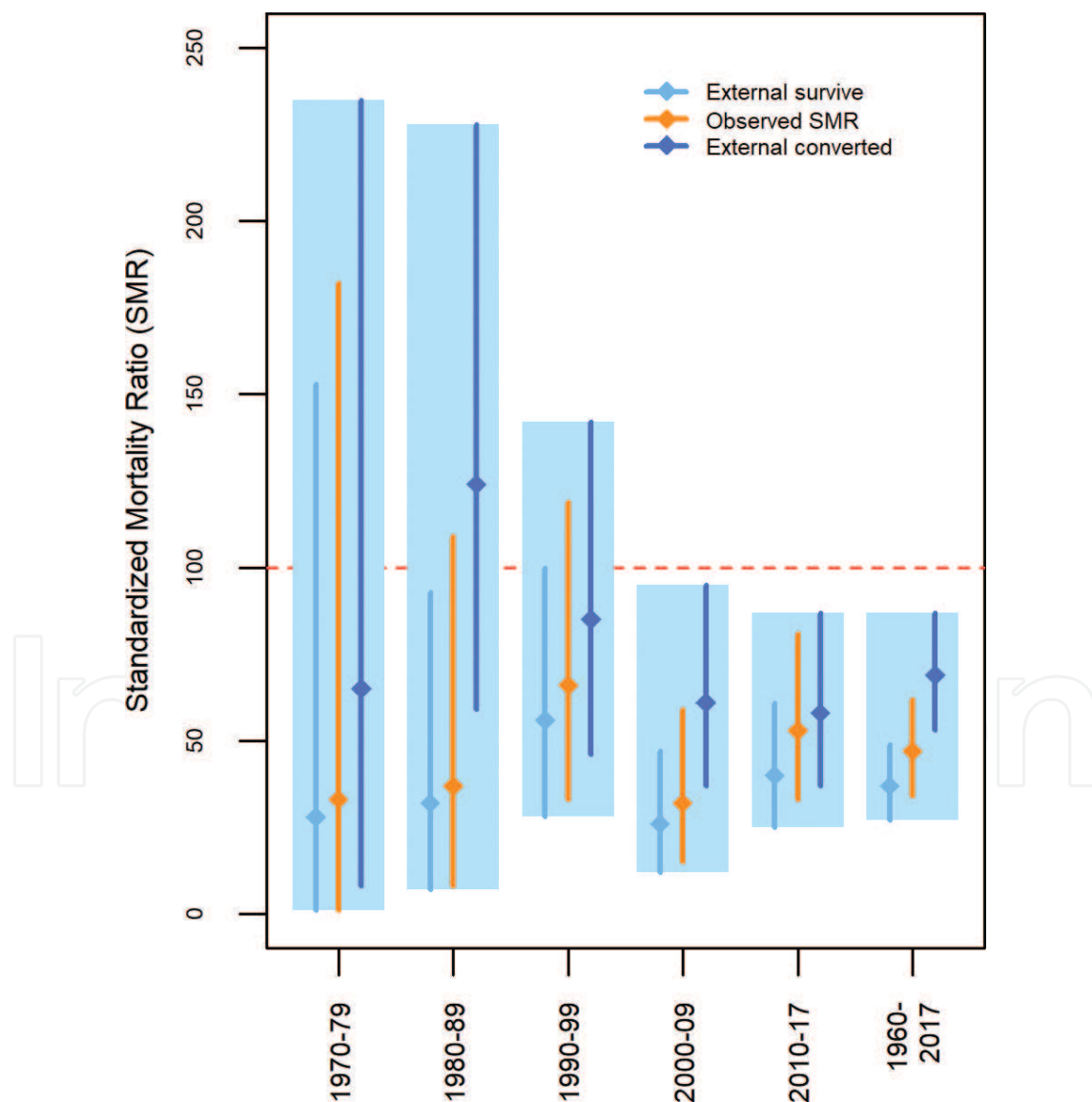


Figure 5. Alternative SMRs for natural-cause mortality among United States astronauts, 1970–2017.

4. Causes of death and comparative mortality for Soviet and Russian cosmonauts

In comparison to astronaut mortality, there has been comparatively little research on cosmonaut mortality. To date, only three studies have been published on this topic, all since 2014 [21–23]. From this research, we know that the patterns of mortality risk of cosmonauts are quite similar to those of astronauts in terms of how they compare to Soviet and Russian general population controls.

Cosmonauts tend to have the same major causes of death as astronauts and, like astronauts, tend to have lower mortality rates for those causes than the general population. This is perhaps unsurprising given the similar vocational backgrounds, similar (and now joint) training and physical readiness criteria required to be either a cosmonaut or astronaut, and the similar levels of biomedical monitoring of cosmonauts throughout their careers [24, 25]. That cosmonauts would be at elevated risk of death due to accidents, especially in the early years of the space programs, might also be expected, and as we shall see, this is indeed true. We refer the reader again to **Tables 1–3** for demographic and actuarial information about the cosmonaut corps.

For comparisons, Russian general population mortality rates were taken from the Human Mortality Database [2] and the Russian Fertility and Mortality Database from the Center for Demographic Studies at the New Economic School [26]. The Human Mortality Database supplied all-cause mortality rates for the years 1960 through 2015; the Russian Fertility and Mortality Database supplied cause-specific rates for the years 1960 to 2014. The latest rates available (2014 or 2015) were used for comparison with cosmonaut data from 2015, 2016, and 2017 as needed.

4.1. Numbers and causes of cosmonaut deaths

Figure 6 shows the causes of death for cosmonauts through 31 October 2017. What should be immediately apparent in **Figure 6** is the relatively high number of deaths due to unknown causes. There were 24 completely unknown causes of death, and a single unknown external cause, for a total of 25 causes of death with some degree of uncertainty as to their causes. The 24 totally unknown causes of death represent 25% of the 96 total cosmonaut deaths. Unknown causes do not pose a problem for an analysis of all-cause mortality. However, depending on which causes these unknown might actually represent, this may substantially alter cause-specific mortality rates and SMRs. We will address these issues further in the sections that follow.

Similar to the astronaut cohort, the most common causes of death for cosmonauts were CVD (25 deaths) and cancer (20 deaths), and accidents (19 deaths), with a small number of deaths by other natural causes (7 deaths). However, external causes of death have accounted for a smaller share of cosmonaut deaths (21%), compared to the astronaut cohort (42%).

4.2. All-cause mortality

Much like United States astronauts, cosmonauts have been at decreased risk of all-cause mortality when compared to the general population [21–23]. This has been shown to be true for the cosmonaut cohort as a whole [21], as well as the subset of cosmonauts who went to space [22, 23].

