frontiers | Frontiers in Space Technologies

TYPE Perspective
PUBLISHED 06 January 2026
DOI 10.3389/frspt.2025.1725575

OPEN ACCESS

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RECEIVED 15 October 2025
REVISED 08 December 2025
ACCEPTED 15 December 2025
PUBLISHED 06 January 2026

CITATION
Hazra S, Palit S, Russomano T, Ghosh G and Sannigrahi P (2026) Enabling living in space through modern innovations in space medicine: a perspective on tissue-on-a-chip technology . *Front. Space Technol.* 6:1725575. doi: 10.3389/frspt.2025.1725575

Enabling living in space through modern innovations in space medicine: a perspective on tissue-on-a-chip technology

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Human spaceflight has evolved from the short missions of the 1960s to more recent, longer-term missions, such as those aboard the International Space Station (ISS) and future missions to the Moon and Mars. These missions have provided valuable insights into the effects of space-based phenomena, such as microgravity, radiation, and isolation, on human physiology. Studies have shown that microgravity causes rapid muscle atrophy (up to 20% in 1–2 weeks) and bone density loss (1%–1.5% per month), and radiation exposure leads to DNA damage, oxidative stress, and immune suppression. Moreover, immune system dysregulation, evidenced by the reactivation of latent viruses like Epstein-Barr and cytomegalovirus, poses significant health risks. Recent advancements in Tissue-on-a-Chip (ToC) technology offer a promising approach to model immune responses in space, enabling real-time monitoring and testing of countermeasures. Ongoing studies, such as the Tissue Chips in Space Initiative, aim to investigate immune responses under microgravity, focusing on the differentiation of immune cells and the effects of space stressors on immune function. These innovations, including wearable biosensors, are paving the way for a personalized approach to astronaut health monitoring due to their potential applications in both space missions and terrestrial healthcare. Future research must address the scalability, cost-effectiveness, and regulatory standards of ToC technology to ensure its integration in long-duration space missions.

KEYWORDS

astronaut, immunity, infection, microgravity, organ-on-a-chip, research, space medicine, space radiation

1 Introduction

Human spaceflight began with short missions in the 1960s, including Yuri Gagarin's orbital spaceflight and NASA's Mercury program. These early efforts established the groundwork for understanding the human body's tolerance to space conditions. As missions lengthened with the Apollo, Skylab, Mir, and Space Shuttle programs, and more recently aboard the International Space Station (ISS), researchers gathered critical data on the effects of such an environment on human physiology. Long-duration missions, such as those currently proposed for the Moon and Mars, present new and complex

challenges, while leading to valuable insights into how the unique conditions of space affect human physiology, especially those dangers characterized by the acronym RIDGE [Radiation, Isolation, Distance from Earth, Gravity, and Environment (closed and hostile)] (Das et al., 2025). The effects of radiation, microgravity (Patel, 2020), and isolation (Arone et al., 2021) have been previously reported and are briefly reviewed here.

In microgravity, antigravity muscles (i.e., soleus and quadriceps) rapidly undergo atrophy due to the absence of mechanical loading, with up to 20% losses during one-to 2-week missions (Fitts et al., 2000). Furthermore, weight-bearing bones in the spine, pelvis, and legs are lost, and bone mineral density deteriorates at a rate of 1%–1.5% per month (Vico et al., 2000). Studies have also found that, in low gravity, fluids shift toward the head, causing facial puffiness, nasal congestion, decreased plasma volume, and altered cardiovascular function, which further causes orthostatic intolerance and cardiac remodeling upon return to Earth's gravity (Lee et al., 2015; Hughson et al., 2016).

