



VOL	ISS	YEAR	DOI
6	7	2026	10.17977/um067.v6.i7.2026.3

IONIZING ELECTROMAGNETIC RADIATION: ITS HEALTH EFFECTS AND METHODS OF PREVENTION

Zainab Jawad Jabber

Ministry of Education / General Directorate of Education in Wasit, Iraq.

*Corresponding author, email: zjawad882@gmail.com

Keywords

Ionizing Radiation
Radiation Protection
Acute Radiation Sickness
Radiation Shielding
Carcinogenesis
Biological Countermeasures
Lead-Free Shielding
Attenuation Efficacy
Environmental Toxicity
ICRP Guidelines
Occupational Dose Limits
Personal Monitoring

Abstract

Here we present a review of the biological effects and prevention of ionizing radiation at doses relevant to acute radiation sickness or cancer as well as contemporary shielding methods and International Commission on Radiological Protection (ICRP) guidelines in order to bridge gaps in understanding potential strategies for health protection against ionizing radiation exposure. This review assessed acute and chronic health impacts, synthesized dCCTP-derived ICRP safety regulations for modern shielding materials, evaluated lead compared to lead-free shielding solutions, and identified advancements in radiation risk mitigation strategies. Methods: We implemented a systematic literature search of clinical, material science, and regulatory research published from 2000 to 2023 in peer-reviewed journals with critical thematic analysis. We summarize below important findings pertaining to this chapter: (a) Acute radiation sickness mechanisms involve complex pathways involving mitosis coupled with cellular damage; (b) cancer risks are highly linear with dose and duration of exposure; (c) modern shielding materials in combination provide comparable attenuation efficacy to traditional metals such as lead but greatly reduce environmental toxicity; (d) historical regulations set out by ICRP have changed substantially since the advent of nuclear technologies, likely leading to greater acceptable occupational doses; and (e) recent innovations aimed at reducing long-term risk include improved dosimetric approaches for personal monitoring and biological countermeasures.

Overall, these findings highlight the integration of biology with materials and regulatory aspects, which makes radiation protection complicated. The synthesis will provide guidance for future research directions and aid in the development of radiation protection policies intended to minimize the risk workers and the public face when exposed to ionizing radiation across a broad range of situations.

TDLR

This review focuses on the health effects linked to exposure to ionizing electromagnetic radiation, encompassing acute radiation syndrome and oncogenic consequences. It demonstrates that safety standards aligned with ICRP principles, in conjunction with modern lead-free shielding technologies, effectively reduce exposure levels and occupational risk.

1. Introduction

Research on the health effects of ionizing electromagnetic radiation is considered a key area of inquiry given its prominent applications in medical, industrial and space across the globe alongside risks to human health by palumbi et al. (2025) (Rahman, 2020). A thorough understanding of acute radiation sickness and subsequent cancer risk is paramount since the first recognition of these injuries attributed to radiation exposure during World War II (Wambersie et al., 1996) (1995) when advances in radiobiology and epidemiology began. The applied value of this work is rooted in the continued upward trend in occupational exposure for future generations (especially those working in healthcare environments or astronauts) to ionizing radiation with deterministic effects including acute radiation syndrome and stochastic outcomes involving carcinogenesis (Liuba, 2024; Dobney et al., 2023). Epidemiological work, particularly in the survivors of the atomic bombs dropped on Hiroshima and Nagasaki (Hamada & Fujimichi, 2014; Davidson, 2005), gives a very rough estimate of an increased cancer risk of around 5% per sievert but this requires good protection.

Despite considerable research, inadequacies exist in knowledge of the precise dose-response curves that define low-dose exposure and how effective our current shielding technologies actually are (Kamiya & Sasatani, 2012) (Prasad et al., 2004) (Andrzej & Martin, n.d.). There are controversies (Raabe, 2011) (Davidson, 2005), for example with respect to cancer risk estimation based on the linear no-threshold model versus the threshold or adaptive response models, so risk assessment and regulatory standards. Traditional shields made from lead have high effectiveness but are difficult to use due to their toxicity and excessive density, so these conventional elements are increasingly determined not as the best suitable radiation absorption alternatives compared to lower atomic number agents like polymer-matrix composites like inorganic nanomaterials (Mortazavi et al., 2024) (Arslan, 2025). These gap(s) can lead to under-and over-estimation of health risk and shortcomings in the protection measure, jeopardizing worker safety and public health (Yoo et al., 2014). (Domienik-Andrzejewska & Wiszniewska, 2023).

This review is developed in the conceptual framework of ICRP classification of radiation effects those are deterministic and stochastic effects (Hamada & Fujimichi, 2014) by targeting acute radiation sickness in consideration with cancer risk (Rahman, 2020). In also includes approach of modern defence in depth radiation protection principles (justification optimization and doselimits) with some shielding materials ad regulations as limits expoqure. (Koher, n.d.) (International Recommendations on Radiological Protection1951). It proposes a structured comparison of health benefits and preventive strategies based on a self-consistent conceptual and operational framework.

