



Population analysis of space travelers

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ABSTRACT

Although many space missions have been completed in the last 60 years, space exploration is still technologically and medically challenging. While large-scale medical studies are impossible in space travelers, meta-analysis allows combining data from small crews that participated in space missions over several decades. Our primary objective was to examine space-travelers' sociodemographic characteristics and spaceflight activities, and their changes with time from the first spaceflight. Our secondary objective was to evaluate the publication practices to assess data availability for health-related meta-analytic studies. Based on state-funded space agencies used as primary sources, and third-party websites used as secondary sources, 565 humans (501 males/64 females) have currently completed spaceflight. The average age of space-travelers increased from 34 ± 4 in the 1960s to 45 ± 4 in the 2010s. While the duration of space missions has increased consistently, the number of missions per year varied in correlation with technological events. Using papers identified in the systematic review of bone health in astronauts, we examined the changes in reporting practices with time. The reported sample size varied from 1 to 58 people, in total providing data for 148 individuals. Data confidentiality significantly improved with time; however, the corresponding decrease in the availability of individual parameters did not allow stratification even by age, sex, and mission duration. Thus, space travelers represent a diverse population suitable for comparative studies, however, it is important to develop reporting practices that ensure consistent, transparent, and ethical presentation of outcomes to support meta-analyses that are critical for understanding the scope of spaceflight-induced health issues.

1. Introduction

Space travel captivates us since the first humans accomplished an orbital spaceflight in 1961 and stepped on the moon surface in 1969 (National Aeronautics and Space Administration 2020). In our imagination, we are already developing the recourses of the Solar system, travel to other planets, and find love in galaxies far-far away. However, the reality of space travel is much more complex, and many spaceflight-related health problems have been identified, including those in the cardiovascular system (Ramsdell and Cohen, 2003), immune system (Crucian et al., 2018), bone and muscle health (Lang et al., 2017), ocular system (Taibbi et al., 2013) and metabolism (Smith et al., 2001). Different technological and behavioral strategies have been attempted to counteract these problems, including exercise regimes (Korth, 2015), nutrition (Government Publishing Office 2014), environmental control (Daues, 2006; Kliss, 2016). While some successes have been reported, the problems are far from being solved (Lang et al., 2017; Aubert et al.,

2016; Fripiat et al., 2016). One potential contributor to the lack of solutions is the nature of space exploration as a technologically difficult and very expensive endeavor, which accommodates only a small number of people at a time, thus precluding any large-scale investigations that would allow to account for biological variability among humans. Combining data from the space travelers who participated in missions performed over a long period of time in an extended meta-analysis can at least partially overcome this problem. An important assumption of such analysis is that the space travel itself is the largest driver of changes, while technological/logistic/demographic co-variables, such as the type of spacecraft, nutrition, and countermeasures underlie secondary effects. In order to explore the potential of such extended secondary meta-analysis, we aimed to qualitatively and quantitatively analyze the population of space-travelers from the first spaceflight till the present time for its suitability for health-related studies. The secondary objective of the study was to evaluate the practices for describing the population of participants in the space-

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related health science using as an example the systematic review of bone health in astronauts (Stavnychuk et al., 2020) to examine the feasibility of extended analysis of published literature.

2. Methods

2.1. Construction of space-traveler database

We considered as space-travelers all humans who went to space according to the Fédération Aéronautique Internationale (FAI) definition (FAI Astronautics Commission 2009). As primary sources, we accessed the websites of official state agencies (National Aeronautics and Space Administration (NASA), Roscosmos, European Space Agency, Canadian Space Agency, Japan Aerospace Exploration Agency, China National Space Administration and Indian Space Research organisation). Secondary sources included third-party websites hosted in the US (Astronauts and Cosmonauts) and Russia (Астронавты и космонавты). Since state-funded sources did not contain information for space travelers of all origins, the space-traveler database was constructed based on the information provided by the third-party websites. Information in the database was cross-validated with the information provided by the state-funded agencies and if a discrepancy arose, the information provided by the state-funded websites was used as a primary source. The following information was included: 1) identification (official and Romanised name, national database ID number, and retirement status); 2) demographics (nationality, sex, year of birth, year of selection, and military background); 3) career statistics (total time spent in space, number of flights, and extra-vehicular activity (EVA) hours); and 4) data on each mission involving the traveler (the name, year, and duration of each mission; ascent/orbit/descent vehicle; and instances of and total EVA time per mission).