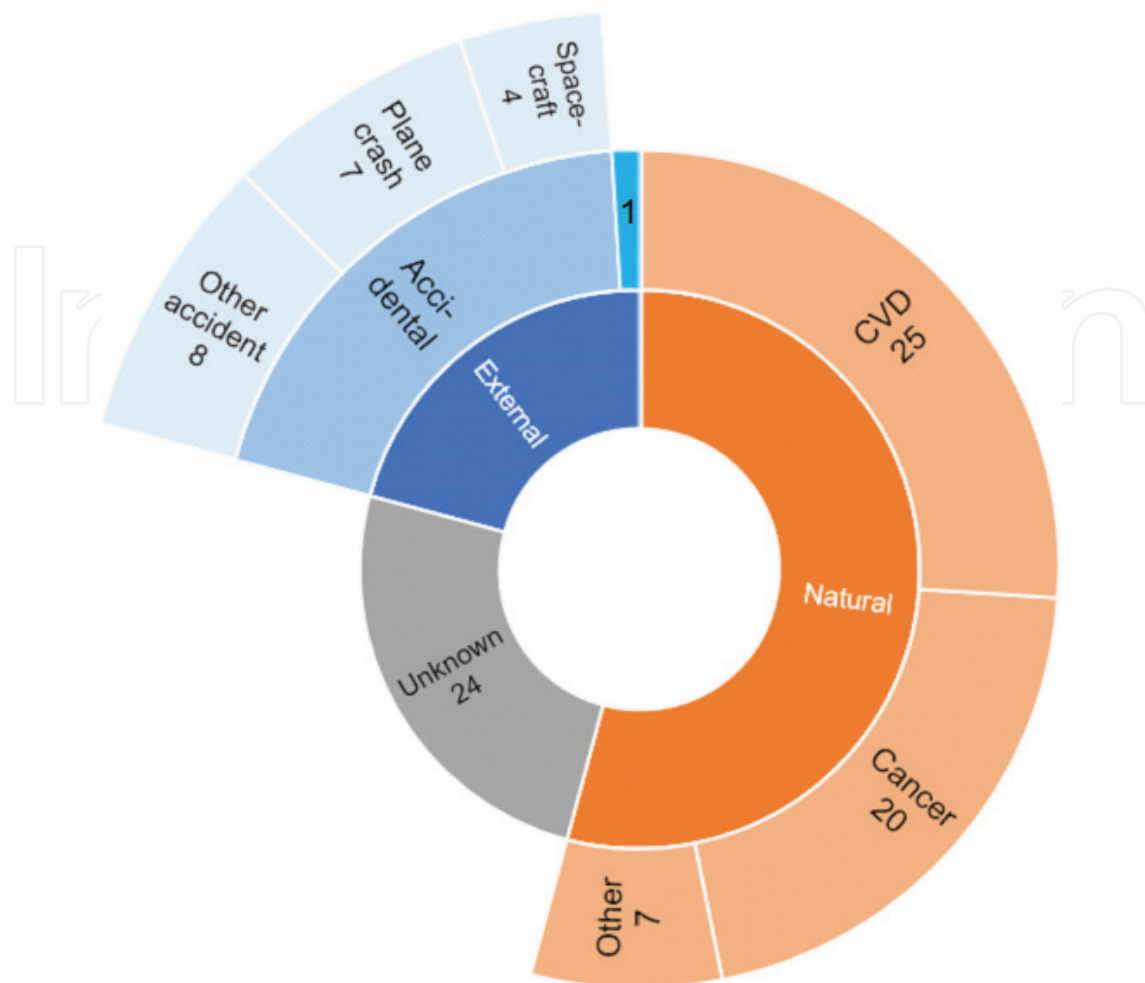


Figure 6. Causes of death for Soviet and Russian cosmonauts, 1960–2017.

The first study of cosmonaut mortality, published in 2014, studied the entire cohort of people who were not only selected for but also completed cosmonaut training [21]. The study reported a dramatic (and statistically significant) reduction in risk of death from all causes. However, SMRs reported in this study were incorrect, as SMRs were computed using probabilities of death for the astronaut cohort rather than mortality rates. While the difference between age-specific probabilities of death and mortality rates may be negligible at young ages, as age increases mortality rates become substantially higher than probabilities of death. This made SMRs and the corresponding bounds on their 95% confidence intervals too low. Because of this, no conclusions can be drawn from the all-cause SMR results from that study alone.

Two additional studies on cosmonaut mortality have been published after the 2014 Reynolds et al. study. These two studies are highly similar to each other in that they use only cosmonauts who went to space. The first, published in 2016 in the Russian journal *Air-Ecosystem and Environmental Medicine*, studied cosmonaut mortality within the cohort of 114 cosmonauts who flew to space at least once [22]. The authors compared the mortality experience of these cosmonauts to that of the general populations of the Moscow region and the Russian Federation as a whole, with follow-up through the end of 2013. Unfortunately, the study

counted observation time as starting with enrollment in the cosmonaut corps, meaning SMRs were incorrect (biased downward) due to an *immortal time bias* [27]. In this instance, the time between selection and the first space mission is guaranteed survival time, as the cosmonauts who may have died before their first space flight would not be included in the analysis. The effect of this is to systematically bias SMRs downward. Once again, this error renders the study inconclusive on the mortality experience of cosmonauts.

A second study published in late 2017 added an additional year of follow-up to the 2016 study and corrected the immortal time bias. This study confirmed that cosmonauts are at reduced risk of death from all causes, reporting SMR of 40 (95% CI = 27–61) for death by all causes in comparison to the Russian Federation [23].

A reanalysis (with correction) of the Reynolds et al. data [21] is presented in **Figure 7**, updated to 31 October 2017. This shows the trend in SMRs for all-cause mortality for cosmonauts over time.

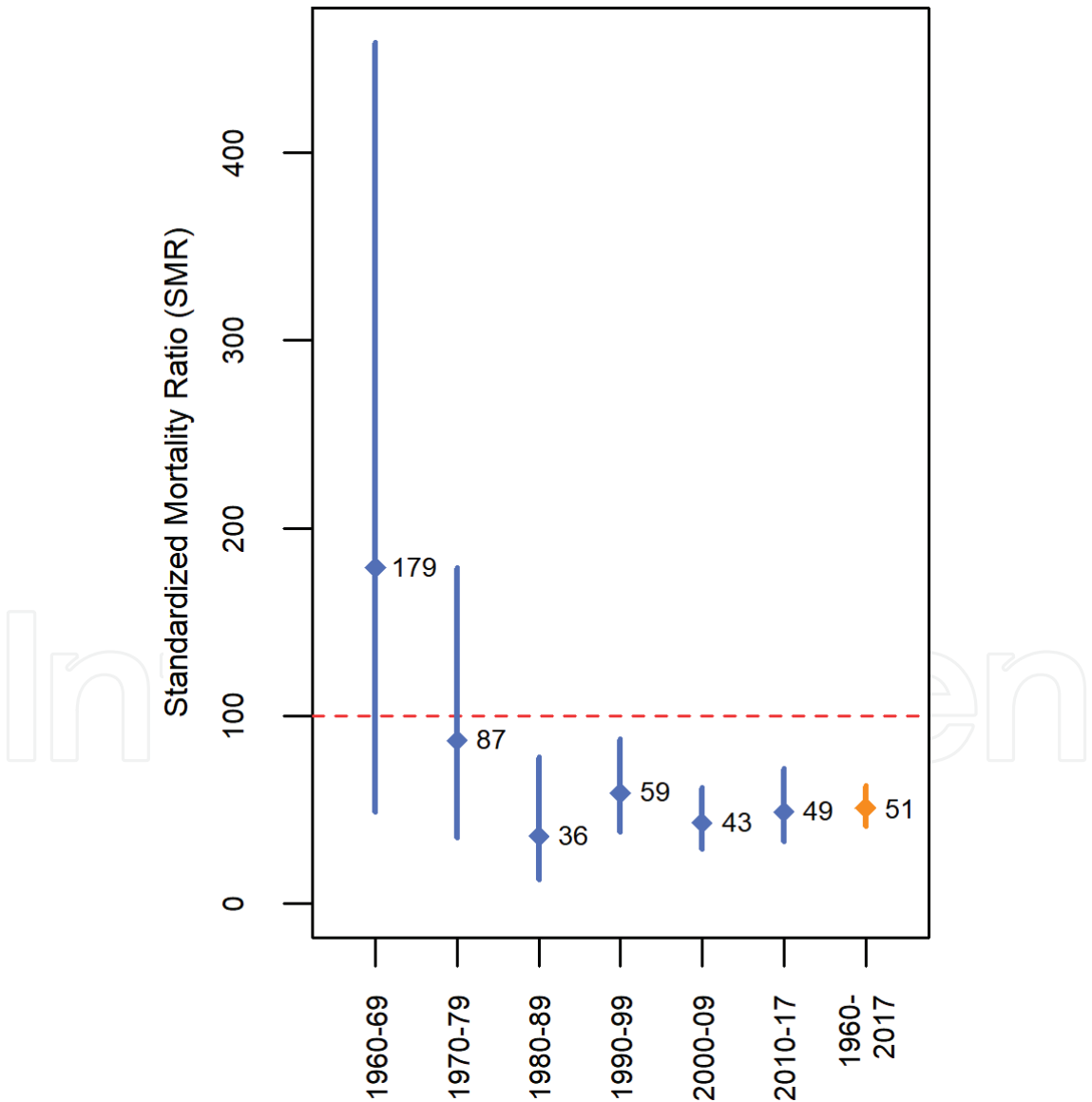


Figure 7. SMRs for all causes of death for Soviet and Russian cosmonauts, 1960–2017.