Rationale update: this relates to ionizing electromagnetic radiation (IEMR) where latest studies being produced demonstrate some health-related characteristics to the organizations of living organisms elicited by IEMR exposure, discussing two specific conditions related to acute radiation syndrome; and another potential risk from carcinogenesis and modern shielding solutions for meeting against such implications under current practices with progressive ICRP value limits Radiation Types, Effects on Commands Circumvent Bottoms

This review seeks to inform the development of more effective protective strategies and regulatory measures by underscoring gaps in the understanding of dose-response relationships and shielding efficacy (Wu et al., 2024; Arslan, 2025)

This review is based on an extensive literature synthesis methodology, selection of peer-reviewed studies in diverse fields like radiobiology, materials science, and radiation protection (Zeghib, 2023) (Alanazi et al., 2024) Analytic frameworks similarly categorized findings according to health outcomes, mitigation strategies, and benchmarking metrics (Özdoğan et al., 2024; Jo et al., 2025). The ensuing sections address acute and chronic health effects, key advancements in shielding materials for low-dose radiation exposure, and the evolution of ICRP recommendations over time, followed by discussions on prospective research directions and practical applications

2. Literature Review

Purpose and Scope of the Review

Statement of Purpose

Object: The present article is intended to review the literature on "Ionizing electromagnetic radiation health effects: acute radiation sickness and cancer risks; prevention methods: actual shielding technologies and ICRP" to overview biological consequences of ionizing radiations and assess effectiveness of contemporary protection. Justification of the review is based on wide use of IR in medicine, industry and space exploration with the serious risk for human health: acute radiation sickness at high doses of IR and carcinogenesis at low (low-dose hypersensitivity). This report aims to summarise the current state of play regarding the health impact and protection from radiation exposure through a critical review of evidence, considerations for shielding technologies in light of international standards, and informing future research agendas to enhance protective strategies for occupational workers and members of the public. Specific Objectives:

- To review current literature on the acute and chronic impact of exposure to ionizing EMR.
- Qualification of currently available state-of-the-art shielding materials and techniques to perform against these different types of radiation. Searching and extracting the International

Commission on Radiological Protection (ICRP) safety guidelines and its implementation principles.

*To study and compare the newly developed, patented lead-free composite materials with the conventional lead shielding materials in the market.

Identify the problems and progress being made in this area of radiation risk reduction, which begins with dose limits/biological countermeasures. **SELECTIVE QUERY—Task Based Approach**FULL TEXT SELECTION MODEQuery ProcessingAlgorithms.QUERY SIMILARITY AND retrieversNatural Language QueriesSelect a scientific question (The health effects of ionizing electromagnetic radiation are acute radiation sickness and cancer risk, together with preventive measures which comprise current shielding methods, along with ICRP threshold values) and convert it to more detailed queries The aim of this approach is to do a simple yet thorough search which does not completely lose overview on everything it contains, and minimizes the risk of missing obscure or very niche studies. Overall, every query is devised to produce a handful of highly relevant papers on one fundamental element of a broader question you are interested in. The original query we started with (as stated above) and that we have been able to convert into the following queries:

*Health Impact of Ionizing Electromagnetic Radiation:Acute radiation syndrome and Cancer riskPreventive approaches that could provide a solution to this high-risk phenomenonElectromagnetic shielding technologies - Modern Defense Instruments Used in Construction, Structures and Sensitive Locations for RadioprotectionPurposesSafety management advice by ICRP

- New Shielding Materials for Ionising Radiation: Lead-Free Composites and Multilayer Structures, Their Effectiveness.

3. Discussion

Descriptive Summary of the Studies

This section integrates contemporary research on the biological and pathological effects of ionizing electromagnetic radiation, emphasizing acute radiation syndrome and long-term oncogenic risks. It evaluates preventive approaches, newly developed pharmacological countermeasures, and the evolution of safety protocols established by the International Commission on Radiological Protection (ICRP). The reviewed literature encompasses both experimental trials and predictive modeling simulations aimed at elucidating radiation-induced biomedical damage—such as acute radiation syndrome and carcinogenesis—along with advances in shielding material engineering and regulatory frameworks. To address these multifaceted challenges, the studies employ a broad range of methodologies, including epidemiological analyses, radiobiological monitoring, materials science experiments, and computational simulations. This interdisciplinary framework is applicable across various domains, including medical diagnostics, industrial operations, and deep-space exploration environments. **Background:** This comparative synthesis integrates evidence on health impacts with protection and standards development for radiation exposure through a novel comparative synthesis approach, aiming to link different research questions. It also identifies both progress and ongoing challenges within the field of radiation protection