2.2. Quantification of data confidentiality

To examine the degree of data confidentiality, we quantified the accuracy with which we could determine the identity of space-travelers from the data disclosed in 57 papers (Amin et al., 2010; Arnaud and Cann, 1995; Berry, 1968; Biryukov and Krasnykh, 1970; Burkhart et al., 2019; Caillot-Augusseau et al., 1998; Caillot-Augusseau et al., 2000; Cavanagh et al., 2010; Collet et al., 1997; Ellman et al., 2010; Grigor'ev et al., 1999; Grigoriev et al., 1998; Johnston and Dietlein, 1977; Keyak et al., 2009; Kozlovskaya and Grigoriev, 2004; Lang et al., 2004; Lang et al., 2006; Leblanc et al., 2011; Leblanc et al., 2013; Leblanc et al., 2000; Mack, 1971; Mack et al., 1967; Mack and Vogt, 1971; McCarthy et al., 2000; Michalski et al., 2019; Miyamoto et al., 1998; Morey-Holton and Arnaud, 1991; Morukov et al., 2005; Morukov et al., 2014; Nicogossian, 1977; Oganov et al., 2006; Oganov et al., 2005; Oganov and Bogomolov, 2011; Oganov et al., 2010; Oganov et al., 1990; Oganov et al., 1992; Oganov et al., 1991; Parker and West, 1975; Prostiakov et al., 2010; Prostyakov et al., 2012; Rice et al., 2004; J. Sibonga et al., 2019; J.D. Sibonga et al., 2019; Smith et al., 2014; Smith et al., 2015; Smith et al., 1998; Smith et al., 1999; Smith et al., 2005; Stupakov et al., 1984; Vico et al., 2000; Vico et al., 2017; Vogel, 1975; Vogel and Friedman, 1973; Vogel and Whittle, 1976; Vose, 1974; Yegorov, 1979; Zwart et al., 2018) systematically identified as reporting the effects of microgravity on human bone (Stavnychuk et al., 2020). Identification was performed based on information about space travelers' age, sex, and occupation, as well as the year, title, and duration of a mission provided by a paper. The accuracy of identification was presented as a ratio between the sample size of the paper and the number of individuals that fit the identification profile.

2.3. Quantification of demographics overlap in publication

To quantify the degree to which space traveler populations overlap

in different papers, we counted the appearance of a particular space-traveler data in all papers where subjects were identifiable.

3. Results and discussion

3.1. Information availability and completeness

We have found that no state-supported agency provided complete datasets for all space travelers, and the formats of data were inconsistent across different agencies. In contrast, secondary sources, third-party websites (Astronauts and Cosmonauts; Астронавты и космонавты), contained comprehensive, up-to-date information on space travelers of all nationalities. We used secondary sources to construct a database of all space travelers, and primary sources to cross-validate the entries (Stavnychuk and Corlett, 2020).

3.2. Changes in the population of space-travelers with the development of space travel

In order to obtain a reasonable size population, meta-analytic studies will need to combine the information from mission performed over several decades, therefore understanding changes in the population of space-travelers with time is important. Historically, the annual number of spaceflights has varied substantially (Fig. 1A), which reflects space technology advancements as well as setbacks revealed by fatal accidents (Fig. 1B). For example, a drastic change in the number of USA