Though mortality for cosmonauts in the 1960s was 179% of that expected, the SMR was not statistically significant. Cosmonauts experienced 87% of the mortality expected in the 1970s, also not significant. From the 1980s onward, the mortality risk for cosmonauts has been statistically significantly *reduced* in comparison to the general population, with SMRs ranging from a low of 36 to a high of 59, and an overall SMR for the 1960–2017 period of 51 (95% CI = 41–63). These long-term and correctly-computed findings solidify the result that cosmonauts are at an overall lower risk of mortality than the Russian general population. They also largely agree with the prior results from the 2016 study by Ushakov et al. [22] even with slightly different cohort definitions. From this, we can conclude that, overall, cosmonauts have been at a lower risk of death from all causes, between 1960 and 2017, than the year-, age- and sex-matched general population of Russia.

4.3. External causes

4.3.1. All external causes of death

As noted above, (known) external causes of death represent just over one-fifth of cosmonaut deaths. Yet, the only previously reported mortality measure in relation to external causes came from the 2016 study, which, as previously mentioned, was biased [22]. Nevertheless, the authors reported that, for the period 1960–2013, cosmonauts who had flown on at least one mission to space had SMR for external causes of death of 42 (95% CI = 16–107) in comparison to the general population of the Russian Federation [22].

Figure 8 shows updated SMRs for all external and accidental causes of death for all trained cosmonauts by decade between 1960 and 2017. The 1960s saw three times the number of deaths from external causes as expected, but this quickly tapered off to cosmonauts having fewer deaths than expected.

Results were generally not statistically significant by decade, but over the entire period from 1960 to 2017, cosmonauts were at significantly lower mortality than the general population, with SMR of 47 (95% CI = 29–72). This overall SMR is quite close to that published by Ushakov et al. [22], in spite of the bias in that article and the differing cohort definitions. Overall, the evidence shows that cosmonauts are at lower risk of death from external causes than is the Russian general population.

4.3.2. Accidental causes of death

Similar to astronauts, the majority of deaths due to external causes (19 of 20 for which causes were known) for cosmonauts have been accidental. Given this, it is not surprising that the pattern of SMRs for accidental deaths (**Figure 8**) is very similar to that for all external causes combined.

SMR of 62 (95% CI = 38–98) for the entire 1960–2017 period is close to the SMR of 52 (95% CI = 19–139) reported by Ushakov et al. [23] The wider confidence interval on the Ushakov SMR is a direct result of the more limited data used in that study (only male cosmonauts who had been to space, with follow-up to the end of 2014).

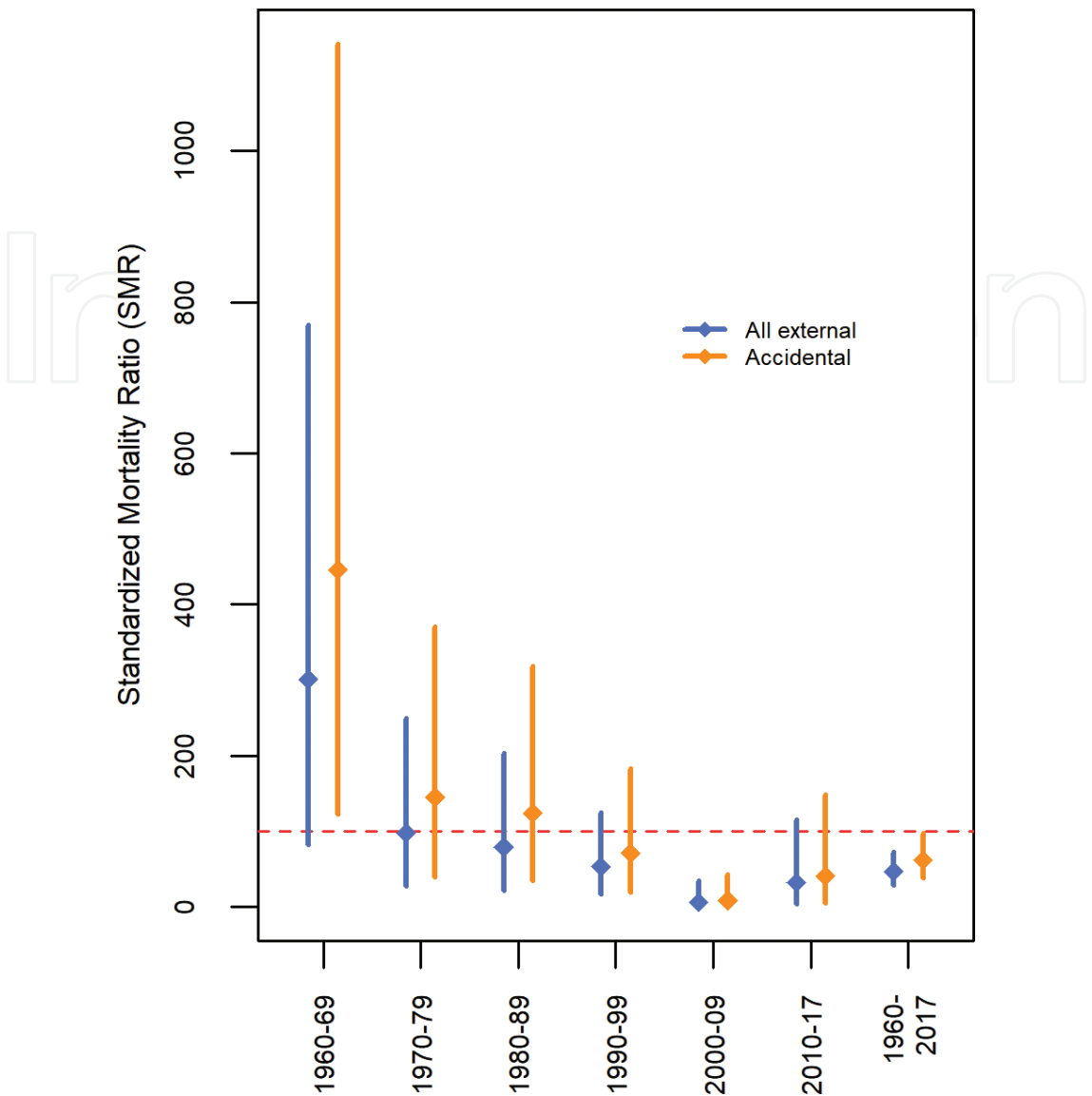


Figure 8. SMRs for all external causes and accidental causes of death for Soviet and Russian cosmonauts, 1960–2017.

