Chapter

Human Health in the Lunar Environment

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Abstract

The lunar environment contains many hazards to human health, some common to extraterrestrial locations, some unique to the Moon. Exposures of particular concern are hypobaric environments, hypogravity, space radiation, and lunar dust. This chapter provides a brief overview of these exposures, as they represent the gravest threats to human health in the lunar environment (i.e., they may affect mortality rates) and then reviews the published studies of mortality of the original twenty-four lunar astronauts who visited the Moon between 1969 and 1972. The chapter closes with a reexamination of lunar astronaut mortality using updated data, including detailed discussion of the interpretation of the results.

Keywords: astronauts, mortality, cardiovascular disease, cancer, Moon

1. Introduction

Though seemingly serene, the lunar environment presents a number of hazards for human health, both acute and chronic. Many of these hazards are common to low Earth orbit (LEO) or deep space, while others are unique to the Moon. As several national space agencies have declared their intentions for further manned lunar exploration and eventual colonization, it is more important than ever to understand the health risks involved.

This chapter provides an overview of the major hazards associated with space exploration in general and examines how those hazards may differ in the lunar environment. The number of health risks inherent in space exploration is staggering, necessitating that this overview be limited in breadth, covering only those risks that are the most serious: hypobaric syndromes, cardiovascular disease, respiratory disease, and cancers. A thorough discussion of any one of these could easily fill a chapter. For this reason, the review is also limited in depth, aiming to provide adequate context for more detailed studies of astronaut mortality related to these risks.

Next, the chapter reviews the research to date on the mortality outcomes of the original twenty-four lunar astronauts and presents the results of an updated investigation of mortality among lunar astronauts, expanding upon the findings from earlier studies.

2. Environmental hazards and health outcomes in the lunar environment

2.1 Hypobaric environments

Lunar atmospheric pressure has been estimated as 3×10^{-15} bar (3×10^{-12} kPa) at night [1]. This presents hypobaric health risks, requiring astronauts to wear space suits or be within the confines of pressurized habitats at all times. The lack of atmosphere on the Moon means that lunar astronauts face the constant threat of decompression sickness when moving between environments of differing pressure, and of ebullism if exposed to the lunar surface without a spacesuit [2, 3].

The danger of decompression sickness is highest for astronauts leaving a lunar habitation or spacecraft to perform an extra-vehicular activity (EVA) on the lunar surface. Spacecraft are typically pressurized to sea-level on Earth, about 101 kPa, whereas US spacesuits are pressurized to only approximately 30 kPa. Astronauts suiting up and exiting the spacecraft or habitation to the lunar surface could develop nitrogen bubbles in the bloodstream or in tissues as dissolved nitrogen condenses under the reduced pressure [2].

Ebullism occurs when bodily fluids vaporize under extremely low atmospheric pressure (or in vacuum). During this process the body will swell as water vapor forms in soft tissues and venous blood. Ebullism is but one effect of exposure to very low pressure; others include cessation of circulation, loss of consciousness, paralysis, and eventual death [3].

2.2 Hypogravity

Life on Earth exists in an environment of constant gravitational acceleration. This ubiquitous force has shaped the evolution of plants and animals on the planet, humans included. The human skeletal structure, cardiovascular system, vestibular system and other physiological characteristics have evolved to function best with a constant downward pull of 9.81 m/s^2 (1 Earth-gravity or 1 G). Astronauts traveling to the Moon will instead encounter lunar gravity, which is approximately 1/6 G. They will also spend time both in LEO and translunar space, which are 0 G or *microgravity* environments. Environments with less than 1 G of gravity may collectively be referred to as *hypogravity* environments.

Hypogravity is directly or indirectly responsible for a number of physiological changes during spaceflight. One of the most important is cardiovascular deconditioning. Cardiovascular deconditioning is the constellation of symptoms that result from weakening of the heart as a result of prolonged periods of decreased cardiac workload. Included among these symptoms are temporary and less serious symptoms such as orthostatic intolerance and reduced aerobic capacity, as well as the potentially more serious outcome of cardiac arrhythmia [4, 5].

Cardiovascular deconditioning during space travel is a result of the redistribution of bodily fluids that occurs under microgravity. Of particular concern is the redistribution of blood throughout the circulatory system. On Earth, the pull of gravity pools blood in the legs and feet, whereas in microgravity the cardiovascular system is easily able to create a more uniform distribution of blood between the upper and lower parts of the body. Once this distribution has been achieved (within hours of entering 0 G), the body perceives the increased volume of blood in the upper half of the body as hypervolemia, and reduces the total volume of water in the body to compensate. The net effect of this is a reduced workload on the heart, which can eventually lead to cardiac atrophy [4, 5].

Short-duration arrhythmias have been recorded on several occasions during spaceflight, but it is unclear if they are the result of underlying, preexisting conditions or are the result of changes induced by spaceflight [6, 7]. One potential explanation for these arrhythmias is the loss of potassium with the reduction of water in the body when adjusting to 0 G [8]. At the time of press, NASA still considers this an open question [7].

Since fluid shifts under reduced gravity are responsible for the cardiovascular changes observed in astronauts after extended stays in LEO, it is logical to assume that the Moon's reduced gravity would lead to a similar, but perhaps lesser, deconditioning. A recent review examined the evidence regarding cardiopulmonary and other outcomes in simulated hypogravity, including simulated lunar gravity. The review found that several physiological measures of cardio-pulmonary efficiency are improved with decreasing gravity levels, and that cardiac stoke volume increases with decreasing gravity, similar to 0 G conditions [9]. However, it is still unknown the extent to which long-term exposure to lunar gravity would attenuate the cardiac deconditioning seen with stays in microgravity.

