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Biological impacts of hypomagnetic fields in space environment: implications for artificial magnetic field provision in long-duration spaceflight

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Life on Earth evolved and exists within the geomagnetic field which currently ranges from approximately 25–65 μT . Voyages beyond Earth's magnetosphere expose astronauts to the unique conditions of deep space, characterized by significantly reduced magnetic fields ranging from 2 to 8 nT. This review examines the growing body of evidence concerning the biological impacts of hypomagnetic and altered magnetic fields on humans and other organisms, highlighting the implications for long-duration spaceflight and space mission. Research using human cell cultures and mammalian models indicates that exposure to varying magnetic field conditions, including hypomagnetic fields (HMF), can induce diverse biological effects. These include changes in cellular proliferation, nervous system function, oxidative stress reactive oxygen species levels, and DNA integrity, with outcomes often dependent on specific field intensity, frequency, and length of exposures. Furthermore, HMF exposure has been shown to affect bacterial behavior and the human microbiome, potentially altering antibiotic resistance and increasing risks of infection, given the compromised immune function astronauts may experience in space. Considering these biological impacts on the wellbeing of astronauts on long-term space mission, providing artificial magnetic fields onboard spacecraft is proposed as a critical strategy to mitigate HMF effects, support astronaut health, and enhance the feasibility and safety of future deep space missions.

KEYWORDS

hypomagnetic field, human spaceflight, human cell line, microbiome, microorganism, microgravity

1 Hypomagnetic field is a key stressor for spaceflight

The geomagnetic field (GMF) supports life on Earth by providing a relatively stable magnetic environment with an average surface intensity of approximately 45 μT . Various organisms including birds, fish, sea turtles, insects, and bacteria rely on GMF environments in their daily lives with respect to navigation, circadian balance, and biochemical regulation. In addition, the GMF forms the magnetosphere which is useful for deflecting charged solar and cosmic particles to protect the biosphere from harmful radiation—an essential prerequisite for the flourishing of life. Nearly every organism on Earth has adapted to

life under exposure to the GMF and rely on it as a persistent environmental factor to maintain their naturally functioning physiology.

A hypomagnetic or hypo-geomagnetic field (HMF) is commonly defined as a magnetic field with intensity below 5 μ T. Such conditions are exceedingly rare on Earth but become increasingly relevant when exploring extraterrestrial environments. With the advancement of human spaceflight and ongoing programs such as NASA's Artemis mission, which aims to return humans to the Moon and prepare for Mars exploration, it is imperative to understand the biological consequences of spaceflight stressors. Among these, HMF exposure has historically received less attention compared with microgravity or ionizing radiation, yet it may play an equally important role in shaping astronaut health and performance during long-duration missions.

Spaceflight exposes biological systems to multiple concurrent stressors. Microgravity alters musculoskeletal and cardiovascular physiology, radiation increases cancer risk and damages to DNA, and isolation and circadian disruption affect neurocognitive performance (Demontis et al., 2017). In this context, HMF conditions represent an additional stressor that could act synergistically with these factors. Evidence from cell culture and limited human data suggests that HMF exposure influences fundamental biological processes, including metabolism, oxidative stress response, proliferation, differentiation, immune regulation, and neural function (Sarimov et al., 2023; Tian et al., 2024). Importantly, many of these responses overlap with or exacerbate the well-documented effects of microgravity, raising questions about additive or combined risks during extended missions.

While astronauts aboard the International Space Station (ISS) remain largely within Earth's magnetosphere and experience only small and negligible reductions in geomagnetic exposure, missions beyond low Earth orbit—including lunar surface stays, with crustal field intensity ranging from 1–100 nT (nT), and deep-space transit to Mars, where background field can be as low as 1 nT in magnitude—will place crews in sustained HMF conditions (Stevenson, 2003). These exposures will likely be measured in weeks to months, at intensities 10,000 times lower than terrestrial GMF levels. The health implications of such prolonged exposure remain uncertain, underscoring the need for systematic study.

