

HEALTH PHYSICS IMPLICATIONS OF SPACE RADIATION FOR ASTRONAUTS

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ABSTRACT

Space radiation poses significant health risks to astronauts, including DNA damage, neurodegeneration, cardiovascular effects, and increased cancer risk. This review consolidates current knowledge on space radiation exposure, shielding technologies, and dosimetry techniques. The systematic review followed PRISMA guidelines, analysing 75 studies from Google Scholar, PubMed, and ScienceDirect. The findings highlight that galactic cosmic ray (GCRs), solar particle events (SPEs) and Van Allen Belt Radiation cause complex biological damage, requiring advanced mitigation strategies. Traditional aluminium shielding is inefficient against high-energy cosmic radiation, prompting research into hydrogen-rich polymers, nanomaterials such as boron nitride nanotubes, and in-situ resource utilization (ISRU) using regolith. Active shielding, such as magnetic and electrostatic barriers, remains experimental. Dosimetry advancements, including silicon-based detectors, Timepix pixel technology, Tissue-Equivalent Proportional Counters and AI-driven predictive models, improve radiation monitoring and risk assessment. Despite progress, challenges persist, including uncertainties in biological responses, optimizing shielding solutions, and real-time radiation exposure prediction. Future research should explore personalized medicine for radiation resilience, hybrid shielding approaches, and AI-integrated radiation risk modelling. Ensuring astronaut safety in deep-space missions requires interdisciplinary collaboration in health physics, space medicine, and engineering to develop robust radiation protection strategies.

KEYWORDS: Space radiation, shielding technologies, dosimetry, astronaut health, deep-space missions.

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1. INTRODUCTION

Space exploration exposes astronauts to a complicated radiation environment that presents significant health risks. In contrast to Earth, where the atmosphere and magnetic field offer protection, astronauts face high-energy ionizing radiation from galactic cosmic rays (GCRs), solar particle events (SPEs), and trapped radiation in Earth's Van Allen Belts (Nelson, 2016). Prolonged exposure elevates the risk of cancer, neurodegenerative disorders, cardiovascular diseases, and acute radiation syndrome (ARS) (Donnelly *et al.*, 2010). As space agencies and private companies plan prolonged missions to the Moon, Mars, and beyond, mitigating these risks is critical.

Health physics is essential in securing astronaut safety by studying radiation exposure, developing shielding technologies, and enhancing dosimetry techniques (Ghimire and Waller, 2025). Long-duration missions require advanced protection strategies, including innovative materials, real-time dosimetry, and biological countermeasures. Optimized shielding systems and accurate radiation monitoring are more urgent than ever, as future missions will necessitate extended stays on planetary surfaces with limited natural protection.

This systematic review consolidates current research on space radiation physics, its biological effects, and emerging protection strategies. It explores areas such as current radiation shielding methods, dosimetry techniques, and gaps in space radiation protection research. By synthesizing progressive advancements, this review offers valuable insights into improving radiation safety for future human space exploration.

2. METHODOLOGY

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure a rigorous and transparent research process as shown in figure 1. The methodology included a structured approach to identifying, screening, and synthesizing relevant literature on space radiation exposure, astronaut health risks, and mitigation strategies, a comprehensive and unbiased assessment, focusing on shielding materials, dosimetry techniques, and

biological countermeasures for long-duration space missions.

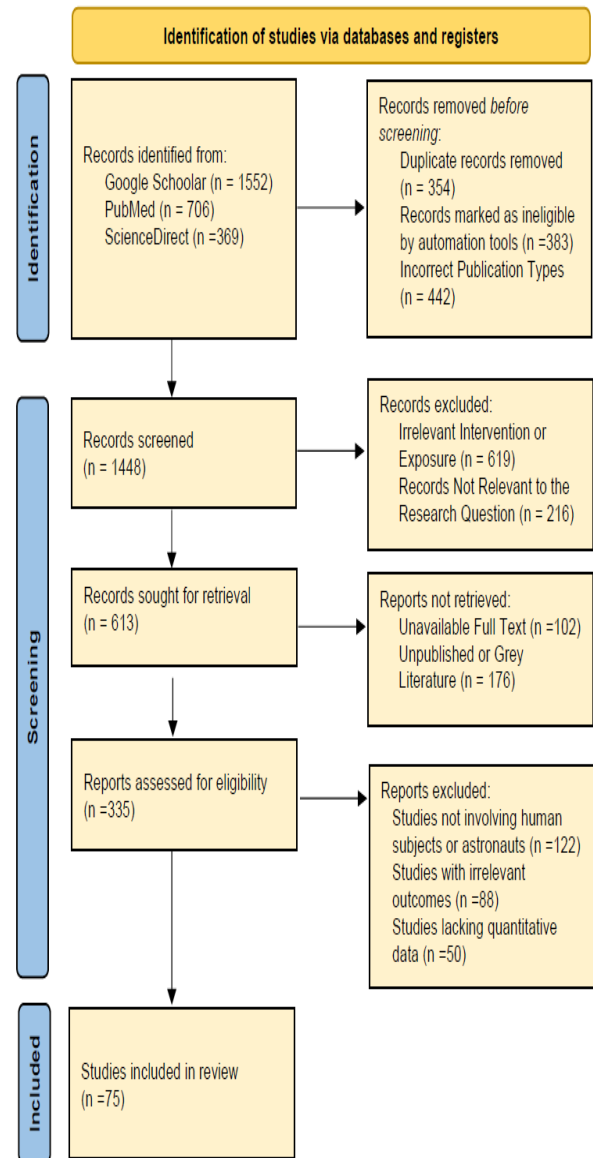


Figure 1: PRISMA Flow Chart. Figure represent the article selection and screening proces for the current review.

2.1 Search Strategy

A comprehensive search was performed across multiple scientific databases, Google Scholar (n = 1552), PubMed (n = 706), and ScienceDirect (n = 369). Key search terms included “space radiation exposure,” “galactic cosmic rays (GCRs),” “solar

particle events (SPEs),” and “radiation shielding for astronauts,” among others. Boolean operators refined results to balance specificity and comprehensiveness.

Selection Process Duplicates (n = 354), ineligible records (n = 383) and (n = 442) incorrect types were removed. Screening of 1448 records excluded 619 for irrelevant interventions and 216 for unrelated research questions.

Eligibility Assessment: From 613 records sought, 102 were unavailable, and 176 were grey literature. Full-text review (n = 335) excluded 122 non-human studies, 88 irrelevant outcomes, and 50 lacking quantitative data.

Final Inclusion: A total of 75 studies met the criteria, offering insights into space radiation risks, shielding, and dosimetry strategies

2.2 Inclusion and Exclusion Criteria

Inclusion criteria focused on studies related to space radiation physics (GCRs, SPEs, and trapped radiation), radiation shielding materials, dosimetry techniques, and biological effects of space radiation on human health. Research on long-duration missions, such as Artemis and Mars programmes, was prioritized. Exclusion criteria removed studies on terrestrial radiation, non-English papers without reliable translations, and non-human biological models lacking astronaut relevance.

