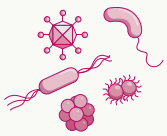
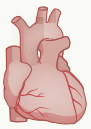
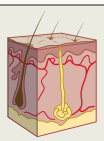
The second space age: omics, platforms, and medicine across orbits

Research	Title of paper	Astronaut data included	Reference
Systemic, host–microbe, and whole body impact			
Whole body 	Molecular and physiologic changes in the SpaceX Inspiration4 civilian crew	I4	Jones, C. W., Overbey, E. G., Lacombe, J. et al. *Nature* (2024) doi: 10.1038/s41586-024-07648-x
	The Space Omics and Medical Atlas (SOMA) and international astronaut biobank	JAXA CFE; I4; NASA twin	Overbey, E. G., Kim, J.K., Tierney, B. T. et al. *Nature* (2024) doi: 10.1038/s41586-024-07639-y
	Collection of biospecimens from the inspiration4 mission establishes the standards for the space omics and medical atlas (SOMA)	I4	Overbey, E. G., Ryon, K., Kim, J.K. et al. *Nat. Commun.* (2024) doi: 10.1038/s41467-024-48806-z
	Aging and putative frailty biomarkers are altered by spaceflight	JAXA CFE; I4	Camera, A., Tabetah, M, Castañeda, V. et al. *Sci. Rep.* (2024) doi: 10.1038/s41598-024-57948-5
	Astronaut omics and the impact of space on the human body at scale	I4	Rutter, L. A., Cope, H., MacKay, M. J. et al. *Nat. Commun.* (2024) doi: 10.1038/s41467-024-47237-0
	Characterizing dehydration in short-term spaceflight using evidence from Project Mercury	None	Reynolds, R. J., Shelhamer, M., Antonsen, E. L. & Carpentier, W. R. *npj Microgravity* (2024) doi: 10.1038/s41526-024-00374-8
Microbiome 	Longitudinal multi-omics analysis of host microbiome architecture and immune responses during short-term spaceflight	I4	Tierney, B., Kim, J.K., Overbey, E. G. et al. *Nat. Microbiol.* (2024) doi: 10.1038/s41564-024-01635-8
	Microbial adaptation to spaceflight is correlated with bacteriophage-encoded functions	I4	Irby, I. & Broddrick, J. T. *Nat. Commun.* (2024) doi: 10.1038/s41467-023-42104-w
	Phylogenomics, phenotypic, and functional traits of five novel (Earth-derived) bacterial species isolated from the International Space Station and their prevalence in metagenomes	None	Simpson, A. C., Sengupta, P., Zhang F. et al. *Sci. Rep.* (2024) doi: 10.1038/s41598-023-44172-w
Organs and tissues			
Heart 	Countermeasures for cardiac fibrosis in space travel: it takes more than a towel for a hitchhiker's guide to the galaxy	JAXA CFE; I4	Paar, V., Jiang, S., Enriquez, A. et al. *Res. Sq.* (2023) [preprint] doi: 10.21203/rs.3.rs-2351744/v1
	Considering clonal hematopoiesis of indeterminate potential in space radiation risk analysis for hematologic cancers and cardiovascular disease	None	Werneth, C. M., Patel, Z. S., Thompson, M. S., Blattnig, S. R. & Huff, J. L. *Commun. Med.* (2024) doi: 10.1038/s43856-023-00408-4
Skin 	Spatial multi-omics of human skin reveals KRAS and inflammatory responses to spaceflight	I4	Park, J., Overbey, E. G., Narayanan, S. A. et al. *Nat. Commun.* (2024) doi: 10.1038/s41467-024-48625-2
	Transcriptomics analysis reveals molecular alterations underpinning spaceflight dermatology	JAXA CFE; I4; NASA twin	Cope, H., Elsborg, J., Demharter, S. et al. *Commun. Med.* (2024) doi: 10.1038/s43856-024-00532-9
Skeletal muscle 	Bioreactor development for skeletal muscle hypertrophy and atrophy by manipulating uniaxial cyclic strain: proof of concept	None	Kamal, K. Y., Othman, M. A., Kim, J.-H. & Lawler, J. M. *npj MIcrogravity* (2024) doi: 10.1038/s41526-023-00320-0
