

Beyond Physical Shielding: The Case for Biological Protection in Deep Space

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The recent Science Advances paper by Houri et al. [1] represents an important advance in space-radiation protection. Using data from the Artemis I mission, the authors provided the first in-space evaluation of wearable, organ-specific radiation protection for human deep-space exploration. Their findings demonstrate the practical potential of targeted shielding and provide valuable evidence for the development of countermeasures against solar particle events (SPEs).

Physical shielding will undoubtedly remain a cornerstone of astronaut radiation protection. Nevertheless, relying on physical protection alone may leave an important vulnerability, particularly when considering rare but extreme solar events. Shielding carries unavoidable mass and volume penalties, its effectiveness depends on particle type and energy, and practical spacecraft designs cannot eliminate exposure to all organs and tissues. Even sophisticated shelters therefore reduce, rather than abolish, radiation-induced biological damage. Our Geant4-DNA modeling of historical SPEs, for example, showed substantial reductions in DNA damage and predicted lethal damage with a multilayer shelter, but protection remained incomplete [2].

This limitation becomes particularly important when considering extreme events. Although the radiation environment of a future event cannot be inferred directly from historical solar storms such as the 1859 Carrington event, such events remind us that solar activity can occasionally reach extraordinary levels. A sufficiently intense SPE occurring during a deep-space mission could challenge even well-designed physical protection systems. In such circumstances, depending on a single protective layer would be unnecessarily risky.

The next generation of space-radiation protection should therefore not be framed as a choice between physical shielding and biological protection. A more resilient approach would integrate both within a layered, multimodal protection architecture.

The concept of biological protection for deep-space missions has been proposed previously. Sihver and Mortazavi [3] argued that physical shielding alone may be insufficient for long-duration exploration beyond low-Earth orbit and outlined complementary biological approaches, including pre-flight assessment of individual radiosensitivity and adaptive responses, support of immune function, and the development of

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radioprotective and radiation-mitigating interventions. Vitamin C and other candidate countermeasures have also been discussed, although their effectiveness and appropriate use in astronauts require rigorous validation before operational implementation.

The biological component of space-radiation protection could now be developed into a broader research framework incorporating several complementary strategies.

Pre-launch biological screening could help characterise inter-individual variation in radiosensitivity, DNA-damage responses, DNA-repair capacity, immune function and, if ultimately validated as clinically meaningful, radioadaptive responses. Such information might eventually contribute to personalised risk assessment and countermeasure selection rather than relying solely on population-average radiation-risk estimates.

Radiobiological conditioning and adaptive-response strategies warrant careful investigation. Exposure to low levels of a stressor can, under some experimental conditions, induce cellular responses that modify the effects of a subsequent challenge. The possible relevance of such adaptive responses to medicine and space exploration has recently been reviewed [4]. However, deliberate induction of radioadaptation in astronauts remains experimental and should not be considered an operational countermeasure until its reproducibility, magnitude, duration and safety have been established.

Radioprotectors and radiation mitigators offer another potentially important layer. Radioprotectors are administered before exposure to reduce radiation-induced injury, whereas mitigators are administered during or after exposure to limit the progression or severity of injury. This distinction is operationally important in deep space: major SPEs may not always provide sufficient warning for optimal pre-exposure intervention, making effective post-exposure mitigation particularly valuable. Considerable research on these agents already exists in terrestrial radiation medicine [5], but translation to spaceflight will require attention to toxicity, stability, dosing, altered pharmacokinetics in microgravity and interactions with other spaceflight stressors.

Immune and haematopoietic countermeasures may be similarly important. Spaceflight itself can alter immune regulation, and immune dysfunction has long been recognised as a potential concern for exploration-class missions [6]. More recent experimental work using hindlimb unloading has also demonstrated changes in immune-cell populations under simulated microgravity [7]. Radiation, microgravity, isolation, altered circadian rhythms and other stressors do not act independently in an astronaut. Countermeasures should therefore increasingly be evaluated against the combined spaceflight environment rather than against radiation alone.

