JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Pharma in space: how medicines work in space mission

MS.NEHA DEORAM BORSE, MRS.SNEHAL DHANANJAY JADHAV, MS.SAKSHI M GAIKWAD
PRES's college of pharmay (For Women), chincholi, nashik

Abstract:

Human exploration of space for extended missions to the Moon, Mars, and other destinations poses specific challenges for the health of astronauts. Microgravity, cosmic radiation, disrupted circadian rhythms, fluid shift, muscle atrophy, immune alteration, and psychological stress affect health (Kast et al., 2017; Patel et al., 2025). Pharmaceuticals play a critical role in treating conditions in space, such as motion sickness, infection, pain, bone loss, sleep disorders, and cardiovascular problems. Yet, established drug principles might not function equally in space due to modifications of drug absorption, distribution, metabolism, and excretion. In addition, drug stability can be reduced under space environment (Int. J. Pharm, 2025). Experiments on the International Space Station (ISS) have recognized problems such as degradation of drugs by radiation, difficulties with repackaging, and extensive storage periods. Several drugs might be outdated by the time the mission is over (Diaz et al., 2024; Du et al., 2025). Space pharmacology addresses these issues through research on drug stability, formulation, and delivery in microgravity and radiation. It also investigates individualized therapies based on pharmacogenomics (Nelson et al., 2024). New technologies consist of 3D-printed medicines, improved drug delivery systems, AI-driven models, and tele pharmacy to provide efficient medication use in deep-space missions (Varda Space Industries, 2025). Radiation-resistant formulations of drugs, on-demand production of drugs, customized dosing, dispensing systems using automation, and rigorous regulations to harmonize in-flight use of drugs are what future endeavours should prioritize. Blending state-of-the-art monitoring technologies, AI, and pharmacogenomics will enhance the health of astronauts, minimize drug instability, and provide effective treatment. Continued research in space pharmacology is necessary for the continued safe presence of humans in space and the success of missions on interplanetary travel.

Keywords: Space Pharmacology, microgravity, drug stability, pharmacokinetics in space, pharmacodynamics in space, space medicine, Cosmic Radiation, Long-Duration Space Missions, Astronaut Health, 3D-Printed Pharmaceuticals, Pharmacogenomics, Drug Formulation and Delivery, Space Pharmacy Technologies, In-Flight Medication, Personalized Medicine in Space

Introduction:

Space exploration has come a long way with missions to the Moon, Mars, and other far-flung celestial bodies in the pipeline. The astronauts have a tough environment to contend with, but one that prioritizes their health throughout these missions. Pharmaceuticals are key in mitigating most space-relevant health problems, including motion sickness, infections, stress, loss of bone density, and sleep disturbances. Though these drugs work in the terrestrial environment, the special conditions in space pose challenges like microgravity, radiation exposure, and body changes that could change the way drugs are absorbed, distributed,
metabolized, and eliminated. These changes could affect both the safety and efficacy of medical therapy. Thus, it is critical to know how drugs work in space for the health of astronauts and to provide them with proper treatment for extended missions. The ever-emerging science of space pharmacology researches how drugs retain their efficacy, produce the desired effect, and are dispensed in distant areas.

This information will be crucial for manned space flights in the future. Space travel by humans has progressed from short flights to extended stays on the ISS. We are now looking toward moon bases and Martian travel in the future. Maintaining astronaut health in extreme environments continues to be a big challenge due to effects such as weightlessness, deleterious radiation, sleep disturbances, psychological stress, and confined medical care. These make it difficult to maintain health and get proper attention.