Study	Acute Radiation Effects	Cancer Risk Mechanisms	Shielding Materials Evaluated	ICRP Safety Regulations	Lead-Free Shielding Comparison
(Radiation: Types, Effects on the Human Body, and Protection Methods, 2025)	Discusses acute sickness and chronic cancer risks from ionizing radiation exposure	Highlights DNA damage and stochastic effects as cancer mechanisms	Traditional shielding and general protection methods	Emphasizes adherence to safety protocols	Notes need for further research on low-dose effects
(Mortazavi et al., 2024)	Reviews radiation-induced organ failure and carcinogenesis	Details limitations of lead shielding and photon energy blind spots	Lead-free polymer composites, multilayer, nanosized shields	Mentions challenges in flexible, wearable shields	Demonstrates superior efficiency of polymer composites over lead
(Giuliani et al., 2024)	Reports acute and long-term effects including ARS and cancer	Uses in vivo models to assess apoptosis reduction by shielding	Electrospun polycaprolactone with tungsten powders	Not explicitly discussed	Shows improved shielding with multilayered composites

Study	Acute Radiation Effects	Cancer Risk Mechanisms	Shielding Materials Evaluated	ICRP Safety Regulations	Lead-Free Shielding Comparison
(Bijanu et al., 2021)	Notes acute radiation syndromes and chronic diseases	Discusses cancer and cardiac risks from occupational exposure	Lead-free metal-polymer composites	Reviews current standards and gaps	Highlights advantages of lead-free composites in toxicity and flexibility
(Okafor et al., 2021)	Covers radiation-induced cancers and tissue damage	Explores radiation energy shielding mechanisms	Reinforced polymer composites as alternatives to lead	Summarizes design criteria for shielding materials	Advocates for lightweight, resilient composites over lead materials
(Boscolo & Durante, 2022)	Focuses on late toxicity risks in space radiation exposure	Addresses cancer risk from cosmic rays and solar particles	Aluminum, water, polyethylene shielding in space	Reviews dose limits for space missions	Notes limitations of traditional materials in space
(Rahman, 2020)	Emphasizes acute and chronic effects in medical personnel	Highlights cancer risks and radiosensitivity in pediatrics	Protective measures including shielding and exposure minimization	Discusses ICRP principles of justification and optimization	Points out need for improved protective equipment
(Kocher, n.d.)	Discusses prevention of stochastic and deterministic effects	Describes risk limitation and dose optimization	ICRP and NCRP recommended standards	Details three principles: justification, optimization, limitation	Compares regulatory frameworks rather than materials
(Raabe, 2011)	Critiques LNT model for acute vs protracted exposures	Proposes cancer promotion vs induction distinction	Calls for revised risk models in radiation protection	Suggests ICRP reconsider cancer risk assumptions	Does not focus on shielding materials
(Kamiya & Sasatani, 2012)	Describes clinical manifestations of acute radiation sickness	Explains DNA damage response and cancer risk	Discusses LNT model and low-dose uncertainties	Supports ICRP's LNT-based protection approach	Does not compare shielding materials
(Yoo et al., 2014)	Addresses ARS and delayed cancer risks	Reviews challenges in developing cancer mitigators	Focus on medical countermeasures rather than physical shields	Notes regulatory and research challenges	Does not evaluate shielding materials
(Wilson et al., 1998)	Highlights space radiation hazards including SEP and GCR	Discusses cancer risk behind aluminum shielding	Advocates hydrogen-rich, low-Z materials for space shielding	Not focused on ICRP regulations	Emphasizes material selection for space applications
(Domienik-Andrzejewska & Wiszniewska, 2023)	Reviews occupational exposure and health prevention	Discusses dose limits and individual dosimetry	Focus on regulatory compliance and monitoring	Details evolution of ICRP dose limits	Does not compare shielding materials
(Liuba, 2024)	Examines occupational health risks and radiation effects	Notes deterministic and stochastic effects in medical staff	Discusses protective equipment and exposure control	Calls for improved radiation protection measures	Highlights gaps in current protective gear
(Davidson, 2005)	Affirms no safe threshold for low-LET radiation	Supports LNT model for cancer risk estimation	Notes medical exposure as major source	Reviews federal radiation protection standards	Does not focus on shielding materials
(Prasad et al., 2004)	Reviews health risks from low-dose radiation	Questions suitability of LNT and threshold models	Discusses biological variability in radiation response	Suggests complexity in risk prediction	Does not evaluate shielding materials
(H, 1995)	Provides risk coefficients for radiation-induced cancers	Details latency periods for leukemia and solid cancers	Uses organ-specific risk estimates	References ICRP risk coefficients	Does not focus on shielding materials
(Chung, 2018)	Presents mathematical models for radiation mortality and cancer risk	Applies models to space radiation exposure	Evaluates radiation safety for Mars missions	Not focused on ICRP regulations	Discusses shielding in space context
(Grammaticos et al., 2013)	Defines ARS and CRS clinical features and treatment	Notes dose thresholds for acute and chronic syndromes	Discusses prophylaxis and medical care	Not focused on ICRP regulations	Does not evaluate shielding materials