	Key genes, altered pathways and potential treatments for muscle loss in astronauts and sarcopenic patients	JAXA CFE; I4	Caicedo, A., Castañeda, V., Díaz J. et al. *Res. Sq.* (2023) [preprint] doi: 10.21203/rs.3.rs-2819258/v1
Brain 	Spatially resolved multiomics on the neuronal effects induced by spaceflight in mice	None	Masarapu, Y., Cekanaviciute, E., Andrusivova, Z. et al. *Nat. Commun.* (2024) doi: 10.1038/s41467-024-48916-8
	Secretome profiling reveals acute changes in oxidative stress, brain homeostasis, and coagulation following short-duration spaceflight	I4; NASA twin	Hourebi, N., Kim, J.K., Overbey, E. G. et al. *Nat. Commun.* (2024) doi: 10.1038/s41467-024-48841-w
	Complex 33-beam simulated galactic cosmic radiation exposure impacts cognitive function and prefrontal cortex neurotransmitter networks in male mice	None	Desai, R. I., Kangas, B. D., Luc, O. T. et al. *Nat. Commun.* (2023) doi: 10.1038/s41467-023-42173-x
Kidney 	Cosmic kidney disease: An integrated pan-omic, physiological and morphological study into spaceflight-induced renal dysfunction	JAXA CFE; I4; NASA twin	Siew, K., Nestler, K. A., Nelson, C. et al. *Nat. Commun.* (2024) doi: 10.1038/s41467-024-49212-1
Cellular			
Immune cells 	Single-cell analysis identifies conserved features of immune dysfunction in simulated microgravity and spaceflight	JAXA CFE; I4; NASA twin	Wu, F., Du, H., Overbey, E. et al. *Nat. Commun.* (2024) doi: 10.1038/s41467-023-42013-y
	Single-cell multi-ome and immune profiles of the Inspiration4 crew reveal conserved, cell-type, and sex-specific responses to spaceflight	I4; NASA twin	Kim, J.K., Tierney B. T., Overbey, E. G. et al. *Nat. Commun.* (2024) doi: 10.1038/s41467-024-49211-2
	Sexual dimorphism during integrative endocrine and immune responses to ionizing radiation in mice	None	Burke, M., Wong, K., Talyansky, Y. et al. *Sci. Rep.* (2024) doi: 10.1038/s41598-023-33629-7
	Influence of the spaceflight environment on macrophage lineages	None	An, R., Blackwell, V. K., Harandi, B. et al. *npj Microgravity* (2024) doi: 10.1038/s41526-023-00293-0
	Combined space stressors induce independent behavioral deficits predicted by early peripheral blood monocytes	None	Rienecker, K. D. A. Grue, K., Paladini, M. S. et al. *Sci. Rep.* (2023) doi: 10.1038/s41598-023-28508-0
	Spatiotemporal expression and control of haemoglobin in space	JAXA CFE; I4; NASA twin	Borg, J., Loy, C., Kim, J.K. et al. *Nat. Commun.* (2024) doi: 10.1038/s41467-024-49289-8

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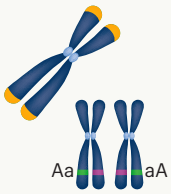
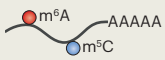
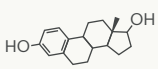
Cellular (continued)			
Mitochondria 	Release of CD36-associated cell-free mitochondrial DNA and RNA as a hallmark of space environment response	JAXA CFE	Husna, N., Aiba, T., Fujita, S.-I. et al. *Nat. Commun.* (2024) doi: 10.1038/s41467-023-41995-z
Chromosomes 	Telomeric RNA (TERRA) increases in response to spaceflight and high-altitude climbing	I4; NASA twin	Al-Turki, T. M., Maranon, D. G., Nelson, C. B. et al. *Commun. Biol.* (2024) doi: 10.1038/s42003-024-06014-x
	Chromosomal positioning and epigenetic architecture influence DNA methylation patterns triggered by galactic cosmic radiation	JAXA CFE	Perdyan, A., Jąkalski, M., Horbacz, M., Beheshti, A. & Mieczkowski, J. *Sci. Rep.* (2024) doi: 10.1038/s41598-024-51756-7
	Arabidopsis telomerase takes off by uncoupling enzyme activity from telomere length maintenance in space	None	Barcenilla, B. B., Meyers, A. D., Castillo-González C. et al. *Nat. Commun.* (2024) doi: 10.1038/s41467-023-41510-4