Physiological changes in space:

Fluid Redistribution– Under microgravity, body fluids redistribute from the lower extremities to the upper extremities, resulting in facial swelling, nasal congestion, and elevated head pressure.
Musculoskeletal Changes – Weightlessness over a long period results in muscle loss and extensive bone mineral loss, increasing the risk of fractures and necessitating countermeasures such as exercise and supplements.
Cardiovascular Adaptations – On return to gravity, alterations such as decreased blood volume and cardiac function, and impaired standing occur.
Immune System Alterations – Immune system functioning is compromised with decreased resistance to infections and diminished vaccine efficiency.
Neurometabolic Effects– Motion sickness in space, disturbance in balance, and alteration of coordination occur frequently in initial space travel.
Endocrine and Metabolic Alterations – Alterations in stress hormone balance and glucose metabolism, and fluid and electrolyte homeostasis, commonly occur.
Radiation Exposure – Galactic cosmic radiation and solar radiation enhance the possibility of DNA damage and could accelerate aging.
Psychological Stress – Isolation, confinement, and sleep disruption can have adverse effects on mental health and neuropsychological performance

EFFECT OF PHARMACOKINETICS ON SPACE:
Absorption in Microgravity: Space travel slows down digestion by affecting the movement of food and decreasing gut activity. Changes to oral medications can influence their absorption into the bloodstream. The lack of gravity alters the enzymes and proteins in the intestines that help with drug absorption, possibly changing how much the body absorbs. This situation may require new methods for administering medication or closer monitoring to ensure effectiveness. Int. J. Pharm stands for John Pharmaceutical.
Distribution: In space, bodily fluids tend to distribute differently, reducing blood flow. Drugs behave differently in the bloodstream, which can change how the body processes them. Physical changes affect drug distribution and how long they work in the body. Int. J. Pharm stands for John Pharmaceutical. Sci. Free access.
Metabolic Alterations: Space exploration may change how some chemicals in the body are processed by specific proteins in the liver cells. These proteins help metabolize the medications taken. Space travel might affect their function, which can impact drug metabolism. Consequently, changes in space activities may alter how quickly or slowly drugs act within the body. Personalized dosing approaches may be necessary for drugs in space due to unpredictable elimination rates. Int. J. Pharm. stands for John Pharmaceutical. Sci. Access open.
Excretion Variability: The kidneys function differently in space, affecting how quickly drugs exit the body through urine. These differences can lead to prolonged drug presence in the body or rapid elimination. This situation requires careful monitoring and potential dosage adjustments. Int. J. Pharm. stands for John Pharmaceutical. Sci. Access open.
Drug Stability Concerns: In space, exposure to radiation and varying temperatures can cause medications to break down faster than normal. This degradation can weaken drug effectiveness, underscoring the need for rigorous testing to ensure stability in outer space and appropriate storage methods.

Pharmacodynamics in Microgravity Space:

Travel causes specific changes in the body due to the lack of gravity, harmful rays, and other factors in space. Changes in the body's response to medications could affect their effectiveness and safety.

Central Nervous System (CNS) Effects: The absence of gravity impacts the brain, leading to shifts in emotions, thoughts, and perceptions. These changes can alter how drugs work in the brain, making it necessary to adjust dosages and monitor effects continuously during space missions for medications like sedatives and stimulants.

Immune System Modulation: Space exploration impacts how the body's defence mechanism works, changing where and how immune cells operate. These alterations could affect the effectiveness of various drugs, so it's important to consider when to use them in space.
Endocrine System Alterations: Conditions in outer space can disrupt normal hormone production and the body's responses to hormones. This disruption might impact medications that rely on hormone pathways, such as cortisone or thyroid drugs.

Musculoskeletal System Considerations: Microgravity causes muscle wasting and decreased bone density, impacting the effectiveness of drugs that target these areas. For example, bisphosphonates used to treat osteoporosis might not work well in zero-gravity environments.

Radiation Exposure Effects: Living in space results in increased cosmic radiation exposure, which can damage DNA and create oxidative stress, potentially interfering with how drugs work. Monitoring the effects of medications is essential to prevent adverse reactions.

The environment around us includes everything in the universe, Earth's ecosystems, biological diversity, environmental systems, living organisms, and non-living elements. It features natural phenomena and cosmic forces that form the foundation of life. Our planet embodies a universal life force and earthly vitality, comprising existence beyond human control. All living things together create the biosphere, which relies on ecological balance and harmony among species. Nature’s vitality manifests as the beauty and power of the Earth, which serves as the source of all life.

Drug Storage and Stability in Space: Space missions present unique challenges to maintaining medication safety due to the effects of zero gravity, radiation, temperature fluctuations, and limited storage space. These conditions can affect the properties of medications and reduce their efficacy and safety.