This review examines current evidence on HMF effects with a focus on human cell culture systems and microbial systems relevant to human health. We explore how HMF impacts metabolism, neurocognition, skeletal health, immune and microbiome regulation, and how these effects may interact with other spaceflight stressors. Furthermore, we aim to clarify the mechanisms by which HMF influences physiology, highlight parallels with microgravity and radiation, and identify key knowledge gaps. Such insights are essential for developing countermeasures to safeguard astronaut health during future lunar and Martian missions.

2 Effects of hypomagnetic field on human cell lines and body

Recent studies have broadened our understanding of the influence of HMFs on human biology, with mechanistic

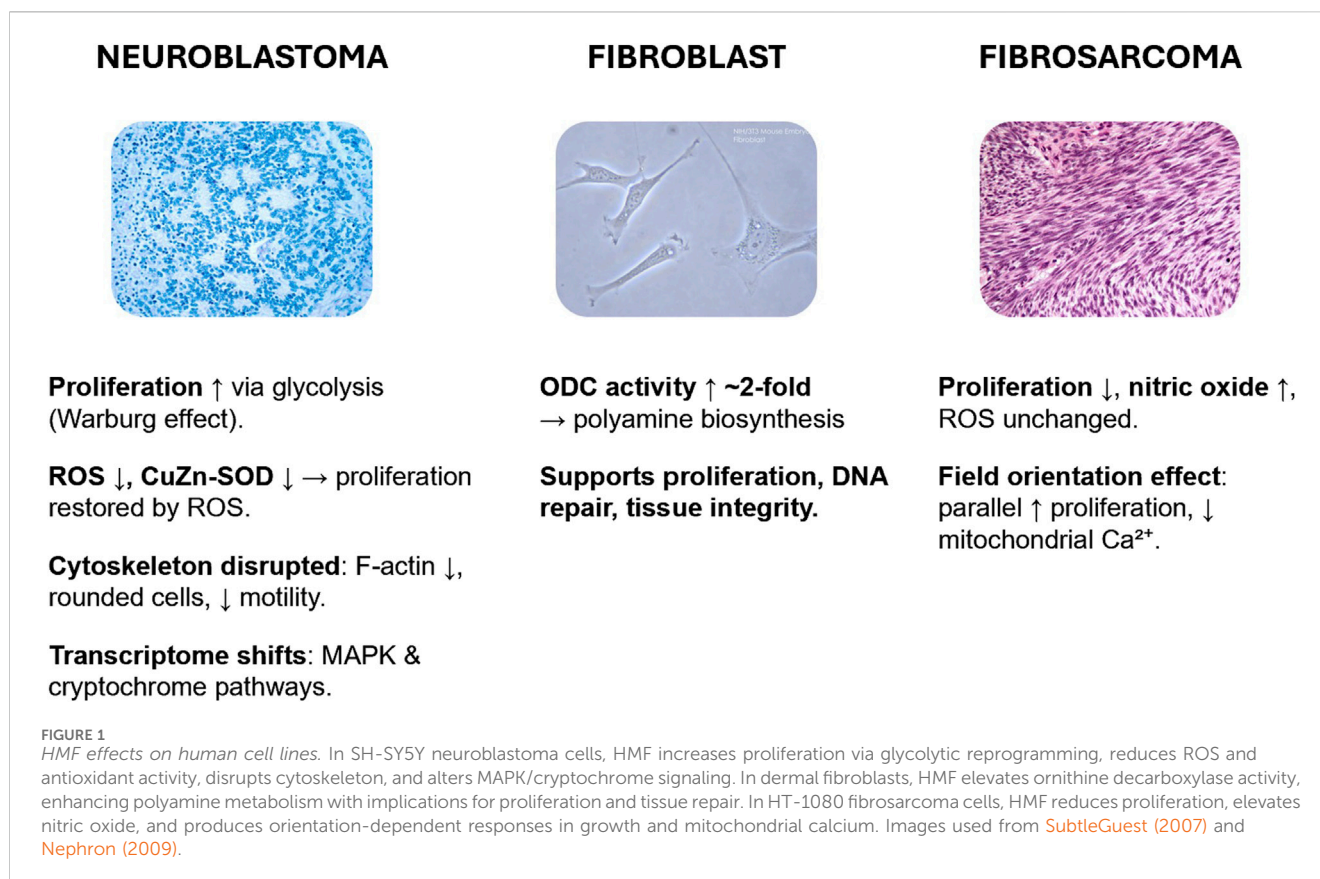
investigations primarily conducted *in vitro*. Frequently examined cell models include SH-SY5Y neuroblastoma cells for neuronal function, embryonic stem cells for developmental plasticity, fibroblasts as a model for structural and connective tissue function, and cancer-derived lines such as HT-1080 fibrosarcoma and breast cancer cells for investigating altered proliferative and metabolic states. In contrast, whole-body studies of HMF effects in humans remain scarce. Practical challenges, such as the difficulty of generating prolonged hypomagnetic environments outside of specialized facilities and the small number of human subjects available for controlled exposure, have limited the scope and statistical power of such investigations (Markin et al., 2023; Kashirina et al., 2023).