2.3 Data Extraction and Synthesis

Data were extracted using a structured framework, categorizing information into space radiation environment, health physics, shielding strategies, dosimetry techniques, and future research gaps. A narrative synthesis approach compared findings, highlighting advancements and unresolved challenges in space radiation protection.

2.4 Quality Assessment and Bias Control

The methodological quality of studies was assessed using PRISMA guidelines, evaluating design, reliability, sample size, relevance, and potential conflicts of interest. Discrepancies in study inclusion or interpretation were resolved through consensus discussions among reviewers to ensure objectivity.

2.5 Limitations of the Study

This review has limitations, including the potential unavailability of classified data and the evolving nature of space radiation research. New breakthroughs may emerge after the review period. Additionally, publication bias could skew results, as studies with positive findings are more often published.

By adhering to this methodology, the review provides a comprehensive, evidence-based assessment of space radiation protection strategies, aiming to advance astronaut safety for future deep-space missions.

3. RESULTS

3.1 Space Radiation Environment & Its Health Effects

3.1.1 Types of Space Radiation

Astronauts on enduring space missions are exposed to complex radiation environments consisting of high-energy charged particles originating from various sources. The primary contributors to space radiation include Galactic Cosmic Rays (GCRs), Solar Particle Events (SPEs), and Van Allen Belt Radiation, each posing unique challenges for radiation protection and health physics as illustrated in figure 2 (Nelson, 2016).

3.1.1.1 Galactic Cosmic Rays (GCRs)

GCRs are high-energy particles from supernova explosions and other cosmic events, mainly protons (~87%), helium nuclei (~12%), and heavier ions (~1%) such as iron and oxygen (Luo *et al.*, 2025). Their high energy and atomic number allow deep penetration into spacecraft and human tissue, causing severe cellular and DNA damage (Naik *et al.*, 2024).

The Radiation Assessment Detector (RAD) on the Curiosity Rover recorded high GCR fluxes due to the declining solar activity and the weakening heliosphere magnetic field, highlighting the necessity for effective shielding (Guo *et al.*, 2021). Accelerator-based studies at NASA’s Space Radiation Laboratory (NSRL) show HZE particle exposure elevates risks of cancer and neurodegeneration (Simonsen *et al.*, 2020).

3.1.1.2 Solar Particle Events (SPEs)

SPEs occur when the Sun ejects energetic protons and heavy ions after solar flares or coronal mass ejections (CMEs), reaching Earth or space within hours (Howard, 2011). Different from the constant GCR background, SPEs are sporadic and can cause acute radiation exposure without proper shielding.

The August 1972 SPE, occurring between Apollo 16 and 17, could have delivered lethal doses (>4 Sv) to lunar astronauts (Wilson *et al.*, 1997). SPE radiation mainly affects the skin and blood-forming organs, increasing ARS risk. Mission planning and real-time solar monitoring are vital for risk mitigation (Huff and Kim, 2009).

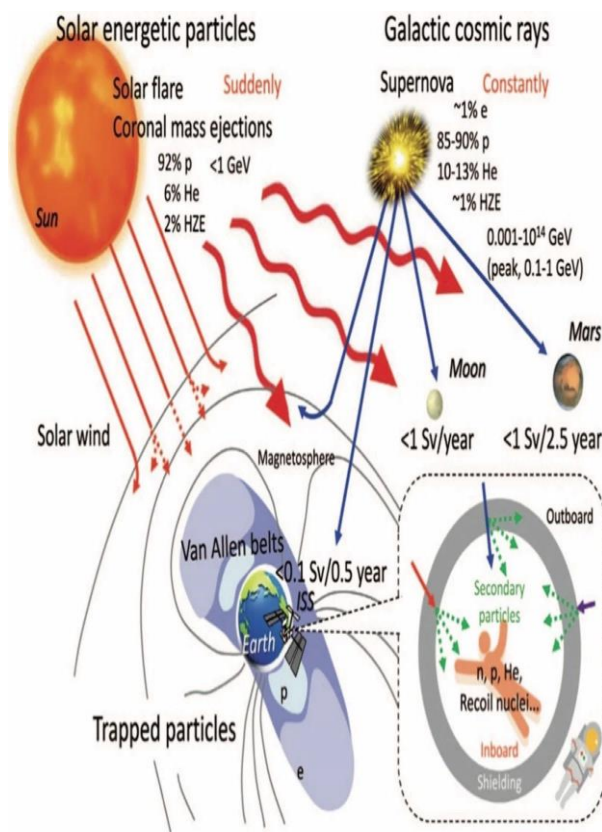


Figure 2: Elements of the space radiation environment (Ask and Newhauser, 2021)

3.1.1.3 Van Allen Belt Radiation

The Van Allen belts, composed of trapped electrons and protons, pose a radiation risk during launch, re-entry, and low Earth orbit (LEO) travel (Li and

Hudson, 2019). The International Space Station (ISS) operates within the South Atlantic Anomaly (SAA), where the inner belt dips closer to Earth, increasing electron exposure (Dachev, 2018).

While exposure is lower than in deep space, prolonged LEO missions lead to cumulative radiation doses. Apollo mission data showed higher doses when crossing the belts, but short exposure minimized health effects (Valinia *et al.*, 2022).

3.2 Biological Effects on Astronauts

Space radiation effects contingent on type, dose, and duration, causing acute and chronic health risks. HZE particles pose significant hazards to astronauts.

3.2.1 Acute vs. Chronic Effects

Acute effects primarily result from high-dose exposure, such as those caused by SPEs. Symptoms of acute radiation syndrome (ARS) comprise nausea, vomiting, fatigue, loss of appetite, skin erythema (radiation burns), hematopoietic suppression (reduced white blood cells, platelets), increased susceptibility to infections, impaired wound healing, temporary cognitive impairment, possible cardiovascular instability, potentially impairing mission performance (Donnelly *et al.*, 2010).

Long-duration space missions pose significant concerns due to chronic radiation exposure, which accumulates over months or years. Chronic exposure has been associated with increased risks of carcinogenesis, including solid tumors and leukemia due to hematopoietic stem cell damage (Dainiak, 2002). Cardiovascular effects, such as endothelial dysfunction, atherosclerosis, myocardial fibrosis, and increased stroke risk, have also been reported (Basavaraju and Easterly, 2002). Neurological consequences include cognitive deficits, memory loss, impaired decision-making, neurodegeneration, and mood disorders (Zablotska *et al.*, 2023). Additionally, chronic radiation exposure is linked to immune system dysregulation, characterized by persistent inflammation and a weakened response to infections (Cassatt, Winters and PrabhuDas, 2023). Ocular effects, such as cataract formation and retinal degeneration, have been documented (Uwineza *et al.*,

2019), alongside gastrointestinal complications, including chronic mucosal damage and an elevated risk of gastrointestinal cancers (ROSWIT, MALSKY and REID, 1972). Musculoskeletal deterioration, manifesting as bone density loss and muscle atrophy, is another critical concern (Willey *et al.*, 2011). In contrast to terrestrial radiation, space radiation exhibits high linear energy transfer (LET) characteristics, leading to complex and often irreparable biological damage.