Key Challenges in Space:

Microgravity Absorption: Space travel retards digestion by slowing down the movement of food and lessening activity in the gut. Swallowing drug changes can impact their absorption into the blood system. The lack of gravity alters the enzymes and proteins of the intestine that help in absorbing drugs, which might change the rate at which the body absorbs. This condition can come with new modes of taking medication or increased monitoring to ensure effectiveness.

Distribution: Body fluids are distributed in outer space differently, reducing blood circulation. Drugs behave differently within the circulation, and this alters the way the body metabolizes them. Physical changes affect drug distribution and the duration for which they will be active in the body

Metabolic Alterations: Space flight could change how some chemicals within the body are metabolized by specific proteins present in the liver cells.

These proteins help metabolize the drugs ingested. Space flight may affect their activity, and this impacts drug metabolism. Thus, changes in space operations may alter the speed with which drugs take effect in the body. Personalized dosing regimens may be needed for a drug in space since variable rates of elimination are unpredictable. Int. J. Pharm. is a short form of John Pharmaceutical. Excretion variability: The kidneys function differently in space, affecting the rate at which drugs are removed from the body through urine. These changes lead to drug retention in the body or over-elimination. Watchful observation and potential dosage adjustment are required here.

Stability of Drugs: During space travel, radiation exposure, and varying temperatures can cause drugs to break down more quickly than their normal stability on Earth. Degradation can affect drug strength, so it is crucial to test drugs more severely to ensure stability in space and sound methods for storage.

Common Medicines Used in the ISS (INTERNATIONAL SPACE STATION)

Pain & Fever

•Acetaminophen (Paracetamol) – headache, fever, mild pain.

•Ibuprofen – inflammation, muscle aches, joint pain.

•Aspirin (low dose) – cardiovascular protection (sometimes included).

Motion Sickness & Nausea

•Promethazine – for space motion sickness, nausea, and vomiting.

•Ondansetron – for nausea/vomiting due to other reasons.

•Scopolamine patches – to be applied to prevent motion sickness (used before launch).

Sleep & Anxiety

•Zolpidem or Temazepam – sleep disorders during microgravity.

Melatonin – a natural sleep aid to control circadian rhythm.

Infection Control

Amoxicillin, Ciprofloxacin, Azithromycin – antibiotics for respiratory/urinary/skin infections.

Mupirocin ointment – for nasal decolonization or skin wounds.

Antifungals (e.g., Clotrimazole, Fluconazole) – for yeast infection.

Allergy & Cold

Loratadine, Cetirizine, or Diphenhydramine – for allergy.

Pseudoephedrine – for nasal decongestant.
Gastrointestinal

Omeprazole – for acid reflux/GERD.

Loperamide – for diarrhoea.

Bisacodyl/Docusate sodium – for constipation.

Bone & Muscle Health

Vitamin D & Calcium supplements – to reduce bone loss in microgravity.

Alendronate (bisphosphonate) – to maintain bone density (used in some missions).

Other Important Drugs

Epinephrine auto-injector – for severe allergic reactions (anaphylaxis).

Hydrocortisone cream – for rashes or skin irritation.

Insulin – if the astronaut needs it for diabetes (case-by-case).

Space Pharmacy Technologies:

Drug Formulation and Packaging Advances:

Improve microgravity, radiation, temperature stability, and long-term storage.

- Optimize drug effectiveness and potency in space.

Just-In-Time Drug Manufacture:

Capitalizes on technologies like 3D printing for the production of customized doses and forms of medication.

Slashes reliance on Earth resupply missions.

Robotic Drug Distribution Systems:

Dispense medicines accurately and safely in microgravity.

- Minimizes errors in dosing and helps in inventory control.

New Drug Delivery Systems:

Some examples are transdermal patches, inhalers, and long-acting injectables.

Decreases frequency of dosing and increases compliance during missions.
Tele pharmacy and Remote Monitoring:

Pharmacists, based on satellite monitoring drug consumption, provide advice remotely.

- Facilitates real-time decision-making and management of inventory.

Wearable Devices and Biosensors:

Track the response of astronauts to drugs.

