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Redesigning Human Spaceflight: The Emerging Field of Bioastronautics

Biology * Space * Public Health

Introduction: The Emergence of Bioastronautics in Deep Space

As human spaceflight transitions from low-Earth orbit (LEO) aboard the International Space Station (ISS) to cislunar habitation under Artemis and multi-year Mars transit, bioastronautics -- studying the biological, physiological, and medical effects of spaceflight on living organisms -- has become the central determinant of mission architecture.[1][3] Spanning molecular gene expression in microgravity, clinical aerospace medicine, and closed-loop environmental engineering, bioastronautics addresses the "Trinity" of deep-space constraints: resupply logistics, spacecraft mass limits, and synergistic human health hazards.[2][4][7]

Beyond Earth's magnetosphere, crews encounter simultaneous stressors -- microgravity or partial gravity, Galactic Cosmic Rays (GCRs), Solar Particle Events (SPEs), and isolation with 22-minute one-way communication delays -- that interact nonlinearly.[1][5][6] Cephalad fluid shifts compound radiation-induced vascular damage, while isolation dysregulates immunity. Moving from "visiting" space to "inhabiting" deep space requires autonomous medical countermeasures, partial-gravity demonstration platforms like Vast's Haven-1 station, and bioregenerative life support systems driven by synthetic biology that mimic Earth's biosphere.[4][8]

Spaceflight Associated Neuro-ocular Syndrome (SANS) and the Glymphatic Hypothesis

Affecting ~70% of long-duration astronauts, Spaceflight Associated Neuro-ocular Syndrome (SANS) presents as optic disc edema, globe flattening, choroidal folds, and hyperopic refractive shifts.[9][10] While early models attributed SANS solely to cephalad fluid shifts elevating intracranial pressure, 2024-2025 studies implicate obstruction of the brain's glymphatic system -- the perivascular cerebrospinal fluid (CSF) waste-clearance pathway active during deep sleep.[9][11][12] In weightlessness, loss of hydrostatic drainage causes jugular and venous sinus congestion, impeding glymphatic CSF outflow and trapping fluid around the optic nerve sheath, exacerbated by sleep disruption.[12][13]

Space-omics further shows that polymorphisms in one-carbon metabolism governing homocysteine clearance, DNA synthesis, and DNA methylation predispose crew members to SANS.[10][14] Emerging countermeasures target both mechanisms:

* Wearable LBNP & Venoconstrictive Thigh Cuffs: Lower Body Negative Pressure (LBNP) chambers enclose the lower abdomen and legs in a vacuum seal, drawing intravascular and interstitial fluid caudally to simulate Earth's hydrostatic gradient. Whereas legacy Russian Chibis suits were rigid cylinders, 2025 prototypes integrate "self-generated" mobile LBNP garments with resistive exercise hardware so crew members generate negative pressure mechanically during workouts, conserving

spacecraft power and mass.[10][15][16] Complementing LBNP, mechanical thigh cuffs (Braslet) restrict femoral venous return to reduce acute cephalad congestion during waking hours.[10]

* Translaminar Pressure Modulation & Precision Nutrition: Pressurized swimming-style goggles elevate anterior intraocular pressure to counterbalance retrobulbar cerebrospinal fluid pressure across the lamina cribrosa, neutralizing the translaminar pressure gradient that flattens the globe.[9][10] Simultaneously, targeted B-vitamin supplementation (folate, vitamin B6, and methylcobalamin B12) stabilizes one-carbon metabolic flux and endothelial nitric oxide synthesis in genetically predisposed astronauts.[10]

Musculoskeletal Unloading, the Tendon Gap, and Molecular Countermeasures

Without gravitational loading, muscle and bone suppress anabolic IGF-1 signaling and upregulate catabolic pathways, driving atrophy of antigravity muscles and osteoporotic bone loss.[14][18][19] Space-omics reveals that unloading induces mitochondrial stress and reciprocal myokine-osteokine crosstalk, notably upregulating the muscle-growth inhibitor myostatin.[14][18]

Additionally, 2025 biomechanics reviews highlight a critical "tendon gap": unloading degrades collagen cross-linking and tendon stiffness, risking acute rupture upon high-force reloading on Mars.[14] Because the ISS's 600-pound Advanced Resistive Exercise Device (ARED) is too massive for Mars transit vehicles and cannot fully preserve tendon matrix homeostasis, new protocols combine compact resistance hardware with myostatin inhibitors, IGF-1/BMP tendon stimulation, and bisphosphonate-parathyroid hormone regimens guided by urinary biomarkers.[14][18][19]