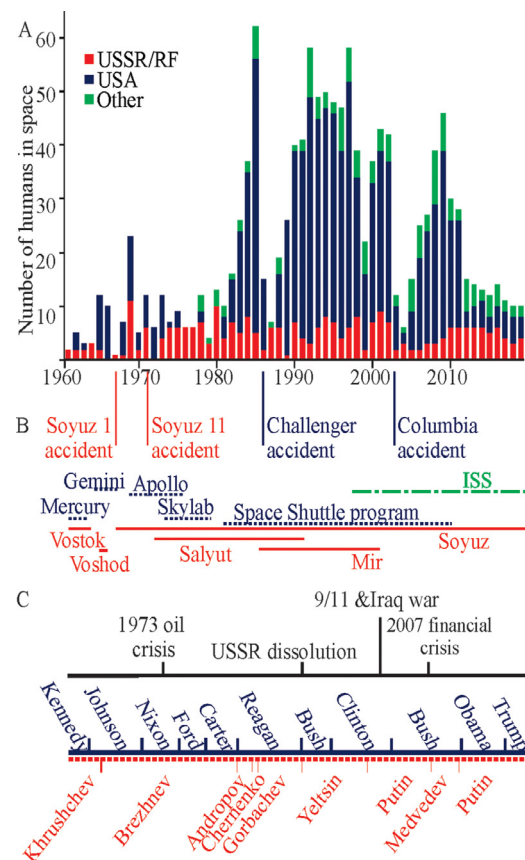


Fig. 1. Chronological analysis of space traveler population. (A) Annual number of humans who travelled to space between 1961 and 2019. USSR/RF: Union of Soviet Socialist Republics/ Russian Federation; USA: United States of America. (B) Timeline of space programs conducted by the USA (dotted line), the USSR/RF (solid line), and the international community for the ISS (dashed line). Fatal accidents are indicated. (C) Timelines of global economic events (top) and major political changes that occurred in the USA (solid line) and the USSR/RF (dotted line).

astronauts sent to space in the 80s and 90s can be attributed to the replacement of Saturn IB launch vehicles used in Skylab missions that transported three astronauts at a time by Space Shuttles that transported up to 8 astronauts per mission, while USSR/Russia space program continuously used Soyuz spacecrafts that carry up to 3 astronauts per mission since 1967. All fatal accidents, Soyuz 1 and 11 in 1967 and 1971, Challenger in 1986, and Columbia in 2003, were followed by either complete cancellation or a large decrease in flights the following year (Fig 1B). Despite NASA and Roscosmos being state-funded agencies, the spaceflights were less influenced by global economy and major political events (Fig 1C), likely due to time delay required for their impact on space-flight activities (Logsdon, 2009; Johnson, 2007).

3.3. The population of space travelers

As of December 2019, 565 humans (501 males/64 females) have completed spaceflights. The USSR and USA started sending humans to space in 1960s, and the majority of space travelers have been from the USA ($n = 344$) or USSR/Russia ($n = 122$), followed by Germany, Japan, China, Canada and France ($n = 10$ –12), Italy and United Kingdom ($n = 5$ –7), $n = 2$ for Belgium, Bulgaria and Netherlands, and $n = 1$ for Afghanistan, Australia, Austria, Brazil, Cuba, Czechoslovakia, Denmark, Hungary, India, Israel, Kazakhstan, Korea, Malaysia, Mexico, Mongolia, Poland, Republic of South Africa, Romania, Saudi Arabia, Slovakia, Spain, Sweden, Switzerland, Syria, United Arab Emirates, Vietnam. In recent years, almost 30% of space travelers at the International Space Station (ISS) are from countries other than the USA and Russia (Fig 1A). Most space travelers were males ($n = 501$), while the population of female astronauts ($n = 64$) continuously increased since the 1980s (Fig 2A). The astronaut age at enrolment into the space program has increased with time but remained lower for females compared to males (Fig 2A). Most male and female astronauts participated in only one mission; however, the number of astronauts involved in multiple missions increased over the years, with Jerry L. Ross performing a record number of 7 spaceflights in his career (Fig 2B–C). While initially, most astronauts had a military background, with time approximately the same number of space travelers were recruited from