Microbiome-directed strategies represent another emerging possibility. The human microbiome is itself exposed to the unusual combination of radiation, microgravity, confinement and altered environmental conditions encountered during spaceflight. Changes in microbial composition, function, virulence and antimicrobial resistance could influence astronaut health during prolonged missions. We have previously proposed that adaptation of the human and spacecraft microbiomes may therefore contribute to the success or failure of long-duration exploration [8]. This remains an emerging field, but it illustrates why biological protection should extend beyond the radiation response of human cells alone.

Synthetic torpor and metabolic modulation are more speculative but potentially transformative approaches. If safe, reversible metabolic suppression can eventually be achieved in humans, it may alter several physiological processes relevant to deep-space travel. Whether such states can meaningfully modify radiation sensitivity or improve survival during extreme exposure remains uncertain and requires dedicated experimental investigation. At present, torpor should therefore be regarded as a research direction rather than an established radioprotective strategy.

Importantly, none of these approaches should be viewed as a substitute for physical shielding. Biological countermeasures are attractive precisely because they could provide additional layers of defence when engineering controls reach their practical limits.

Our recent work on physical protection illustrates the same principle from the engineering side. Monte Carlo simulations show that not only the amount but also the arrangement of shielding materials can influence protection against SPE radiation [9]. Experimental and computational studies of lithium- and cadmium-containing polymer composites have likewise demonstrated the potential for developing multifunctional materials capable of attenuating secondary neutrons while retaining useful mechanical properties [10]. Together with the Artemis I results [1], these findings show that considerable scope remains for improving physical protection.

Yet engineering optimisation alone cannot capture the full biological complexity of the astronaut. Responses to radiation occur within organisms simultaneously adapting to microgravity, altered immune function, disrupted circadian rhythms, confinement, nutritional changes and other environmental stressors. The protection problem is therefore fundamentally multidisciplinary.

The central question should consequently not be: Is physical protection or biological protection better? Rather, it should be: How much additional protection can be achieved by intelligently combining them?

For routine exposure, optimised physical shielding and operational dose management will remain the primary defence. During a severe SPE, astronauts could additionally move to a dedicated storm shelter and use wearable protection for radiosensitive organs. But in an exceptionally intense event, biological and pharmacological countermeasures could provide an additional margin of safety when residual exposure remains unavoidable.

A comprehensive protection architecture for deep-space exploration might therefore be conceptualised as:

Physical shielding + biological protection + pharmacological countermeasures + physiological adaptation + operational preparedness

A further layer may eventually come from active electromagnetic shielding. Electric and magnetic fields have long been investigated as potential methods for deflecting charged particles before they reach a spacecraft or habitat [11]. Unlike passive shielding, active systems could in principle reduce charged-particle exposure without an equivalent increase in bulk shielding mass. However, practical implementation faces substantial engineering challenges, including field strength and geometry, system mass, power and cryogenic requirements, reliability, and the complex energy and charge spectrum of space radiation [11]. Active shielding should therefore be regarded as a promising complementary technology requiring substantial further development rather than as a near-term replacement for passive shielding.

The Artemis I findings demonstrate how far targeted physical protection has progressed [1]. The logical next step is to build outward from that success. Future spacecraft should not rely on a single barrier between astronauts and the space-radiation environment. Instead, physical shielding, active technologies, biological resilience, pharmacological countermeasures and operational procedures should be developed as interacting components of the same protection system.

In deep space, redundancy is not merely an engineering principle; it should also be a radio-biological one. The spacecraft must protect the astronaut from radiation, but when physical protection reaches its limits, the astronaut's biology may need to provide another line of defence.

Authors' Contribution

SMJ. Mortazavi and JS. Welsh conceived the original idea and drafted the Editorial. JJ.

Bevelacqua managed the literature review process to support the work. All authors critically reviewed the manuscript and approved the final version for publication.

Conflict of Interest

SMJ. Mortazavi and JS. Welsh, as the Editorial Board Members, were not involved in the peer-review and decision-making processes for this manuscript.

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