2.3 Space radiation

Just as life on Earth has been shaped by the Earth's gravitational pull, it has also been influenced by the Earth's radiation environment. The types of and amounts of radiation typically found on Earth differ from those in space. In general, the amount of background radiation on Earth is lower than that in space, particularly for cosmic radiation. As a consequence, life on Earth has evolved in an environment comparatively devoid of ionizing radiation, and thus is not generally resistant to it.

Ionizing radiation in outer space is primarily particulate: protons, electrons, and heavy atomic nuclei. Fast-moving ions may come from deep space (galactic cosmic rays, or GCR) or may be ejected from the Sun during a solar particle event (SPE). Protons are also encountered as particles ejected from the Sun as part of an SPE [10, 11]. Since the Moon has very little atmosphere and a weak magnetic field, the lunar surface is unprotected from cosmic radiation and thus under constant bombardment from it [12].

Exposure to ionizing radiation can have effects that occur either relatively soon after the dose (within 24 hours to several weeks) or relatively late after the dose (months or even years later). The short-term effects are called acute effects, while those that occur later are termed late effects. For astronauts living and working on the Moon, there is considerable risk for both acute and late effects.

2.3.1 Acute radiation syndrome

Acute Radiation Syndrome (ARS) is the collection of health effects that occur after a rapid, whole-body dose of ionizing radiation. Typical effects of ARS include retching and vomiting, which has been observed in animal models of SPE irradiation at doses as low as 0.5 Gy. Hematological changes and immune system suppression have been observed in various irradiated animals, as has damage to lung tissues, impaired cardiac function, and skin damage. Finally, fatigue has been observed as a common outcome of acute radiation exposure, both in cancer patients receiving radiotherapy and in animal models of SPE radiation effects [10].

Just as for astronauts in LEO or deep space, the risk of ARS for astronauts in the lunar environment is greatest for astronauts who may be on EVA during an SPE, as they will not have the benefit of spacecraft or lunar habitat shielding [12]. Though the most likely risks attached to SPEs are acute effects, a SPE of sufficient size could prove lethal to lunar astronauts, and such events have been observed in the recent past [12]. Even when SPEs are not of sufficient size to be outright lethal, doses absorbed during an SPE could still result in an ARS episode, and would contribute to the risk of late effects, as detailed below.

2.3.2 Carcinogenesis and heart disease

The primary late-effect health concern from space radiation is radiation-induced carcinogenesis. Leukemias, breast, lung, and gastrointestinal tumors have all been observed after exposure to ionizing radiation on Earth, and thus it is speculated that space radiation could yield similar problems, perhaps at higher rates [11, 13]. While there have been no reports of increased incidence of cancer among astronauts to date, this is likely due to insufficient radiation doses stemming from successful radiation control strategies as practiced by NASA, and relatively brief journeys in LEO or to the Moon [14, 15].

Though epidemiologists continue to surveil the astronaut population for cancer mortality, a growing concern is the degenerative tissue effects that space radiation may have on the cardiovascular system, as accumulated damage to the vasculature may induce heart disease [10, 16]. Recent research has failed to find any increased incidence of heart disease among astronauts, even when controlling for known cardiovascular risk factors. Instead, astronauts were found to have a much lower incidence of cardiovascular disease in comparison to both the US general population and a specially matched control population [17]. Furthermore, there was no difference in risk between astronauts who had spaceflight experience in comparison to those who did not.

2.4 Lunar dust

The surface of the Moon is covered in a meters-thick layer of loose rock and fine dust known as *lunar regolith*. This substance is the result of meteorite collisions with the Moon breaking down exposed lunar bedrock over the course of billions of years [18]. The mean size of regolith dust particles from the Apollo and Luna samples are between 60 and 80 μm, though ultra-fine particles (those with sizes measured in nanometers) have been documented as well [18, 19]. It is estimated that approximately 10% of the very fine particulate component (<10 μm) is in the respirable range [20].

Respirable particles of lunar regolith have unique properties which make them potentially more toxic than dusts found on Earth. Much of the fine particle regolith material is created by localized vaporization and fracturing when micrometeorites impact the lunar surface and the existing regolith material. This creates particles that are jagged and sharp, as well as highly chemically reactive. Without substantial atmosphere and weather to grind down and react with the particles, they remain jagged and chemically reactive [20–22]. Finally, regolith particles of respirable size are near-ubiquitous with nanophase iron (np-Fe^0) spheres (super-fine iron dust with particles measured on a nanometer scale) [21]. These physical and chemical properties of lunar regolith make it potentially harmful for human skin, eyes, and, most importantly, airways.

Lunar regolith poses a respiratory health risk in much the same way that respirable dust on Earth does. The inhalation of respirable particles (<10 μm) into the airway can irritate the airway linings and bronchi, and dust may lodge in the lungs themselves, promoting fibrous growths. This effect may be exacerbated by hypogravity, as simulation studies using animals have shown differential patterns of particle deposition under reduced gravity conditions [23–25]. Because of its jagged shape, lunar dust adheres to spacesuits, and, during the Apollo lunar missions, became airborne inside the lunar and command modules after lunar surface excursions.

Exposure to silica on Earth is known to be associated with pneumoconiosis, increased risk of lung infection, chronic obstructive pulmonary disease, cancers of the airway, certain autoimmune disorders, and chronic renal disease [26]. While it is not known for sure, it is reasonable to assume that lunar dust would also be associated with these conditions, since, as mentioned above, its physical and chemical properties make it more toxic than silica dust on Earth.

Safe human levels of exposure to lunar regolith have been estimated through animal studies [27, 28]. These studies have estimated the same exposure level to

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be in the range of 0.5–1.0 mg/m^3 for a 6-month lunar surface deployment. Still another study estimated a human no adverse effect level (NOAEL) for intermittent exposure on a 6-month mission as 0.4 mg/m^3 [29]. For comparison, the US Occupational Safety and Health Administration (OSHA) sets a time-weighted average permissible exposure limit (PEL) for respirable fused silica dust of 5 mg/m^3 in an 8-hour shift of work. Respirable fused silica dust currently has no threshold limit value, but OSHA recommends that airborne concentrations of respirable particles be kept below 3 mg/m^3 for insoluble particles of low toxicity [30].

