

# Medical Care in Space and Extreme Environments: Challenges, Technologies, and Future Directions

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## Abstract

Delivering effective medical care in space and other extreme environments presents significant challenges due to limited medical resources, communication delays, and harsh environmental conditions. As human exploration expands beyond low Earth orbit toward long-duration missions to the Moon and Mars, medical systems must evolve to support autonomous and resilient healthcare solutions. Space medicine faces unique physiological and psychological challenges, including microgravity-induced bone and muscle loss, cardiovascular deconditioning, immune system suppression, radiation exposure, and increased mental stress resulting from isolation and confinement. This paper reviews the major challenges associated with space medicine and examines emerging medical technologies designed to support astronaut health during long-duration missions. Key developments discussed include telemedicine, artificial intelligence–assisted diagnostics, wearable biosensors, regenerative medicine, robotic surgery, and pharmaceutical innovations tailored for space environments. In addition, lessons learned from terrestrial extreme environments—such as polar research stations and deep-sea missions—are analyzed as valuable analogs for space healthcare systems. The paper concludes by highlighting future directions in space medicine aimed at increasing medical autonomy, enhancing mission safety, and enabling sustainable human presence beyond Earth.

## Keywords

Space Medicine; Extreme Environments; Long-Duration Space Missions; Autonomous Healthcare; Telemedicine; Microgravity; Space Radiation; Astronaut Health

## 1. Introduction

Human space exploration is entering a new era characterized by extended missions beyond low Earth orbit and plans for sustained presence on the Moon and Mars. Ensuring astronaut health under such conditions is a critical requirement for mission success. Unlike terrestrial healthcare systems, medical care in space must operate under extreme constraints, including limited equipment, restricted resupply, delayed communication with Earth, and exposure to hazardous environments.

## **2. Medical Challenges in Space Environments**

Microgravity leads to muscle atrophy, bone density loss, cardiovascular changes, and immune system suppression. Radiation exposure increases long-term health risks, while psychological stress from isolation and confinement affects mental well-being and performance.

## **3. Medical Technologies for Space Missions**

Medical technologies for space missions include compact diagnostic tools, wearable biosensors, AI-assisted decision support systems, robotic surgery, and regenerative medicine such as 3D bioprinting.

## **4. Telemedicine and Remote Healthcare**

Telemedicine enables remote medical consultation and support for astronauts and has direct applications in extreme and isolated environments on Earth.

## **5. Pharmaceutical Challenges**

Medications may degrade in space due to radiation and microgravity, prompting research into personalized medicine and on-demand drug production.

## **6. Lessons from Terrestrial Extreme Environments**

Studies conducted in polar stations, submarines, and analog habitats provide valuable insights for improving medical preparedness and resilience during long-duration missions.

## **7. Future Directions**

Future developments will focus on autonomous medical systems, AI integration, regenerative medicine, and enhanced psychological support strategies.

## **8. Conclusions**

Space medicine is essential for enabling sustainable human exploration beyond Earth. Advances in technology and autonomous healthcare will play a critical role in mission success.