Mortality Among International Astronauts

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INTRODUCTION: Research on the mortality of space explorers has focused exclusively on U.S. astronauts and Soviet and Russian cosmonauts. However, other nations have organized space programs over the last 40 yr and the European Space Agency, the Canadian Space Agency, the China National Space Administration, and the Japan Aerospace Exploration Agency all offer an opportunity for further study of the mortality of space explorers.

METHODS: We used biographical and vital data abstracted from public sources for European, Canadian, Chinese, and Japanese astronauts. Using general population mortality rates from the Human Mortality Database and mortality rates derived from the cohort of U.S. astronauts, we computed standardized mortality ratios.

RESULTS: The groups displayed different preferences in selection of astronauts. As there were no deaths in any of the four groups, the point estimates for standardized mortality ratios were all 0. However, the European cohort experienced a statistically significant reduction in all-cause mortality risk in comparison to the European general population as well as in comparison to U.S. astronauts.

DISCUSSION: The healthy worker effect predicts that all study cohorts should have lower all-cause mortality risk in comparison to their general populations. The general population of Japan has mortality rates low enough that any reduction in mortality risk may remain undetectable in the Japanese cohort. Continued surveillance of these populations in the coming decades will make them a useful addition to the evidence base for astronaut mortality.

KEYWORDS: astronauts, cosmonauts, death rates.

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Understanding the health risks faced by space explorers is an important part of the overall goal of safely exploring and colonizing deep space and other planets. Monitoring the causes and rates of death among space explorers is a major component of this understanding. Prior research on the mortality of space explorers has focused exclusively on U.S. astronauts and Soviet and Russian cosmonauts.[8] In comparison to their general populations, these groups have been found to be at greatly reduced risk of death from natural causes (i.e., chronic disease) while simultaneously being at varying degrees of increased risk from external causes (primarily accidents). Studies have also focused on looking for excess risk among subgroups of astronauts and cosmonauts, such as people who have exclusively visited low Earth orbit, or those who have traveled to the Moon.[7,8,12] Still other work has examined the association between cosmic radiation dose and mortality.[2,6] To date, none of these studies have found evidence of excess mortality risk due to space travel.

While the U.S. and Russian space programs offer the largest numbers, the longest follow-up, and the most exposure to the space environment in their cohorts, there are groups of astronauts from other nations available for study. In particular, the European Space Agency (ESA), the Canadian Space Agency (CSA), the China National Space Administration (CNSA), and the Japanese Aerospace Exploration Agency (JAXA) have all selected and trained astronauts over the past several decades. However, since the total number of people from these agencies is comparatively small, and since none of them have yet died, the inferences we might draw from analysis of comparative mortality are quite limited. Nevertheless, we describe these three cohorts of space explorers and report expected numbers of deaths to date using their general populations and U.S. astronauts as standard populations.

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METHODS

Source Data and Study Population

We gathered data on astronauts from the four agencies from published biographies on space agency websites and spacefacts.de.[1,3,5] From these biographies we abstracted details such as national origin, race, date of birth, sex, education, military service background, pilot status, and date of selection. We then constructed a longitudinal dataset tracking each individual from date of selection to either date of death or the common study close date of 31 December 2018, whichever came first.

It should be noted that the CNSA cohort includes all Chinese astronauts selected since 1996. China selected 19 individuals for their space program in 1970, but later cancelled the program and returned the would-be astronauts to military service. As no biographical details are available for these individuals they have not been included here.

U.S. astronaut data were obtained from our pre-existing database, which has been described previously.[9] Astronaut data were used as the basis for a set of mortality rates stratified by age, which we used to generate expected numbers of deaths in the three study cohorts.

We also downloaded general population mortality rates from the Human Mortality Database.[11] The rates came in 5 × 10 format, meaning 5-yr age strata and decennial strata of calendar year. For purposes of matching space explorer follow-up time to general population mortality rates in the ESA cohort, we matched astronauts from Denmark, the Netherlands, Sweden, Switzerland, and Germany to German mortality rates. Astronauts from Belgium, the United Kingdom, and France were matched to French mortality rates. Astronauts from Spain and Italy were matched to Italian mortality rates.