Similarly, radiation exposure has been shown to present complex health risks to astronauts. For example, solar particle events (SPEs) cause prodromal symptoms, skin injury, hematological alterations, and immune suppression, particularly during extravehicular activities with limited shielding. Galactic cosmic ray (GCRs) radiations and high linear energy transfer (high-LET) particles further damage DNA, produce oxidative stress, and induce epigenetic remodeling. These effects collectively heighten the risk of degenerative changes, cancer, and central nervous system impairments. These risks are compounded by the synergistic interactions between microgravity and environmental stressors, alongside inter-individual variability in radio sensitivity (Chancellor et al., 2014).

Meanwhile, isolation has been found to disrupt the circadian rhythm, and limited social contact has been shown to affect mood, sleep, and performance (Kanas and Manzey, 2008). Other consequences of long-term space flight have been studied as well, such as appetite suppression and microbiota changes that can lead to bad nutrition and an impaired immune system (Russomano, 2023). Immune systems are already suppressed in space environments, enabling latent virus reactivation (Crucian et al., 2015); however, this area of study is relatively novel to the field as a whole, and the limited results in immune dysregulation and heightened susceptibility to infections continue to hinder long-duration exploration. These vulnerabilities present a clear reason for the development of space-adapted biomedical technologies that safeguard astronaut health and translate into transformative advances for terrestrial healthcare systems.

2 Immunity and infection in space: what we know and how it happens

2.1 Tracing immunity beyond earth: a historical perspective on infection in space

Many human space missions, including those undertaken by NASA's Mercury program, Apollo, Skylab, and the recent Axiom 4 mission, have primarily focused on assessing the tolerance that humans and plants have to acute space stresses, such as microgravity and radiation (NASA, 2025; NASA, 1962; NASA, 1958; NASA, 1973; ISRO, 2025). While these pioneering flights provided foundational insights into the physiological demands of space travel, they offered very little information regarding immune function. As mission durations were extended aboard the Mir Space Station and the International Space Station (ISS), clinical evidence highlighted significant alterations in astronaut immunity (Crucian et al., 2015). Among the most consistently documented phenomena was the reactivation of latent herpesviruses, including Epstein-Barr virus (EBV), varicella-zoster virus (VZV), and cytomegalovirus (CMV) (Mehta et al., 2017; Mehta and Pierson, 2007).

Additionally, astronauts frequently exhibited skin rashes (Cope et al., 2023), hypersensitivity reactions (Crucian et al., 2018), and delayed wound healing (Babocs et al., 2025), indicating both inflammatory dysregulation and impaired tissue repair. Immune profiling further revealed changes in leukocyte distribution and cytokine secretion patterns, suggesting a complex, bidirectional influence of space-related stresses that encompasses both immune suppression (i.e., increasing susceptibility to infection) and immune hyperactivity (i.e., contributing to allergic or inflammatory manifestations) (Crucian et al., 2018). Furthermore, unlike more readily measurable musculoskeletal or cardiovascular adaptations, immune alterations, such as T cell, leukocyte, and erythrocyte counts (Tastan et al., 2025; Anderson et al., 2018), in space are subtle, highly variable between individuals, and strongly influenced by various factors, including psychological stress (Crucian et al., 2018), nutrition (Tang et al., 2021), microbiome composition (Etlin et al., 2024), and genetic predisposition (Jacob et al., 2023). This complexity renders immune changes less predictable and more challenging to mitigate, emphasizing the need for targeted research to safeguard astronaut health during long-term missions.

2.2 Mechanisms of immune dysfunction: from space-bound factors to cellular pathways

Recent advances in understanding immune dysfunction during spaceflight have shifted from observational studies to detailed molecular investigations, which have helped to uncover complex pathways that disrupt immune homeostasis. For example, single-cell analyses of human peripheral blood mononuclear cells exposed to simulated microgravity have shown significant alterations in critical immune pathways within 25 h (Wu et al., 2024). These changes impact cellular processes like cytoskeletal organization, interferon signaling, pyroptosis, temperature-shock responses, and innate inflammatory pathways, including coronavirus pathogenesis and IL-6 signaling. Notably, microgravity-induced cytoskeletal disruption reduces ICAM-1 expression in monocytes/macrophages, impairing T cell activation and innate immune responses. The cytoskeleton, crucial for cell morphology, migration, antigen recognition, and signal transduction, plays a critical role in immune function and mechanotransduction, making it a target for space-related immune alterations. Specifically, significant increases have been noted in IL-8, IL-1ra, TNF-α, GM-CSF, and VEGF, suggesting ongoing inflammation, leukocyte recruitment, angiogenesis, and thrombocyte regulation.

