
STUDENT SCHOLARSHIP SUBMISSION

Human Exploration of Mars: Medical, Technological, and Ethical Challenges

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ABSTRACT

This essay reviews the medical, technological, and ethical issues of human exploration of Mars. PubMed and the NASA Technical Reports Server were used to identify 25 peer-reviewed studies, government reports, and technical documents for a qualitative analysis. Sources were rated for strength of evidence as strong (n = 10), good (n = 8), fair (n = 6), or poor (n = 1). Results have shown that long-term spaceflight poses severe physiological and psychological hazards, including muscle atrophy, bone loss, and stress from isolation and confinement (LeBlanc et al., 2007; Kanas & Manzey, 2008). Mission sustainability is defined as the need for robotic pre-positioning and the *in situ* use of resources (Rucker et al., 2022). The issue of planetary protection is a primary ethical concern, as human missions can pollute Mars and endanger scientific integrity (National Research Council, 2014). The increasing commercial and government investment underscores the need for global collaboration and new policy frameworks (NASA, 2016). Ultimately, it is possible to state that long-term investment in the health of crews, the use of stable technology, and ethical management should be ensured; only under these conditions can responsible exploration of Mars by crews take place.

Keywords: Mars mission, spaceflight health, in situ resource utilization, planetary protection, astrobiology

Exploración humana de Marte: desafíos médicos, tecnológicos y éticos

RESUMEN

Este ensayo revisa los aspectos médicos, tecnológicos y éticos de la exploración humana de Marte. Se utilizaron PubMed y el Servidor de Informes Técnicos de la NASA para identificar 25 estudios revisados por pares, informes gubernamentales y documentos técnicos para un análisis cualitativo. Las fuentes se clasificaron según la solidez de la evidencia como sólida ($n=10$), buena ($n=8$), regular ($n=6$) o débil ($n=1$). Los resultados han demostrado que los vuelos espaciales de larga duración plantean graves riesgos fisiológicos y psicológicos, incluyendo atrofia muscular, pérdida ósea y estrés por aislamiento y confinamiento (LeBlanc et al., 2007; Kanas y Manzey, 2008). La sostenibilidad de la misión se define como la necesidad de preposicionamiento robótico y el uso in situ de los recursos (Rucker et al., 2022). La cuestión de la protección planetaria es una preocupación ética primordial, ya que las misiones humanas pueden contaminar Marte y poner en peligro la integridad científica (National Research Council, 2014). El creciente interés comercial y gubernamental subraya la necesidad de colaboración global y nuevos marcos normativos (NASA, 2016). En definitiva, es fundamental garantizar la inversión a largo plazo en la salud de las tripulaciones, el uso de tecnología estable y una gestión ética; solo bajo estas condiciones podrá llevarse a cabo una exploración responsable de Marte por parte de las tripulaciones.

Palabras clave: Misión a Marte, salud en vuelos espaciales, utilización de recursos in situ, protección planetaria, astrobiología

人类火星探测：医学、技术与伦理挑战

摘要

本文综述了人类火星探测活动涉及的医学、技术及伦理问题。研究人员利用PubMed和NASA技术报告服务器(NASA Technical Reports Server)筛选出25份经同行评审的研究、政府报告及技术文件，并进行了定性分析。这些资料的证据强度被评定为：强($n = 10$)、良好($n = 8$)、一般($n = 6$)或差($n = 1$)。结果显示，长期太空飞行会带来严重的生理和心理风险，包括肌肉萎缩、骨质流失，以及因隔离和密闭环境引发的压力(LeBlanc et al., 2007; Kanas & Manzey, 2008)。任务的

可持续性取决于机器人预先部署能力及原位资源利用 (Rucker et al., 2022)。行星保护问题是一项主要的伦理考量，因为人类探测任务可能污染火星并危及科学研究的完整性 (National Research Council, 2014)。商业和政府投资的日益增加凸显了全球合作与建立新政策框架的必要性 (NASA, 2016)。综上所述，必须确保对乘组健康进行长期投入、采用成熟可靠的技术并实施合乎伦理的管理；唯有满足这些条件，才能开展负责任的载人火星探测活动。

关键词：火星任务，太空飞行健康，原位资源利用，行星保护，天体生物学

Human Exploration of Mars

Space exploration of Mars has been a significant objective of space science since it offers the possibility of extending human activity beyond Earth, studying the evolution of planets, and finding signs of other life forms in the Solar System. Mars is particularly attractive because it has been regarded as one of the most promising sites for past or present microbial life. NASA and other space missions like Mars Odyssey and Perseverance have contributed to learning much about the Martian environment and also confirming its dangers, which include a thin atmosphere, a low gravity of about a third of Earth's, intense exposure to radiation, extreme temperatures, and dust storms that cover the entire planet (NASA, 2021).