The Human Mortality Database does not contain mortality rates for mainland China and we were unable to locate any such rates on the Internet. However, the Human Mortality Database does contain mortality rates for Taiwan. We therefore used mortality rates from Taiwan for the general population comparison for Chinese astronauts. We note that these rates may be overly optimistic and that rates for mainland China could be higher, just as mortality rates in the Soviet Union were consistently higher than nations in Western Europe and the United States.

This study relied upon publicly available data found on the Internet, and we made no attempts to contact the space explorers or their families. The study was therefore exempt from institutional review.

Statistical Methods

We describe the demographic characteristics of the three study cohorts in terms of median and median absolute deviation (MAD) for continuous variables and counts and percentages for categorical variables. The median and MAD are alternatives to the mean and standard deviation that are less sensitive to outliers, particularly in smaller datasets.

Standardized morality ratios (SMRs) have been used to index the mortality experience of astronauts and cosmonauts against standard populations.[8,9,12] However, as there have been no deaths in any of the four study cohorts, all SMRs have a value of 0. As such, we do not report the SMRs here, but instead plot only the expected numbers of deaths computed from mortality rates for the various comparison populations. Nevertheless, SMRs can still reach statistical significance even when no deaths are present if the lack of deaths presents a large enough deviation from the expected number. Thus, we computed the number of expected deaths necessary for an SMR of 0 to reach significance at the 95% level of confidence to test whether the deficit of deaths was significant.

General population mortality rates were matched to the cohort in their 5 × 10 format, while mortality rates for U.S. astronauts were computed and matched to the study cohort only in 5-yr age strata. We chose to compute the rates in this way because prior analysis of U.S. astronaut data has not revealed any secular trends in mortality,[6,7] and stratifying the data by age but not decade makes the rates more robust and reliable.

RESULTS

Table I provides the summary of demographic characteristics for the three study cohorts. The ESA contributed 29 individuals

Table I. Demographic and Actuarial Characteristics of Astronauts.

CHARACTERISTIC	ESA (*N* = 29)	CSA (*N* = 14)	CNSA (*N* = 21)	JAXA (*N* = 9)
Age at selection, median (MAD)	34.0 (4.1)	34.1 (6.3)	31.5 (1.7)*	33.0 (4.3)
Year of selection, median (MAD)	1992 (8.9)	1992 (13.3)	1998 (0.0)	1999 (14.8)
Follow-up time, (yr) median (MAD)	26.6 (9.5)	26.1 (12.6)	21.0 (0.5)	19.9 (14.9)
Follow-up time, (yr) total	681.3	338.9	301.6	238.1
Male, *N* (%)	25 (86.2)	11 (78.6)	19 (90.5)	9 (81.8)
Highest education, *N* (%)				
Bachelor's	12 (41.4)	1 (7.1)	20 (95.2)	2 (18.1)
Master's	5 (17.2)	5 (35.7)	1 (4.8)	3 (27.3)
Doctorate (Ph.D. or M.D.)	12 (41.4)	8 (57.1)	0 (0.0)	6 (54.5)
Military, *N* (%)	16 (55.1)	5 (35.7)	21 (100.0)	2 (18.1)
Pilot, *N* (%)	17 (58.6)	9 (64.3)	21 (100.0)	2 (18.1)

ESA = European Space Agency; CSA = Canadian Space Agency; CNSA = China National Space Administration; JAXA = Japanese Aerospace and Exploration Agency; MAD = median absolute deviation.

* Date of birth missing for 5 astronauts, reducing sample to 16 for this attribute.

to the study, the CSA provided 14, the CNSA 21 (though 5 missing dates of birth among Chinese astronauts reduced the effective sample size to 16), and JAXA 11. The median age at selection for all agencies were similar, between 31 and 34 yr of age. The recency of the programs yields a median year of selection in the early 1990s for the ESA and CSA, and the late 1990s for the CNSA and JAXA. As a result, the median follow-up time is similar for the ESA and CSA, and shorter for the CNSA and JAXA. Similarly, the ESA had the most total follow-up time accrued at 681.3 person-years, in comparison to 338.9 for CSA astronauts, 301.6 for CNSA astronauts, and 238.1 for JAXA astronauts.