3.2.2 DNA Damage and Cancer Risk

Space radiation, particularly HZE particles, induces DNA double-strand breaks (DSBs), chromosomal aberrations, and genomic instability, all of which contribute to increased cancer risk (Moreno-Villanueva *et al.*, 2017). Unlike X-rays or gamma rays, which cause localized damage, HZE particles create dense ionization tracks, leading to clustered DNA damage, which is difficult for cellular repair mechanisms to correct (Asaithamby and Chen, 2011).

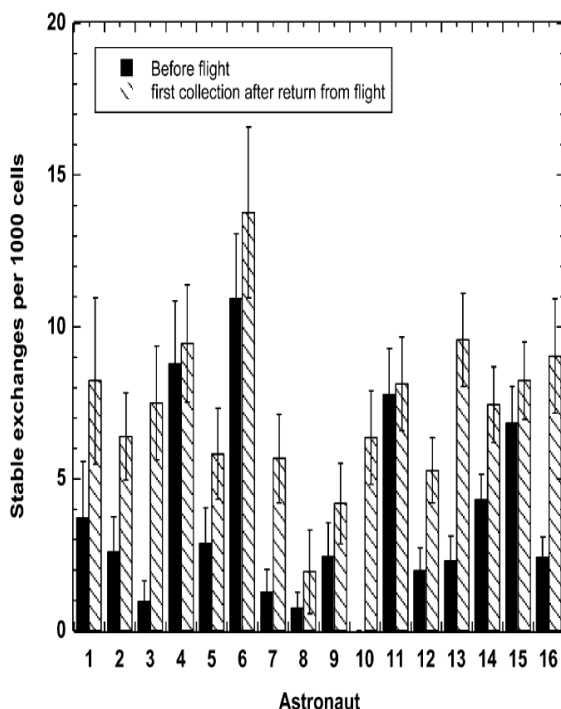


Figure 3: The yield of stable exchanges in astronauts' blood lymphocytes before and after their long-duration missions. Astronauts are numbered 1–16, with exchange values representing

whole genome equivalent yields per 1,000 cells (George, Chappell and Cucinotta, 2010).

Following lengthy ISS missions (95–215 days), Figure 3 displays increased stable chromosomal exchanges, primarily reciprocal translocations, in the blood lymphocytes of 16 astronauts. There is significant inter-individual variability in both pre- and post-mission values (George, Chappell and Cucinotta, 2010). This variation most likely results from operational, physiological, and genetic variations. Individual susceptibility to radiation-induced genomic damage may be influenced by a number of factors, including age, previous radiation exposure, antioxidant capacity, and polymorphisms in DNA repair genes (such as ATM, XRCC1, TP53, and RAD51) (Hornhardt *et al.*, 2014). Mission-specific exposure, lifestyle, and immunological status may also influence these results. Although sample sizes are still small, NASA's Longitudinal Study of Astronaut Health (LSAH) supports this by reporting a higher incidence of leukemia and solid tumors among astronauts with higher radiation exposure (Strigari *et al.*, 2021).

3.2.3 Neurological Impacts (Cognitive Deficits)

HZE particles present a distinct threat to the central nervous system (CNS), contributing to the broader risks that space radiation poses to astronaut health. Male mice exposed to low doses (≤ 30 cGy) of helium ions (^4He) showed higher neuroinflammation, cognitive deficits, and elevated expression of inflammatory markers (TLR4 and HMGB1). In contrast, female mice displayed changes in dendritic structure but did not experience the same decline in dendritic spine density as males. These findings suggest sex-specific differences in CNS responses to space radiation, potentially influencing astronaut health risk assessments (Parihar *et al.*, 2020). Individuals with polymorphisms in genes related to oxidative stress responses (e.g., SOD2, GPX1), neuroinflammation (e.g., IL-6, TNF- α), or DNA repair (e.g., PARP1, XRCC1) may exhibit enhanced vulnerability to space radiation (Vogrinic *et al.*, 2023). Additionally, chronic low-grade inflammation or pre-existing neurodegenerative predispositions (such as APOE $\epsilon 4$ genotype linked to Alzheimer's risk) could

amplify the neurological consequences of cosmic radiation exposure (Di Battista, Heinsinger and Rebeck, 2016).



Figure 4: Temporary sleep station on the ISS with polyethylene panels and water storage above for enhanced radiation shielding (National Aeronautics and Space Administration (NASA), 2003).

3.3 Radiation Shielding Strategies for Long-Duration Missions

Protecting astronauts from space radiation is a fundamental challenge for long-duration missions, such as those planned for Mars exploration. Spacecraft shielding must balance radiation protection effectiveness, material feasibility, weight constraints, and integration into mission design. This section reviews both traditional shielding approaches and emerging technologies, including polyethylene composites, multifunctional nanomaterials, in-situ resource utilization (ISRU)-based materials, and active shielding systems.

3.3.1 Traditional Shielding Approaches - Aluminum and Conventional Spacecraft Materials

Historically, aluminum (Al) has been the primary shielding material for crewed spacecraft due to its

mechanical strength, structural integrity, and availability in aerospace applications. Aluminum effectively attenuates solar particle events (SPEs) and lower-energy space radiation; however, it is less effective against Galactic Cosmic Rays (GCRs) and high-energy heavy ions (Finckenor, 2018).

One major limitation of aluminum is secondary radiation production. When high-energy particles, such as iron ions from GCRs, collide with aluminum, they generate secondary neutrons and other fragmentation products, which can be more biologically damaging than the primary radiation (Cucinotta, Kim and Chappell, 2012).

To address these challenges, NASA has explored alternative materials with superior shielding properties, particularly those rich in hydrogen, which is more effective in reducing linear energy transfer (LET) and secondary radiation production.

3.3.2 Innovative & Advanced Shielding Technologies

3.3.2.1 Polyethylene and Hydrogen-Rich Materials

Hydrogen-rich materials, such as polyethylene (PE) and water, provide superior protection against GCRs and secondary radiation due to their higher hydrogen content (KAUL, BARGHOUTY and DAHCHE, 2004). Polyethylene, a lightweight polymer composed of carbon and hydrogen, has been studied as an alternative to aluminum. The Radiation Shielding Experiment (RSX) on the ISS demonstrated that polyethylene is approximately 30% more effective than aluminum in absorbing radiation from HZE particles is shown in figure 4. However, the shielding effectiveness follows the law of diminishing returns, with additional thickness providing progressively less protection (National Aeronautics and Space Administration (NASA), 2003).