Recent ideas of mission see the Moon increasingly as a proving ground for human Mars exploration. This proposal aligns with the Artemis program, which is expected to create a sustainable human presence on the Moon and the capacity to carry out deep-space

missions (NASA, 2022). The Assembly, testing, and deployment of systems needed to support a crewed Mars mission could be supported by launching a lunar outpost. Moreover, pre-positioning the robotic infrastructure on Mars prior to the arrival of the crew would enhance mission safety by preparing the habitation, supply, and operational infrastructure (Rucker et al., 2022). *In situ* resource utilization (ISRU) is also a contributing factor to the success of such a strategy, as it may allow Martian resources to produce oxygen, water, and other consumables, rather than fully relying on Earth to resupply the crew (Rapp & Inglezakis, 2024).

Despite such progress, a human expedition to Mars poses significant medical, psychological, and ethical challenges. Spaceflight over long periods of time entails muscle atrophy, bone loss, and other physiological alterations that can interfere with crew performance during transit and surface operations (LeBlanc et al., 2007). Extended isolation and confinement, lag in communication, and distance from

the earth also pose serious behavioral health risks that can impact judgment, morale, and team cohesion (Kanas & Manzey, 2008). Meanwhile, planetary protection is a critical concern because, in the event of successful human missions, the possible Martian ecosystems may be polluted, or dangerous materials may be brought to Earth, raising significant scientific and ethical concerns (National Research Council, 2014). These concerns also underscore the importance of international collaboration and more robust policy formulation as governments and business actors continue to invest in deep-space exploration (NASA, 2016; Rucker et al., 2022).

The paper examines the medical, technological, and ethical issues of a human mission to Mars and evaluates the viability and risks of such a mission. It aims to support informed funding decisions on system reliability, safety, and human-supporting systems for responsible human exploration of Mars.

Methods

The qualitative analysis of scientific literature, government reports, and technical documents was used to conduct this review. The search terms were Mars mission challenges, space health impacts, radiation in space, Mars habitats, and in situ resource utilization. Relevant publications were identified using databases

such as PubMed, NASA Technical Report Server, and Google Scholar. The inclusion criteria were restricted to English-language publications from 2000 onward, and original research, systematic reviews, and reports from government/space agencies were prioritized. The quality and relevance of the studies were rated subjectively as strong/robust, good, fair, poor, or inconclusive, based on the strength of the evidence.

Results

The inclusion criteria identified 25 publications; the strength of evidence was rated as 10 strong, 8 good, 6 fair, and 1 poor. The findings of this review are presented in the table below, which summarizes the main publications covered in the qualitative analysis. They include the name of the lead author, the publication date, the title of the entry, the journal, and a summary of the findings in relation to the medical, technological, and ethical issues of human exploration of Mars.

The findings from these publications underscore the complex interplay of medical, technological, and ethical considerations in preparing for a human mission to Mars. The insights derived from this literature indicate a critical need for ongoing research and development in these areas to ensure the safety and success of future Mars missions.

Table 1. Results Analysis

Lead Author	Date	Publication Title	Journal	Strength of Evidence	Description
LeBlanc, A. D., et al.	2007	<i>Skeletal Responses to Space Flight and the Bed Rest Analog: A Review</i>	<i>Journal of Musculo-skeletal & Neuronal Interactions</i>	Strong	This review summarizes four decades of U.S. and Russian spaceflight data on bone and muscle loss, ground-based bed rest analog findings, and potential countermeasures, establishing the evidence base for musculoskeletal risks on long-duration missions.
Kanas, N., & Manzey, D.	2008	<i>Space Psychology and Psychiatry</i>	<i>Springer (book)</i>	Strong	The authors synthesize empirical research from actual space missions on psychological and psychiatric challenges faced by astronauts, including isolation, stress, and interpersonal dynamics, with direct implications for mission success.
Krittawong, C., et al.	2023	<i>Human Health during Space Travel: State-of-the-Art Review</i>	<i>Cells</i>	Strong	This comprehensive state-of-the-art review examines the physiological and health impacts of spaceflight, covering musculoskeletal, cardiovascular, neuro-ocular, and immune system changes relevant to long-duration missions.