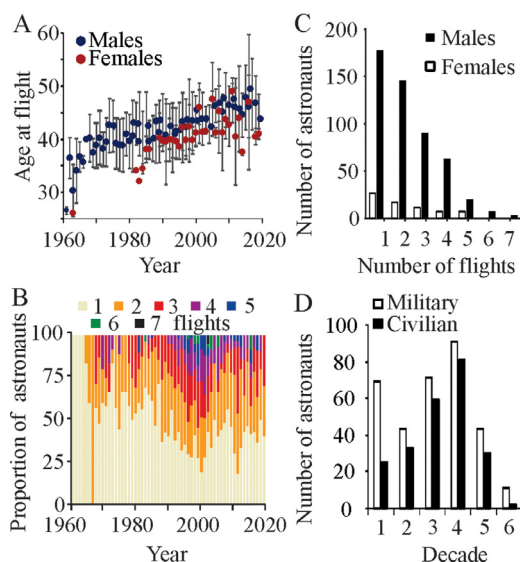


Fig. 2. Demographic characteristics of space traveler population. (A) Average age of male and female space travelers during spaceflights. Means \pm SD, $n = 1135$ missions completed by 501 male space travelers, $n = 143$ missions completed by 64 female space travelers. (B) Time-dependent change in the proportion of space travelers who participated in one or multiple missions. (C) Number of male and female space travelers who participated in their n^{th} mission. (D) Proportion of space travelers recruited from military or civilian background in the 6 decades of spaceflight.

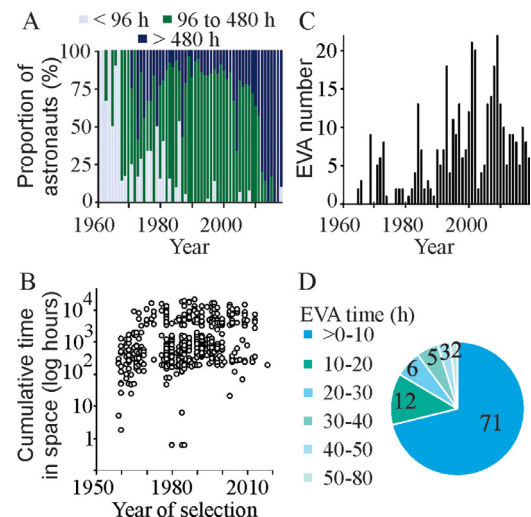


Fig. 3. Spaceflight activities of space travelers. (A) Proportion of space travelers that participated in short (< 96 h), intermediate (96 to 480 h) and long (> 480 h) spaceflights. (B) Cumulative number of spaceflight hours of each astronaut as a function of the year of selection into a space program. (C) Number of extravehicular (EVA) operations per year. (D) Proportion of space travelers who performed indicated number of cumulative EVA hours.

military and civilian environment (Fig 2D).

The time astronauts spent in space increased through spaceflight history, with a recent trend towards missions lasting > 480 h, which is likely related to the launch of the ISS program in 1998 (Fig 3A). Of interest, when we examined the total number of hours spent in space per space traveler, two sub-populations of astronauts emerged: those who participated in short missions (< 30 days), and those who served on longer missions (Fig 3B). Since the first spacewalk performed by Alexei Leonov in 1965, the number of times extravehicular activity (EVA) was performed steadily increased (Fig 3C). From 176 astronauts who performed spacewalks, the majority (106 astronauts) had less than 20 h of EVA, while 43 performed more than 30 h of EVA (Fig 3D), with the record of 16 EVAs, lasting for the total of 82 h and 22 min held by Anatoly Solovyev. Thus, the space traveler population is abundant and diverse both in their sociodemographic background and in their space-related activities.

3.4. Reporting practices

To analyze the practices for describing participants in manuscripts focused on the health issues in space travelers, we used the selection of 57 papers identified using a systematic search of studies reporting on bone health of astronauts (Stavnicuk et al., 2020). The sample sizes of reported populations varied between 1 and 58. While the average sample population size increased over the years (Fig 4A), the studies reporting large-scale statistics were still rare. Next, we attempted to identify space-travelers from the information disclosed in a paper, such as age, sex, mission name, and duration. In early publications, most astronauts were identified uniquely or as one of two mission members; however, in recent years identification has become more difficult (Fig 4B). In one of the most recent papers (J. Sibonga et al., 2019), not only the astronaut identification was impossible, but also the important spaceflight characteristics, such as mission duration, were absent, reducing the usefulness of the reported data for the secondary data analysis. Using 30 papers that published data on astronauts' bone density between 1965 and 2010, we examined the extent of the overlap in reported populations. We found that data for the same astronauts were often reported across multiple publications, sometimes as individual data and sometimes as part of groups of a different size (Fig. 4C). The extent of overlap was the greatest in papers on Gemini and early Apollo