All four cohorts were overwhelmingly male, with the CNSA having 90% men, and the other three agencies composed of approximately 80% men. The Chinese cohort was entirely selected from the military, while the CSA and JAXA tended to select civilians. The ESA was close to evenly split on this dimension. These choices reflect in the educational levels of the groups as well, as all but one of the Chinese astronauts (95%) has a Bachelor's degree, whereas the other three agencies have comparatively high percentages of Master's and Doctoral degrees.

All CNSA selectees were air force pilots. The number of pilots in the ESA and CSA was greater than the number of astronauts selected from the military, however, suggesting at least some of the astronauts obtained private pilot licenses. Only two JAXA astronauts were pilots, one military and one commercial.

Fig. 1 displays the median age of the cohorts in each year. Since no cohort members have died, each line generally trends upward in a linear fashion each year as the entire cohort gets 1 yr older. Periodic drops in the median age are years in which new astronauts were selected into a cohort. By 2018, the median age among ESA and CSA astronauts was approximately 60 yr, while the medians for CNSA and JAXA were both 52 yr.

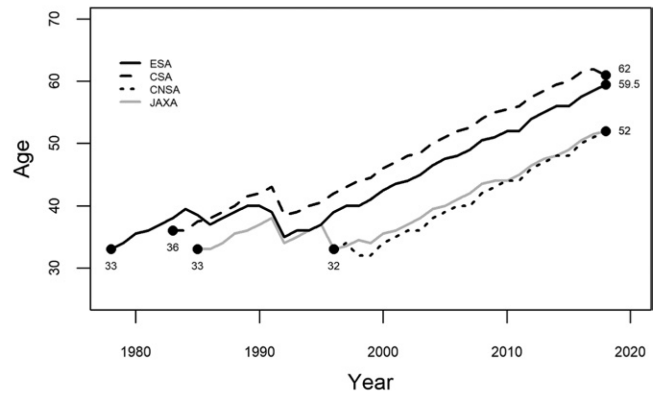

Fig. 1. Median age of the agency cohorts in each year.

Fig. 2 provides four plots of the accrued follow-up time and expected numbers of deaths for the various study cohorts over time. The horizontal dotted line in each panel represents the threshold of three expected deaths, the number required for zero observed deaths to demonstrate a statistically significant SMR (with two-sided *P*-value of 0.05). Panel A shows expected deaths from all causes using the general population as the standard, while panel B shows deaths from all causes using