Epigenetic 	Direct RNA sequencing of astronaut blood reveals spaceflight-associated m6A increases and hematopoietic transcriptional responses	I4	Grigorev, K., Nelson, T. M, Overbey, E. G. et al. *Nat. Commun.* (2024) doi: 10.1038/s41467-024-48929-3
Endocrine effects 	Spaceflight induces changes in gene expression profiles linked to insulin and estrogen	JAXA CFE; I4	Mathyk, B. A., Tabetah, M., Karim, R. et al. *Commun. Biol.* (2024) doi: 10.1038/s42003-023-05213-2
	Understanding how space travel affects the female reproductive system	JAXA CFE; I4	Mathyk, B., Imudia, A. N., Quaas, A. M. et al. *npj Women's Health* (2024) doi: 10.1038/s44294-024-00009-z
Countermeasures			
Drugs 	Space radiation damage rescued by inhibition of key spaceflight-associated miRNAs	JAXA CFE; I4; NASA twin	McDonald, J. T., Kim, J.K., Farmerie L. et al. *Nat. Commun.* (2024) doi: 10.1038/s41467-024-48920-y
Omics and computation			
AI analysis 	Explainable machine learning identifies multi-omics signatures of muscle response to spaceflight in mice	None	Li, K., Desai, R., Scott, R. T. et al. *npj Microgravity* (2023) doi: 10.1038/s41526-023-00337-5
	Biomonitoring and precision health in deep space supported by artificial intelligence	None	Scott, R. T., Sanders, L. M., Antonsen, E. L. et al. *Nat. Mach. Intell.* (2023) doi: 10.1038/s42256-023-00617-5
	Harmonizing heterogeneous transcriptomics datasets for machine learning-based analysis to identify spaceflown murine liver-specific changes	None	Ilangovan, H., Kothiyal, P., Hoadley, K. A. et al. *npj Microgravity* (2024) doi: 10.1038/s41526-024-00379-3
	Biological research and self-driving labs in deep space supported by artificial intelligence	None	Sanders, L. M., Scott, R. T., Yang, J. H. et al. *Nat. Mach. Intell.* (2023) doi: 10.1038/s42256-023-00618-4
Omics analysis 	NASA GeneLab derived microarrays studies of *Mus musculus* and *Homo sapiens* organisms in altered gravitational conditions	None	Adamopoulos, K. I., Sanders, L. M. & Costes, S. V. *npj Microgravity* (2024) doi: 10.1038/s41526-024-00392-6
	Analyzing the relationship between gene expression and phenotype in space-flown mice using a causal inference machine learning ensemble	None	Casaletto, J., Scott, R., Myrick, M. et al. *Res. Sq.* (2023) [preprint] doi: 10.21203/rs.3.rs-2332064/v1
Perspective			
	A second space age spanning omics, platforms, and medicine across orbits	JAXA CFE; I4; NASA twin	Mason, C. E., Green, J., Adamopoulos, K. I. et al. *Nature* (2024) doi: 10.1038/s41586-024-07586-8
	Ethical considerations for the age of non-governmental space exploration	None	Seylani, A., Galsinh, A. S., Tasoula, A. et al. *Nat. Commun.* (2024) doi: 10.1038/s41467-023-44357-x
	Biological horizons: pioneering open science in the cosmos	I4	Costes, S. V., Gentemann, C. L., Platts, S. H. & Carnell , L. A. *Nat. Commun.* (2024) doi: 10.1038/s41467-024-48633-2
	Inspiration4 data access through the NASA Open Science Data Repository	I4	Sanders, L., Grigorev, K. A., Scott, R. T. et al. *npj Microgravity* (2024) doi: 10.1038/s41526-024-00393-5
	Exploring protective alleles for precision health in human spaceflight	NASA twin	Rutter, L. A., MacKay, M., Cope, H. et al. *Nat. Commun.* (2024) doi: 10.1038/s41467-024-49423-6

I4, Inspiration4 mission; JAXA CFE, JAXA cell-free epigenome study; NASA twin, NASA twin study.