2.5 Other risks

As part of its Human Research Program (HRP), NASA maintains a list of thirty-four health risks associated with deep space exploration [31]. Although they are not organized by cause, at least half of these risks are related to the environmental conditions reviewed here: vacuum, hypogravity, cosmic radiation, and celestial dust (including lunar dust). Many of the rest of the risks are comprised by categories of occupational hazards such as inadequate design and engineering, psychological and performance issues, inadequate training, and the physical hazards associated with EVA. Interested readers are encouraged to investigate the list published by NASA and learn more about these risks.

3. Mortality risk for lunar astronauts

Though humans have spent relatively little time on the lunar surface, health risks associated with the lunar environment are myriad. It is therefore possible that lunar astronauts have faced premature mortality risk because of their time in orbit around the Moon or on its surface. This section first reviews the existing literature on lunar astronaut mortality, and then updates those findings with a new original analysis of the data.

3.1 Prior studies of lunar astronaut mortality

Studies of lunar astronaut mortality have focused on searching for evidence of increased mortality due to either cancer or cardiovascular disease, either of which the literature suggests may be elevated with sufficient exposure to ionizing radiation in outer space.

The first study to isolate lunar astronauts in a mortality analysis attempted to examine if a larger proportion of lunar astronauts had died of cardiovascular disease than might be expected given a general population comparison cohort or in comparison to non-lunar astronauts (including members of pre-NASA experimental flight programs administered by the US Air Force) [32]. To do this however, the authors used a cross-sectional statistical method inappropriate to the data [33, 34]. This approach led the researchers to conclude, erroneously, that lunar astronauts had indeed experienced an excess proportion of deaths due to cardiovascular disease in comparison to the general population, as well as in comparison to astronauts who never went to space and astronauts who only flew on missions to low Earth orbit. A reanalysis of the data (using methods appropriate to longitudinal cohort studies) told a different story: lunar astronauts were at reduced risk of mortality from cardiovascular disease in comparison to the general population, and showed no differences in risk in comparison to other groups of astronauts [34]. This conclusion was further supported by a study of cardiovascular disease incidence which, as described above, found no increase in the incidence of cardiovascular disease for any astronauts [17].

A recent study of cosmic radiation exposure and mortality risk analyzed data from all 73 astronauts selected before 1970 [15]. The study used recorded radiation doses as the exposure measurement, and looked at several cancer and CVD outcomes. Results indicated significant reductions in mortality risk from all cardiovascular disease, ischemic heart disease, all cancers, and all-cause mortality, even though they found a greater than five-fold increase in risk of death by external causes. Though this study was not exclusively of lunar astronauts, lunar astronauts did make up one-third of the study group. These results agree with prior studies, and are further suggestive of a lack of excess mortality risk in the lunar cohort from cancer, CVD or any other natural cause.

3.2 Updated analysis of lunar astronaut mortality

This analysis compares the mortality rate of lunar astronauts to that of all other NASA astronauts for several cause-of-death categories, and with follow-up through 31 October 2018.

3.2.1 Data

Data for this analysis were those of all male NASA astronauts selected between 1959 and 2013. As there have been no female lunar astronauts, I limited the dataset to males. I counted follow-up time for non-lunar astronauts as the date of selection until either death or 31 October 2018, whichever came first. To avoid immortal time bias, follow-up time for lunar astronauts was from the date of the first lunar mission until either death or 31 October 2018 [35]. A total of 314 non-lunar astronauts contributed 7534 person-years of observation time and 50 deaths, while the 24 lunar astronauts contributed 1002 person-years of observation and 12 deaths.

3.2.2 Causal model

Figure 1 displays a causal diagram for astronaut mortality in the form of a directed acyclic graph (DAG). The diagram shows the theorized causal relationship between several measured factors, unmeasured factors, and the outcome, mortality. In this DAG, Year has a direct effect on other potential explanatory variables as well as a direct effect on mortality rate. This makes Year a confounder of the relationship between the exposure of interest – being a lunar astronaut – and mortality rate. This in turn means that the paths leading from Year to Mortality Rate are biasing paths as well. Controlling for Year removes this confounding, so I included Year in all models. Similarly, Age at Selection confounds the relationship between being a lunar astronaut and mortality through its causal effect on being a lunar astronaut and on current age. I therefore adjusted for current age in all models as well.

The circle for "other factors" represents any of an unlimited set of potential confounding variables that were not measured in the data. This set of unnamed factors are also assumed to be influenced by year of selection, and themselves have a causal effect on becoming a lunar astronaut as well as mortality rate. This makes these other factors confounders as well. However, as they are unmeasured, there is no way to control for any residual confounding that these factors may introduce.

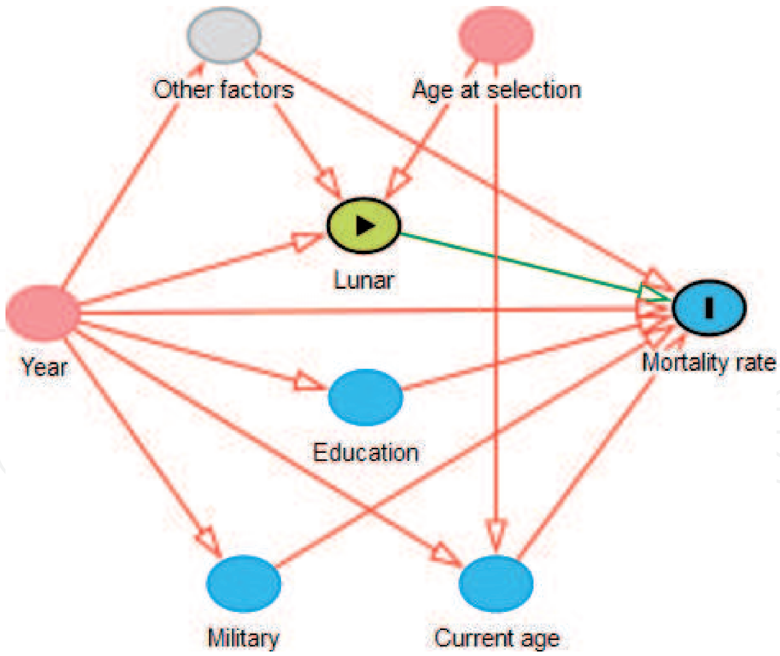

Figure 1.
Causal diagram for lunar astronaut mortality.