3.3.2.2 Multifunctional Nanomaterials

Recent advancements in nanotechnology have led to the development of multifunctional shielding materials, which integrate radiation protection, structural integrity, and lightweight design.

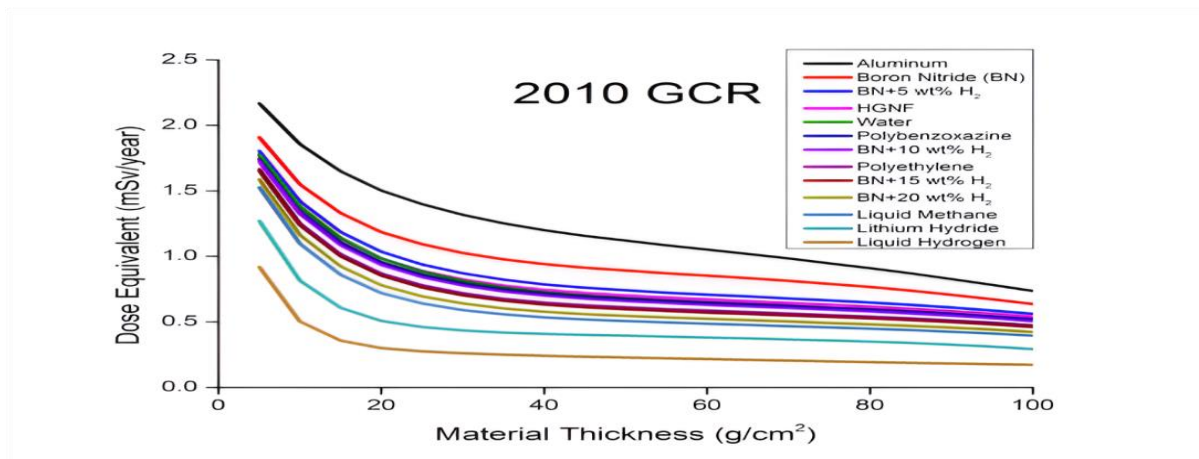


Figure 5: Annual dose equivalent for various shielding materials of different thicknesses against Galactic Cosmic Rays (GCR) during the 2010 solar minimum. (Gohel, Makwana and Soni, 2022)

Boron nitride nanotubes (BNNTs) enhance polymer composites for space radiation protection, but structural vacancies can weaken mechanical properties. Hydrogen can bind to these vacancies, improving shielding but potentially degrading durability (Darwish *et al.*, 2019). Using density functional theory, Darwish *et al.* analyzed how divacancies affect the mechanical properties of double-walled BNNTs (DWBNTs). Results show armchair DWBNTs lose 5–25% stiffness, while zigzag ones lose 3–15%, with structural deformations varying by configuration. These findings help assess DWBNTs' resilience in space radiation environments.

While polyethylene offers effective shielding against high-energy particles, its poor mechanical properties restrict its structural use. Enhancing it with carbon nanotubes or graphene improves its overall performance, but their effect on radiation shielding remains unclear. Using NASA's HZETRN2015 code, (Laurenzi, Zanet and Santonicola, 2020) evaluated polyethylene-based nanocomposites with single-walled carbon nanotubes (SWCNTs) and graphene oxide (GO) at varying loadings in different space radiation environments. Comparisons with boron carbide-filled composites show that GO nanoplatelets provide the best reinforcement, maintaining shielding properties comparable to pure polyethylene at low filler concentrations (1–5 wt%).

The study by (Gohel, Makwana and Soni, 2022) evaluates shielding materials using OLTARIS and HZETRN for 2010 Solar minimum GCR is shown in figure 5. Materials tested include aluminum, polyethylene, polybenzoxazine, lithium hydride, liquid hydrogen, liquid methane, hydrogenated graphite nanofibers (HGNF), and boron nitride storing hydrogen. Results show liquid hydrogen provides the best shielding, followed by lithium hydride, liquid methane, boron nitride, polyethylene, polybenzoxazine, HGNF, and aluminum. Dose equivalents for liquid hydrogen and polyethylene at varying densities were also analyzed.

3.3.2.3 Water and Regolith-Based Shielding (In-Situ Resource Utilization - ISRU)

Using locally available resources, such as water and planetary regolith (lunar or Martian soil), for radiation shielding is a promising strategy for deep-space missions.

Water, due to its high hydrogen content, is an effective GCR shield. NASA has proposed dual-use water storage tanks around crew compartments to serve as both life support and radiation protection (Cohen and Flynn, 2012).

As shown in figure 6, using Martian regolith for habitat shielding is a cost-effective alternative to transporting materials from Earth. Simulations

indicate that a 5-meter-thick regolith layer could reduce GCR exposure by ~50%, providing long-term radiation protection for Mars surface missions (Al Zaman and Kunja, 2023).

Regolith shielding was tested during NASA's Lava Tube Analog Missions, which demonstrated that natural geological formations could reduce radiation exposure significantly. The ESA's Moon Village concept also proposes underground shelters using 3D-printed regolith structures (Labeaga-Martínez *et al.*, 2017).

3.3.2.4 Active Shielding Concepts (Magnetic/Electrostatic Shields)

In contrast to passive shielding, active shielding aims to deflect or trap radiation using electromagnetic fields. Magnetic Shields are inspired by Earth's magnetic field, NASA has studied superconducting magnetosphere concepts, where strong magnetic fields would deflect incoming charged particles away from the spacecraft (Ferrone *et al.*, 2023). Electrostatic Shields are positively charged electrostatic barriers have been proposed to repel high-energy protons from solar radiation. While theoretical models suggest feasibility, practical implementation remains challenging due to power requirements and spacecraft integration constraints (Tripathi, 2016). Despite their potential, active shielding systems remain in the experimental phase, requiring further technological advancements.

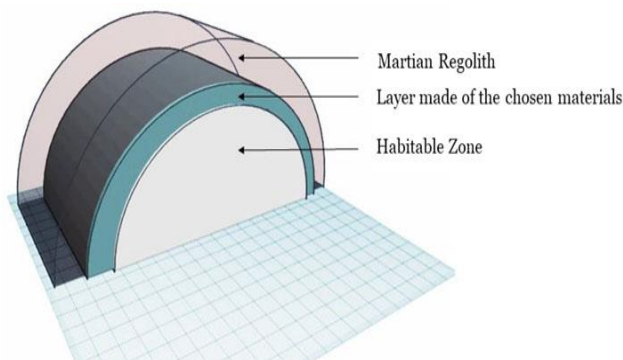


Figure 6: Schematic of a habitation module with radiation shielding for Mars (Al Zaman and Kunja, 2023).