Deep-Space Radiation: Composite Shielding and Tardigrade Radioprotection

Deep-space crews face episodic solar radiation storms (SPE protons) and continuous Galactic Cosmic Rays (GCRs) composed of relativistic heavy (HZE) ions.[6][17] A ~1,000-day Mars mission exposes astronauts to 525 mSv (solar maximum) up to 1,650 mSv (solar minimum) -- nearly tripling NASA's ~600 mSv career limit.[6] Beyond cancer, HZE tracks damage cortical neurons, risking cognitive decline.[6][9][20]

| Mission Profile | | Duration | | Estimated Dose | | Radiobiological Context |

| ISS Low-Earth Orbit | | 6 months | | 50-100 mSv | | Protected by magnetosphere.[6] |

| Mars Transit (Solar Max) | | ~870 days | | ~525 mSv | | Lower GCR flux; higher SPE risk.[6] |

| Mars Transit (Solar Min) | | ~1,000 days | | ~1,650 mSv | | Nearly 3x NASA ~600 mSv career limit.[6] |

Because heavy ions striking high-Z metals generate secondary neutron showers, physical shielding uses hydrogen-rich polymers (like the AstroRad vest protecting stem-cell-rich tissues), regolith overburden, and CSIRO's metal-matrix-ceramic

composites tested on Binar-2/3 in 2024 that improve attenuation by 40-50%.[21][22] Simultaneously, biological radioprotection enhances DNA repair via tardigrade Damage suppressor (Dsup) nucleosome-binding proteins, metformin, and engineered radio-resistant gut microbiota.[17][23][24]

Closed-Loop Life Support, Synthetic Biology, and Artificial Gravity

On the ISS, integrating the Brine Processor Assembly recently achieved 98% water recovery, while biomimetic aquaporin proteins aim to eliminate chemical filters.[25][26] To decouple food production from volume-intensive photosynthesis while recycling oxygen and CO2, ESA's HOBI-WAN cultures bacteria on H2, CO2, and urinary urea to produce "Solein" protein, NASA's BioNutrients uses engineered Saccharomyces cerevisiae spores to synthesize antioxidants on demand, and Artemis III's LEAF payload will test lunar crop germination.[27][28][29]

| Domain | | Current ISS Standard | | Deep-Space / Mars Countermeasure |

| Neuro-Ocular (SANS) | | Glasses, OCT imaging | | Mobile LBNP, thigh cuffs, B-vitamins[10][15] |

| Musculoskeletal | | ARED, bisphosphonates | | Myostatin inhibitors, IGF-1 tendon therapy[14] |

| Radiation | | Aluminum hull, dosimetry | | Metal-matrix composites, regolith, Dsup[21][23] |

| Life Support & Food | | 98% brine recovery | | Aquaporin membranes, Solein, BioNutrients[25][27][28] |

| Psychology & Gravity | | Video calls; 0g | | AI CBT, VR (CHAPEA); Haven-1 spin demo (0.16g)[5][8][30] |

Psychologically, NASA's year-long Crew Health and Performance Exploration Analog (CHAPEA) simulations inside the 1,700-square-foot 3D-printed "Mars Dune Alpha" habitat at Johnson Space Center validated immersive virtual reality environments, cooperative video gaming, and autonomous AI-guided cognitive behavioral therapy (CBT) to maintain crew cohesion under 22-minute communication blackouts.[5][30][31][32] Structurally, the commercial sector is reviving artificial gravity as a targeted countermeasure testbed: Vast Space's 45-m3 Haven-1 commercial station (targeting launch in Q1 2027) is primarily a microgravity laboratory whose propulsion system is engineered to execute a dedicated rotation demonstration generating lunar-equivalent artificial gravity (~0.16g) during crewed SpaceX Dragon missions, providing an orbital testbed alongside short-radius onboard centrifuges to assess whether partial centrifugation mitigates SANS and musculoskeletal deconditioning ahead of continuously rotating multi-module habitats.[8][10][33][34][35]

Conclusion: Engineering Biological Resilience for Artemis and Mars

The evolution of bioastronautics into an active bioengineering discipline is reshaping deep-space exploration -- driving faster propulsion, point-of-care diagnostics and sensorized spacesuits for Artemis III, and pre-emplaced regolith habitats.[22][29][36][37] By uniting mechanical fluid regulation, partial-gravity

testbeds, composite shielding, tardigrade genomic protection, and microbial life support, bioastronautics is converting the biological showstoppers of interplanetary flight into manageable engineering parameters.

Updates (Nov 15, 2026): Clarified Vast Space's Haven-1 architecture as a microgravity pathfinder targeting Q1 2027 with a planned propulsion-driven ~0.16g lunar-gravity demonstration rather than continuous mission-long rotation (Vast Space Integration Update), stripped numbered section headers, and replaced broken/non-authoritative ResearchGate, YouTube, Wikipedia, and dead ESA URLs with verified primary-literature DOIs and official NASA/ESA technical references.