3.2.3 Statistical methods

To estimate if lunar astronauts have experienced higher age-specific mortality risk since their lunar missions, I modeled their mortality due to various causes of death. To do this I fit a series of Poisson regression models to discreet time-interval data. These data break the total follow-up period for each individual into smaller intervals with both fixed and time-varying covariates, including a variable containing the length of the interval and an indicator of death or survival on the interval. By using the log of the time on each interval as an offset, the model estimates the log of the mortality rate (rather than the count of deaths) as a linear function of the covariates. The resulting model provides mortality rate ratios (MRR) for the estimated parameters, which can be interpreted as relative risks of death.

I fit two sets of models for each of 4 outcomes, for 8 models in total. The outcomes I examined were: death by any natural cause, death by cancer, death by CVD, and death from all other (non-cancer/non-CVD) natural causes. The first set of models used a single term to differentiate lunar astronauts from all other astronauts. The other set of models used two binary terms to differentiate three groups of astronauts: those who orbited the Moon, those who walked on the Moon, and all non-lunar astronauts.

I assessed statistical significance and estimated confidence intervals around parameter estimates using standard errors generated from the robust sandwich variance estimator. This technique guards against violations of the assumption of the Poisson distribution that the mean is equal to the variance [36]. Significance testing on parameters was conducted at the $\alpha < 0.05$ level.

To assess how much bias may be present in the data, I checked covariate balance on 4 baseline covariates between lunar and non-lunar astronauts, using standardized mean differences (SMDs). Covariates with SMDs of less than 0.1 are considered to be in balance between two groups [37]. To test the statistical significance of the differences, I used t-tests for differences in continuous variables and chi-square tests with continuity correction for categorical variables. Imbalance and significant differences in baseline covariates may be an indicator of uncontrolled confounding in both measured and unmeasured variables [37].

3.2.4 Results

Table 1 displays demographic and actuarial characteristics of the lunar cohort of astronauts.

All of the lunar astronauts were selected to NASA between 1959 and 1966, all were male, and all were of White race/ethnicity. Of the 24 cohort members, 23 of them (96%) had a military background. Twelve (50%) of the astronauts had a Bachelor's degree, 10 (42%) had Master's degrees, and 2 (8%) had Doctoral degrees. The average age at first lunar mission was 39.0 years, and, as of 31 October 2018, the astronauts have been followed for an average of 41.8 years. **Figure 2** shows the breakdown of lunar astronaut deaths by lunar mission role and causal category.

Half of the lunar astronauts have died (12/24). Eight of these deaths were in the lunar surface group, and 4 in the lunar orbit group. Of the 12 total deaths, 3 of them were due to cancer, 3 were due to cardiovascular disease, and the remaining 5 were due to other natural causes. The single death due to external causes was experienced by a lunar surface astronaut.

Figure 3 provides a plot of the SMDs between the full lunar cohort and the rest of the astronaut corps for 4 baseline covariates. The figure shows that age, year of selection, education, and history of military service are all unbalanced between lunar and non-lunar astronauts, as each of their SMD values are greater than 0.1 (i.e., to the right of the red, vertical, dashed line). Statistical tests confirmed that the differences in these covariates are statistically significant, with p-values all less than 0.01 (values not pictured in **Figure 2**).

	All lunar astronauts (N = 24)		Landed on the Moon (N = 12)		Orbited the Moon only (N = 12)	
Characteristic	**n**	**(%)**	**n**	**(%)**	**n**	**(%)**
White	24	100.0	12	100.0	12	100
Males	24	100.0	12	100.0	12	100
Military experience	23	95.8	11	91.7	12	100
Education						
Bachelor	12	50.0	5	41.7	7	58.3
Master	10	41.7	5	41.7	5	41.7
PhD	2	8.3	2	8.3	0	0.0
	Mean	**(sd)**	**Mean**	**(sd)**	**Mean**	**(sd)**
Age, years						
Selection	32.8	1.9	32.6	2.2	33.0	1.6
First lunar mission	39.0	2.6	39.4	3.9	38.6	2.0
Death	73.2	13.5	78.7	9.4	64.3	16.4
End of study (survivors)	86.6	2.8	85.5	2.7	87.2	2.8
Follow-up time	41.3	11.9	41.6	10.0	41.0	14.1
Year of selection	1964	2.0	1963	2.1	1964	1.9
Year of lunar mission	1970	1.4	1970	1.4	1970	1.4

Table 1.
Lunar cohort characteristics.