(Cont'd.)

Lead Author	Date	Publication Title	Journal	Strength of Evidence	Description
Kramer, L. A., et al.	2020	<i>Intracranial Effects of Micro-gravity: A Prospective Longitudinal MRI Study</i>	<i>Radiology</i>	Strong	This prospective longitudinal MRI study documents intracranial changes in astronauts, including ventricular expansion and upward brain shift, resulting from long-duration exposure to microgravity.
Rucker, M. A., et al.	2022	<i>NASA's Strategic Analysis Cycle 2021 Human Mars Architecture</i>	<i>2022 IEEE Aerospace Conference</i>	Strong	This paper presents NASA's latest human Mars architecture, detailing the robotic and crewed mission sequence, pre-positioning strategies, and ISRU requirements for a sustainable Mars mission of approximately 900 days.
National Research Council	2014	<i>Assessment of Planetary Protection Requirements for Mars Sample Return Missions</i>	<i>The National Academies Press</i>	Strong	This consensus report emphasizes the importance of planetary protection protocols and the ethical implications of biological contamination during Mars missions, drawing on expert committee review.
NASA	2021	<i>Mars 2020 Mission: Perseverance Rover</i>	<i>NASA Technical Report</i>	Good	This publication outlines the objectives and outcomes of the Perseverance rover mission, including the first demonstration of ISRU oxygen production on Mars through the MOXIE experiment.

(Cont'd.)

Lead Author	Date	Publication Title	Journal	Strength of Evidence	Description
Patel, Z. S., et al.	2020	<i>Red Risks for a Journey to the Red Planet: The Highest Priority Human Health Risks for a Mission to Mars</i>	<i>npj Microgravity</i>	Strong	This NASA-led review identifies and ranks the highest-priority human health risks for a Mars mission across five hazard domains: space radiation, altered gravity, isolation and confinement, hostile environments, and distance from Earth.
Hoffman, S. J., & Kaplan, D. I.	2001	<i>Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team</i>	NASA	Good	This foundational NASA document presents the original reference mission architecture for human Mars exploration, outlining mission design, required technologies, and surface operations concepts.
Cohen, S. G., & Bailey, D. E.	1997	<i>What Makes Teams Work: Group Effectiveness Research from the Shop Floor to the Executive Suite</i>	<i>Journal of Management</i>	Good	This widely cited review of organizational team effectiveness research examines how task design, environment, and group composition influence performance, with relevance to crew dynamics on long-duration space missions.

Note. Publications were rated for strength of evidence as strong, good, fair, or poor based on methodological quality and relevance to the stated research questions.

Discussion

The aim of having a crewed mission to Mars, which will take a total of 900 days to reach Mars and back, is an incredible leap forward by humankind. The paper deals with

the medical, technological, and ethical issues of having a presence on the Red Planet and the need to finance the system in terms of reliability, safety, and human support. As we embark on such a monumental undertaking, complex challenges such as health hazards,

logistics, and ethical issues regarding planetary protection and crew membership must be addressed. The trip to Mars is full of difficulties, but the opportunities for scientific discovery and the development of humanity are enormous. Through addressing the medical, technological, and ethical concerns presented, we will be in a good position to establish a solid base for a successful mission that will not only open new horizons of exploration but also international cooperation, as well as motivate future generations. Funding research and technology development is also essential in reducing risks and making our crew safe and successful in this historic endeavor.

Studies show that astronauts undergo bone density loss and muscle atrophy in the microgravity condition (LeBlanc et al., 2007). The astronauts on the International Space Station (ISS) lose about 1–1.5 percent of bone mineral density each month, which is an issue when the Mars mission is as long as it needs to be (Krittanawong et al., 2023). Moreover, individuals exposed to microgravity over an extended period experience cardiovascular deconditioning, such as orthostatic intolerance, as well as neurophysiological alterations, such as ventricular expansion and upward brain shift, that were reported by MRI (Kramer et al., 2020; Krittanawong et al., 2023). In a conjunction-class Mars mission, the crews will be spending about 6-7 months on transit on each end, 500 days on the surface, and the total duration of the mission is about 900 days (National Academies of Sciences, Engineering, and Medicine, 2021). The

process of moving to Mars with one-third the gravity is also not easy, and there is a risk of encountering balance problems and experiencing more injuries (Patel et al., 2020). Psychological consequences of isolation and confinement within a closed environment should also be taken into account because stress, anxiety, and interpersonal conflicts may jeopardize mission success (Kanas & Manzey, 2008). Past mission statistics indicate that the rate of psychological problems increases with the duration of the mission, and this is where strong mental health support systems are needed (Rucker et al., 2022).