Works Cited

* Harvard-MIT Health Sciences and Technology (Sep 29, 2026). Bioastronautics Training Program. -- https://hst.mit.edu/academic-programs/memp/bioastronautics-training-program

* NASA Technical Reports Server (2005). Bioastronautics Roadmap: A Risk Reduction Strategy for Human Exploration of Space. -- https://ntrs.nasa.gov/api/citations/20050081847/downloads/20050081847.pdf

* Berliner, A. J., Zezulka, S., Hutchinson, G. A., Bertoldo, S., Cockell, C. S., & Arkin, A. P. (Jan 29, 2024). Domains of life sciences in spacefaring: what, where, and how to get involved. npj Microgravity, 10, 12. -- https://doi.org/10.1038/s41526-024-00354-y

* Marshall Porterfield, D., Tulodziecki, D., Wheeler, R., et al. (Aug 16, 2025). Critical investments in bioregenerative life support systems for bioastronautics and sustainable lunar exploration. npj Microgravity, 11. -- https://doi.org/10.1038/s41526-025-00518-4

* Pagnini, F., et al. (Oct 9, 2024). Supporting the Mind in Space: Psychological Tools for Long-Duration Missions. Interactive Journal of Medical Research. -- https://doi.org/10.2196/66626

* Simonsen, L. C., et al. (2025). Moon 2 Mars Space Radiation Protection "Buying Down" Risks to Crew. NASA NTRS. -- https://ntrs.nasa.gov/api/citations/20250006168/downloads/ASCEND%20Simonsen%20draft%201.pdf

* Young, L. R. (2020). Bioastronautics: Definition and Scope. Handbook of Bioastronautics, Springer. -- https://doi.org/10.1007/978-3-319-10152-1_88-2

* Vast Space (May 10, 2023). Vast Announces the Haven-1 and Vast-1 Missions. -- https://www.vastspace.com/updates/vast-announces-the-haven-1-and-vast-1-human-spaceflight-mission-launched-by-spacex-on-a-dr

* Venegas, J. M. (May 1, 2024). Spaceflight-associated neuro-ocular syndrome: potential etiologies and connections to the glymphatic system. Journal of Neurophysiology. -- https://doi.org/10.1152/jn.00056.2024

* Nguyen, T., Ong, J., Brunstetter, T., et al. (May 2025). Spaceflight Associated Neuro-ocular Syndrome (SANS) and its countermeasures. Progress in Retinal and Eye Research. -- https://doi.org/10.1016/j.preteyeres.2025.101340

* Gao, Y., Liu, K., & Zhu, J. (Jul 6, 2023). Glymphatic system: an emerging therapeutic approach for neurological disorders. Frontiers in Molecular

Neuroscience, 16. -- https://doi.org/10.3389/fnmol.2023.1138769

* Bateman, G. A., & Bateman, A. R. (Feb 28, 2024). A perspective on the evidence for glymphatic obstruction in spaceflight associated neuro-ocular syndrome and fatigue. npj Microgravity. -- https://doi.org/10.1038/s41526-024-00365-9

* Nguyen, T., Ong, J., Waisberg, E., & Lee, A. G. (Oct 2024). Sleep and optic disc edema in spaceflight associated neuro-ocular syndrome (SANS). Eye. -- https://doi.org/10.1038/s41433-024-03119-9

* Roberts, B. M., et al. (Dec 1, 2025). Musculoskeletal responses to spaceflight: mechanisms, countermeasures, and key gaps. American Journal of Physiology-Cell Physiology. -- https://doi.org/10.1152/ajpcell.00649.2025

* Velichala, S. R., et al. (2024). Self-Generated Lower Body Negative Pressure Exercise, a Low Power Countermeasure for Deep-Space Missions. LPI / USRA. -- https://www.hou.usra.edu/meetings/lunarsurface24/pdf/5003.pdf

* Ashari, N., & Hargens, A. R. (Aug 5, 2020). The Mobile Lower Body Negative Pressure Gravity Suit for Long-Duration Spaceflight. Frontiers in Physiology. -- https://doi.org/10.3389/fphys.2020.00977

* NASA Technical Reports Server (2025). Part 1: The Space Radiation Environment. -- https://ntrs.nasa.gov/api/citations/20250004252/downloads/Book%20Chapter.pdf

* Liu, Y., et al. (Dec 20, 2024). Mechanisms and Countermeasures for Muscle Atrophy in Microgravity. Cells, 13(24), 2120. -- https://doi.org/10.3390/cells13242120