Conversely, adaptive/T-regulatory cytokines, including IL-2, IFN-γ, IL-17, IL-4, IL-5, and IL-10, have shown minimal alterations, indicating preserved but potentially dysfunctional adaptive immune responses (Khune et al., 2024).

As for the effect of microgravity, significant impairments have been noted in key nuclear factors like NF-κB, AP-1, and STAT pathways, which are crucial for regulating genes involved in signal transduction, DNA repair, apoptosis, and metabolic processes, including the production of pro-inflammatory cytokines and chemokines. This downregulation compromises T cell activation and function (Parafati and Giza, 2023). T cell signaling analyses have shown that microgravity disrupts the IL-2 signaling pathway, which is vital for T cell proliferation and differentiation, by impairing IL-2 and receptor expression. This leads to dysfunction in cell proliferation, differentiation, apoptosis, and DNA repair. Biomarker analyses of astronauts during long-duration spaceflight aboard the ISS revealed significant increases in plasma concentrations of IL-3, IL-15, IL-12p40, IFN-α2, and IL-7, indicating immune system mobilization (Kennedy, 2014). Macrophage differentiation from hematopoietic stem cells is also affected by microgravity (i.e., impaired proliferation and reduced numbers of macrophages).

Additionally, several immune pathways are consistently reduced in microgravity, including PKR in interferon response, JAK/STAT signaling, and pyroptosis. In contrast, pathways like Sirtuin signaling, fibrosis signaling, and HIF1α signaling become hyperactivated. Radiation exposure alters cytokine profiles, impairs leukocyte proliferation, and disrupts both innate and adaptive immunity. The cumulative effects of space radiation accentuate immune suppression and dysregulation, increasing susceptibility to infections and malignant transformation (Crucian et al., 2009; Chancellor et al., 2014). While nutritional adequacy is vital for maintaining immune competence during space missions, its suboptimal intake (in terms of vitamins, minerals, fats, and amino acids), often observed on long-term missions, leads to immune dysregulation by impairing the production and function of lymphocytes, macrophages, and various cytokines. Furthermore, deficiencies in Vitamin D, Zinc, and essential amino acids have also been linked to increased vulnerability to infection and poor immune recovery after illness. Therefore, dietary interventions and supplementation are considered critical countermeasures for immune support in space (Parafati and Giza, 2023).

Moreover, it has been sufficiently shown that space conditions enhance the virulence and resilience of certain pathogens, which leads astronauts to experience shifts in gut and skin microbial communities, often leading to dysbiosis and an increased risk of infection. Therefore, maintenance of a balanced microbiome through the use of probiotics and personalized microbiome engineering is emerging as an important intervention to restore immune equilibrium in space (Kennedy, 2014). Additionally, the individual genetic variability has a decisive role in astronaut immune responses during spaceflight, as specific genetic markers within the major histocompatibility complex (MHC) and related immune-regulating genes are known to affect susceptibility to immune dysfunction, autoimmunity, and infection under space radiation. Identification and screening for genetic risk factors are becoming integrated into astronaut selection and health management strategies (Khune et al., 2024).