4.4. Natural causes

Natural causes of death are responsible for more than 50 cosmonaut deaths to date (**Figure 6**). Primary among them have been cancer and cardiovascular disease, with a small number of assorted other natural causes.

No prior research has reported measures of mortality for all natural-cause deaths for cosmonauts. **Figure 9** shows SMR for natural causes (darker blue), CVD (orange), and cancer (lighter blue) for 1960 to 2017.

SMRs for all natural causes of death in all decades (darker blue) were below 100, though they only reached statistical significance in the 1980–1989 period and remained significant thereafter. SMRs ranged between 0 and 76, with SMR of 33 (95% CI = 25–43) for the entire 1960–2017 period, indicating that cosmonauts were at one-third the risk of death by natural causes as the general population of Russia.

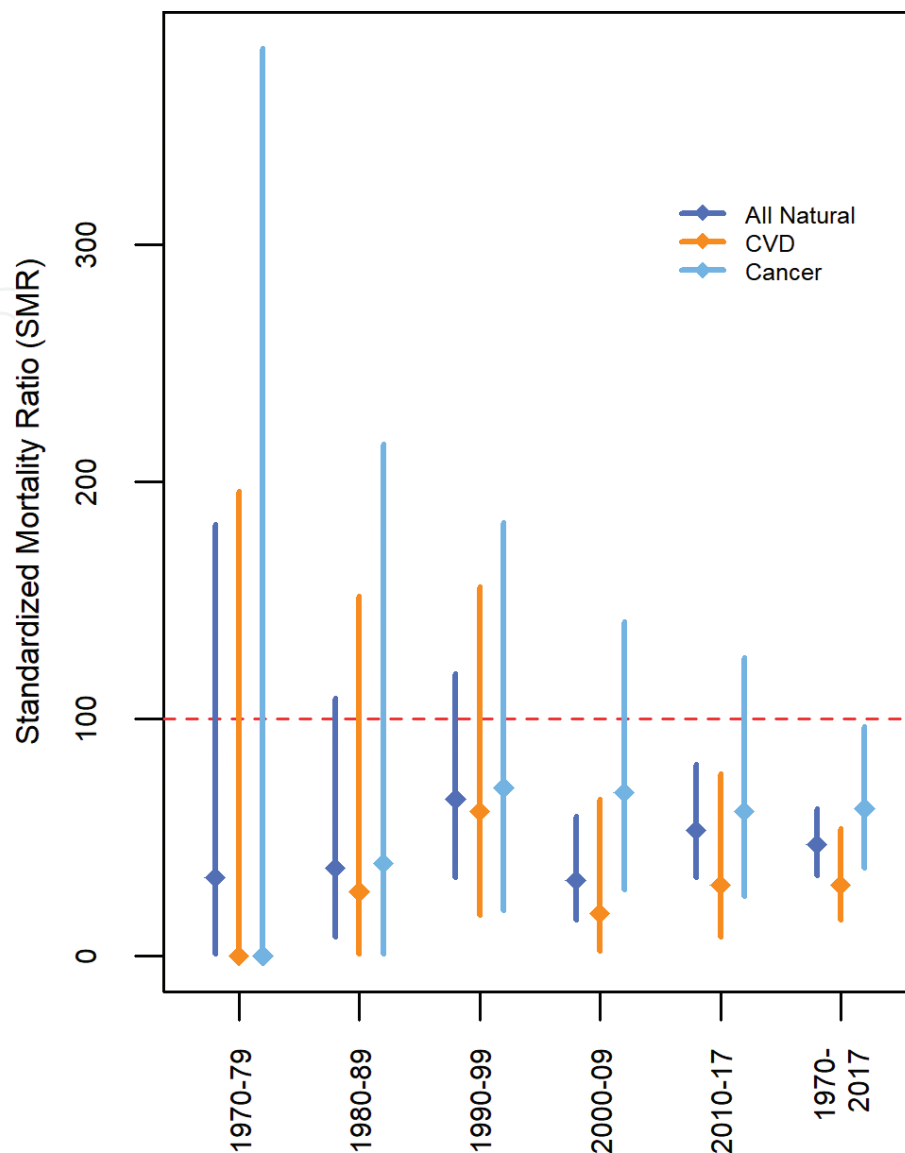


Figure 9. SMRs for all natural-cause, CVD, and cancer mortality among Soviet and Russian cosmonauts, 1960–2017.

4.5. Cardiovascular disease

One of the major components of death by natural causes, CVD has been responsible for 25 out of 52 (48%) of the known natural-cause deaths among cosmonauts. Prior research reported that cosmonauts who have been to space at least once had between 35% and 40% risk of death by CVD compared to the general population through the end of 2014 [22, 23].

Looking to **Figure 9** once again, we can see SMRs for the trained cosmonaut cohort (orange). Interestingly, there were no deaths from CVD in either the 1960s (not shown) or 1970s. From 1970 to 2017, SMRs show decreased risk of death from CVD, with SMRs ranging from 0 to 62. Overall, the SMR from 1960 to 2017 is 28 (95% CI = 18–41).

The trend here may be due in some part to missing information on CVD deaths in the decades since 1990. In those decades, there have been 25 deaths from unknown causes. Depending on how many of those deaths were due to CVD, this could be enough to push some of these

SMRs to reflect significantly increased risk for cosmonauts. (See Section 4.7 below for further discussion and analysis of this point.) Nevertheless, based on **Figure 9** and the prior research, it appears that cosmonauts are at decreased risk of CVD mortality compared to the Russian general population.

4.6. Cancer

The other major component of natural causes of death for cosmonauts is cancers of various types. Previous studies of cosmonaut mortality reported cosmonauts who had been to space as having an SMR of approximately 75 for death by cancer [22, 23].

Figure 9 also shows SMRs for cancer in the wider cosmonaut cohort (lighter blue points and lines). While most SMRs over time are not statistically significant, the SMR of 60 for the entire period from 1960 to 2017 did reach significance (95% CI 36–92). As with natural causes and CVD, SMRs for cancer from 1990 onward could be influenced by the number of unknown causes of death that might rightly be attributed to cancer. Section 4.7 explores this possibility.

4.7. The effects of unknown causes

One potential limitation of the cause-specific analyses presented for cosmonauts is the 24 deaths due to unknown causes. Depending on the distribution of the true causes of these deaths, they could dramatically alter the cause-specific SMRs reported here. In order to explore this possibility, we recomputed SMRs under various assumptions about the distribution of the unknown causes of death.

We assumed for these analysis that the unknown causes were cancer deaths, CVD deaths, or deaths due to other natural causes. This allows us to more deeply explore the question of whether space travel is shortening the longevity of space explorers through increased rates of death by chronic disease, a question of primary concern (that accidents related to space travel will shorten the lives of some astronauts is accepted).

As reflected in **Figure 10**, the 1990–1999 period had 3 unknown deaths, the 2000–2009 period had 5 deaths with unknown causes, and the 2010–2017 period had 16 deaths with unknown causes.

To see the effect these deaths may have on natural-cause SMRs, we recomputed SMRs assuming that all deaths due to unknown causes in a period were due to each respective cause in turn (natural causes overall, CVD or cancer). The result is **Figure 11**.

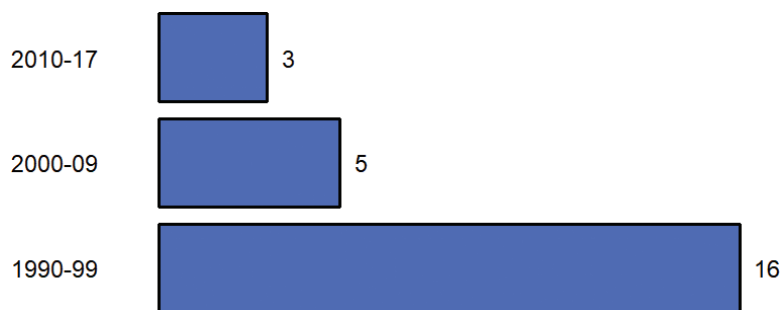


Figure 10. Distribution over time of deaths by unknown causes for Soviet and Russian cosmonauts.