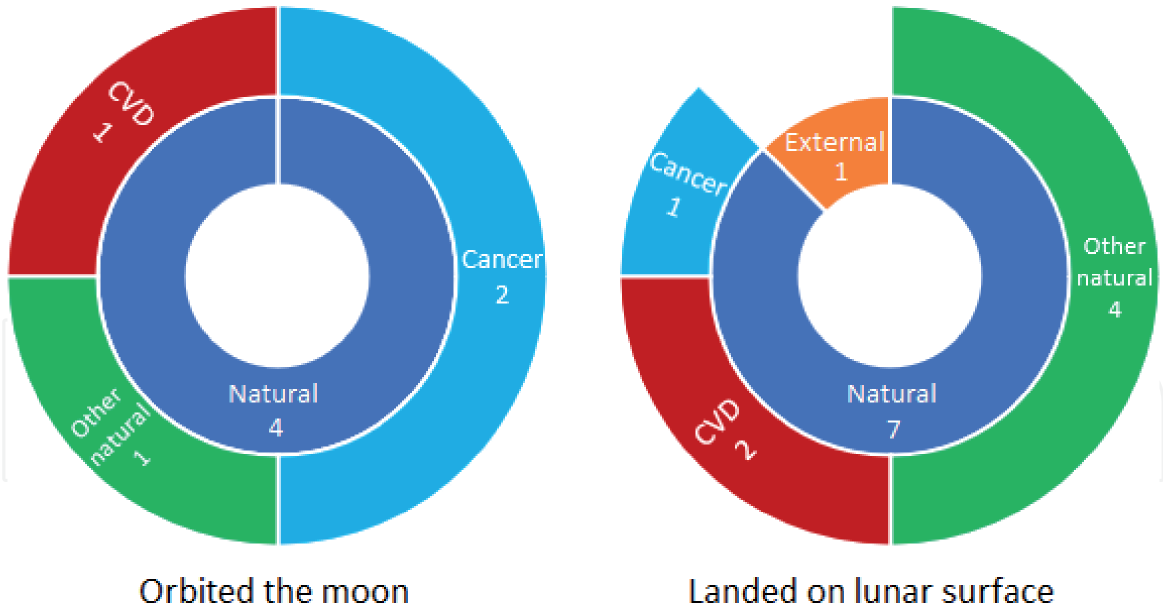

Figure 2.
Distribution of deaths by cause among lunar astronauts as of 31 October 2018.

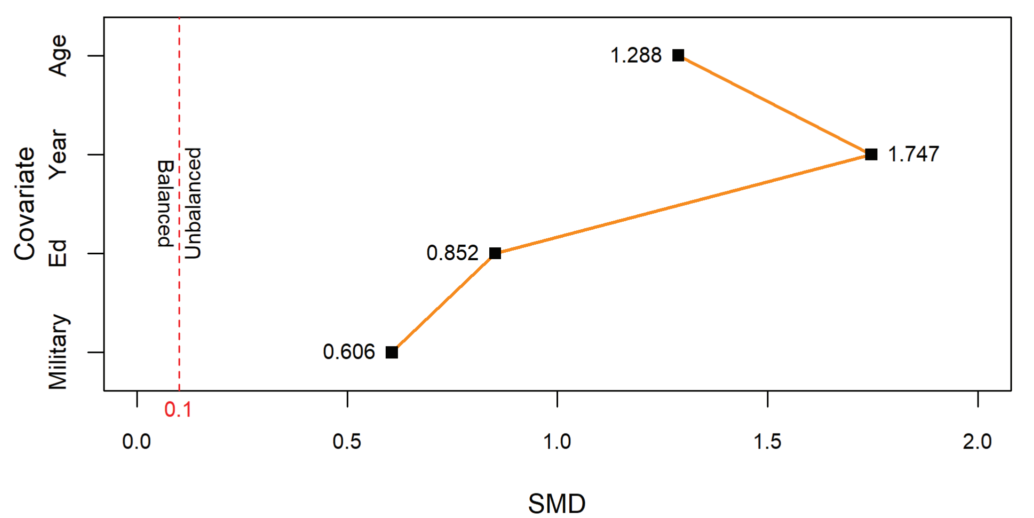

Figure 3.
Standardized mean differences (SMDs) for baseline covariates between lunar and non-lunar astronauts.

Figure 4 displays the MRR point estimates (blue squares) and 95% confidence intervals (blue lines), for the age, year terms, and the lunar covariate in each of the first four models. Looking at the point estimates for all covariates in all models, we see that none of them are statistically significant predictors of mortality rate. The estimates attached to age were all between a 5% and 22% increase in mortality rate per additional year past selection. Estimates for year of selection, calendar year, and being a lunar astronaut were all close to 1.0 with confidence intervals that included 1.0.

Figure 5 shows the MRRs for the second set of models, in which the lunar astronauts are further divided into orbital and surface subgroups. Once again age shows a consistent (though still statistically insignificant) increase in the mortality rate for all cause-of-death groups, with MRRs nearly identical to those in **Figure 4**. The point estimates for having orbited the Moon were less than 1.0 in all outcome models except cancer, although none of them were statistically significant. The largest estimated reduction in risk for astronauts who orbited the Moon was an MRR of 0.35 (95% CI = 0.03–3.52), for CVD.

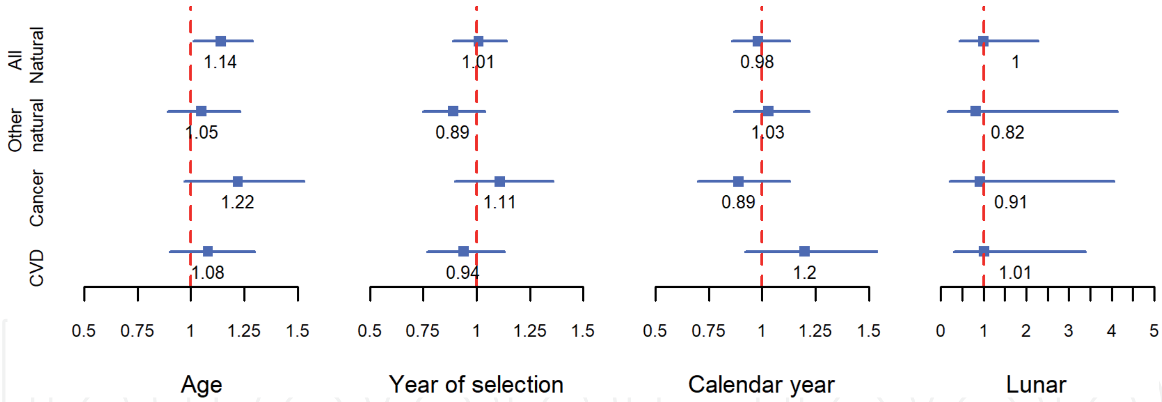

Figure 4.
Mortality rate ratios from Poisson models of mortality rates for all lunar astronauts.