All together, these findings, which mostly come from the Inspiration-4 mission, JAXA Cell-Free Epigenome mission, NASA Twins Study, and mouse studies on the ISS, have shown that advances in mechanistic knowledge have led to more sophisticated monitoring tools, like tissue-on-chip (ToC) technology and advanced biomarker platforms, which replicate organ-immune interactions and cellular crosstalk under space conditions. These tools enable functional immune response assessments and real-time countermeasure testing, surpassing traditional methods (Baylor College of Medicine, 2025). Additionally, salivary biomarkers have emerged as non-invasive alternatives to plasma monitoring, with studies showing decreases in GM-CSF, IL-12p70, IL-10, and IL-13 during spaceflight. The correlation between plasma and salivary cytokine profiles provides operational benefits for continuous immune monitoring during missions.

3 Can modern technology redefine immunity-related challenges in space?

As immunity declines with age, the body becomes more vulnerable to illness, but immune system dysfunction is not just an issue for older adults; it is also something that affects people with chronic illnesses, such as CMV (Picarda and Benedict, 2018). Interestingly, astronauts experience similar immune system disturbances in space, where microgravity, radiation, and stress create an environment that mirrors and amplifies the immune vulnerabilities seen on Earth, as discussed above. Therefore, protecting astronaut immunity requires a multi-pronged approach that combines preventive, diagnostic, and therapeutic strategies. Current countermeasures primarily focus on reducing baseline risk before departure. Pre-flight vaccination and viral prophylaxis remain cornerstones, designed to minimize reactivation of latent viruses and prevent opportunistic infections (Cowen et al., 2024). This is coupled with in-flight health monitoring procedures, such as the detection of latent virus reactivation through saliva or blood-based PCR assays or immunologic assays including intracellular cytokine production (IL-2, IFN-g, IL-4, IL-10), cytotoxic T cell function (perforin, TNF, degranulation), Th17 cells, regulatory T cells, and antigen-presenting cells. These approaches provide valuable but limited insights, as they are reactive rather than predictive (Cowen et al., 2024). Also, nutritional supplements like Vitamin D, probiotics, and antioxidants support bone, gut, and immune health in space, while structured sleep, exercise, and psychological care help counter stress-driven immune dysregulation. In the case of pharmacotherapies, cytokine therapies (e.g., IL-7), immune checkpoint modulators, antivirals, and long-shelf-life antimicrobials have been found to be the most promising choices.

Here, technological innovations such as tissue-on-a-chip, or ToC (Figure 1) devices (Ma et al., 2021) present a predictive tool to not only monitor immunogenic reactions in space but also take necessary actions when needed. Additionally, their size and the ability to produce results autonomously make them the ideal candidate for the diagnostic revolution, enabling rapid, point-of-care analyses of immune biomarkers on-board spacecraft without the need for bulky laboratory infrastructure (Mu et al., 2022).

