

Space Radiation: Impact on Astronauts and Preventive Measures

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Space radiation poses a significant threat to astronaut health, making it a critical consideration for long-duration and deep space missions. The harsh space environment, dominated by high-energy galactic cosmic rays and solar particle events, can lead to a range of adverse health effects. These include increased cancer risk due to DNA damage, central nervous system dysfunction, cardiovascular complications, acute radiation sickness, cataract formation, immunosuppression, reproductive system damage, hematopoietic suppression, and accelerated skin aging. As space missions extend beyond low Earth orbit, the cumulative exposure to ionizing radiation necessitates robust preventive strategies. This review explores the biological impact of space radiation and evaluates current mitigation efforts, including the use of hydrogen-rich shielding materials, storm shelters, strategic mission planning, and pharmacological interventions such as antioxidants and gene therapy. The integration of engineering, medical, and operational countermeasures is essential to safeguard astronaut health and ensure mission success. Continued research and innovation are vital to address the complex challenges posed by space radiation and to support the future of human space exploration.

1. INTRODUCTION

Space radiation significantly impacts astronauts, making it a critical area of concern for future space missions. The unique environment of space exposes astronauts to high-energy cosmic rays, which can lead to various health issues, including increased risks of cancer and cardiovascular diseases. Moreover, the central nervous system may suffer damage, affecting cognitive function and behavior, while acute radiation sickness can occur from sudden exposure to solar flares. Such health challenges underscore the importance of developing effective mitigation strategies to ensure astronaut safety during extended space travel. Understanding these impacts is crucial for mission planning and the advancement of human space exploration.

A. Health Impacts of Space Radiation

Among the numerous health impacts of space radiation, the increased cancer risk is paramount, primarily due to DNA damage from high-energy cosmic rays. These rays have the potential to penetrate cells and induce double-strand breaks in DNA, significantly compromising its integrity and leading to mutations. According to Simonsen and Slaba [1], understanding these mechanisms is crucial for developing improved risk assessment models for astronauts. The breakage and faulty repair processes increase the likelihood of carcinogenesis, requiring advanced modeling and mitigation strategies to predict and manage this risk. Furthermore, continuous assessment and monitoring of

these genetic alterations are integral to ensuring effective protection and safeguarding astronaut health during and after missions.

Additionally, space radiation poses significant risks to the central nervous system (CNS), leading to cognitive function impairments, memory deficits, and altered behavioral responses. These neurological challenges result from the exposure to high-energy cosmic rays and other forms of space radiation that can disrupt neural communication pathways and damage brain cells. According to Onorato et al. [2], the consequences of such damage to CNS health are profound, necessitating further research to forecast and mitigate their impact on astronauts. The onset of impaired cognitive function not only jeopardizes mission success due to decreased decision-making abilities but also affects astronaut quality of life during and after missions. As space exploration extends beyond low Earth orbit, understanding these CNS effects becomes vital to developing protective measures that ensure both the health and performance of astronauts in deep space.

Moreover, acute radiation sickness (ARS) is a particularly concerning outcome of high-dose radiation exposure during events such as solar flares. This syndrome is characterized by a rapid onset of symptoms including nausea, vomiting, and profound fatigue, occurring due to the extensive damage to rapidly dividing cells. As described by Sihver and Mortazavi [3], the cellular damage occurs when astronauts encounter severe solar

particle events (SPEs), leading to doses surpassing the threshold for ARS. This exposure compromises the gastrointestinal system and bone marrow, resulting in hematopoietic deficiencies and a weakened immune response [4]. Understanding the etiology of ARS is essential for developing effective countermeasures, as timely intervention can mitigate these symptoms and improve recovery outcomes for those affected during space missions.

Furthermore, space radiation contributes to the development of cataracts among astronauts by causing damage to the lenses of their eyes. The lenses, composed of transparent and flexible cells, are susceptible to the ionizing effects of radiation, which induce opacification and the formation of cataracts. This damage leads to early-onset cataracts, characterized by clouding of the lens, impairing vision and potentially jeopardizing mission-related tasks that require acute visual acuity. Highlighting the mechanisms of such lens damage emphasizes the importance of protective measures in space to delay or prevent cataract formation [5]. As cataracts remain a significant concern for prolonged space missions, safeguarding ocular health through solutions such as enhanced shielding and routine eye examinations becomes critical for maintaining the visual capability of astronauts during and after their journeys.