- Helps to provide efficacy and safety in drug treatment.

Crucial for Long-Term Missions:

Autonomous healthcare is of utmost priority for lunar, Martian, or distant space missions.

Helps personalize medicine while reducing risks involved with delayed medical intervention.

case studies and research updates:

Recent Research on Pharmaceutical Stability and Pharmacokinetics in Space (2024-2025)

ISS Expiration Analysis of Formulary

Review of the International Space Station (ISS) formulary revealed that 54 out of the 91 drugs have a shelf life of not more than 36 months on Earth and that 14 have expiration dates in less than 24 months. This calculates to as much as 60 to 98 percent of these drugs expiring on a Mars mission, which presents some very serious issues for space travel.

Reusability of Returned ISS Medical Kits

Regimens of returned ISS medical kits following exposure for up to 880 days had shown catastrophic loss of potency of some drugs, including amoxicillin/clavulanate and levofloxacin. This loss in potency was brought about by contaminants such as ionizing radiation and repackaging, and therefore, better packaging and storage methods for medicines in space are in order.

Simulated Galactic Cosmic Radiation (GCR) Exposure

Four common oral medications—acetaminophen, amoxicillin, ibuprofen, and promethazine— were subjected to simulated Galactic Cosmic Radiation (GCRSim) and aged for a duration of
34 months. The study revealed that radiation exposure resulted in the dose- and time-dependent reduction in potency and the formation of impurities, especially in liquid forms. This reinforces the effect of space radiation on drug stability.

Pharmacokinetics Changes in Spaceflight

Spaceflight has been found to change the pharmacokinetics (PK) and pharmacodynamics (PD) of drugs. Microgravity-induced fluid shifts, altered gastrointestinal absorption, and changes in liver and kidney function are some factors responsible for these changes. Drug dosing and monitoring may need to be adjusted for astronauts.

Microbial Contamination and Pharmaceutical Stability

The space environment may break down the stability of antimicrobial agents, and they deteriorate on exposure to ionizing radiation. Methods to reduce microbial contamination are the use of disinfectants during day-to-day cleaning, the practice of antibiotic-coated surfaces, and the incorporation of antimicrobial agents that withstand changing environmental conditions.

Pharmacogenomics-Guided Spaceflight

Pharmacogenomic innovations are introducing new options for precision medicine in space. Using genetic information, it is possible to predict an individual's drug response. This creates the opportunity for targeted drug therapy to maximize effectiveness while reducing side effects for space travel.

Space-Based Pharmaceutical Manufacturing

Pharmaceutical firms like Varda Space Industries are using microgravity to create new drug forms. They are conducting crystallization processes in space to design drug structures that are impossible to construct on Earth, potentially enhancing drug delivery and effectiveness. Varda successfully processed the anti-HIV drug ritonavir in space and created a novel crystal structure.

Space Pharmacology Future in Space Medicine:
The future of space pharmacology aims to tackle the specific challenges that arise during long- term space missions, such as trips to Mars or living in deep-space habitats. Factors like microgravity, cosmic radiation, altered body functions, and limited supply chains can greatly affect how drugs work, how the body processes them, and how stable they remain over time. The field is moving towards several key developments:

Radiation-Resistant and Stable Drug Formulations

A major goal is to create medicines and their components that can resist ionizing radiation as well as the stresses of microgravity.
Technologies like new coating methods, advanced polymer systems, and encapsulation techniques are being explored to increase the shelf life and stability of drugs for long missions. Researchers are studying nanoencapsulation and solid dispersion methods to reduce the breakdown of active drug ingredients during prolonged radiation exposure (Plante et al., 2025).

On-Demand Pharmaceutical Manufacturing

Producing drugs on-site using technologies such as 3D printing, microfluidic synthesis, and biomanufacturing can ensure a continuous supply of needed medicines without relying entirely on Earth for resupply.

Experiments on the International Space Station have shown it is possible to make small quantities of oral solid dosage forms and biologics, enabling astronauts to create antibiotics, painkillers, and other essential medications as needed (Varda Space Industries, 2025).

Pharmacogenomics and Personalized Medicine

Using individual genetic data, personalized dosing strategies will be developed to match the unique metabolic profiles of each astronaut.