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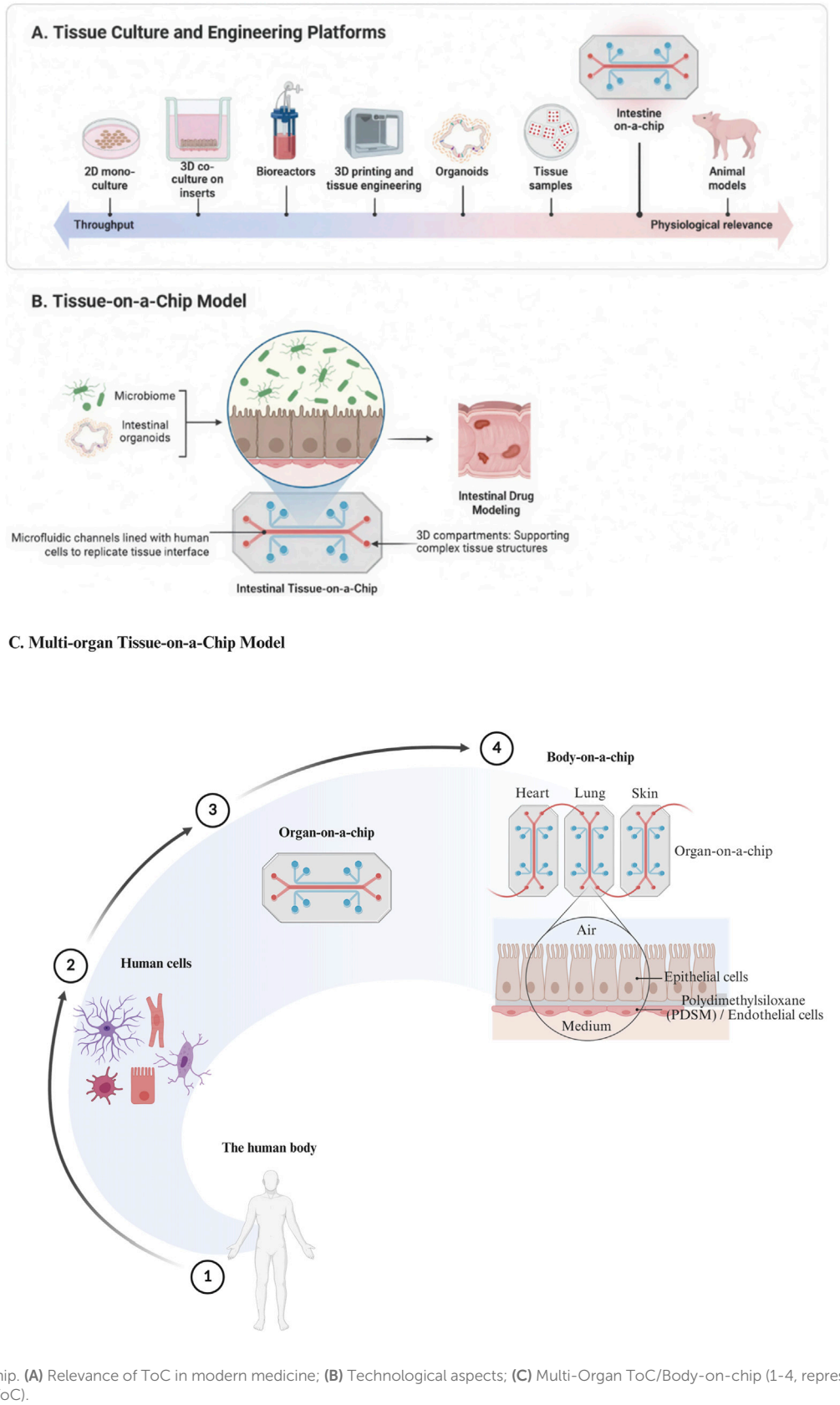

FIGURE 1
Tissue-on-a-Chip. **(A)** Relevance of ToC in modern medicine; **(B)** Technological aspects; **(C)** Multi-Organ ToC/Body-on-chip (1-4, represent steps for setting up ToC).

Similarly, wearable biosensors provide continuous monitoring of physiological stresses (Segerstrom and Miller, 2004), circadian rhythms (Al-Abri et al., 2023), and other indirect indicators of immune health, offering a dynamic picture of astronaut resilience. Collectively, these innovations extend the toolkit for immune monitoring and modulation.

ToC presents a miniaturized platform, with microfluidic systems that could mimic physiological organ-immune interactions in humans, unlike wearables that primarily track biomarkers, and replicate the physiological architecture (Figure 1A) and cellular crosstalk (Figure 1B) of human tissues, enabling functional assessments (Sung et al., 2013) of immune responses under simulated space conditions. This allows researchers to monitor and predict how astronaut immunity might react to microgravity, radiation, or novel pathogens, offering a level of mechanistic insight beyond traditional diagnostics. Additionally, compared with nutritional or pharmacological countermeasures, which act after dysregulation occurs, ToC models provide a platform for proactively testing countermeasures in real-time, reducing risk during missions.