3.4 Comparative Analysis of Shielding Methods

Table 1 illustrates a comparative evaluation of shielding technologies, considering key factors such as effectiveness, feasibility, weight, and integration into mission architecture.

Table 1: Comparative Assessment of Shielding Technologies

Shielding Method	Effectiveness (GCR/SPE)	Weight Considerations	Feasibility for Mars Missions
Aluminum (Traditional)	Moderate (SPE), Low (GCR)	Heavy	Limited for long-duration missions
Polyethylene (PE)	High (GCR & SPE)	Lighter than Al	Strong candidate for spacecraft walls
Nanomaterials (BNNT, Graphene)	High (GCR & Secondary)	Lightweight	Under research, promising for future
Water Shielding	High (GCR & SPE)	Dual-use, heavy storage	Feasible with water recycling systems
Regolith-Based (ISRU)	High (Surface Habitat)	Requires excavation	Practical for Mars/Lunar bases
Magnetic Shielding	Theoretical High (GCR)	High power requirement	Requires further research & testing

Each shielding strategy presents unique trade-offs, and future missions may employ hybrid approaches combining passive and active shielding.

3.4. Dosimetry Techniques for Space Radiation Monitoring

Effective radiation monitoring is essential for astronaut safety during deep-space missions. Space radiation exposure varies based on solar activity, mission duration, spacecraft shielding, and extravehicular activities (EVAs). Advanced dosimetry techniques are required to assess radiation doses accurately and implement real-time exposure countermeasures. This section explores passive dosimeters, active dosimetry systems, real-time monitoring technologies, and associated challenges in space dosimetry.

3.4.1 Passive Dosimeters

3.4.1.1 Thermoluminescent Dosimeters (TLDs)

Thermoluminescent dosimeters (TLDs) are commonly used in space missions for long-term dose recording. TLDs contain materials such as lithium fluoride (LiF) or calcium fluoride (CaF₂), which store radiation-induced energy (McKeever (INVITED), 1986). TLDs, commonly used in space radiation dosimetry, measure absorbed doses from ionizing radiation by trapping electrons in materials such as LiF, CaSO₄, and Al₂O₃ (Moscovitch and Horowitz, 2006; Del Sol Fernández *et al.*, 2016). Upon heating, trapped energy is released as light, proportional to the dose. They lack real-time exposure data and underestimate high-LET radiation due to trap saturation. Calibration with known doses is required (Horowitz *et al.*, 2017). Data from spacecraft show dose rates increasing with altitude, e.g., 0.3 mGy/day on the ISS and higher in the South Atlantic Anomaly due to trapped protons. TLDs have been extensively used in past missions, including Skylab, Mir, the International Space Station (ISS), and Apollo missions (Benton, 2012).

3.4.1.2 Optically Stimulated Luminescence (OSL) Dosimeters

Optically stimulated luminescence (OSL) is widely used for dating archaeological and geological materials by measuring radiation doses absorbed by minerals such as quartz and feldspar (McKeever, 2001). The method involves stimulating trapped electrons with light and measuring the emitted

luminescence to determine the absorbed dose. OSL is calibrated using known radiation doses and helps estimate sample age.

Despite early research into OSL for personal dosimetry, its adoption remains limited due to challenges in finding suitable luminescent materials. Various phosphors, including MgS, CaS, and BeO, have been tested, but issues such as signal fading and photon energy dependence hinder widespread use. Innovations like pulsed OSL (POSL) using Al₂O₃:C improve sensitivity and allow multiple readings without signal loss. OSL offers advantages over thermoluminescence (TL), including all-optical readout, high sensitivity, rapid processing, and potential use in plastic-based dosimeters (McKeever, 2003). OSL dosimeters were deployed on the ISS Radiation Assessment Detector (RAD), confirming their reliability for space radiation monitoring (Gaza *et al.*, 2017).

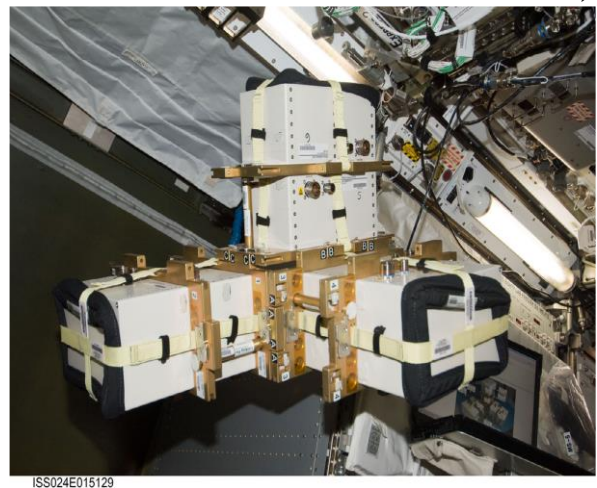


Figure 7: ALTEA in the USLab in the XYZ configuration (Narici *et al.*, 2015)

3.4.2 Active Dosimetry Systems

3.4.2.1 Silicon-Based Detectors

Silicon-based radiation detectors are widely used in active space dosimetry due to their ability to convert ionizing radiation into electrical signals for real-time monitoring. These detectors have been integrated into NASA's Radiation Assessment Detector (RAD) on the Mars Science Laboratory and ESA's ALTEA (Anomalous Long-Term Effects in Astronauts)

experiment on the ISS as shown in Figure 7 (Narici *et*

al., 2015). One key limitation of silicon detectors is

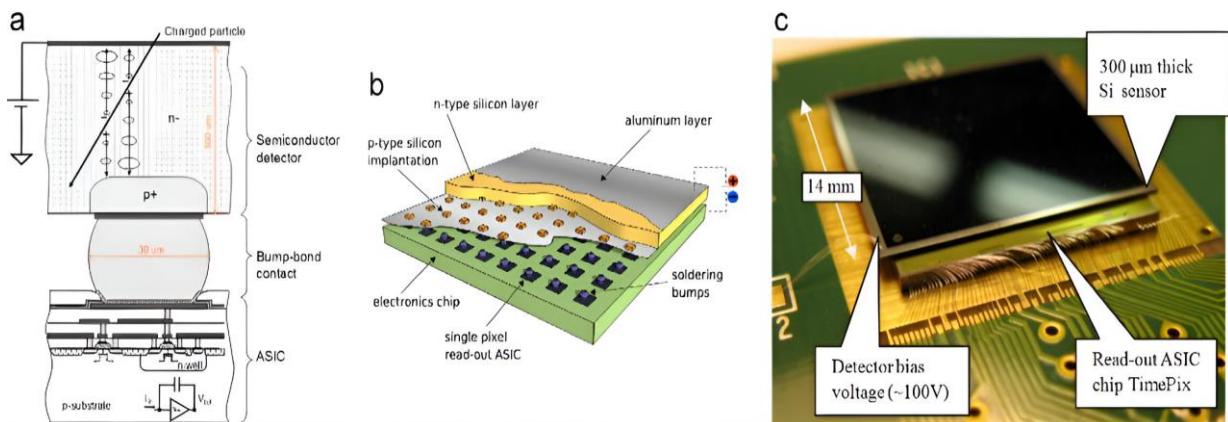


Figure 8: Illustration at the pixel scale: (a) Hybrid semiconductor pixel detector Timepix (b) 300 mm silicon sensor (14mm × 14mm), bump-bonded to a 256 × 256 pixel ASIC Timepix readout chip (65,536 channels) (c) Integrated per-pixel electronics enable fast, dark-current-free single-particle detection (Granja and Pospisil, 2014).

their higher sensitivity to secondary radiation and fragmentation effects, which can lead to dose measurement uncertainties (Hassler *et al.*, 2012).