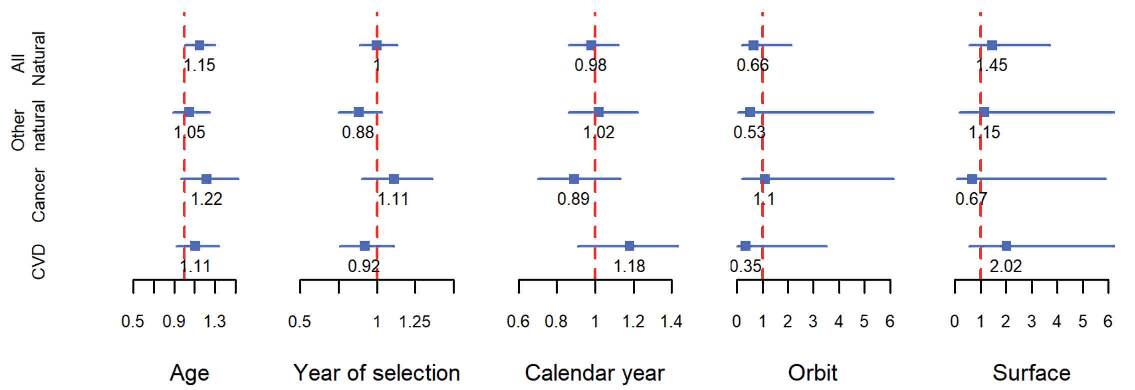

Figure 5.
Mortality rate ratios from Poisson models of mortality rates for orbital and surface lunar astronauts.

None of the MRRs for lunar surface astronauts were statistically significant. However, point estimates suggest approximately double the mortality risk from CVD (MRR = 2.02; 95% CI = 0.55–7.36), but about two-thirds the mortality risk from cancer (MRR = 0.67; 95% CI = 0.08–5.90). The net effect of these mixed results was an MRR for all natural causes of 1.45 (95% CI = 0.56–3.70).

3.2.5 Discussion

The models presented here fail to demonstrate any statistically significant increase in mortality risk for lunar astronauts in comparison to non-lunar astronauts. There are three potential reasons for this: (a) the models lack the statistical precision to discriminate excess risk from random variation; (b) the MRRs for lunar astronauts are confounded and thus misleading; or (c) lunar astronauts bear no excess mortality risk in comparison to other astronauts.

In regards to statistical precision of the models, small numbers of astronauts suggest, and prior studies have demonstrated poor statistical power in analyses of astronaut health [14, 15]. One study showed that adequate power was achieved for cancer mortality outcomes only when relative risks exceeded 4.0 for astronauts with radiation doses above the median [14]. Yet another study of 73 astronauts (including all 24 lunar astronauts) reported that, under reasonable assumptions about excess risk, statistical power was less than 6% [15]. Furthermore, power did not markedly improve even when assuming 10 times the number of observed deaths or 10 times the dose-dependent excess relative risk [15]. As statistical power is a function of sample size, the power of an even smaller subgroup analysis (such as lunar astronauts) would be lower still. Thus, it is entirely possible that the MRRs observed here are genuine differences, but that low statistical power alone means we cannot reliably distinguish them from random variation.

Another consequence of small sample size is the limited ability to adjust for other potential confounding variables in the models of **Figures 4** and **5**, even when such variables are available. Because of this, the MRR estimates presented here may be confounded by other unmeasured factors that are not accounted for in the causal or statistical models. If so, this confounding could mask significant differences in mortality risk between lunar and non-lunar astronauts. **Figure 3** provides evidence of differences between lunar and non-lunar astronauts on at least 4 measured covariates, which may be evidence of confounding. Furthermore, the causal diagram of **Figure 1** suggests more unobserved confounding is possible. Of particular concern are unmeasured lifestyle factors such as tobacco use, alcohol use, diet, and exercise.

Though it is possible that low statistical precision or confounding is obscuring increased risk for lunar astronauts, it nevertheless seems implausible given the small exposure the lunar astronauts had to the major hazards of the lunar environment – hypogravity, cosmic radiation, and lunar dust. Specifically:

a. The total time of exposure to hypogravity for lunar astronauts pales in comparison to astronauts who have completed multiple shuttle missions or long-duration stays on the ISS. The mean time in space for lunar astronauts was 18.7 days, whereas the mean time in space for non-lunar astronauts (among those who have been to space) is 76.8 days. The average mission time for lunar astronauts was 8.7 days accrued on an average of 2 missions, while the average mission time for non-lunar astronauts was 26.1 days accrued on an average of 3 missions each. So, if exposure to hypogravity creates excess mortality risk – either in relation to total exposure time or unique number of exposures – non-lunar astronauts should be at greater risk than lunar astronauts. This is especially true if 0 G is more deleterious than lunar gravity, since the entirety of hypogravity exposure for non-lunar LEO astronauts has been in 0 G.

b. The doses of ionizing space radiation received by lunar astronauts are not extreme among astronauts or in comparison to Earth-based radiation workers. For example, as of 1993, lifetime cosmic radiation doses received by all astronauts, lunar included, were noted to be smaller than those received from medical diagnostic doses, [38] while a more recent report notes that only a third of the astronauts selected before 1970 received total space radiation doses greater than 11 mGy [33]. It should be noted that with the doses of space radiation received by all astronauts to date – even among those at the highest end of absorbed dose – that no acute effects have been observed, and only mildly increased risk of minor late effects has been observed [39, 40].