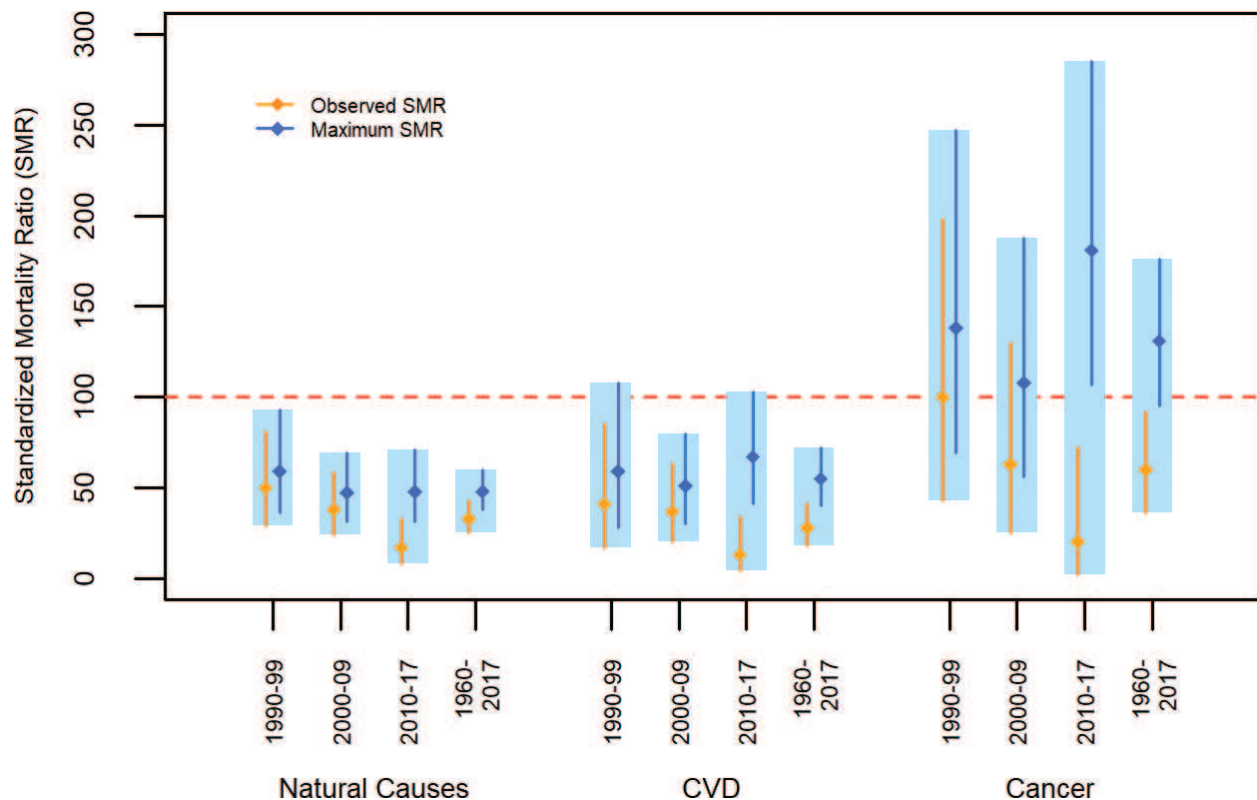


Figure 11. Alternative SMRs for Soviet and Russian cosmonauts, 1990–2017.

In **Figure 11**, the orange points and lines represent observed SMRs and 95% confidence intervals for natural causes, CVD and cancer (exactly as in **Figure 9**), omitting from the analyses all unknown causes. The blue points and lines in **Figure 11** are SMRs and 95% confidence intervals calculated by counting all deaths due to unknown causes as deaths due to the respective cause (natural causes overall, CVD or cancer). As in **Figure 6**, the light blue rectangular zone surrounding these sets of SMRs shows the total range of possibility for true SMR (with 95% CI) by cause. As in the prior SMR figures, the red dashed line is drawn across 100, the point of parity with the general population.

4.7.1. Cosmonaut natural-cause SMRs revisited

Observed SMRs for death by all natural causes combined in **Figure 11** show significantly reduced risk for cosmonauts in comparison to the general population, even with the inclusion of the unknown causes within this causal category. The light blue interval for the entire study period 1960 to 2017 shows that the true value of SMR for the entire study period of 1960 to 2017 is likely to be between 25 and 60, whatever the truth about the unknown causes of death may be. In total, we conclude that, though the value of SMRs reported in Section 4.4 above may be too low due to misclassification of some deaths, the overall conclusion remains the same: cosmonauts are at reduced risk of death from natural causes.

4.7.2. Cosmonaut CVD SMRs revisited

The implications of categorizing all unknown causes of death as CVD deaths have similar implications to the overall natural-cause death analysis, although in this case SMRs for two of

the decades would no longer be statistically significant (**Figure 11**). The overall conclusion for the period from 1960 to 2017 also does not change: cosmonauts are at significantly lower risk of CVD mortality than the Russian general population.

4.7.3. Cosmonaut cancer SMRs revisited

Figure 11 demonstrates that the impact of reassigning deaths with unknown causes has the most dramatic effect when all are counted as cancer deaths. In this case, all SMR point estimates that were below 100 are now above 100, though in most cases the confidence intervals continue to include 100 (thus failing to reach the level of statistical significance).

The results of these exploratory analyses for cancer suggest that cosmonauts likely have little difference in cancer-specific mortality rates compared to those of the Russian general population between 1960 and 2017.

5. Astronauts vs. cosmonauts

Having examined the mortality experience of astronauts and cosmonauts separately, we can conclude that both groups have similar patterns of mortality in comparison to general population control groups: lower mortality rates overall, with higher rates of accidental deaths (more so for astronauts) and much lower rates of death from chronic diseases. We now turn our attention to how astronauts and cosmonauts compare directly to one another. Given the similarity in selection criteria, background, training, and career duties, we might expect to find similar mortality rates for astronauts and cosmonauts over the last 60 years. However, given that mortality rates for the Russian general population are known to be higher than those in the United States, we may find some differences.

To explore these possibilities, we computed SMRs using the observed age-, sex-, and period-specific mortality rates among United States astronauts to generate expected numbers of deaths for cosmonauts based on their corresponding age-, sex-, and period-specific exposure times. The ratios of observed cosmonaut deaths to expected deaths determined in this way thus provided SMRs for cosmonauts compared to astronauts.

5.1. All-cause mortality

Figure 12 displays SMRs for cosmonauts in comparison to astronauts for death by all causes. In all but two decades, cosmonauts were at significantly greater risk of death than astronauts; only in the 1960s were cosmonauts at reduced risk of death, and only in the 1980s was there no significant difference between the two groups of space explorers.

What is perhaps most striking about **Figure 12** is that from 1990 to 2017 cosmonauts were more than twice as likely to die as astronauts. Confidence intervals for individual decades are wide, but over the entire period from 1960 to 2017, cosmonauts experienced a nearly doubling of risk compared to astronauts (SMR = 186, 95% CI = 150–228).