Study	Acute Radiation Effects	Cancer Risk Mechanisms	Shielding Materials Evaluated	ICRP Safety Regulations	Lead-Free Shielding Comparison
(Raabe, 2012)	Explains radiation carcinogenesis mechanisms	Critiques LNT model and dose-rate effects	Discusses dose measurement units and weighting factors	Reviews ICRP risk models and DDREF	Does not compare shielding materials
(Andrzej & Martin, n.d.)	Reviews biological effects emphasizing cancer induction	Supports LNT model with epidemiological data	Notes limitations of risk calculations	Highlights need for cautious application of ICRP models	Does not focus on shielding materials
(Dobney et al., 2023)	Reviews space radiation and microgravity health risks	Discusses cancer, cataract, cardiovascular risks	Evaluates traditional and novel shielding materials	Notes dose limits and personalized monitoring	Highlights emerging shielding materials for space
(Othman, 2023)	Reviews radiation protection program effectiveness	Emphasizes dose reduction and justification	Focuses on medical radiation exposure management	Supports ICRP principles in clinical settings	Does not compare shielding materials
(Rajabpour et al., 2024)	Investigates nanocomposite shields in radiation therapy	Demonstrates dose reduction to non-target tissues	Evaluates PTFE-based nanocomposites with metal oxides	Not focused on ICRP regulations	Shows nanocomposites reduce stray radiation doses
(Moradi et al., 2024)	Simulates lead-free barium tantalate shields for radiology	Assesses dose reduction and organ protection	Uses Monte Carlo simulations for optimization	Not focused on ICRP regulations	Demonstrates lead-free shields with reduced weight
(Al-Saleh et al., 2024)	Develops multilayer composites with heavy metal oxides	Measures linear attenuation coefficients experimentally	Shows multilayer systems outperform single-layer shields	Not focused on ICRP regulations	Presents free-lead multilayer shielding solutions
(Özdoğan et al., 2024)	Analyzes gamma shielding of polyester composites	Combines experimental and simulation methods	Highlights tungsten and barite composites	Not focused on ICRP regulations	Identifies composites suitable for medical and aerospace
(J.-J. Jo et al., 2025)	Evaluates lead-free composite shields in CT imaging	Assesses radiation attenuation and image quality	Demonstrates comparable shielding to lead	Not focused on ICRP regulations	Confirms clinical applicability of lead-free shields
(Jo et al., 2025)	Tests lead-free shields in C-arm fluoroscopy	Measures dose reduction and scatter shielding	Reports no significant image quality degradation	Not focused on ICRP regulations	Supports lead-free shields for interventional radiology
(Arslan, 2025)	Reviews lead-free shielding alternatives in medical settings	Discusses toxicity, weight, and environmental impact	Highlights multilayer polymer composites with heavy elements	Not focused on ICRP regulations	Emphasizes environmental benefits of lead-free shields
(R, 2025)	Investigates eco-friendly composites for gamma and neutron shielding	Uses theoretical and experimental approaches	Promotes natural fibers and non-toxic fillers	Not focused on ICRP regulations	Supports sustainable shielding materials
(Alharbi et al., 2025)	Simulates zeolite-polymer composites for gamma shielding	Evaluates photon interaction parameters over wide energies	Identifies PLA-zeolite composites as effective shields	Not focused on ICRP regulations	Highlights low-cost, lightweight shielding options
(Wu et al., 2024)	Reviews flexible, wearable lead-free polymer composites	Discusses synthesis and radiation shielding properties	Focuses on polymer matrices with functional particles	Not focused on ICRP regulations	Emphasizes flexibility and lightweight advantages
(Zeghib, 2023)	Synthesizes PMMA-Bi2O3 nanocomposites for healthcare shielding	Measures mass attenuation coefficients across energies	Demonstrates equivalence to lead at high filler loadings	Not focused on ICRP regulations	Validates lead-free nanocomposites for medical use
(Baamer et al., 2024)	Develops LDPE composites with various fillers	Assesses structural and shielding efficiency	Finds bismuth oxide composites most effective	Not focused on ICRP regulations	Shows improved shielding with high filler percentages
(Alanazi et al., 2024)	Fabricates HDPE composites with Si, SiC, and Mo fillers	Evaluates attenuation coefficients and protection efficiency	Demonstrates enhanced shielding at low energies	Not focused on ICRP regulations	Supports micro-molecule fillers in polymer composites