3.4.2.2 Timepix Detectors

Timepix is an advanced hybrid pixel detector used in space dosimetry. Developed by CERN, it provides high-resolution particle tracking and energy deposition measurements shown in figure 8. Timepix has been successfully tested on the Space Application of Timepix based Radiation Monitor (SATRAM) is a spacecraft platform radiation monitor on board the Proba-V satellite launched in an 820 km altitude low Earth orbit in 2013 to monitor cumulative dose rate along the satellite orbit (Granja *et al.*, 2016). Advantages of Timepix include, real-time monitoring capabilities, particle type identification (protons, heavy ions, secondary electrons), compact size, making it suitable for astronaut personal dosimetry (Granja and Pospisil, 2014).

3.4.2.3 Tissue-Equivalent Proportional Counters (TEPCs)

TEPCs are designed to mimic human tissue response to space radiation, allowing for accurate estimation of biological dose equivalents (Ali, 2014). These dosimeters use gas-filled detectors that simulate human tissue and measure linear energy transfer

(LET), providing direct insight into radiation risk. TEPCs were part of NASA's Radiation Environment Monitor (REM) system used on the ISS (Zeitlin and Johnson, 2020) as shown in figure 9. While highly accurate, TEPCs suffer from complex calibration requirements and high-power consumption, limiting their widespread use in future missions (Bilski *et al.*, 2006).

3.4.3 Real-Time Monitoring Systems

3.4.3.1 Personal Wearable Dosimeters

To enhance astronaut safety, wearable dosimetry has gained significant attention. The Crew Passive Dosimeter (CPD) system, used on the ISS, employs small, lightweight detectors worn on astronaut uniforms for continuous monitoring (Benton and Benton, 2001).

NASA and ESA have been developing flexible dosimeter patches embedded into astronaut spacesuits and clothing. These systems incorporate radiation-sensitive polymer films that provide continuous exposure tracking and wireless data transmission to spacecraft monitoring systems (Date *et al.*, 2021).

3.4.3.2 AI-Based Predictive Modeling for Exposure Assessment

Artificial Intelligence (AI) is increasingly integrated into radiation exposure modelling, with AI-driven

dosimetry using machine learning algorithms trained

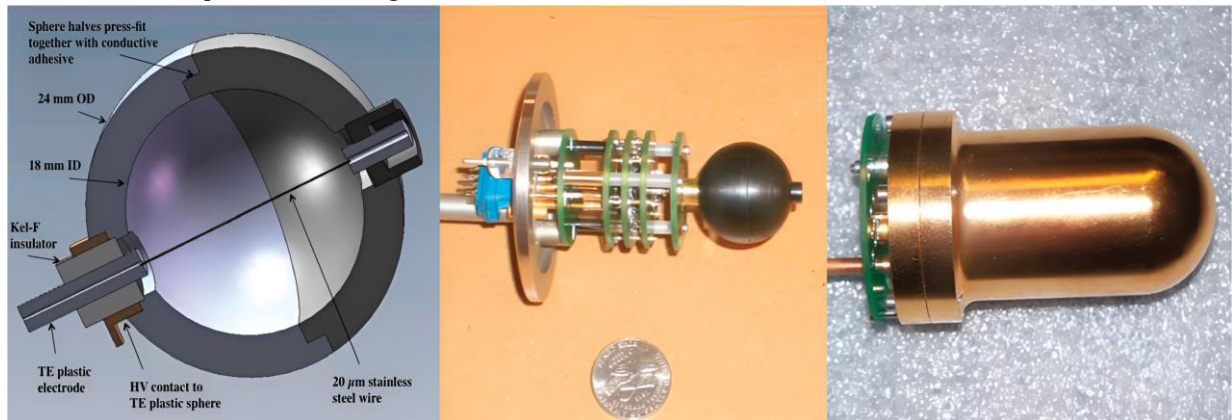


Figure 9: (Left) TEPC detector assembly, (Center) with pre-amplifier circuit boards before wire cage and vacuum chamber installation, and (Right) enclosed in a gold-plated vacuum chamber (Straume *et al.*, 2015).

on historical data to predict astronaut risk in real time. NASA's Automated Radiation Assessment Model (ARAM) applies deep learning to estimate radiation exposure in various space environments, predict the intensity and duration of solar events, and dynamically optimize shielding strategies based on real-time conditions (Gaza *et al.*, no date). AI-assisted dosimetry is expected to be crucial for future Mars and deep-space missions, where rapid exposure prediction is essential for astronaut safety (Currie and Rohren, 2023).

3.4.4 Limitations & Challenges in Space Dosimetry

Despite advancements in dosimetry, several technical and operational challenges remain:

3.4.4.1 Calibration Issues in Microgravity

One of the key issues is the calibration of dosimeters, both passive and active, which require periodic adjustments to maintain accuracy. In microgravity, the physical behaviour of dosimeters changes, complicating the calibration process. Energy deposition mechanisms in space differ from those on Earth, making it difficult to apply Earth-based calibration standards effectively. Additionally, gas-filled detectors, such as Tissue Equivalent Proportional Counters (TEPCs), are commonly used in space radiation measurements. However, microgravity causes fluctuations in gas density, which affects the

dosimeter's response, leading to errors in measurement, particularly during long-duration missions (Straume *et al.*, 2015).

Semiconductor-based dosimeters, such as silicon detectors, also face challenges in space. High-energy particles can induce radiation damage in these detectors, such as charge trapping and displacement damage, which alters their response over time (Du, 2023). This degradation reduces the reliability of dosimetry, particularly in long-term missions where accurate measurement is crucial. Additionally, simulating radiation transport and energy deposition in space is complex. The varying nature of space radiation, including Galactic Cosmic Rays (GCRs) and Solar Particle Events (SPEs), requires precise models to account for different energy spectra, particle types, and their interactions with shielding. These simulations are challenging to calibrate accurately in the microgravity environment.