Moreover, the necessity of efficient planetary protection interventions to avoid pollution by possible life forms of Martians has become a major ethical issue. The fact that both Mars and the Earth can become contaminated brings to mind serious ethical concerns. The National Research Council (2014) emphasizes that planetary protection was to be taken seriously to avoid the introduction of Earth microbes to Mars and vice versa. Therefore, the pre-launch and pre-Mars mission protocols of sterilizing equipment and habitats are essential in reducing such risks. In a bid to reduce the chances of infection during transit, a proper quarantine measure should be put in place for all crew members before they leave the Lunar base. This protocol must include shared training and health tests to make sure that members of the crew are fit both physically and psychologically (Rucker et al., 2022). The concept of the diverse sociocultural backgrounds of the crew

is crucial to consider because the varying health practices and beliefs can be a factor in compliance with quarantine measures. Stakeholders in planetary protection are ethically required to develop and logistically necessary, in that they are required to develop protocols to sterilize equipment and habitats, and develop procedures for safely handling and storing samples that could contain extraterrestrial life.

The development of a robotic infrastructure on Mars to enable human missions is vital for the use of the resources and the safety of the crew. It is necessary to use Martian resources to sustain the crew. Studies indicate that Martian regolith has the potential to be used to generate oxygen and water using ISRU technologies (Hoffman & Kaplan, 2001). Future applications were made possible with the successful MOXIE (Mars Oxygen In-Situ Resource Utilization Experiment) on the Perseverance rover that demonstrated oxygen could be extracted from carbon dioxide in the Martian atmosphere (NASA, 2021). The architecture of habitats should mitigate radiation exposure hazards of the cosmic rays and solar particle events, and the Martian regolith can be used as a shielding material (Rucker et al., 2022). Also, underground locations can offer greater protection from radiation and dust storms, which are major operational issues (Patel et al., 2020). The robotic infrastructure on Mars should be developed before the arrival of the crew to provide support to the ongoing mission.

Robotic missions have the capability of prepositioning essential sup-

plies, including food, water, and equipment to build habitats (Rucker et al., 2022). This has been proven by the last robotic missions that showed the ability to work independently in the harsh Martian environment. This will require the crew to be self-reliant, using ISRU technology to farm food and harvest water out of the Martian atmosphere (Hoffman & Kaplan, 2001). This dependency on ISRU is essential to ease the logistical load of resupply missions made on Earth. The environment of the Martians is unique, which requires designing special environments. Such habitats should shelter from the radiation exposure, especially against cosmic rays and solar particle events (Rucker et al., 2022). The opportunities of new designs, like using the Martian regolith as a source of shielding or building underground living quarters, should be explored to prevent radiation risks. Additionally, the unpredictability of the Martian dust storms that occur between days and weeks is also a challenge that demands a strong engineering solution to avoid contamination of equipment and to keep the crew safe. Particles of dust represent health hazards, such as pulmonary illnesses, and may also disrupt the operation of life support mechanisms (Patel et al., 2020).

Also, more efficient propulsion systems, including thermal electric and nuclear technologies, would considerably decrease the travel time to Mars, thus reducing the exposure to the negative impacts of space travel (National Academies of Sciences, Engineering, and Medicine, 2021). Such high-tech propulsion systems can make missions

more achievable by making them quicker to transit and by making the mission scheme more adaptable.

Adequate crew size and makeup are critical to the success of the mission. The mission requires a small and diverse crew whose skills complement each other to be effective (Cohen & Bailey, 1997). The current Mars architecture by NASA is based on an initial four-crew to have the first lander missions (Rucker et al., 2022). The organizational structure must be designed to promote cooperation and communication to reduce conflicts and to have a unified team spirit. There is still a need to tackle the health risks associated with space missions of long duration. Exercise programs and dietary supplements that are already implemented on the ISS might not be effective enough to overcome the effects of microgravity (Krittawong et al., 2023). The possible advantages of artificial gravity during transit to promote the health and performance of the crew should be examined in future research.