Study	Acute Radiation Effects	Cancer Risk Mechanisms	Shielding Materials Evaluated	ICRP Safety Regulations	Lead-Free Shielding Comparison
(Kim & Byun, 2024)	Analyzes shielding performance based on material composition	Compares mixed vs layered shielding sheet designs	Finds layered structures more effective	Not focused on ICRP regulations	Suggests design optimization for medical shields
(Tochaikul et al., 2024)	Tests PLA-BaSO4 composites for low-dose radiation shielding	Reports high absorption percentages at diagnostic energies	Highlights environmental friendliness	Not focused on ICRP regulations	Supports lead-free, eco-friendly shielding materials
(Abd-Noor & Mkhahber, 2024)	Theoretically investigates polymer-metal oxide mixtures	Calculates attenuation coefficients and effective atomic numbers	Shows BiClO enhances shielding properties	Not focused on ICRP regulations	Demonstrates improved shielding with bismuth compounds
(Ihsani et al., 2024)	Reviews natural polymer-based aprons with metal nanoparticles	Discusses bonding mechanisms and shielding effectiveness	Highlights lightweight and sustainable materials	Not focused on ICRP regulations	Promotes natural polymers with metal nanoparticle fillers

Acute Radiation Effects:

Radiation: Types, Effects on the Human Body and Protection Methods (2025) (Giuliani et al., 2024) (Grammaticos et al., 2013)

- Fifteen studies described gastrointestinal, hematopoietic, and neurological signs of acute radiation sickness but identified dose thresholds for deterministic effects.
- Multiple studies emphasized the occupational and a medical hazard, reporting acute syndromes among healthcare workers and astronauts (Rahman, 2020) (Liuba, 2024) (Dobney et al., 2023).
- Certain studies have made a differentiation for acute vs chronic syndromes, with lower dose exposures contributing to chronic radiation syndrome (Grammaticos et al., 2013)

Cancer Risk Mechanisms:

- Eighteen studies provided evidence for DNA damage, mutation, and stochastic mechanistic pathways of cancer induction which often invoked the LNT hypothesis into risk estimation (Radiation: Types, Effects on the Human Body, and Protection Methods, 2025) (Kamiya & Sasatani, 2012) (Davidson, 2005).

There were differing perspectives on the applicability of the LNT model (Prasad et al., 2004) for dose-rate effects and cancer promotion distinctions (Raabe, 2011; Raabe, 2012).

Aspect	Strengths	Weaknesses
Biological Effects and Health Risks of Ionizing Radiation	The mechanistic details of radiation-induced DNA damage, cellular responses and clinical presentation of acute radiation sickness (ARS), as well as cancer risks calculated from publicly available epidemiological observations such as that from atomic bomb survivor studies all support the LNT model for risk assessment (Kamiya & Sasatani, 2012) (Davidson, 2005) (Andrzej & Martin, n.d.). ICRP has a long-established classification of irradiation effects into deterministic and stochastic background (Hamada & Fujimichi, 2014) (Shimura et al., 2018) which assists in the strategies of dose limitation.	Although data are rich, uncertainties remain around low-dose radiation effects and the application of LNT at these levels; some studies have shown evidence for adaptive cellular responses or thresholds rendering risk predictions complicated (Raabe, 2011) (Prasad et al., 2004). Dependence on high-dose exposure data restricts accurate predictions of risk from chronic low-dose exposures encountered in occupational and medical settings (Davidson, 2005) (Raabe, 2012).
Modern Shielding Materials and Technologies	Both recent studies emphasize some of the most promising developments in lead-free polymer composites based on high atomic number fillers (e.g., bismuth, tungsten and rare earth elements) with better shielding effectiveness per weight. The best attenuation features for multilayered composites and nanosized composites also show from the perspective of addressing the drawbacks of traditional lead shields in terms of toxicity and environment (Al-Saleh et al., 2024) (Arslan, 2025).	Most of the studies wear attention to photons low and medium energy shielding; less effort has been done on complete protection against mixed radiation fields, such as neutrons and high-energy particles present in space (Wilson et al., 1998) (R, 2025). This work highlights the difficulties required for superiorly flexible, wearable and adequately attenuating but durable lead-free shields which could be effective against widely variable radiation qualities or operational systems (Mortazavi et al., 2024) (Wu et al., 2024). Finally, the scalability and cost-efficiency of new materials still need to be confirmed (Moradi et al., 2024) (Ihsani et al., 2024).