   Furthermore, the doses received by lunar astronauts would have to exceed those of non-lunar astronauts in order for lunar astronauts to be observed as at greater radiation-induced risk of mortality. Radiation dose is highly correlated with time in space, so just as non-lunar astronauts have logged considerably more time in space, they also have larger doses of cosmic radiation. Were cosmic radiation doses in the astronaut cohort as a whole at harmful levels we might therefore expect to see lunar astronauts at *reduced* mortality risk in comparison to non-lunar astronauts.

c. Though lunar dust is known to be more toxic than most dust found in industrial settings on earth, the astronauts' exposure to it was limited in both intensity and duration. Exposure to lunar dust was isolated, with direct contact limited to the time at rest in the lunar module and the trip back to earth in the command and service modules. All told this would equate to mere days of exposure at most. Workers on Earth who develop pneumoconiosis and other respiratory diseases typically only do so after repeated, sustained exposure to dust [26]. Based on what is known about dust exposure for workers on Earth, such brief exposure to lunar dust would therefore be unlikely to cause any lasting health problems, and thus unlikely to be a source of increased mortality for lunar astronauts.

In short, the exposures faced by lunar astronauts, though almost certainly harmful in sufficient quantity, were likely of inadequate intensity and duration to cause long-term excess mortality risk on historic missions.

4. Conclusions

The lunar environment poses a number of health risks for human explorers, some exotic and some familiar. Chief among them are hypobaric environments, hypogravity, cosmic radiation, and lunar dust. All of these, in sufficient doses, have the potential to cause a number of deleterious health effects.

The risk of hypobaric injury and death from the lack of atmosphere is omnipresent for astronauts living and working on the Moon. Deconditioning of the cardiovascular system in microgravity is a well-known hazard which is likely only partially abated by the Moon's low-gravity environment. Without appropriate protection, the radiation environment on the Moon is capable of producing an array of both acute and chronic health problems. Finally, lunar dust, as a highly fragmented and highly reactive substance, has the potential to cause respiratory illness, which may be exacerbated by differential patterns of particle deposition in the lungs under hypogravity conditions.

There have been only 24 individuals who have thus far visited the Moon, and to date they have shown no evidence of increased mortality rates for having done so. Yet, because of the small size of the cohort, it is possible that moderate increases in mortality risk from some causes may be in play. It is also possible that mortality estimates are confounded by uncontrolled factors. However, it seems unlikely that lunar astronauts are subject to excess mortality risk in comparison to non-lunar astronauts as a result of lunar missions. The duration of exposure to hypogravity and dose of cosmic radiation were low in comparison to non-lunar astronauts. Lunar astronauts' exposure to lunar dust was episodic and likely below the exposure threshold needed to trigger respiratory disease and thus increased mortality risk.

Though humanity currently has little direct experience with the lunar environment, our knowledge will continue to grow as humans return to the Moon in the decades to come. What we learn about how to successfully colonize the Moon will teach us valuable lessons that will allow us to colonize Mars and beyond. It thus becomes critical to continue to study human health in extraterrestrial environments, learning what we can as we can. The small steps of such ongoing efforts will thus enable the giant leaps that follow.

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Conflict of interest

The author has no conflict of interest to report.

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References

[1] National Aeronautics and Space Administration. Moon fact sheet. Available at: https://nssdc.gsfc.nasa.gov/planetary/factsheet/moonfact.html [Last Accessed: 10-01-2019]

[2] Norfleet WT. Decompression-related disorders: Decompression sickness, arterial gas embolism, and ebullism syndrome. In: Barratt MR, Pool SL, editors. Principles of Clinical Medicine for Spaceflight. New York: Springer; 2008

[3] Billings CE. Barometric pressure. In: Parker JF, West VR, editors. Bioastronautics Data Book. 2nd ed. Washington D.C.: National Aeronautics and Space Administration; 1973

[4] Clement G. Fundamentals of Space Medicine. 2nd ed. New York: Springer; 2014

[5] Hamilton DR. Cardiovascular disorders. In: Barratt MR, Pool SL, editors. Principles of Clinical Medicine for Spaceflight. New York: Springer; 2008

[6] National Aeronautics and Space Administration. Risk of cardiac rhythm problems during spaceflight. Houston: Lyndon B. Johnson Space Center. Available at: https://humanresearchroadmap.nasa.gov/evidence/reports/Arrhythmia.pdf [Last Accessed: 10-01-2019]

[7] National Aeronautics and Space Administration. "HRR—Risk—Risk of Cardiac Rhythm Problems". Available at: https://humanresearchroadmap.nasa.gov/Risks/risk.aspx?i=79 [Last Accessed: 10-01-2019]

[8] Nicogossian AE, Doarn CR, Hu Y. Evolution of human capabilities and space medicine. In: Nicogossian et al., editors. Space Physiology and Medicine: From Evidence to Practice. 4th ed. New York: Springer; 2016

[9] Richter C, Braunstein B, Winnard A, Nasser M, Weber T. Human biomechanical and cardiopulmonary responses to partial gravity—A systematic review. Frontiers in Physiology. 2017;**8**:583

[10] Chancellor JC, Scott GB, Sutton JP. Space radiation: The number one risk to astronaut health beyond low earth orbit. Life (Basel). 2014;**4**(3):491-510

[11] Jones JA, Karouia F. Radiation disorders. In: Barratt MR, Pool SL, editors. Principles of Clinical Medicine for Spaceflight. New York: Springer; 2008

[12] Lockwood M, Hapgood M. The rough guide to the Moon and Mars. Astronomy & Geophysics. 2007;**48**(6):6.11-6.17

[13] Huff J et al. Risk of Radiation Carcinogenesis. NASA Human Research Program, Available at: https://humanresearchroadmap.nasa.gov/Risks/risk.aspx?i=96 [Last Accessed: 10-01-2019]