Moreover, the versatility of ToC models extends beyond space, as they serve as powerful translational tools for terrestrial immunology and infection biology, bridging the gap between reductionist cell culture and complex human physiology. By integrating ToC systems into astronaut health monitoring, space agencies can achieve a predictive, mechanistic, and personalized approach to immune resilience by enabling donor-matched assays, using crewmembers' PBMCs (Peripheral Blood Mononuclear Cells) or iPSC-derived immune lineages, to evaluate individual variability in cytokine responses, barrier integrity, and drug or vaccine reactivity under simulated microgravity conditions (Palasantzas et al., 2023; Pham et al., 2025). When integrated with multi-omic profiles and longitudinal biomarkers of immune status, these functional chip readouts could support pre-flight risk stratification, prioritization of countermeasures, and tailored timing of prophylaxis, although such applications require rigorous benchmarking. However, to strengthen the translational value of the in-flight values, ToC research must address key limitations, including variability in cell sources and matrices, lack of standardized culture media and cytokine panels, inter-laboratory reproducibility gaps, and the absence of prospective *in vivo–in vitro* correlation (IVIVC) datasets linking chip predictions with actual in-flight immune outcomes. Additionally, enabling any personalised or on-board use will require automated, low-power, radiation-tolerant hardware validated under mission-relevant conditions.

Further, as the ToC integrates multiple engineering layers into a miniaturized platform that replicates human organ-level physiology, the device architecture consists of microfluidic channels lined with human cells, porous membranes that enable nutrient and signal exchange, and 3D compartments supporting complex tissue structures (Figures 1B,C). Fabrication of these channels relies heavily on polydimethylsiloxane (PDMS/porous membrane) for its gas permeability and ease of soft lithography, although alternative thermoplastics, hydrogels, glass, and engineered elastomers are increasingly adopted to reduce drug absorption, with assembly achieved through plasma treatment, adhesives, or thermal bonding. Fluidics and control systems sustain continuous perfusion to mimic blood circulation, using micro-pumps, valves, and robotic flow controllers to regulate shear stress, automate routing, and scale multi-organ interactions. Integrated sensing and readouts allow real-time monitoring via electrical sensors such as TEER (Trans-Epithelial Electrical Resistance) and impedance spectroscopy, microelectrode arrays for electrophysiology, transparent windows and fluorescent reporters for optical tracking, and biochemical assays through effluent sampling. For system integration, multiple organ chips (Figure 1C), such as heart, lung, and skin, can be fluidically linked into a "body-on-a-chip" guided by scaling principles and computational fluid dynamics (CFD) to maintain physiologically relevant gradients. Finally, the computational and modeling layer leverages CFD, pharmacokinetic/dynamic models, and emerging AI tools to optimize design, predict human responses, and translate in-chip data to *in vivo* outcomes, making organ-on-a-chip a powerful convergence of biology and engineering (Ahmed, 2022).

Currently, there are two ongoing projects through the *Tissue Chips in Space Initiative* that aim to address the effects of microgravity on the immune response under a variety of conditions. In one, 1UG3TR002192, researchers are studying immunosenescence (i.e., gradual decline and dysfunction of the immune system due to aging or disease), where the researchers are using microgravity as an analog for accelerated physiological processes by studying the terminal differentiation of $CD8^+$ effector memory T cells (i.e., TEMRA cells), implicated in dysregulated adaptive immune responses, with a ToC setup at 1G, in simulated[1] and real microgravity (Low and Giulianotti, 2019). The study aims to reveal how immunosenescence impacts bone healing and vascular recovery, which are two critical aspects of astronaut health during long-duration missions. Furthermore, by assessing both in-flight changes and post-flight recovery, the project aims to provide valuable insight into whether immune dysfunction in space is reversible or leads to long-term impairment. Ultimately, this work helps to identify immune-related risks for astronauts and open avenues for countermeasures that enhance regenerative capacity and improve resilience against injury and disease during and after space travel (Schrepfer, 2017).