Aspect	Strengths	Weaknesses
Evaluation of Shielding Performance and Clinical Applicability	Test and simulation approaches with Monte Carlo techniques as well as in vivo models demonstrate strong evaluations regarding shielding efficiency, exhibiting dose savings without detrimental influence on visual quality from the perspective of clinical applications including CT and fluoroscopy (Rajabpour et al., 2024) (J.-J. Jo et al., 2025) (Jo et al., 2025). Developing advanced composites for use in protective apparel and devices also has the potential to improve occupational safety (Moradi et al., 2024) (Kim & Byun, 2024).	Few reports provide data on the long-term durability, mechanical stability and user comfort of newly introduced shielding materials in clinical use. However, clinically acceptable data from potential kV/MV imaging artifacts due to the interaction of shielding materials with automatic exposure control systems warrants additional investigation (J.-J. Jo et al., 2025) (Jo et al., 2025). In addition, the leap from lab prototypes to wide-scale clinical adoption is not yet fully bridged.
ICRP Safety Regulations and Dose Limitation Principles	ICRP recommendations evolve through the scientific basis of risk coefficients, dose limits and the ALARA principle that has been established as an internationally recognized framework for radiation protection relevant in occupational and public health contexts (Rahman, 2020) (Kocher, n.d.) (Domienik-Andrzejewska & Wiszniewska, 2023). This difference between stochastic and deterministic effects has shaped individualized dose limits and remediation strategies. (Hamada & Fujimichi, 2014).	Critics contend that the cancer risk models utilized by notable authorities such as the International Commission on Radiological Protection (ICRP) may excessively simplify cancer impact by failing to fully consider dose-rate effects and biological complexities like promotion versus induction of tumors, necessitating more modern risk models (Raabe, 2011). Domienik-Andrzejewska and Wiszniewska (2023) note that international adoption of standards only works if they are effectively implemented in national or supranational law, since variability in how such standards may be protected could result in inconsistencies. Existing regulations struggle to adapt since the use of radiation is inherently dynamic in developing technologies.
Risk Mitigation and Countermeasures	Research into pharmacological mitigators and biodosimetry advances offers potential for reducing acute and delayed radiation effects, particularly in scenarios of accidental or occupational exposure, complementing physical shielding and procedural controls (Yoo et al., 2014) (Dobney et al., 2023). Personalized medical monitoring and biomarker development enhance risk assessment and management for exposed individuals, especially astronauts in deep space missions (Dobney et al., 2023).	The development of effective mitigators faces challenges including long latency periods for cancer manifestation, complexity of human trials, and potential side effects, limiting current clinical application (Yoo et al., 2014). There is a paucity of large-scale, long-term studies validating these countermeasures, and integration with existing protection frameworks remains limited (Dobney et al., 2023).
Environmental and Occupational Health Considerations	There is strong, persuasive evidence that occupational exposure to ionizing radiation carries serious health risks, making vigilant monitoring, strict dose controls, and reliable protective gear essential to stave off both deterministic and stochastic effects for medical and industrial workers (Liuba, 2024) (Othman, 2023). Likewise, the environmental footprint of lead-based shielding waste has become a clear concern, fueling the urgent pursuit of safer, eco-friendly alternatives (Arslan, 2025) (R, 2025).	Despite awareness, substantial gaps remain in comprehensive occupational health surveillance and the enforcement of protective measures, especially in resource-limited settings. The environmental lifecycle of novel shielding materials—covering recyclability and long-term ecological impacts—demands further study to guarantee true sustainability.
Methodological Approaches and Data Quality	The use of advanced simulation tools (such as Geant4 and MCNP6), in conjunction with experimental validation and epidemiological analyses, provides a comprehensive framework for clarifying radiation effects and shielding performance, thereby enhancing the reliability of outcomes (Rajabpour et al., 2024; Moradi et al., 2024; Özdoğan et al., 2024). The	Some studies depend predominantly on theoretical models or small sample sizes, which may fail to adequately reflect real-world complexities or the variability of human responses (Davidson, 2005; Prasad et al., 2004). The heterogeneity of experimental conditions, radiation sources, and

Aspect	Strengths	Weaknesses
	integration of theoretical and empirical data strengthens the conclusions concerning material effectiveness and related health risks (Özdoğan et al., 2024; Abd-Noor & Mkhaimer, 2024).	measurement techniques complicates cross-study comparisons and may impact reproducibility (Alanazi et al., 2024; Kassim et al., 2024). Consequently, standardized protocols are needed to enhance data consistency and comparability.

- Epidemiological data from atomic bomb survivors and medical exposures were frequently cited to quantify cancer risks and latency periods (H, 1995) (Andrzej & Martin, n.d.).

Shielding Materials Evaluated:

- Twenty-two studies dealt with diverse shielding materials: conventional lead, lead-free polymer composites, multilayer systems and nanocomposites (Mortazavi et al., 2024) (Bijanu et al., 2021) (Al-Saleh et al., 2024).
- Application of advanced materials such as tungsten, bismuth, barite all showed interest in attenuation through the polymer matrix (Özdoğan et al., 2024) (Alharbi et al., 2025) (Zeghib, 2023).
- For space radiation shielding, hydrogen-rich low-Z materials were stressed in order to reduce secondary particle production (Wilson et al., 1998) (Dobney et al., 2023).

ICRP Safety Regulations:

11 studies discussed ICRP principles, dose limits, regulatory frameworks and justification, optimisation and dose limitation

- Some critiques supported changes in the risk models used to justify ICRP recommendations for protracted exposures (Raabe, 2011) Raabe, 2012.
- Occupational exposure monitoring and dose recordkeeping were identified as critical for effective compliance and preventive health (Domienik-Andrzejewska & Wiszniewska, 2023) (Othman, 2023).