Environmental factors in space, such as temperature fluctuations, electromagnetic interference, and material degradation, further complicate dosimeter calibration (Wrbanek and Wrbanek, 2020). For example, thermal cycling in space can induce changes in dosimeter responses, leading to measurement inaccuracies that must be accounted for during calibration (Wrbanek and Wrbanek, 2020). Moreover, dosimeters often experience time-dependent

sensitivity degradation due to prolonged exposure to high radiation flux, known as radiation damage (Yang *et al.*, 2024). This degradation reduces the effectiveness of radiation detectors over extended missions, necessitating recalibration or replacement, which poses logistical challenges during long-term space travel.

3.4.4.2 Data Transmission & Real-Time Monitoring Difficulties

Spacecraft face data transmission limitations due to bandwidth constraints, which delay real-time radiation exposure analysis. The distance from Earth restricts communication, making it challenging to monitor astronaut exposure during high-risk events like Solar Particle Events (SPEs), where timely intervention is critical (Valinia *et al.*, 2022).

Radiation-induced electronic failures, such as single-event upsets (SEUs), further complicate this issue. These failures, caused by high-energy particles from Galactic Cosmic Rays (GCRs), can damage dosimetry systems, leading to data corruption or loss and impacting exposure assessments (O'Bryan *et al.*, 2000).

To address these challenges, future missions will require radiation-hardened electronics, redundant dosimetry systems, and improved calibration protocols to ensure reliable data collection and accurate exposure monitoring over long-duration missions.

3.5 Risk Assessment & Radiation Protection Guidelines

Understanding and alleviating the risks associated with space radiation is crucial for ensuring astronaut safety during long-duration missions, such as Mars exploration. Space radiation exposure differs significantly from terrestrial radiation hazards due to the higher energy levels of cosmic radiation, the prolonged duration of exposure, and the lack of a protective atmosphere or magnetic field (Simonsen *et al.*, 2000). This section explores current radiation exposure limits and standards, the challenges in setting safe thresholds for deep-space missions, and strategies for reducing astronaut radiation risks

through mission planning and pharmacological countermeasures.

3.5.1 Current Exposure Limits & Standards

Several space agencies and international organizations have established radiation protection standards for astronauts based on epidemiological data, terrestrial radiation studies, and computational risk models. The primary guidelines come from NASA, the European Space Agency (ESA), and the International Commission on Radiological Protection (ICRP).

3.5.1.1 NASA Radiation Exposure Limits

NASA sets astronaut radiation exposure limits using career dose constraints based on increased lifetime cancer risk. The NASA Space Radiation Standard (NPR 1800.1) establishes: A 3% excess risk of cancer mortality as the upper limit for an astronaut's career exposure, Individualized exposure limits based on age, sex, and mission duration (e.g., younger astronauts have lower allowable doses due to longer lifespans), Annual dose limits for ISS missions, typically around 50–500 mSv, depending on mission specifics (Cucinotta, 2014) & (References, 2023).

3.5.1.2 ESA and International Guidelines

ESA follows similar guidelines to NASA but has additional constraints based on European radiation protection standards. ESA's Space Radiation Safety Framework includes: A 1,000 mSv lifetime dose cap for low-Earth orbit (LEO) astronauts, A focus on individualized radiation risk assessments, considering genetic susceptibility to radiation-induced cancers (Seedhouse, 2018).

The International Commission on Radiological Protection (ICRP) recommends that space agencies adopt a cautious approach, using dose limits that consider both deterministic (acute) and stochastic (long-term cancer) effects. ICRP suggests a mission-based dose limit of 1 Sv for deep-space exploration but emphasizes the need for further research into biological uncertainties (Cucinotta and Ph, 2010).

3.5.1.3 Mars Mission Considerations

For Mars missions, astronauts could accumulate doses exceeding current lifetime limits due to prolonged

exposure to Galactic Cosmic Rays (GCRs) and Solar Particle Events (SPEs). NASA's Human Research

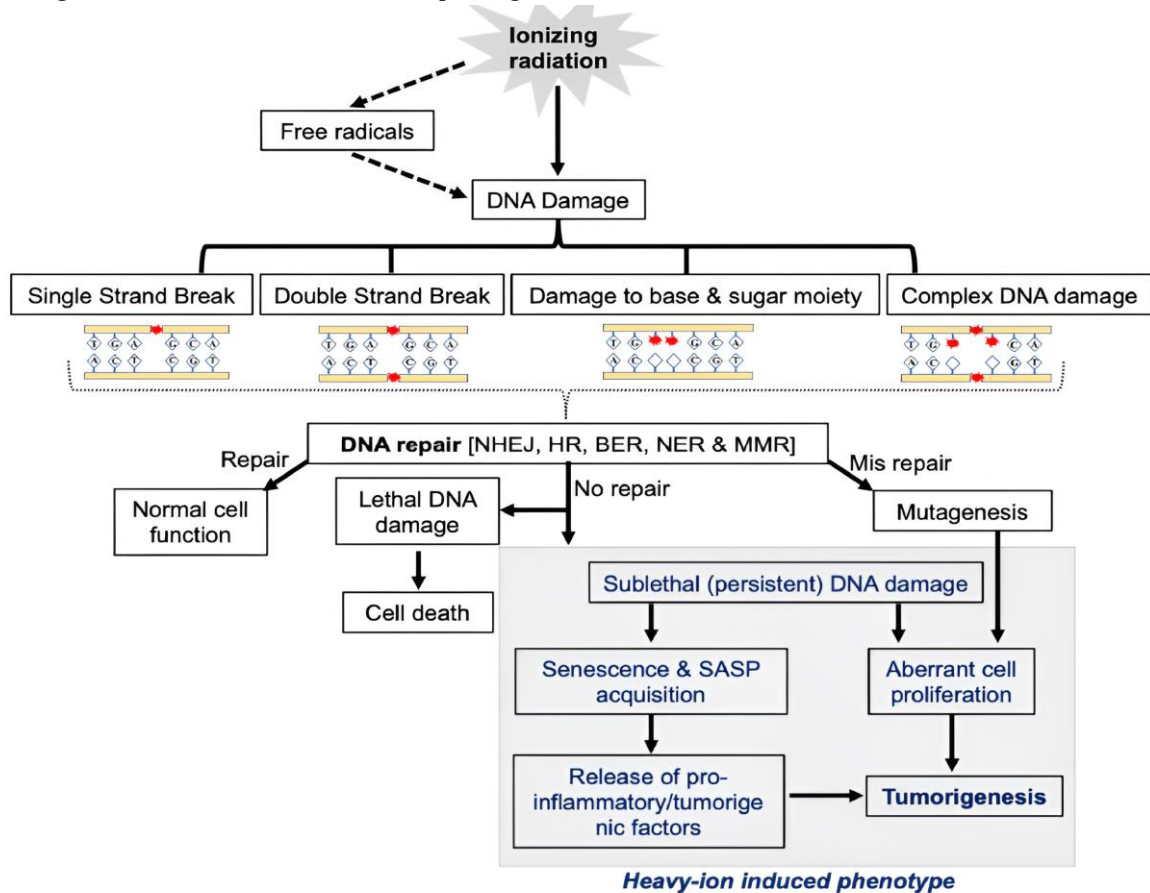


Figure 10: The pivotal role of DDR in heavy-ion radiation-induced persistent DNA damage, senescence/SASP, and GI carcinogenesis (McPhee, Charles and Administration, 2009)

Programme (HRP) is actively investigating how exposure limits might need adjustment for future deep-space missions, as current standards may be too restrictive for multi-year expeditions, as illustrated in Figure 9 (McPhee, Charles and Administration, 2009).