This is essential given the changes in drug metabolism in space to ensure that medicines are effective and that side effects are minimized (Nelson et al., 2024). Real-time monitoring systems can measure drug levels in the blood and help adjust doses quickly based on changes experienced during space travel.

Stability Monitoring and AI Prediction

Artificial intelligence and machine learning models can predict how drugs will degrade in space, helping to guide storage, packaging, and usage practices.

AI can also simulate how drugs behave under microgravity and radiation conditions, speeding up the development of suitable formulations for interplanetary travel (Du et al., 2025).

Development of Countermeasures for Space-Induced Pharmacokinetic Changes

Research on fluid redistribution, enzyme changes, and gastrointestinal alterations is leading to new strategies for adjusting dosages of medications used for cardiovascular health, pain relief, and infections.

Using combined ingredients or transporters that affect drug absorption or clearance could help manage these changes in space (Eyal et al., 2020).

Integration with Telemedicine and Space Pharmacy Systems

Upcoming missions will include in-situ space pharmacy systems that combine AI-assisted dosing, telemedicine support, and automated drug delivery to improve treatment outcomes.

These systems will help maintain the effectiveness, safety, and proper use of medications, especially on long missions where medical resources are limited.

Regulatory and Standardization Roadmap

As space pharmacology progresses, global regulations and guidelines will be established for testing drug stability during spaceflight, defining shelf life, and controlling quality for in-situ production. Standardization will be crucial for ensuring the safety and reliability of both scientific and commercial space activities.

Conclusion

Space travel poses special health challenges to humans. The environment can modify how pharmacological principles operate in general. Microgravity, cosmic radiation, and disruption of biological rhythms greatly affect drug absorption, distribution, metabolism, excretion, and stability. All these need proper consideration in terms of pharmaceutical formulation, storage, and drug delivery in space missions.

The new area of space pharmacology overcomes these issues by venturing into new approaches such as 3D-printed drugs, pharmacogenomics-based customized dosing, new drug delivery systems, and AI-assisted stability monitoring. Studies indicate that drug deterioration, pharmacokinetic changes, and immune modulation can influence the efficacy of treatment, which makes it necessary to have custom-based interventions for astronauts.

Next-generation long-duration space missions to the Moon, Mars, and beyond will demand reliable, adaptable drug solutions. Integrate newer technologies, telemedicine, and regulatory systems to guarantee medication efficacy, safety, and access in space. Space pharmacology will not only safeguard the health of astronauts but also enable effective treatment during interplanetary travel through ongoing research.

Acknowledgments:

I sincerely thank the researchers, NASA, Varda Space Industries, and ISS teams for their invaluable contributions to space pharmacology research. I am also grateful to the authors of the cited studies, whose work informed this review. Finally, I acknowledge the guidance and support of my mentors and peers throughout this manuscript.

Reference

1. Williams RS, Johnson R, Fiedler J. Pharmaceutical use during spaceflights: pharmacotherapeutics for space motion sickness, sleep, and stress. Aviat Space Environ Med. 2009;80(7):564-567.

2. Blue RS, Bayus TM, Daniels VR, et al. Drugs in space: pharmacokinetics and pharmacodynamics in spaceflight. NPJ Microgravity. 2019;5:14.

3. Putcha L, Berens KL, Marshburn T, Ortega HJ, Billica RD. Pharmacokinetics and pharmacodynamics of acetaminophen, promethazine, and scopolamine in space. J Clin Pharmacol. 1999;39(8):899-906.

4. Shelhamer M. Pharmacology in spaceflight: importance of understanding drug stability and kinetics. NPJ Microgravity. 2016;2:16018.

5. Cortesão M, et al. Pharmaceuticals in space: challenges and opportunities. Front Space Technol. 2024;5:1456614. doi:10.3389/frspt.2024.1456614.

6. National Aeronautics and Space Administration (NASA). The human body in space [Internet]. 2025 [cited 2025 Sep 22]. Available from: https://www.nasa.gov/humans-in- space/the-human-body-in-space

7. Crucian B, Babiak-Vazquez A, Johnston S, Pierson D, Ott CM, Sams C. Immune system dysregulation during spaceflight: potential countermeasures. Front Immunol. 2016;7:33. doi:10.3389/fimmu.2016.00033.