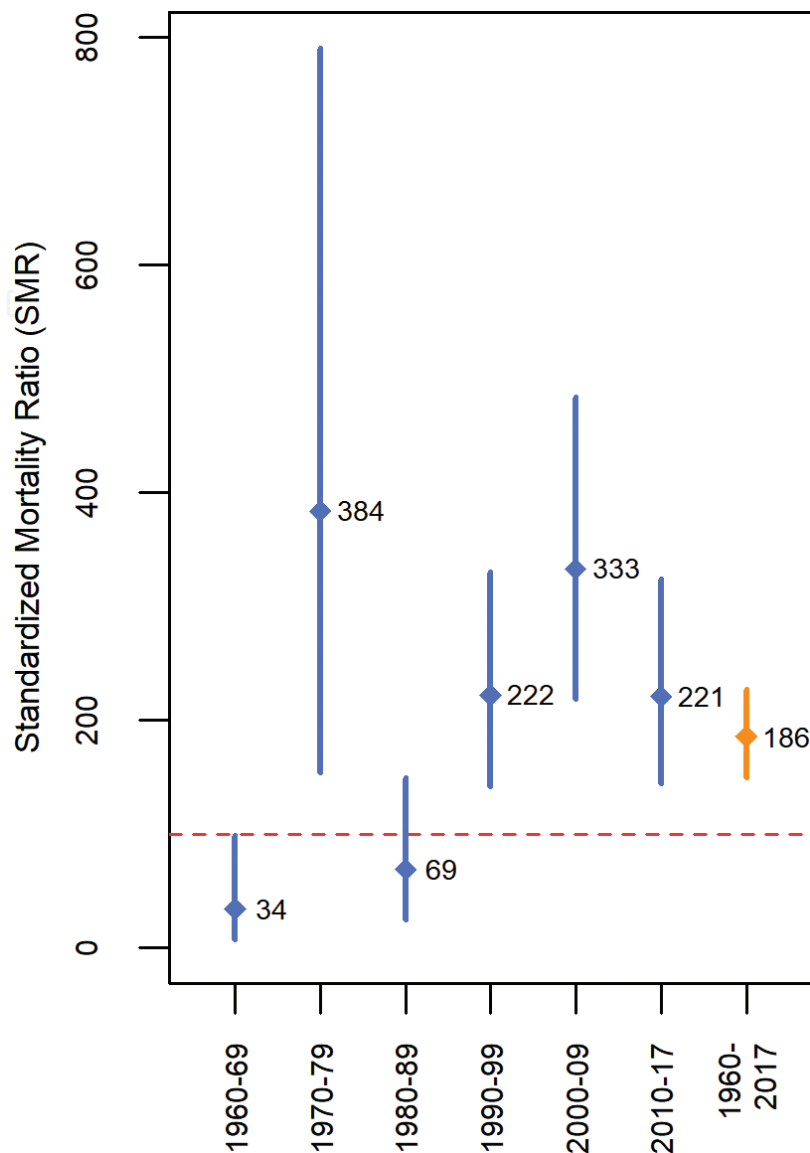


Figure 12. SMRs for all causes of death among Soviet and Russian cosmonauts compared to United States astronauts, 1960–2017.

5.2. External causes

5.2.1. All external causes

No measures of mortality have been previously reported comparing rates of death from all external causes between cosmonauts and astronauts. We report cosmonaut to astronaut SMRs for all external causes here for the first time.

In **Figure 13**, we see that the external-cause SMRs for periods before the year 2000 are similar to those for death by all causes, which might be expected given that astronauts and cosmonauts were relatively young in those years and most deaths observed were externally caused deaths. In the case of the 1960s, SMR for all causes and external causes is identical, as the only causes of death to both astronauts and cosmonauts in the 1960s were accidental, a subset of external causes.

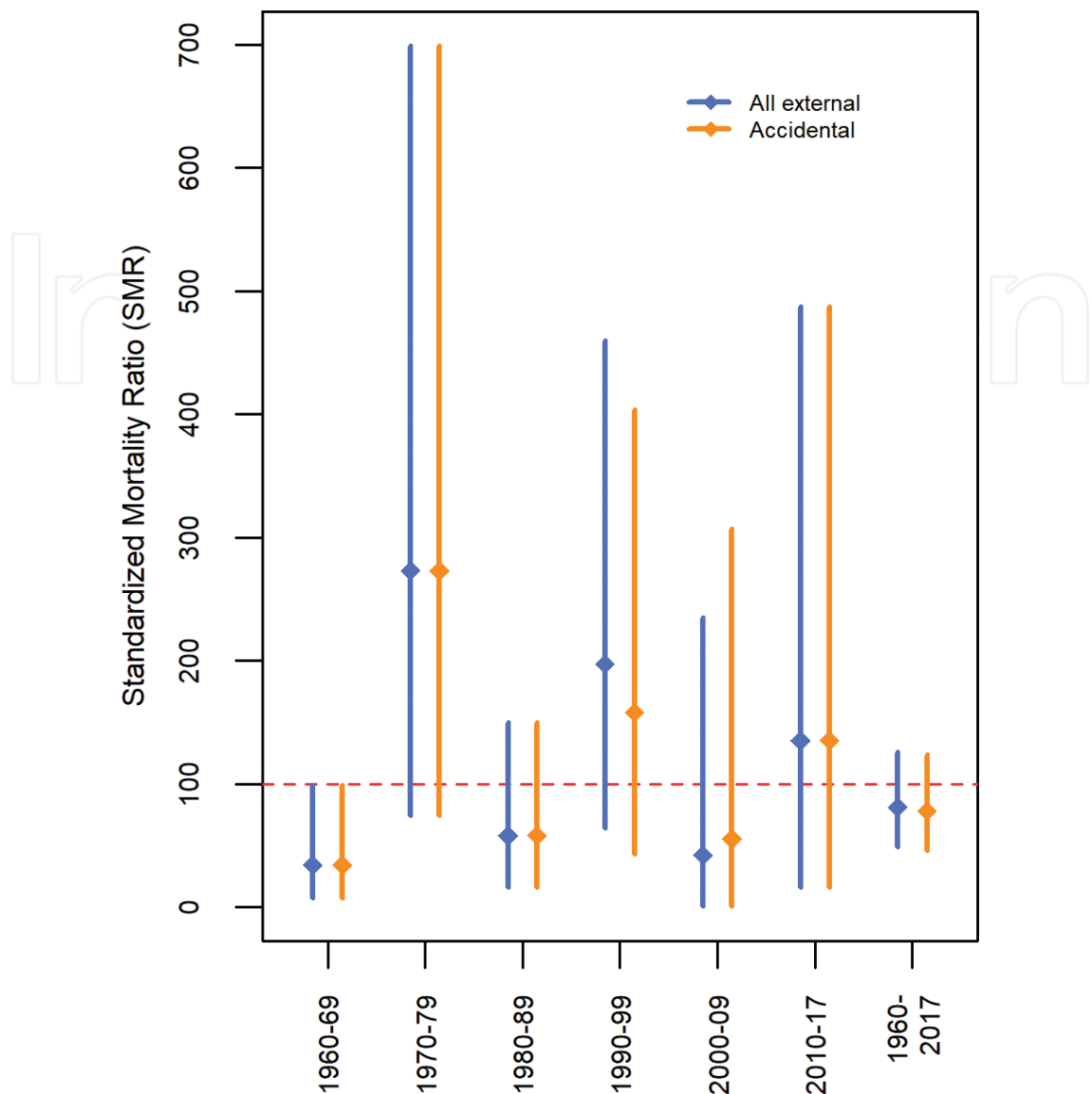


Figure 13. SMRs for all external and accidental causes of death among Soviet and Russian cosmonauts compared to United States astronauts, 1960–2017.