At the cellular level, HMF exposure has been shown to alter proliferation, differentiation, and other gene expression pathways, elevate and suppress oxidative stress responses, and even reorganize cytoskeletal structures (Sarimov et al., 2023; Tian et al., 2024). Importantly, these responses are not uniform across different human cell types, as summarized in Figure 1. Instead, the magnitude, direction, and sensitivity of changes appear to depend strongly on baseline cellular phenotype and metabolic state (Sarimov et al., 2023; Tian et al., 2024). This variability underscores the importance of studying multiple human-derived models in parallel, as different tissues may experience distinct vulnerabilities during prolonged exposure to reduced magnetic environments such as those encountered in deep-space missions. To better understand the cellular basis of these effects, the following sections review findings from specific human cell models, highlighting how neuronal, developmental, connective tissue, and cancer-derived lines each reveal distinct pathways of magnetic field sensitivity.

2.1 SH-SY5Y human neuroblastoma

Exposure of human neuroblastoma SH-SY5Y cells to HMF induces a range of metabolic, proliferative, structural, and transcriptomic changes that together highlight the cellular sensitivity of neuronal models to altered magnetic environments. One of the most consistent findings is an increase in cell proliferation, which has been closely associated with a metabolic shift toward anaerobic glycolysis, reminiscent of the Warburg effect. This is evidenced by elevated glucose consumption and enhanced lactate dehydrogenase (LDH) activity, with the proliferative response strongly dependent on glucose availability, suggesting that HMF-driven metabolic reprogramming is substrate-sensitive (Wang et al., 2022).

The redox state within the cell appears to be a critical mediator of HMF responses as multiple redox molecules are direct downstream byproducts of glycolysis pathways within the cell. HMF exposure reduces intracellular levels of reactive oxygen species (ROS), including hydrogen peroxide and superoxide anion, which coincides with a decrease in activity and accelerated denaturation of the key antioxidant enzyme CuZn-superoxide dismutase (CuZn-SOD). Importantly, restoring ROS levels with exogenous hydrogen peroxide reverses the proliferation-promoting effect, underscoring that altered redox balance is central to the HMF-induced phenotype (Zhang et al., 2017).



Structural changes are also evident, particularly in the cytoskeleton. HMF disrupts actin assembly, leading to reduced F-actin content, fewer cellular processes, and a more rounded morphology. These alterations diminish cell adhesion and migration, in line with transcriptional downregulation of genes linked to cytoskeletal dynamics and motility (Mo et al., 2016). Such changes may have broader implications for neuronal development, synaptic connectivity, and migration under altered geomagnetic conditions.

At the transcriptional level, large-scale transcriptome profiling has identified over 2,400 differentially expressed genes following HMF exposure. These genes cluster in pathways associated with macromolecule localization, protein transport, RNA processing, and brain function. In particular, the MAPK pathway and cryptochrome signaling have been implicated as potential early mediators of the cellular response to magnetic field depletion, linking HMF effects to core processes of neuronal signaling and circadian regulation (Mo et al., 2014).