In another project, 1UG3TR002198, researchers are utilizing microgravity to investigate immune responses to lung infection using a lung-bone marrow tissue chip. The research intends to examine how neutrophils (from the bone marrow) are mobilized in response to bacterial infection by *Pseudomonas aeruginosa,* in space. The researchers hypothesized that immunosuppression in microgravity could arise from the loss of both local and systemic responses to bacterial infection. The project is phased to be completed in two modules (Low and Giulianotti, 2019). The 1st phase[2] is comprised of *"Model Development and Validation"* phases, where researchers have proposed to create two complementary tissue chip models to investigate mechanisms of compromised immunity on the ISS (Paris et al., 2019; Bellissimo et al., 2020; Tran et al., 2022; Georgescu et al., 2024). These included:

1 Current stage of the project as per the latest available data. In-flight results are yet to be received and published.

2 Current stage of the project as per the latest available data. Flight operations are yet to be launched.

1. Airway-on-a-chip: A 3-layer device with airway and vascular components, designed to study susceptibility to lung infections by *Pseudomonas aeruginosa* under microgravity.
2. Bone marrow-on-a-chip: A system to examine how neutrophils are mobilized from the marrow in response to physiological cues that trigger their release.

Once the above stage has been validated, these devices would be packaged into remotely controllable, space-ready modules (bio-modules) and deployed aboard the ISS (2nd stage of the study), with parallel ground-based controls at 1G, supported by research partners who would support device hardening of the tissues on the chips for spaceflight, remote operability, and real-time data transmission, thus making way for the launch of the biological module. Thereafter, post-flight analyses would be completed, and if the results reflect the physiological principles that control recruitment of innate immune cells to infected organs, the bio-modules would be re-packaged and deployed for a second visit to the ISS for a re-analysis in microgravity. Thus, achieving the goal of the project, which was to test the feasibility of microfluidic devices to reflect physiological principles while being delivered to orbit, and to provide access to modular components that can be interconnected to understand the integrated behavior of complex human immune responses in microgravity (Worthen, 2017).

Thus, although projects focusing on immune research in space are in their initial days (Mu et al., 2022), there is substantial research occurring in the field, such as with the *"Tissue Chips in Space Initiative"*. The National Center for Advancing Translational Sciences (NCATS) aims to transform the tissue chip platform into more accessible systems so that stakeholders can operate them without requiring highly specialized expertise (NCATS, 2023). However, this is only possible when the perspective of the Global South is taken into consideration, with respect to project, institutional, and inter-government collaboration, especially due to the common issue of the over-pollution of the space environment and the need to frame space policy based on existing environmental frameworks (Donou-Adonsou, 2024; Palit et al., 2025).

4 Future directions

ToC technology has exhibited particular advantages in understanding biological effects in space sciences for developing space medicine, especially when it comes to the much-needed physiological relevance in astronauts, rather than just high-throughput screening (Figure 1A). When taking from the complexity involved in biological experiments, miniaturized and autonomous microfluidic platforms or ToC or lab-on-a-chip devices enable multiplexed assays with minimal sample volumes, making them ideally suited to spacecraft constraints such as mass, volume, and power, while supporting point-of-care health monitoring (Ardila, 2025). Furthermore, the addition of integrated sensing modalities, such as TEER (Transepithelial/endothelial electrical resistance), impedance, optical reporters, and microelectrode arrays, could provide real-time functional readouts of barrier integrity, electrophysiology, and biomarker secretion, enabling early detection of immune dysregulation during missions (Shi et al., 2025; Yau et al., 2023). Moreover, these systems could be deployed in real or simulated microgravity environments to pre-screen countermeasures such as drugs, vaccines, nutritional strategies, and probiotics for efficacy and safety before astronaut application. Beyond mission relevance, space-adapted ToC data could accelerate terrestrial drug discovery and advance personalized medicine by offering human-relevant models that reduce dependence on present clinical trials (CTs), especially as participant numbers in terms of astronaut data in a cross-sectional CT would be low (Evans and Ball, 2001).