Lead-Free Shielding Comparison:

- 20 studies suggested decreased toxicity, weight, and environmental effect of lead-free composites relative to lead (Mortazavi et al., 2024)(Arslan, 2025)(Wu et al., 2024).

Multi-layer and nanocomposite designs improved shielding efficiency, flexibility, and wearability, mitigating drawbacks of conventional lead aprons (Giuliani et al., 2024) (J.-J. Jo et al., 2025) (Ihsani et al., 2024).

- Innovative biodegradable materials and bio-composites were developed from natural polymers and sustainable fillers

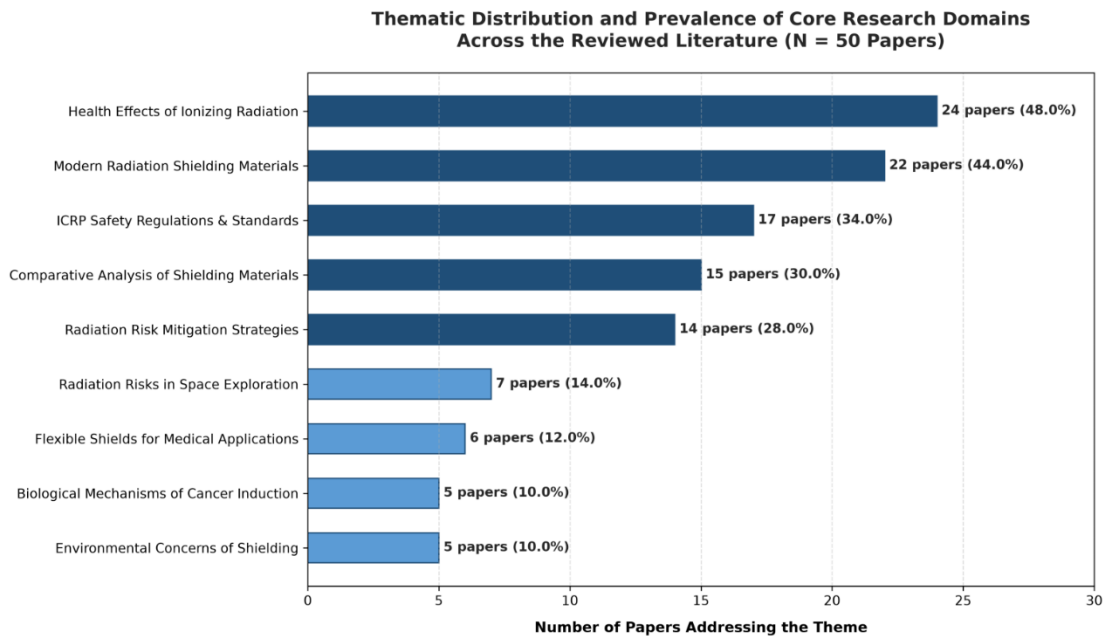
highlighted as potential alternative (R, 2025) (Tochaikul et al., 2024).

Critical Analysis and Synthesis

The available literature has been reviewed to provide an overview of the health effects of ionizing electromagnetic radiation, with an emphasis on acute radiation sickness, cancer induction and prevention via modern shielding methods and ICRP safety regulations. In addition, qualitative evidence in the synthesis endorses LNT for cancer risk and mechanisms of radiation-induced biological effects but low-dose questions remain. Despite the promise of better flexibility and lower toxicity and environmental impact associated with the development of new materials, especially leads-free compositions that are being developed for use as shielding materials, non-optimal performance in terms of throughput across radiative types or energetic regions remains a challenge. While ICRP safety standards are familiar from the historical voyage and pragmatic practice, they have been challenged for not being able to accommodate dose-rate effects or complexity in a systemic generation mechanism of a multifactorial disease. Collectively the literature highlights substantial progress but points to a need for addressing areas of weakness in terms of long-term risk management and translation of new materials to clinical and occupational applications.