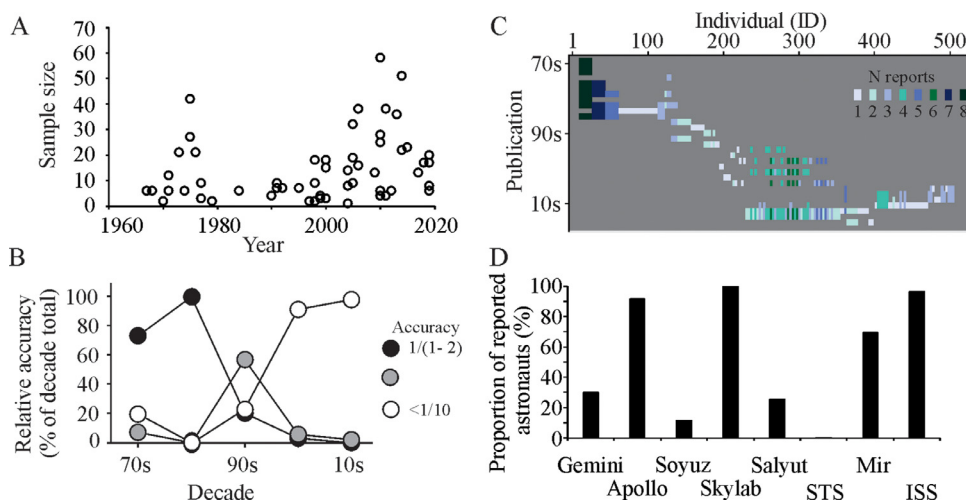


Fig. 4. Reporting practices in spaceflight studies. (A) The sample size of the reported population as a function of publication year. (B) Space traveler identification accuracy defined as high [1/(1–2): astronaut identified uniquely or as one of 2 candidates], intermediate [1/(3–10): space traveler identified as one of 3–10 candidates] or low (<1/10) as a function of publication decade. (C) The degree to which bone density data of a particular space traveler is repeatedly reported in multiple publications. The space traveler ID in order of their flight year was plotted on the x-axis, and the manuscript ID in order of the publication year was plotted on the y-axis. The darker shade indicates the larger the number of papers (1 to 8) that reported data from the same individual after the same flight. (D) The proportion of space travelers from different space programs whose data was reported in literature out of all space travelers who participated in the program.

missions, as well as for papers reporting measurements from long-term missions on Mir and ISS, while reports on Skylab and Salyut missions had fewer overlapping populations. Almost all space travelers' data from Skylab, Mir, and ISS appeared in at least one study (Fig. 4D). Salyut missions were underrepresented despite being conducted in long-term space station stays. Bone density changes were rarely measured in Soyuz and STS missions, as they were mostly short-duration flights.

4. Conclusion

Our study demonstrates that the population of space travelers is relatively large and complex, potentially providing an opportunity to examine the influence of age, sex, spaceflight duration, number of missions, and EVA time on spaceflight-related health outcomes. Since spaceflight studies are typically underpowered due to small sample sizes (few astronauts per space mission), meta-analysis can potentially improve data analysis. However, the reporting of spaceflight outcomes was found to be somewhat deficient, with multiple instances of over-reporting (such as reporting the data from the same individuals included in groups of different sizes) and under-reporting (such as not providing sufficient information for meta-analytic studies). Therefore, there is an urgent need to develop reporting practices that ensure consistent and transparent reporting of outcomes tailored to this type of research, while adhering to the highest ethical standards. Although conflicting mechanisms and motivations for funding of space exploration by national states may impede such developments, a longstanding history of successful international collaborations – as demonstrated by the construction and utilization of the ISS – provides the groundwork for such a task.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to

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