In addition, the cardiovascular system is notably affected by space radiation, which can lead to an increased risk of heart disease among astronauts. Ionizing radiation has the ability to damage the endothelial cells lining blood vessels, promoting inflammation and accelerating atherosclerosis development. This can result in narrowed or blocked arteries, significantly elevating the likelihood of cardiovascular events, including myocardial infarction or stroke, which could severely impact astronauts' health during long missions. Notably, research suggests that the extent of radiation-induced cardiovascular damage may vary with the intensity and duration of exposure, necessitating personalized protective strategies for astronauts [6]. Nevertheless, the identification of these cardiovascular risks emphasizes the need for continued refinement of both preventative and therapeutic approaches to enhance astronaut safety in future space explorations.

Similarly, space radiation weakens the immune system, leading to increased susceptibility to infections among astronauts. The exposure to cosmic rays and other forms of space radiation compromises the function of immune cells, thereby diminishing the body's ability to fend off pathogens [7]. As the immune system becomes impaired, astronauts face a heightened risk of contracting illnesses that could severely impact mission performance and long-term health. This immunosuppression is particularly concerning during extended space missions, as it not only elevates the likelihood of infections but also complicates recovery processes. To address this challenge, implementing robust protective strategies and continuous health monitoring are paramount to safeguard astronaut immune health throughout their missions.

Likewise, radiation exposure presents considerable challenges to fertility and reproductive health in astronauts, influencing both male and female reproductive organs. High-energy cosmic rays have the potential to alter reproductive cell function, resulting in decreased fertility and hormonal imbalances. According to research findings, damage to the ovaries and testes could harm gametogenesis, impacting the ability of astronauts to conceive and leading to potential genetic abnormalities in offspring [8]. Moreover, radiation-induced hormonal fluctuations may also contribute to menstrual irregularities and impaired sperm production, which complicate reproductive planning for

astronauts embarking on prolonged missions. Comprehensive studies identifying and quantifying these reproductive risks are essential for formulating targeted protective measures, ensuring astronauts can embark on space missions without compromising their reproductive capabilities.

Consequently, space radiation also causes bone marrow suppression, impairing the production of blood cells and leading to conditions such as anemia and reduced immunity. This phenomenon poses a significant threat to astronauts, as bone marrow is essential for generating the cells that support oxygen transportation and immune system functions. Kernagis et al. [4] emphasize that the hematopoietic system's vulnerability to radiation necessitates comprehensive monitoring and timely interventions. Anemia, resulting from the diminished production of red blood cells, can lead to severe fatigue and decreased endurance, adversely affecting the capabilities necessary for prolonged space missions. Furthermore, the reduction in immune cell production underscores the heightened risk of infections, highlighting the critical need for protective measures and continuous health surveillance to ensure astronaut safety and performance during space travel.

Additionally, space radiation accelerates skin aging and heightens the risk of skin cancer among astronauts. The exposure to cosmic rays and high-energy particles results in the generation of reactive oxygen species, leading to oxidative stress that damages skin cells and accelerates dermal aging processes [9]. This oxidative damage can also directly affect DNA within skin cells, elevating the potential for mutations that precipitate the onset of cancer. As a result of prolonged space missions, these effects are compounded, increasing the likelihood of astronauts developing skin cancer, necessitating the implementation of protective measures. Such preventive strategies should focus on enhancing skin shielding and applying topical antioxidants, thus mitigating these detrimental effects and ensuring the preservation of skin health during and after space missions.

B. Prevention and Mitigation Strategies

To mitigate the harmful effects of space radiation, the use of shielding materials such as polyethylene and hydrogen-rich plastics is essential. These materials are particularly effective in absorbing high-energy particles, thereby reducing the radiation dose received by astronauts. According to Manning and Singletary [10], when incorporated into spacecraft design, these materials significantly diminish the radiation quantity whole body effective dose equivalent (E) caused by galactic cosmic rays. Polyethylene is favored due to its high hydrogen content, which enhances its capacity to block harmful particles, while hydrogen-rich plastics offer a flexible and lightweight solution for enhanced protection. Implementing such materials in the structural design of both spacecraft and space habitats is a proactive measure, seeking to preserve astronaut health and mission success amid the persistent threat posed by cosmic radiation.