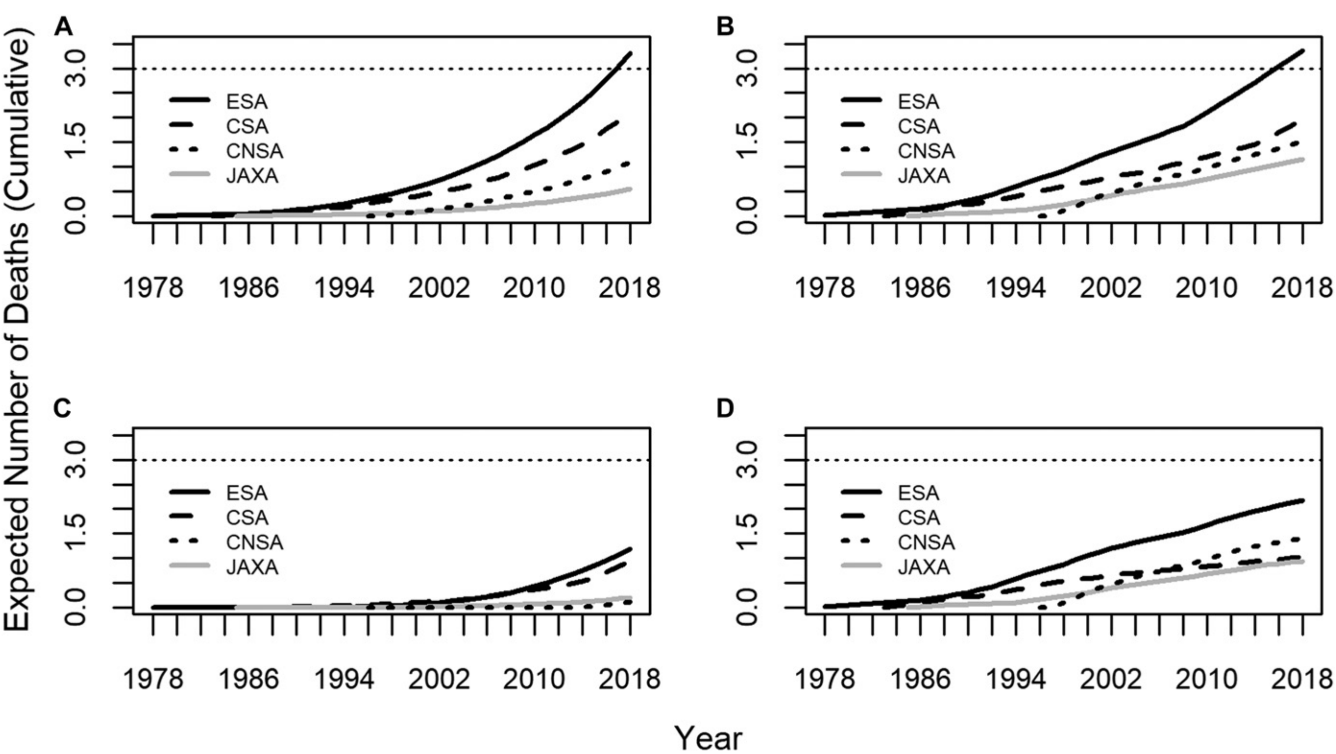

Fig. 2. Cumulative expected deaths by outcome and space agency. A) All-cause mortality in comparison to respective general populations; B) all-cause mortality in comparison to U.S. astronauts; C) natural-cause mortality in comparison to U.S. astronauts; D) external-cause mortality in comparison to U.S. astronauts. ESA = European Space Agency; CSA = Canadian Space Agency; CNSA = China National Space Administration; JAXA = Japanese Aerospace and Exploration Agency.

mortality rates from U.S. astronauts as the standard. Panels C and D show the expected numbers from all natural causes and all external causes, respectively, and both use mortality rates from U.S. astronauts as the standard.

The ESA cohort, being the largest and oldest, accrued the most expected deaths in each of the four panels. As panels A and B make clear, the expected deaths for the ESA cohort broke the threshold of significance for all-cause mortality, both in comparison to the general population of the several European nations, as well as in comparison to U.S. astronauts.

In spite of having accrued almost 350 yr of follow-up through 2018, Canadian astronauts did not realize an expected number of deaths sufficient to make their SMR of zero statistically significant. Because of the recency of selection of the CNSA astronaut corps, follow-up is only available from the 1990s onward, and the expected numbers of death for all outcomes are extremely low. As such, none of the SMRs for CNSA astronauts were statistically significant.

Comparatively low general population mortality rates in Japan resulted in less than one expected death from all causes. In comparison to U.S. astronauts, there was just one death expected from external causes and none from natural causes, even though the age range on JAXA astronauts spanned from 40 to 70 by the end of follow-up, with more than half of the astronauts over 50 yr of age by that time (Fig. 1).

DISCUSSION

The rarity of space travel continues to plague epidemiological investigations into astronaut health. The small numbers of available individuals to study means that statistical power is generally low, particularly for investigations of diseases such as cancer and cardiovascular disease, which have long latency periods.[2,6] It is therefore advantageous to study all available astronaut cohorts, even if they do not yet offer large amounts of observed follow-up.