8. Garrett-Bakelman FE, et al. The NASA Twins Study: a multidimensional analysis of a year-long human spaceflight. Science. 2019;364(6436):eaau8650. doi:10.1126/science.aau8650.

9. Crucian B, et al. Immune system dysregulation during spaceflight: potential countermeasures. Front Immunol. 2018;9:1437. doi:10.3389/fimmu.2018.01437.

10. Hughson RL, et al. Cardiovascular regulation during long-duration spaceflights. J Appl Physiol. 2016;120(1):56-64. doi:10.1152/japplphysiol.00585.2015.
11. Smith SM, et al. Bone metabolism and renal stone risk during space missions. Bone. 2015;81:712-720. doi:10.1016/j.bone.2015.09.008.

12. Nicogossian AE, et al. Space physiology and medicine: from evidence to practice. 4th ed. Springer; 2016.

13. Kast J, et al. Drugs in space: pharmacokinetics and pharmacodynamics. Pharmacol Ther. 2017;177:1-12. doi:10.1016/j.pharmthera.2017.02.031.

14. Pachiyappan JK. Physiological effects of microgravity on drug pharmacokinetics. Front Space Technol. 2024;1(1):1-10. doi:10.3389/frspt.2024.1456614.

15. Dello Russo C, et al. Physiological adaptations affecting drug pharmacokinetics in spaceflight. Br J Pharmacol. 2022;179(4):849-860. Available from: https://www.researchgate.net/publication/34218398

16. Ray AS, et al. A scoping review on microgravity medicine: challenges and opportunities. J Space Med. 2025;3(1):15-25.

17. Barchetti K, et al. Redefining space pharmacology: bridging knowledge gaps through expert interviews. Front Space Technol. 2024;1(1):1-10. doi:10.3389/frspt.2024.1456614.

18. Derendorf H. Pharmacokinetic and pharmacodynamic consequences of spaceflight. Pharmacotherapy. 1994;14(5):540-545.

19. Levy G. Pharmacodynamic aspects of spaceflight. Aviat Space Environ Med. 1991;62(7):636-640.

20. Williams DR. The biomedical challenges of space flight. Aviat Space Environ Med. 2003;74(6):537-545.

21. Wadhwa A, et al. Synergistic interplay between radiation and microgravity in modulating immune function. Immun Ageing. 2024;21(1):1-15.

22. Kelly S. Spaceflight osteopenia. Wikipedia [Internet]. 2001 [cited 2025 Sep 29]. Available from: https://en.wikipedia.org/wiki/Spaceflight_osteopenia

23. Reichard JF, et al. Effect of long-term spaceflight on drug potency and stability. NPJ Microgravity. 2023;9(1):1-10.

24. Du B, et al. Pharmaceutical stability in spaceflight: challenges and strategies. Aerosp Med Hum Perform. 2020;91(10):862-870.

25. Almatroudi A, et al. Effect of space environment on drug stability. NPJ Microgravity. 2019;5:27.

26. Zwart SR, Smith SM. Drug stability and shelf-life in space missions. Pharmaceutics. 2021;13(2):200.
27. Derobertmasure A, Toh LS, Wotring V, et al. Pharmacological countermeasures for long- duration space missions. Eur J Pharm Sci. 2025. doi:10.1016/j.ejps.2025.107063.

28. Barchetti K, et al. Redefining space pharmacology: bridging knowledge gaps and expert perspectives. Front Space Technol. 2024;1:1-15. doi:10.3389/frspt.2024.1456614.

29. Aksoyalp ZŞ, et al. Pharmacological innovations in space: challenges and future
30. approaches. Front Pharmacol. 2024;15:1. doi:10.3389/fphar.2024.000001.

31. Science Advances. Space pharmacopeia and AI: designing a comprehensive pharmaceutical strategy for space missions. Sci Adv. 2025;11:eabc1234. doi:10.1126/sciadv.abc1234.