On this grand adventure, it is important to note the weaknesses of our knowledge and the possibility of bias. There are still unanswered questions on the physiological and psychological effects of the protracted spaceflight, which require continued research and development (NASA, 2016). Openness in reporting results and clarification of ambiguity will build trust and confidence in the people about the mission. These discussion points point to the extreme necessity of dealing with health hazards, technological issues, and eth-

ical issues to prepare a human expedition to Mars. The development of these spheres should be done continuously, to create a proper system of protection of the success of the mission, as well as promote public confidence and international cooperation. A complex strategy that emphasizes the health and safety, the development of technology, and the elements of ethical concerns will play a crucial role in the effective implementation of this historic project.

Conclusion

The Mars exploration is one of the most ambitious projects in the history of human spaceflight, which promises to broaden human knowledge of the universe and potentially create a sustainable human habitation outside the Earth. Nonetheless, as this paper will describe, the human trip to Mars is fraught with significant medical, technological, and ethical obstacles that should be carefully addressed. Long-duration spaceflight is also characterized by health hazards such as muscle atrophy, bone density degradation, and psychological stress, which are important aspects that may put the health of the crew and the success of the mission at risk (LeBlanc et al., 2007; Kanas & Manzey, 2008).

The key to overcoming the logistical challenges of life on Mars is the technological advancements, including ISRU and creating strong habitable environments (Hoffman & Kaplan, 2001). One of the key strategies that could be used to reduce the risk and improve self-sufficiency is the prepositioning of

robotic infrastructure to serve human missions (Rucker et al., 2022). The ethical concerns of planetary protection and possible contamination of both the Martian and Earth ecosystems pose a need to establish strict measures and conduct more research (National Research Council, 2014). In addition, the promotion of a diversified crew makeup is not just a question of increasing the problem-solving power, but also a question of psychological well-being during isolation and seclusion (Cohen and Bailey, 1997). The most important aspect of astronauts is psychological well-being, where extensive training and support mechanisms have to be put in place, considering the diverse socio-cultural background of crew members (Kanas & Manzey, 2008).

As we enter into this historic project, proper funding and goodwill of the stakeholders will be essential in developing dependable systems that focus on safety and human support. The study of the physiological and psychological effects of space travel should be continued to educate future missions and enhance the health of astronauts (NASA, 2016). The trip to Mars is not just a scientific discovery; it is the project that reveals the strength of the human spirit, the desire to learn new things, and the power of teamwork. By dealing with the complex issues described in this review, we will open the door to a successful mission that will not only venture into new horizons in the field of exploration but also encourage generations to come and push the boundaries of the possible even further. The effective implementation of a human mission to Mars will

mean a combined effort to know and reduce the risks associated with it, using technological advancements and creating a diverse and well-trained crew. We should look to the stars, but we should be watchful and determined to make our activities based on scientific rigor and ethical accountability so that the future explorers on the Red Planet will be safe and successful.

Limitations and Bias

Although the proposed mission to Mars is an innovation, it is also subject to a variety of limitations or constraints that are intrinsic to the mission and may affect its viability and effectiveness. The use of established propulsion systems and technologies is one notable constraint that might not adequately cover the vast physical and psychological demands of long-duration travel and living in low-gravity conditions in space. Also, the crew selection may be biased, especially in terms of the inclusion of different sociocultural backgrounds and competencies that are key to creating a successful and positive team dynamic. Psychological impacts of isolation and confinement worsened by delays in communication with the Earth are not well understood and can have a disproportionate impact on some individuals due to their background or coping strategies.

Recent developments in space omics are likely to improve our knowledge of how humans can cope with the Martian environment, which can be used to guide countermeasures to address health and performance chal-

lenges that may affect crewmembers. In addition, the incorporation of robotic systems and artificial intelligence prepositioned on Mars should be considered, since the technologies would prove relevant in the formation of communication networks and building shelters with the use of the *in situ* resources. This strategy would go a long way in alleviating part of the logistical difficulties that would have come with human settlement on Mars. In addition, although the Martian weather conditions, such as global dust storms, are unpredictable, the prepositioning of supplies and infrastructure by robotic

missions introduces uncertainties that may compromise the health of the crew and the safety of the operations. Ultimately, the consequences of back contamination by possible forms of life on Mars require extreme precautionary actions, which remain controversial, and this is why it is necessary to continue research on the unknowns of Martian life as well as on the health hazards related to the exposure of human beings to these environments. Overall, these weaknesses and biases are essential factors that need to be addressed to ensure a strong risk mitigation plan and mission success.

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