In comparison to the expected number of deaths generated by the composite European general population over the entire 1978–2018 period, the complete absence of observed deaths among ESA astronauts represents a significant reduction in mortality risk. This is a function of the size and age of the European cohort: over the last 3 decades, sufficient numbers of ESA astronauts reached ages of high risk for death by chronic disease. As noted in the Results, the significant reduction in all-cause mortality risk for ESA astronauts in comparison to U.S. astronauts is largely due to the absence of externally caused deaths in all periods and the lack of natural-cause deaths in the most recent periods.

U.S. astronauts have been shown to be at much greater risk of accidental death than the U.S. general population, Soviet and Russian cosmonauts, and professional basketball players.[8,10,11] This increase in mortality risk is mainly due to multiple aircraft crashes, three spacecraft disasters, and a small number of other motor vehicle accidents. Thus, it is unsurprising that ESA astronauts are at a lower risk of externally caused death than are U.S. astronauts, as fewer of them are pilots and, in general, they have much less spaceflight experience than U.S. astronauts.

That the other groups of astronauts do not display any significantly reduced mortality risk is a function of cohort size. The complete deficit of deaths will eventually become significant for all outcomes in all four cohorts if the astronauts age sufficiently. Given the strong evidence for the healthy worker effect (HWE) for working populations in general, and the magnitude of this effect among U.S. astronauts and Soviet and Russian cosmonauts in particular, we have little doubt that the astronauts under study here will eventually be found to have significantly lower mortality rates than their respective general populations.[4] In addition, previous research has demonstrated Soviet and Russian cosmonauts to be at greatly increased risk of death by natural-cause mortality compared to U.S. astronauts.[8] It is thus unclear both the extent to which the four cohorts here would be at reduced risk in comparison to their general populations, and also unclear what we should expect the comparative mortality to be between these cohorts and U.S. astronauts. If the U.S.-Russian experience is any indicator, the answer may depend largely on the relative size of general population mortality rates from each country of origin in comparison to those of the U.S. general population.

The results for CNSA astronauts should be interpreted with caution. The expected number of deaths for this group was generated using general population mortality rates from Taiwan, and it is unclear whether this is optimistic or pessimistic, particularly over time. If Taiwan's mortality rates are lower than those of mainland China, this means that the expected numbers reported here are too low. However, unless the expected deaths obtained using mortality rates for China were at least twice those obtained by using rates from Taiwan, the astronauts would still not show a significant reduction in all-cause mortality rates with the current data. This combined with the small size of the Chinese cohort makes observing a significant mortality reduction in this group highly unlikely, even though the HWE predicts astronauts should be at reduced risk in comparison to their general populations.

The Japanese general population is notorious for having the world's highest life expectancy at birth, which means comparatively low age-specific mortality rates across the lifespan.[11,13] This can be seen in Fig. 2, panel A, as the expected numbers of deaths by natural causes is low when using general population rates, even in a population that is rapidly aging (Fig. 1). This raises the possibility that JAXA astronauts may not derive any detectable survival benefit from the HWE. In comparison to the Japanese general population, the entire current JAXA cohort would need to survive to 2035 before they would register a significant reduction in mortality risk in comparison to the Japanese general population.

Combining cohorts into a larger group could yield statistically significant reductions in mortality for all outcomes under study (though the point estimate of the SMRs would still be zero). Given that three of these agencies are close partners with NASA, this is a tempting way to increase statistical power. However, we maintain that combining the cohorts with each other (or with NASA astronauts) is at this point premature, as there still exists the potential for national origin effects, such as the potential lack of a discernible HWE in the JAXA cohort. Once deaths have occurred in these cohorts (i.e., when death rates become defined), the groups may be used in multivariate models to test for effects of national origin; until that time, stratifying on national origin provides equivalent control in the SMRs.

Continued observation of these cohorts with periodic updates to the findings will be essential in understanding how they compare to both their general populations and other groups of space travelers. By examining all the available evidence, we can begin to understand the long-term health consequences of space exploration. Such understanding is essential to the success of space programs now and in the future.

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