3.6.3.1 Synergy between Health Physics, Space Medicine & Engineering

Radiation protection in space is a complex challenge that requires expertise from multiple disciplines, each contributing unique insights and innovations to safeguard astronauts from the harmful effects of cosmic radiation. Unlike Earth, where the atmosphere and magnetosphere provide significant protection,

space travellers are exposed to high levels of ionizing radiation, including high linear energy transfer (LET) particles from galactic cosmic rays (GCRs) and solar particle events (SPEs). Effective radiation protection strategies integrate advancements in health physics, space medicine, and aerospace engineering to mitigate these risks.

A critical area of focus is health physics and radiation biology, which aims to understand the biological impact of space radiation on human cells and tissues (Furukawa *et al.*, 2020). Heavy ions from cosmic rays and other high-LET radiation seriously damage DNA, raising the risk of degenerative diseases and cancer

(Figure 10) (McPhee, Charles and Administration, 2009). For real-time monitoring, biomarkers such as γ -H2AX, 53BP1, micronuclei, and changes in gene expression are being investigated. Individual radiation responses are revealed by omics techniques (transcriptomics, proteomics, and metabolomics), allowing for customized countermeasures (Ainsbury *et al.*, 2023). For in-flight diagnostics, it is crucial to develop portable biosensors and minimally invasive techniques (such as blood tests and exosomal RNA) (Kalligossfyri, Lamprou and Kalogianni, 2024).

To lessen radiation damage, scientists are creating pharmaceutical strategies in space medicine (Mahalmani and Medhi, 2023). To lessen the effects of radiation, researchers are looking into radioprotective agents like immune modulators, DNA repair enhancers, antioxidants (like vitamin C, NAC, and SOD mimetics), and DNA repair enhancers (ATM, PARP1, and DNA-PKcs activators) (Checker *et al.*, 2021). TLR agonists and interleukin treatments may support immune homeostasis in times of stress. Genomic and proteomic profiling in personalized medicine allows for the customization of countermeasures and the prediction of individual susceptibility (Pavez Lori  *et al.*, 2021).

Another essential aspect of space radiation protection is aerospace engineering and materials science, which focuses on designing effective shielding solutions for spacecraft and habitats (Carolina *et al.*, 2017). Traditional radiation shielding, such as aluminium-based materials, offers some protection but is not sufficient against high-energy cosmic rays (Finckenor, 2018). Innovative materials, including hydrogen-rich polymers, boron nitride nanotubes, and multifunctional composite structures, are being developed to enhance shielding efficiency while minimizing weight—an essential factor in space missions (KAUL, BARGHOUTY and DAHCHE, 2004), (Darwish *et al.*, 2019), (Gohel, Makwana and Soni, 2022). Furthermore, AI-driven computational modelling is revolutionizing spacecraft architecture by optimizing the placement and composition of shielding materials to maximize protection with minimal mass (Ud-Din Khan *et al.*, 2020). Adaptive shielding technologies, which dynamically adjust to changing radiation environments, are also being

explored to provide real-time protection against unpredictable solar events (AbdelKader *et al.*, 2024).

4. DISCUSSION

This systematic review highlights the significant risks posed by space radiation and the need for integrated, multi-faceted strategies to ensure astronaut safety. The complex radiation environment comprising GCRs, SPEs, and Van Allen belt radiation presents major challenges for long-duration missions.

4.1 Biological Risks and DNA Damage

As evidenced by the increased chromosomal exchanges in astronauts' post-mission, high-LET radiation from GCRs produces dense ionisation tracks that cause clustered DNA damage and ongoing genomic instability (Kumar *et al.*, 2023). Such damage is more dangerous than that from low-LET sources like X-rays and raises the risk of cancer. Additionally, sex-specific cognitive effects are revealed in animal studies, highlighting the significance of individualised risk assessment (Sridharan *et al.*, 2016).

4.2 Shielding Technologies: Efficacy and Challenges

Although common, aluminium shielding is insufficient to protect against GCRs and can produce dangerous secondary radiation (Horst *et al.*, 2022). Polyethylene and other hydrogen-rich materials cut exposure by about 30% (Naito *et al.*, 2021), and regolith shielding based on ISRU could reduce Martian surface radiation by 50% (Llamas, Aplin and Berthoud, 2022). Although advanced materials like graphene composites and BNNTs perform better, more testing is necessary to determine their long-term durability and shielding consistency (Reyes *et al.*, 2024).

4.3 Dosimetry: Progress and Limitations

Although they do not provide real-time data, passive dosimeters (TLDs, OSLs) are still useful. Although active systems like Timepix and TEPCs enhance radiation profiling and LET analysis, they have calibration and durability issues in microgravity (Alvarez *et al.*, 2017). With the potential to provide

individualised protection, AI-powered systems provide adaptive shielding techniques and real-time exposure prediction (Ozobu, Adikwu, and Odujobi, 2025) (Ozobu, Adikwu and Odujobi, 2025).

4.4 Research Gaps and Future Directions

The lack of in-situ validation for numerous shielding technologies and our incomplete knowledge of radiation–microgravity interactions are two important gaps. Future research should focus on hybrid shielding systems, which combine passive and active techniques, and precision medicine, which uses pharmacogenomics and genetic screening to customise treatments like DNA repair enhancers and antioxidants.

5. CONCLUSION

This review emphasises that space radiation is still a major health risk for astronauts, especially on deep-space missions where exposure to GCR and SPE is inevitable. Traditional shielding techniques are insufficient to address the complex biological reactions, which include DNA damage, neurodegeneration, and cancer risks.

Interdisciplinary approaches are essential to overcoming current constraints, as evidenced by promising developments in personalised medicine, AI-integrated dosimetry, and hydrogen-rich and nanomaterial-based shields. However, real-time adaptation to changing space environments and thorough in-flight validation is necessary for these innovations.

Future research should concentrate on AI-guided dosimetry, customised radioprotective interventions, and hybrid shielding designs to guarantee astronaut safety and mission success. Ultimately, health physicists, engineers, space physicians, and molecular biologists will need to continue working together to protect human life in space.

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