From 2000 onward, the all-cause and external-cause SMRs diverge, as the cohorts’ age and other causes of death are observed more frequently among astronauts and cosmonauts. None of the decade-specific results are statistically significant, nor is the overall SMR of 81 (suggesting a somewhat lower risk of externally caused deaths for cosmonauts, but with 95% CI = 49–126).

5.2.2. Accidents

SMRs comparing rates of accidental death among cosmonauts to those of astronauts were reported in the first published study on cosmonaut mortality [21]. SMRs showed an insignificant reduction in risk in the Soviet era, an insignificant increase in risk in the Roscosmos era, and an insignificant reduction in risk for the overall 1960–2013 period (SMR = 88; 95% CI = 54–136) [21].

Our updated analysis comparing rates of accidental deaths in the two groups decade-by-decade is also given in **Figure 13**. SMRs show us that cosmonauts were at particularly lower risk of accidental death in the 1960s (owing to several astronaut plane crash deaths and three astronaut deaths in the Apollo 1 fire), and then again in the two decades that experienced space shuttle disasters (1980–1989 and 2000–2009). As with all external causes, the results here do not reach a level of statistical significance (aside from 1960 to 1969, which barely reaches significance).

Most noticeable in **Figure 13** is the fact that SMRs for all external causes are largely identical to those for accidental causes, since most of the deaths by external causes in both cohorts are accidental in nature. Only in the 1990s and the 2000s are SMRs for the two different, and even then only slightly.

From this, we might conclude that the occupation of cosmonauts and astronauts demands of them that they lead comparably risky lives and that the estimates of relative risk for them within particular periods have more to do with chance timing than systematic differences in risk of accidents.

5.3. Natural causes

5.3.1. All natural causes

Figure 14 displays cosmonaut/astronaut SMRs for natural causes of death (darker blue), CVD mortality (orange), and cancer mortality (lighter blue). Since there were no deaths to astronauts or cosmonauts by natural causes in the 1960s, it is impossible to define an SMR for that period. Few natural-cause deaths in the 1970s and 1980s result in wide confidence intervals for those periods, with no significant evidence of excess mortality for either cosmonauts or astronauts.

In general, cosmonauts have been at higher risk of death by natural causes after 1989. The exception is the 2010–2017 period, when there was essentially no difference between the two cohorts. However, this result is highly suspect, as this period contains 16 deaths in the cosmonaut cohort that are of unknown cause. If we examine the possible range of SMRs as we did in Section 4.7, adding as few as 9 deaths to the cosmonaut death count would render significant SMR of 175 (95% CI = 104–276). If all 16 deaths from unknown causes were actually deaths from natural causes, the SMR would be 243 (95% CI = 157–358). Either value certainly seems plausible, and the net effect is that we should not rule out the possibility of a significant increase in mortality for cosmonauts in this period.

There were cosmonaut deaths from unknown causes in the 1990–1999 and 2000–2009 periods as well. However, since the observed SMRs in **Figure 14** already show statistically significant increases in mortality risk for cosmonauts, adding more deaths from natural causes would only further increase SMR values. For example, assuming all three deaths from unknown causes in the 1990s were truly from natural causes would raise SMR to 229 (95% CI = 138–357) up from the current 193 (95% CI = 110–313). Assuming all five deaths from unknown causes in 2000–2009 were from natural causes would raise SMR to 453 (95% CI = 296–664).

Given the SMRs (and hypothetical SMRs from assumptions about the distribution of causes of death among unknowns), we conclude that cosmonauts are at higher risk of death by natural causes than are astronauts from 1990 through 2017.

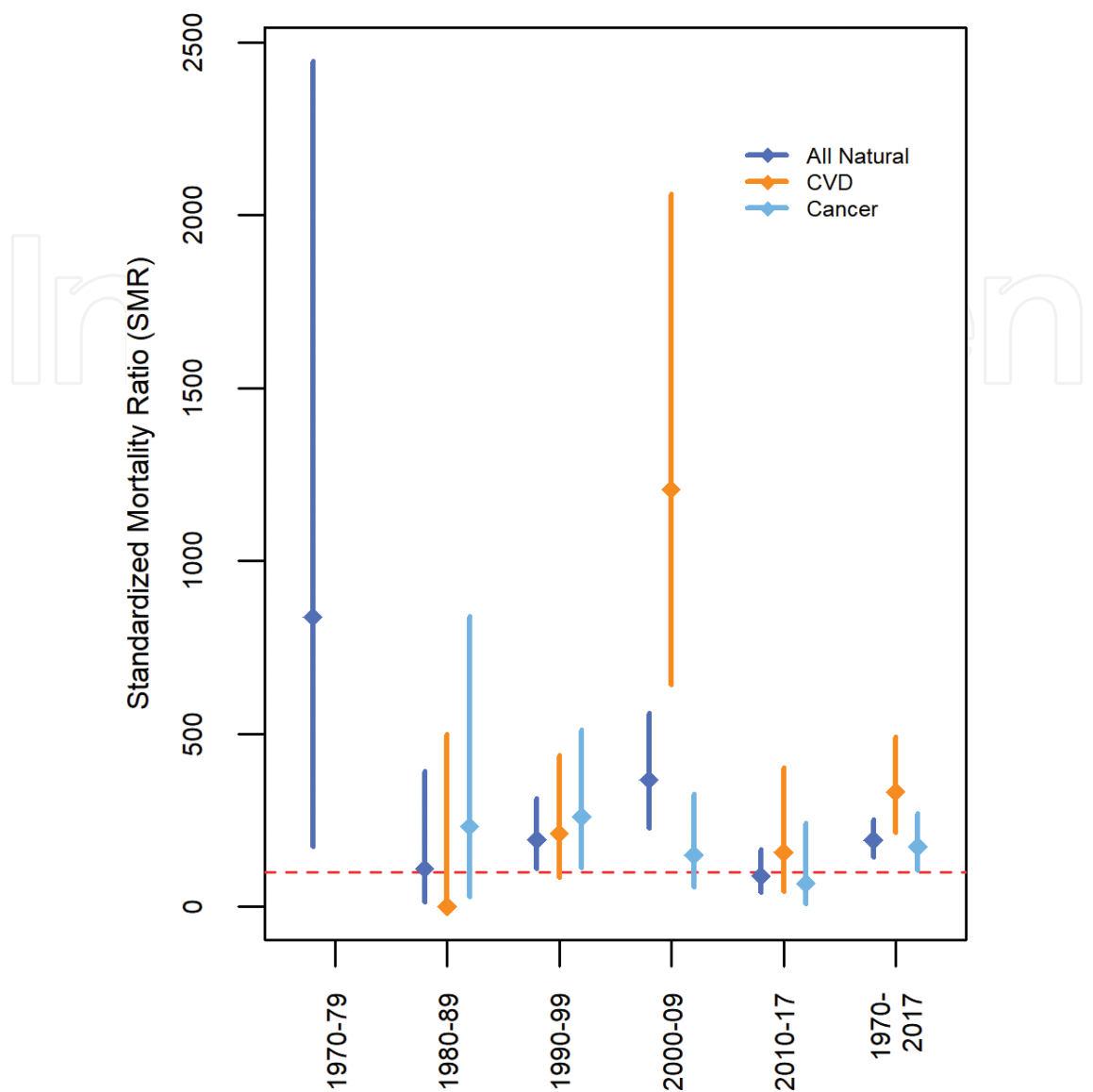


Figure 14. SMRs for all natural-cause, CVD, and cancer mortality among Soviet and Russian cosmonauts compared to United States astronauts, 1960–2017.