Moreover, storm shelters play a vital role in providing protection for astronauts against solar particle events, which can expose them to excessive radiation levels. Constructed as heavily shielded compartments within spacecraft, these shelters are designed to mitigate the acute effects of high-dose radiation exposure by significantly reducing the amount of ionizing radiation that reaches individuals. According to Sihver and Mortazavi [3], large solar particle events can increase radiation doses well beyond safe thresholds, making storm shelters essential for maintaining astronaut health. The effectiveness of these shelters relies on their materials and design, utilizing high-density com-

ponents to absorb and deflect harmful particles. In essence, the strategic integration of storm shelters into spacecraft supports the broader goal of ensuring astronaut safety during unpredictable and intense solar activity, thereby enhancing the overall resilience of space missions.

Furthermore, strategic mission planning is essential in reducing astronauts' exposure to hazardous space radiation. By avoiding extravehicular activities during periods of high solar activity, such as solar flares and coronal mass ejections, the risk of acute radiation doses can be minimized. According to Hu et al., [11], careful monitoring and forecasting of solar weather can inform the scheduling of spacewalks, thereby enhancing astronaut safety. In addition, designing radiation-hardened spacecraft using advanced materials significantly decreases the penetration of cosmic rays and solar particles into inhabited areas. This dual approach of operational foresight and engineering innovation not only protects crew members but also optimizes mission success by allowing for safer and more efficient space exploration endeavors.

Additionally, medical and biological solutions provide essential avenues for counteracting the detrimental effects of space radiation on astronauts. Radioprotective drugs, such as antioxidants, melatonin, and amifostine, are being explored for their potential to mitigate radiation-induced damage by scavenging harmful free radicals and protecting cellular structures [7]. These drugs offer a pharmacological layer of defense, specifically targeting the oxidative stress pathways energized by high-energy particles in space. Investigative advances in gene therapy are also paving the way for more profound protection strategies, with research focusing on enhancing DNA repair mechanisms and cellular resilience against radiation exposure [5]. The integration of these medical and biological innovations emblemizes a proactive approach to safeguarding astronauts' health, emphasizing both immediate and potential future solutions to minimize radiation risks and ensure the safety of space missions.

Summary of the major health impacts of space radiation on astronauts and corresponding preventive or mitigation strategies employed to reduce these risks during space missions.

2. CONCLUSION

In summary, space radiation imposes a range of health challenges for astronauts, highlighting the urgent need for effective prevention and mitigation strategies. The risks include increased cancer incidences due to DNA damage, central nervous system disorders, acute radiation sickness, cataracts, cardiovascular issues, compromised immune systems, reproductive health effects, bone marrow suppression, and skin-related conditions. These health threats emphasize the necessity of implementing and advancing protective measures such as improved shielding, storm shelters, mission planning, and medical interventions. Addressing these concerns is critical not only for the safety and health of astronauts but also for the long-term success of space missions. As human exploration expands into deeper space, the ongoing development of sophisticated strategies to counteract these radiation effects will be paramount for the sustainability of future space endeavors.

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Table 1. Summary of the major health impacts of space radiation on astronauts and corresponding preventive or mitigation strategies employed to reduce these risks during space missions.

Health Impact	Description	Preventive/Mitigation Strategies
Cancer Risk	DNA damage from cosmic rays leads to mutations and carcinogenesis	Shielding (polyethylene), radioprotective drugs, cancer risk modeling
CNS Damage	Cognitive impairments, memory loss, behavioral changes	Research into neural protection, limiting exposure, gene therapy
Acute Radiation Sickness (ARS)	Symptoms like nausea, vomiting from high-dose solar events	Storm shelters, real-time solar monitoring, immediate medical intervention
Cataracts	Lens opacification and vision loss due to ionizing radiation	Eye protection, shielding, routine ocular exams
Cardiovascular Issues	Endothelial damage, increased risk of atherosclerosis and heart disease	Antioxidants, shielding, personalized exposure limits
Immune System Suppression	Increased susceptibility to infections	Immuno-monitoring, radioprotective agents, immune-supportive therapies
Reproductive Health Risks	Hormonal imbalance, reduced fertility, gamete damage	Reproductive cell shielding, hormone therapy, mission planning
Bone Marrow Suppression	Anemia, low immunity due to reduced blood cell production	Hematopoietic monitoring, cytokine therapy, supportive care
Skin Aging & Skin Cancer	Oxidative stress, DNA mutations in skin cells	Topical antioxidants, protective clothing, reduced EVA exposure