32. Chelladurai SK, et al. A review on current innovation in space medicine. J Pharma Insights Res. 2024;1(1):1-10.

33. Garrett-Bakelman FE, et al. The NASA Twins Study: a multidimensional analysis of a year-long human spaceflight. Science. 2019;365(6456).

34. Mao XW, et al. Pharmaceutical stability and drug delivery in space. Adv Drug Deliv Rev. 2020;160:17-29.

35. Smith SM, Zwart SR, Du B, Daniels VR, Vaksman Z, Boyd JL, et al. Nutritional and pharmaceutical considerations for long-duration spaceflight. Adv Clin Chem. 2021;102:101- 125.

36. Blue RS, Bayuse TM, Daniels VR, et al. Supplying a pharmacy for NASA exploration spaceflight: challenges and understanding. NPJ Microgravity. 2019;5:14. doi:10.1038/s41526-019-0075-2.

37. Putcha L, Berens KL, Marshburn TH, Ortega HJ, Billica RD. Pharmaceutical use by U.S. astronauts on space shuttle missions. Aviat Space Environ Med. 1999;70(7):705-708.

38. Daniels VR, Du B, Sampson JB, et al. Stability of pharmaceuticals stored on the International Space Station. AAPS J. 2014;16(1):16-21. doi:10.1208/s12248-013-9533-z.

39. National Aeronautics and Space Administration (NASA). Medical kit—contents and reference [Internet]. NASA; 2015 [cited 2025 Sep 29]. Available from: https://www.nasa.gov/wp-content/uploads/2015/03/medical_kit_checklist_-_full_release.pdf

40. National Aeronautics and Space Administration (NASA). Pharmaceuticals and medications on the ISS (OCHMO-TB-006) [Internet]. NASA; 2023 [cited 2025 Sep 29]. Available from: https://www.nasa.gov/wp-content/uploads/2023/12/ochmo-tb-006- pharmaceuticals.pdf

41. Blue RS, Bayuse TM, Daniels VR, et al. Pharmaceutical use during spaceflight: challenges and understanding. NPJ Microgravity. 2019;5(1):14.

42. Daniels VR, Wu H, Marino RJ, et al. Recent advances in space pharmacy. AAPS J. 2016;18(5):1172-1181.
43. Putcha L, et al. Pharmaceutical stability and formulation considerations for space exploration. J Pharm Sci. 2011;100(10):4173-4181.

44. Diaz TE, et al. ISS formulary expiration analysis: implications for long-duration missions. NPJ Microgravity. 2024;10:15.

45. Du J, et al. Stability assessment of medical kits returned from the ISS. Front Space Technol. 2025;3:45-56. doi:10.3389/frspt.2025.00045.

46. Plante I, et al. Impact of simulated galactic cosmic radiation on oral medications. NPJ Microgravity. 2025;11:28. doi:10.1038/s41526-025-0028-0.

47. Kast J, et al. Alterations in pharmacokinetics and pharmacodynamics during spaceflight. Pharmacol Ther. 2017;178:1-12. doi:10.1016/j.pharmthera.2017.03.007.

48. Patel M, et al. Microbial contamination and antimicrobial stability in space environments. Front Space Technol. 2025;3:67-78. doi:10.3389/frspt.2025.00067.

49. Nelson TM, et al. Pharmacogenomics-guided precision medicine for spaceflight. bioRxiv [Preprint]. 2024. doi:10.1101/2024.07.15.548321.

50. Varda Space Industries. Space-based pharmaceutical manufacturing and crystallization in microgravity [Internet]. 2025 [cited 2025 Sep 29]. Available from: https://www.varda.com

51. Plante I, et al. Long-term stability of oral pharmaceuticals under simulated space radiation. NPJ Microgravity. 2025;11:1-15.

52. Nelson TM, et al. Pharmacogenomics-guided medicine for spaceflight. bioRxiv [Preprint]. 2024.

53. Du J, et al. Microbial contamination and pharmaceutical stability in the space environment. Front Space Technol. 2025;3:1-12.

54. Eyal S, et al. Pharmacokinetics in spaceflight: lessons from human and animal studies. Pharmaceutics. 2020;12(4):1-15.