5.3.2. Cardiovascular disease

Cardiovascular disease is a cause of death for which both astronauts and cosmonauts have greatly reduced mortality risk in comparison to the general populations of the United States and Russia, respectively. The evidence for this relative to cosmonauts may not be as convincing given the high numbers of deaths of unknown causes, however (see Section 4.7 above). In the prior cosmonauts-to-astronauts comparison, cosmonauts were noted to have a significant increase in mortality due to CVD between 1960 and 2013 (SMR = 364, 95% CI = 225–557) [21].

Figure 14 only includes SMRs for CVD starting with the 1980–1989 period since there were no astronaut deaths from CVD between 1960 and 1979, again making SMRs impossible to define for those two decades (orange points and lines). Cosmonauts experienced no deaths from CVD in the 1960s, but did experience one CVD death in the 1970s.

Three out of the four decade-specific SMRs for CVD in **Figure 14** are not statistically significant. Only the SMR for 2000–2009 was large and statistically significant (SMR 1206, 95% CI = 642–2062). The large confidence interval on this estimated SMR is evidence of the small number of deaths in the astronaut cohort (from which the comparison mortality rates were derived). This small number of deaths led to low mortality rates and thus a low expected number of deaths. This extreme SMR would grow larger if any of the unknown causes of deaths among cosmonauts in that period were in fact deaths due to CVD. However, the very low number of observed deaths among astronauts in this period makes the estimate somewhat unstable.

Like in the prior study [21], overall SMR is statistically significant at 332 (95% CI = 215–491), heavily influenced by the 2000–2009 period. As noted in prior sections, the number of deaths from unknown causes could change the results of recent SMRs. If even one additional death were added to the tally for the 1990–1999 period, SMR would be 243 (95% CI = 105–478), a statistically significant result. Similarly, a reassignment of some unknown causes of death in 2000–2009 and in 2010–2017 could easily raise these to a level of statistically significant elevated risk of CVD mortality for cosmonauts. From the observed data and hypothetical SMRs under various assumptions about unknown causes of death, we can conclude that cosmonauts have been at greater risk of dying from CVD since the 1990s.

5.3.3. Cancers

Cosmonauts have previously been reported to be at elevated risk of cancer mortality in comparison to United States astronauts [21]. Though SMRs for the Soviet and Russian periods were not significant separately, the overall 1960–2013 SMR was significant at 177 (95% CI = 108–274) [21].

Updated SMRs for cancer mortality for Soviet and Russian cosmonauts in comparison to United States astronauts are shown as light blue points and lines in **Figure 14**. Periods for which SMR could not be calculated include 1960–1969 or 1970–1979; there were no astronaut deaths due to cancer in either of those periods.

SMRs for cancer show that in comparison to United States astronauts, Soviet and Russian cosmonauts have largely been at increased risk of death from cancer, though most SMRs are not statistically significant. The exceptions are 1990–1999 and the overall 1970–2017, both of which demonstrate a statistically significant increased risk for cosmonauts. SMR of 67 for 2010–2017 (95% CI = 8–241) is the only SMR that shows a reduction in risk, and not coincidentally, this is in the period in which there are comparatively many observed cosmonaut deaths due to unknown causes.

If we were to add three more deaths to the count of cancer deaths for cosmonauts in the 1990–1999 period, SMR would rise to 356 (95% CI = 178–638). As few as three extra deaths in the 2000–2009 period would drive SMR to significance at 224 (95% CI = 102–425), and six additional deaths in the 2010–2017 period would yield significantly increased SMR of 267 (95% CI = 115–527). Finally, assuming all 24 deaths from unknown causes were due to cancers would increase the overall 1980 to 2017 SMR to 392 (95% CI = 284–529). Even without these potential extra deaths, SMR seen here is highly similar to that reported previously, at 173 (95% CI = 104–271) vs. 177 (95% CI = 108–274) [21]. As with mortality due to CVD and natural causes, we conclude that cosmonauts are at increased risk of death due to cancer in comparison to United States astronauts.

6. Chapter summary

In this chapter, we have examined the mortality of astronauts and cosmonauts in comparison with the general populations of their respective nations, with specially selected controls, and in comparison with one another. The results of prior research and the new analyses presented here indicate that both astronauts and cosmonauts have much lower rates of death by chronic disease (such as CVD and cancers) than do their respective general populations. However, the mortality rate from plane crashes and spacecraft accidents over the years has made both groups of space explorers more likely to die from external causes in general and accidental death in particular, than is expected in the general population. The net effect is that all-cause mortality risk for space explorers is still lower than that of the general population.

Careful interpretation is needed for the reduced risk of chronic disease among astronauts and cosmonauts. Space agencies to date have intentionally tried to limit the potential harmful exposures from space radiation. This has included both projecting and measuring the lifetime dose of radiation for individual astronauts [28]. The evidence gathered thus far seems to indicate that few to no astronauts or cosmonauts have received detrimental doses of space radiation and that we will only begin to understand the mortality risks space radiation can bring once humans start performing longer missions, such as to Mars or beyond.

When comparing cosmonauts to astronauts, we see that astronauts tend to have a slightly higher risk of accidental death compared to cosmonauts, but a significant reduction in the risk of CVD and cancer. The net difference places cosmonauts at an overall greater all-cause mortality risk than United States astronauts.

The lower death rate among cosmonauts from accidental causes is due to fewer plane crashes among cosmonauts, fewer spacecraft accidents, as well as fewer deaths per spacecraft accident (owing to the smaller, 3-person crews in Soviet spacecraft as compared to 7-person crews on United States space shuttles). The reduction in risk due to accidental causes was most pronounced in the 1960s and 1970s, periods of relatively many accidental deaths for both nations. The combined loss of 11 United States astronauts in space shuttles in 1986 and 2003 coincided with no Russian spacecraft accidents in the same period. From this perspective, we could rate the Soviet and Russian space programs as “safer” than the United States program.

The reason behind the greater rate of death by CVD and cancer among cosmonauts is unclear. The most obvious explanation would be lifestyle differences between the United States and Russia, as reflected in the greater mortality risk for these diseases in the general population death rates between Russia and the United States. This could be most salient after retirement from active duty of astronauts and cosmonauts, as the mortality rate from CVD and cancers begin to climb steeply after age 50, in both the United States and Russia [4, 26]. Differences in diet and greater alcohol consumption and tobacco use in Russia/Ukraine than in the United States may explain the risk differences between the groups, especially if those habits were consistent over a period of years [29].

Still another possibility, though less likely, is differing occupational exposures between the cohorts, particularly radiation dose while in space. We are aware of no published work to date that has examined the relationship between time in space or radiation dose and cosmonaut death rates from cancers or cardiovascular disease. However, given the similarity of the Soviet/Russian and the United States space programs over the years, and their explicit

partnership over the last 17 years collaborating on the International Space Station, the overall dose per person-day in space in recent years is likely equivalent.

Finally, the quality of medical care could be an explanation for the differential mortality rate due to chronic diseases. Even among equal rates of incidence, differences in the accessibility or effectiveness of treatment for CVD and cancers could lead to a higher case-fatality rate in cosmonauts compared to astronauts. This could result in cosmonauts dying younger of the same diseases afflicting astronauts, driving up SMRs.

The balance of evidence accumulated to date regarding mortality of space explorers suggests that they are, overall, at less risk of death on an age- and gender-matched basis than the baseline risks in their respective countries of origin. As humans continue to explore space, and in particular as they engage in longer trips deeper into space, it may be inevitable that the unique exposures they will face will ultimately lead to some increased risk of mortality due to at least some particular causes (tragic accidents and radiation-related cancers perhaps chief among them). However, it may be worth bearing in mind that as a profession, being an astronaut or cosmonaut is not a terribly risky business. Based on the research reviewed here, as well as the original research presented for the first time, the job of space explorer should not make any top 10 lists of the world's deadliest jobs.

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