2.2 Human dermal fibroblast

HMF exposure has been shown to modulate fundamental enzymatic activity in human fibroblasts, a non-cancerous model relevant to connective tissue function. Notably, HMF significantly increases the activity of ornithine decarboxylase (ODC), the rate-limiting enzyme in polyamine biosynthesis, producing approximately a two-fold elevation at key field strengths. ODC

plays a critical role in polyamine-mediated cell proliferation, DNA stabilization, and repair, indicating that HMF may directly influence cellular growth dynamics in non-neuronal, non-malignant human cells (Bajtoš et al., 2024).

This finding suggests that even cells typically considered quiescent or non-transformed retain sensitivity to magnetic cues at the metabolic level. Polyamine production, via ODC upregulation, could enhance fibroblast proliferation and influence wound healing or tissue integrity under reduced geomagnetic conditions. However, the underlying processes connecting HMF exposure to ODC activation remain unclear.

2.3 HT-1080 human fibrosarcoma

In the context of long-term space missions, including lunar and Martian colonization, the study of cancer cell models under HMF conditions provides important insights into how altered magnetic environments may influence disease biology. HT-1080 fibrosarcoma cells, widely used as an experimental model for connective tissue cancer, have recently been examined to assess their responses to magnetic field depletion.

Exposure to HMF has been shown to reduce cellular growth rates in HT-1080 cultures, while selectively altering redox balance. In particular, cellular nitric oxide levels increase significantly, whereas other ROS remain largely unchanged relative to cultures maintained under normal geomagnetic field conditions (Gurhan et al., 2021). These findings suggest that HMF influences signaling

pathways linked to nitric oxide metabolism more strongly than general oxidative stress.

Interestingly, the orientation of the static magnetic field relative to the cell layer exerts an additional layer of control. When field lines are aligned parallel to the culture plane, HT-1080 cells exhibit enhanced proliferation and reduced mitochondrial calcium concentrations compared to perpendicular or oblique orientations (45°) at the same field strength (Gurhan et al., 2021). This highlights not only the sensitivity of tumor cells to magnetic field intensity but also to vector orientation, pointing to anisotropic cellular responses to magnetic environments.

3 Effects of hypomagnetic fields on microorganism and microbiome

The human body is host to trillions of microorganisms and relies heavily on the microbiomes in the intestines, skin, and airways to maintain overall health. Both microgravity and HMF significantly influence microbial physiology, bacterial growth rates, motility, and metabolism which indicates the potential for bodily disfunction under such conditions (Sarimov et al., 2023; Tian et al., 2024). Therefore, it is crucial to preserve the natural function of microbiomes on human spaceflight missions to reduce antibiotic resistance, preserve microbial physiology, and maintain magnetic and structural sensing capabilities to ensure immune health in astronauts.

Research on microbiome exposure to HMF remains largely unexplored with an underwhelming body of work reported in the literature. However, microorganisms like *Pseudomonas*, *E. coli*, and *Enterobacter*, all commonly found in soil, water, and gut environments, exhibit significantly altered responses to common antibiotic medications. Depending on the specimen and medication, exposure to HMF below 500 nT, and as low as 40 nT, can either increase or decrease the minimum inhibitory concentration (MIC) of antibiotic required to prevent bacterial growth by as much as 90% (Poiata et al., 2003; Creanga et al., 2004).

Structural changes such as maximum relative viscosity in *E. coli* can also be affected by HMF, where fields at 30, 60, and 80 nT decreased viscosity by 18% while fields at 45, 70, and 95 nT increased viscosity by the same amount (Binhi et al., 2001). Magnetic sensing in magnetotactic microorganisms, such as *Magnetospirillum magneticum*, can also be affected by HMFs. These microbes have evolved unique properties allowing for sensitivity to magnetic field environments. When exposed to HMF below 500 nT, these bacteria exhibited both downregulation and upregulation of genes related to production of magnetite nanoparticles needed for production of magnetosomes which was accompanied by an overall decrease in the size of magnetosomes (Wang et al., 2008).

More recently, microbial viability and abundance was investigated on various surfaces of the China Space Station (CSS) following a low-earth orbit of about 6 months. In total, 103 types of bacteria were found on board with dominant bacteria strains such as *Pseudomonas*, *Stenotrophomonas*, *Bacillus*, and *Staphylococcus*. Three billion colony-forming units of culturable bacteria were found per 100 square centimeters with an average viability of 65%, showing that various types of microorganisms can persist for long periods of time in HMF conditions. It is important to note that just over half of the microorganisms collected from the CSS have human origins. This

provides insight into how microbiome ecosystems are generated in HMF conditions and the potential hazards associated with astronaut health in space (Zhang et al., 2025).