[14] Reynolds RJ. Development of a location exposure matrix for ionizing radiation in extraterrestrial environments and its application in the study of mortality for U.S. astronauts. Texas Medical Center Dissertations (via ProQuest). Paper AAI3604553

[15] Elgart SR et al. Radiation exposure and mortality from cardiovascular disease and Cancer in early NASA astronauts. Scientific Reports. 2018;**8**(1):8480. DOI: 10.1038/s41598-018-25467-9

[16] Patel Z et al. Risk of Cardiovascular Disease and Other Degenerative Tissue Effects from Radiation Exposure. NASA Human Research Program. Available at: https://humanresearchroadmap.nasa.gov/Risks/risk.aspx?i=98 [Last Accessed: 10-01-2019]

[17] Ade CJ, Broxterman RM, Charvat JM, Barstow TJ. Incidence rate of cardiovascular disease end points in the National Aeronautics and Space Administration astronaut corps. Journal of the American Heart Association. 2017;**6**:e005564. DOI: 10.1161/JAHA.117.005564

[18] McKay DS, Heiken G, Basu A, Blanford G, Simon S, Reedy R, et al. The lunar regolith. In: Heiken G, Vaniman D, French B, editors. Lunar Sourcebook. Cambridge: Cambridge University Press; 1991

[19] Greenberg PS, Chen D-R, Smith SA. Aerosol measurements of the fine and ultrafine particle content of lunar regolith. NASA Technical Reports Server, 2007. Available at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20070031906.pdf

[20] Cain JR. Lunar dust: The Hazard and astronaut exposure risks. Earth, Moon, and Planets. 2010;**107**:107-125

[21] McKay DS, Cooper BL, Taylor LA, James JT, Thomas-Keprta K, Pieters CM, et al. Physicochemical properties of respirable-size lunar dust. Acta Astronautica. 2015;**107**:163-176

[22] Grün E, Horanyi M, Sternovsky Z. The lunar dust environment. Planetary and Space Science. 2011;**59**:1672-1680

[23] Darquenne C, Prisk GK. Deposition of inhaled particles in the human lung is more peripheral in lunar than in normal gravity. European Journal of Applied Physiology. 2008;**103**:687-695

[24] Darquenne C, Prisk GK. Particulate deposition in the human lung under lunar habitat conditions. Aviation, Space, and Environmental Medicine. 2013;**84**:190-195

[25] Darquenne C, Borja MG, Oakes JM, Breen EC, Olfert IM, Scadeng M, et al. Increase in relative deposition of fine particles in the rat lung periphery in the absence of gravity. Journal of Applied Physiology. 2014;**117**:880-886

[26] Leung CC, Yu ITS, Chen W. Silicosis. Lancet. 2012;**379**:2008-2018

[27] James JT, Lam C, Scully RR. Comparative Benchmark Dose Modeling as a Tool to Make the First Estimate of Safe Human Exposure Levels to Lunar Dust. NASA Technical Reports Server, 2103. Available at: https://ntrs.nasa.gov/search.jsp?R=20130012803 [Last Accessed: 10-01-2019]

[28] Scully RR, Lam CW, James JT. Estimating safe human exposure levels for lunar dust using benchmark dose modeling of data from inhalation studies in rats. Inhalation Toxicology. 2013;**25**(14):785-793

[29] Lam C, Scully RR, Zhang Y, Renne RA, Hunter RL, McCluskey RA, et al. Toxicity of lunar dust assessed in inhalation-exposed rats. Inhalation Toxicology. 2013;**25**(12):661-678

[30] United States Department of Labor, Occupational Safety and Health Administration. OSHA Occupational Chemical Database. Silica, fused, respirable dust. Available at: https://www.osha.gov/chemicaldata/chemResult.html?recNo=442 [Last Accessed: 10-01-2019]

[31] National Aeronautics and Space Administration. Human Research Roadmap. Available at: https://humanresearchroadmap.nasa.gov/Risks/ [Last Accessed: 10-01-2019]

[32] Delp MD, Charvat JM, Limoli CL, Globus RK, Ghosh P. Apollo lunar astronauts show higher cardiovascular disease mortality: Possible deep space radiation effects on the vascular endothelium. Scientific Reports. 2016;**6**:29901

[33] Cucinotta FA, Hamada N, Little MP. No evidence for an increase in circulatory disease mortality in astronauts following space radiation exposures. Life Sciences and Space Research. 2016;**10**:53-56

[34] Reynolds RJ, Day SM. Mortality due to cardiovascular disease among Apollo lunar astronauts. Aerospace Medicine and Human Performance. 2017;**88**(5):492-496

[35] Jones M, Fowler R. Immortal time bias in observational studies of time-to event outcomes. Journal of Critical Care. 2016;**36**:195-199

[36] Zou G. A modified poisson regression approach to prospective studies with binary data. American Journal of Epidemiology. 2004;**159**(7):702-706

[37] Austin PC. The use of propensity score methods with survival or time-to-event outcomes: Reporting measures of effect similar to those used in randomized experiments. Statistics in Medicine. 2014;**33**:1242-1258

[38] Peterson LE, Pepper LJ, Hamm PB, Gilbert SL. Longitudinal study of astronaut health: Mortality in the years 1959-1991. Radiation Research. 1993;**133**(2):257-264

[39] Chylack LT Jr, Peterson LE, Feiveson AH, Wear ML, Manuel FK, Tung WH, et al. NASA study of cataract in astronauts (NASCA). Report 1: Cross-sectional study of the relationship of exposure to space radiation and risk of lens opacity. Radiation Research. 2009;**172**(1):10-20

[40] Chylack LT Jr, Feiveson AH, Peterson LE, Tung WH, Wear ML, Marak LJ, et al. NASCA report 2: Longitudinal study of relationship of exposure to space radiation and risk of lens opacity. Radiation Research. 2012;**178**(1):25-32