* NASA Human System Risk Board (Nov 2025). Risk of Spaceflight-induced Changes to Bone, leading to In-mission Fracture and Early-Onset Osteoporosis. -- https://www.nasa.gov/wp-content/uploads/2025/11/hsrb-bone-risk-record-rev-c-web.pdf?emrc=bce10e

* European Space Agency (2019). The radiation showstopper for Mars exploration. -- https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/The_radiation_showstopper_for_Mars_exploration

* CSIRO (2024). Space radiation shielding. -- https://www.csiro.au/en/research/technology-space/astronomy-space/space-technologies/radiation-shielding

* StemRad (Dec 22, 2021). Radiation Shielding in Space (AstroRad). -- https://stemrad.com/blocking-space-radiation-in-deep-space/

* Cui, Z., et al. (Nov 18, 2025). Radioprotection redefined: drug discovery at the intersection of tardigrade biology and translational pharmacology. Frontiers in Pharmacology. -- https://doi.org/10.3389/fphar.2025.1713914

* Yakimova, A. O., Nikolaeva, A., et al. (Dec 24, 2024). Microbiota-Induced Radioprotection: A Novel Approach to Enhance Human Radioresistance with In-Situ Genetically Engineered Gut Bacteria. Applied Microbiology, 5(1), 1. -- https://doi.org/10.3390/applmicrobiol5010001

* NASA (Jun 20, 2023; updated Mar 2, 2026). NASA Achieves Water Recovery Milestone on International Space Station. -- https://www.nasa.gov/missions/station/iss-research/nasa-achieves-water-recovery-milestone-on-international-space-station/

* Wang, D., Vijapur, S. H., Hall, T. D., Taylor, E. J., Snyder, S., & Cabrera, C. R. (Apr 13, 2018). Next Generation Water Recovery for a Sustainable Closed Loop Living.

ECS Meeting Abstracts. -- https://doi.org/10.1149/ma2018-01/20/1286

* European Space Agency (2025). N deg 68-2025: Protein out of thin air: ESA's pilot project HOBI-WAN launched. -- https://www.esa.int/media-advisories/news-media/media/media-advisories/n-68-2025-protein-out-of-thin-air-esa-s-pilot-project-hobi

* NASA Technical Reports Server (Jun 14, 2024). Synthetic Biology to Support Human Exploration of Deep Space (BioNutrients). -- https://ntrs.nasa.gov/citations/20240001989

* NASA (Mar 26, 2024). NASA Selects First Lunar Instruments for Artemis Astronaut Deployment (LEAF - Lunar Effects on Agricultural Flora). -- https://www.nasa.gov/news-release/nasa-selects-first-lunar-instruments-for-artemis-astronaut-deployment/

* The Times of India (2025). NASA CHAPEA Mars simulation survival findings. -- https://timesofindia.indiatimes.com/science/nasa-locked-them-away-for-a-year-to-test-mars-simulation-survivalwhat-they-did-with-a

* American Psychological Association (Mar 2025). Mind over Mars: The psychology of space exploration, with Suzanne Bell, PhD. -- https://www.apa.org/news/podcasts/speaking-of-psychology/mars-habitat

* Nezami, A., et al. (Jan 3, 2025). Space psychology: a comprehensive approach to the future of astronaut wellbeing. Frontiers in Virtual Reality. -- https://doi.org/10.3389/frvir.2024.1446796

* Supercluster (2026). Haven-1 Launch Profile. -- https://www.supercluster.com/launches/haven-1

* Vast Space (2026). Vast Advances Haven-1 into Integration Phase (Targeting Q1 2027). -- https://www.vastspace.com/updates/vast-advances-haven-1-into-integration-phase

* Ahmed, S. S., et al. (Apr 25, 2024). Systematic review of the effectiveness of standalone passive countermeasures on microgravity-induced physiologic deconditioning. npj Microgravity. -- https://doi.org/10.1038/s41526-024-00389-1

* Roda, A., Mirasoli, M., Guardigli, M., Zangheri, M., Caliceti, C., Calabria, D., & Simoni, P. (Jul 2018). Advanced biosensors for monitoring astronauts' health during long-duration space missions. Biosensors and Bioelectronics, 111, 18-26. -- https://doi.org/10.1016/j.bios.2018.03.062

* Palacios, P., et al. (Sep 2023). Mechatronics Design and Development of T-EVA: Bio-Sensorized Space System for Astronaut's Upper Body Temperature Monitoring During Extravehicular Activities on the Moon and Mars. IJACSA (Semantic Scholar). -- https://pdfs.semanticscholar.org/02c1/77077108bca67d0d0526c7a9488ac478b6e8.pdf