Microgravity and HMF environments clearly influence microbial systems but the effect of these changes within the human body remains largely unknown. Further research on HMF interactions with microbiomes is required to fully understand how to properly treat sickness, limit changes in gene expression, and maintain natural microorganism health in astronauts during deep-space missions.

4 Implications for human spaceflight and deep-space mission

4.1 Skeletal fragility and space-induced osteoporosis

Skeletal fragility has long been recognized as a central health risk for astronauts, traditionally attributed to microgravity-induced unloading of the musculoskeletal system. However, the severity of bone loss observed in spaceflight often exceeds Earth-based analogues such as disuse osteoporosis, suggesting that additional mechanisms contribute to skeletal decline (Vico et al., 2000; LeBlanc et al., 2007). Emerging evidence indicates that HMFs exacerbate microgravity-induced bone loss and impair post-mission bone recovery (Yang et al., 2018; Xue et al., 2019). Rodent models exposed to HMF conditions exhibit reduced bone mineral density, thinner trabeculae, and decreased biomechanical strength compared with controls maintained under geomagnetic fields (Yang et al., 2018; Xue et al., 2019). Mechanistic studies further suggest that HMF exposure is associated with iron overload and altered redox balance, which compromise bone microstructure and reduce resistance to mechanical stress (Yang et al., 2018; Xue et al., 2019). These findings suggest that the absence of geomagnetic cues not only accelerates skeletal degeneration in space but also undermines the potential for recovery after returning to Earth.

4.2 Neurocognitive function

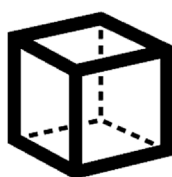
In addition to musculoskeletal health, neurocognitive function is increasingly recognized as a vulnerable target of hypomagnetic exposure. HMF conditions can impair neurogenesis and are consistently associated with elevated oxidative stress and altered circadian gene expression in neuronal and stem cell models (Blaber et al., 2015; Zhang et al., 2021; Luo et al., 2022). For astronauts, these effects are especially concerning given the intense and tightly scheduled operational demands of long-duration missions. Cognitive performance, memory retention, and rapid decision-making under stress are mission critical. Furthermore, circadian rhythm disruption, potentially exacerbated by both HMF and altered light-dark cycles in orbit, can further contribute to sleep loss and mood disturbances. Such impairments not only reduce individual performance but also compromise group cohesion and teamwork, directly affecting the execution of highly technical and cooperative tasks essential for spacecraft operations and planetary exploration.

MITIGATION STRATEGIES

MAGNETIC FIELD PROVISION

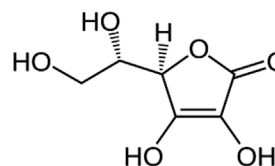


Provide **GMF** on spacecraft

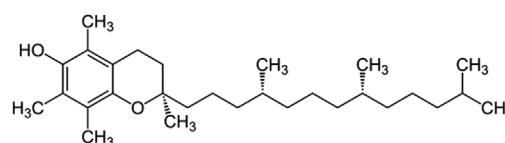


Provide **shielding and sufficient EMF background**

DIETARY & PHARMACEUTICAL



Vitamin C: antioxidant and immune system activity



Vitamin E: antioxidant

FIGURE 2

Mitigation strategies for hypomagnetic field (HMF) effects in spaceflight. Restoration of a geomagnetic-like field within spacecraft or planetary habitats offers the most direct approach but is limited by mass, power, and volume constraints, as well as the need to define minimum exposure parameters and avoid interference with instrumentation. Complementary pharmaceutical and nutritional countermeasures—such as antioxidant supplementation, dietary adjustments, or pharmacological modulation of mitochondrial and redox pathways—may help buffer oxidative stress.