Still, some concerns remain in the global research ecosystem, apart from those mentioned above. These include concerns regarding the scalability of ToC platforms, particularly in standardizing culture media, manufacturing processes, materials, and protocols, as well as ensuring reproducibility, cost-effectiveness, and seamless integration across global research initiatives (Srivastava et al., 2024; Alver et al., 2024). Furthermore, regulatory agencies need to validate the technology, conduct validation tests, and put in standards so that the results produced could suffice the need for having human volunteers in CTs (for screening of drugs in space) while being able to keep maintaining the gold standard of IVIVC being the most predictive model for describing the relationship between the *in vitro* property of an oral dosage form and relevant *in vivo* response for clinical use (Bonaccorsi, 2024). As for an integrated research and technology development roadmap, a short-term (~0–3 years) goal would require establishing standardized protocols, harmonized SOPs for cytokine panels, barrier-integrity metrics such as TEER, and quantitative imaging outputs, to ensure reproducibility across laboratories engaged in Tissue Chips in Space initiatives (Shi et al., 2025). Simultaneously, ground-based validation pipelines should benchmark chip responses against *ex vivo* human samples and data from murine or clinical space-analog studies to initiate robust IVIVC modeling. Concurrently, microfluidic automation must mature through the development of low-power pumps, valves, and embedded sensors to support closed-loop operation with minimal crew involvement (Sutherland et al., 2022). In the mid–long-term (~3–6 years or more) plan, systems must undergo in-flight qualification and radiation-tolerance testing, including the transition from PDMS to more stable thermoplastics, while validating thermal, vibration, and launch resilience. Multi-organ immune platforms integrating bone marrow, lymph node, lung, and skin should be constructed to recapitulate adaptive and innate immune trafficking under controlled perturbations such as vaccination or microbial challenge (Low and Giulianotti, 2019; Giri and Tsao, 2022). Conversely, if left unaddressed, the dynamic nature of the ToC ecosystem could undermine inclusivity, restricting contributions from emerging research ecosystems and reinforcing existing imbalances in space science. In addition, governance and ethical considerations, from intellectual property ownership to data-sharing frameworks, will shape whether these technologies evolve as shared scientific assets or proprietary tools controlled by a few commercial actors.

5 Conclusion

The effects of space travel on the human body, particularly on immunity, present a multifaceted challenge for long-duration missions. Microgravity, radiation, and isolation are primary space stresses that lead to immune dysregulation, increased susceptibility

to infections, and altered physiological processes. While significant progress has been made in understanding these effects, the complexity of immune dysfunction in space remains poorly understood, and its mitigation requires innovative solutions. The integration of ToC technology offers promising advancements, enabling high-fidelity models to study immune responses in microgravity and test potential countermeasures in real-time. These technologies not only enhance our ability to protect astronauts' health but also open new avenues for medical advancements applicable to Earth. Future research should focus on refining these technologies, addressing concerns about scalability and reproducibility, and integrating them into long-term space health strategies. By leveraging these advances, space agencies can ensure astronaut resilience and safeguard human health on deep-space missions.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SH: Conceptualization, Project administration, Writing – original draft, Writing – review and editing. SP: Writing – original draft, Writing – review and editing. TR: Writing – original draft, Writing – review and editing. GG: Writing – original draft, Writing – review and editing. PS: Writing – original draft, Writing – review and editing.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Acknowledgements

The authors would like to thank Ryan Kirby (Meridian Academy, Massachusetts, United States) for his efforts in refining the tone of the manuscript.

Conflict of interest

Authors SH and SP was employed by LIFE-To & Beyond Foundation®.

Authors SP and TR was employed by InnovaSpace.

Authors SP and TR was employed by ACES Worldwide.

The remaining author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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