4.3 Immune and metabolic systems

The immune and metabolic systems represent another axis of vulnerability to HMF conditions. Changes in microbial health, motility, and growth rates due to microgravity conditions have critical implications for infection risk in closed spacecraft environments and for the stability of bioregenerative life support systems. Increased virulence of opportunistic pathogens, together with the reactivation of latent viruses such as herpesviruses observed in astronauts, pose a heightened risk during long-duration missions (Rooney et al., 2019; Acres et al., 2021; Mehta et al., 2022). The combined stress of microgravity, radiation, and HMF may therefore synergistically weaken host defenses while enhancing microbial aggressiveness, creating a dual challenge to astronaut health and mission sustainability.

5 Mitigation strategies and future directions

5.1 Restoration of the geomagnetic field around space habitats

Among the proposed strategies, as summarized in Figure 2, the restoration or correction of a geomagnetic field within spacecraft or planetary habitats represents the most direct approach to mitigating HMF effects. In principle, artificial generation of a stable magnetic

field provides the simplest conceptual solution, re-establishing environmental cues that human biology and microbial ecosystems have evolved under.

However, the practical challenges are substantial. Any magnetic shielding or field-generation system must be designed within the strict constraints of spacecraft mass, power consumption, and volume, all of which are at a premium during launch and extended missions. Furthermore, the minimum exposure parameters necessary to achieve biological protection—field strength, spatial uniformity, daily duration of exposure, and threshold timescales—remain poorly defined. Until these parameters are empirically characterized, defining system requirements for spacecraft integration is not possible. Another consideration is the potential for artificial magnetic fields to interfere with sensitive onboard instrumentation and experiments, which places additional requirements on system tunability and shielding.

5.2 Pharmaceutical and nutritional countermeasures

With the limited mass, power, and volume available for space missions, implementation of GMF inside spacecraft and space station environments could be infeasible for specific mission profiles. In parallel with physical countermeasures to assist in mitigating HMF effects, pharmaceutical and nutritional strategies

are being considered. Antioxidant supplementation or diet modification may buffer against the oxidative stress consistently observed under HMF conditions, though their application in spaceflight conditions is largely unknown. Targeted pharmacological interventions aimed at preserving mitochondrial function or modulating redox balance may also offer protection, but their efficacy has yet to be systematically validated in space-relevant conditions. Diet-based strategies, such as increasing intake of polyphenols or vitamins C and E, are attractive due to their feasibility, but detailed studies on dose, timing, and long-term safety under altered EMF conditions are lacking. Nevertheless, the efficacy and safety of these countermeasures are largely unexplored with respect to HMF conditions present during spaceflight.

5.3 Future direction and research gaps

Despite progress, major gaps remain in our understanding of mitigation strategies. Continued interdisciplinary research across biomedical and engineering sciences is essential to develop countermeasures against HMF effects, particularly for long-duration missions to other planetary bodies. The following sections outline several key research gaps that need to be prioritized. First and most importantly, the combined influence of multiple space stressors, including microgravity, HMF, ionizing radiation, isolation and confinement effects (ICE), circadian disruption, and psychological stress—must be systematically investigated, as these factors are likely to interact nonlinearly.

Second, the long-term effects of HMF on reproduction remain almost entirely unexplored. This knowledge gap is particularly relevant for both human health and microbial disease dynamics, since altered reproductive cycles in pathogens or commensal organisms could have significant implications for infection risk.

Third, further study of the human and animal microbiome under space-relevant magnetic environments is needed to better understand how altered host-microbe interactions may compromise astronaut health. Finally, the feasibility of engineering large-scale EMF provision systems for habitats, potentially leveraging superconducting coils, modular Helmholtz configurations, or hybrid shielding systems, represents a critical engineering challenge for the future of deep-space exploration. Ultimately, advancing interdisciplinary research at the interface of biomedicine and engineering is essential to overcome these critical knowledge gaps and to engineer the resilient systems needed for humanity's enduring expansion into space.

Author contributions

ND: Conceptualization, Data curation, Project administration, Visualization, Writing – original draft, Writing – review and editing.

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JK: Data curation, Writing – original draft, Writing – review and editing. FB: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – original draft, Writing – review and editing.

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