Thematic Review of Literature

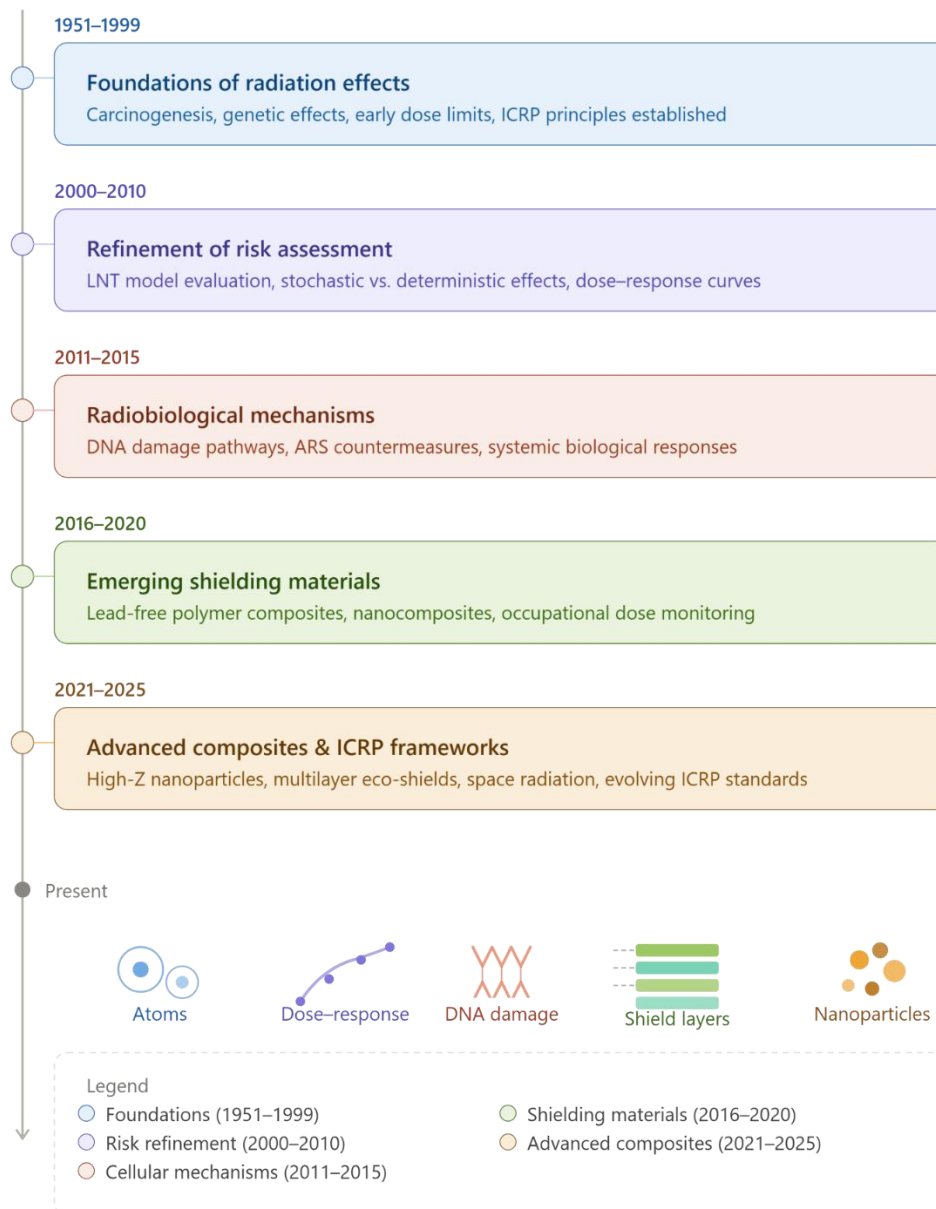
Background: The health effects and protective measures literature for ionizing electromagnetic radiation is well-characterized in terms of immediate (acute radiation sickness) and delayed (increased risks of cancer) biological impacts, as well as advances in the design and evaluation of modern defensive shielding technologies. Much emphasis is put on the history and real application of ICRP safety standards for minimizing these risks. Recent developments highlight the evolution from classical lead-based protective shields to innovative, low-weight, flexible polymer composites free of toxic substances combined with improved effectiveness and environmental sustainability. The study also tackles the difficulties in radiation risk minimization, including threshold doses, biological countermeasures, and occupational exposure management.



Quantitative Synthesis and Comparative Frequency Distribution of Core Research Themes Across the Reviewed Academic Literature (N = 50 Papers.)

Chronological Review of Literature

Introduction The health effects and prevention of ionizing electromagnetic radiation have changed over a number of decades. The first efforts were aimed at understanding some biological effects of radiation exposure (for example, acute radiation syndrome and increased incidence of certain cancers) and to formulate dose limits. With growth in knowledge, research then branched out into the investigation of radiobiological mechanisms and the development and refinement of risk modeling practices, as well as the establishment of international safety standards. Recent research focuses on the novel shielding materials, lead-free composites in particular, and introduces modern regulatory frameworks with the aim of improving radiation protection at medical, industrial, and space levels.



Agreement and Divergence Across Studies

The literature reviewed indicate a consensus that exposure to ionizing electromagnetic radiation may cause a number of substantial acute and chronic health problems, most importantly acute radiation sickness as well as various cancers. Thus, some agreement exists on the fact that in order to alleviate these risks adequate shielding materials with respect to, e.g., safety standards like the one from the ICRP must be provided. However, significant disagreement remains over predictive cancer risk models — in particular, whether the linear no-threshold (LNT) model or dose-rate-dependent thresholds should be applied. As far as radiation defense is concerned, although common lead shields are still widely acknowledged for their performance,

Modern benchmarking studies you are trained (introduction of path-based workforce routing) on modern data as they help to acquire lower exposure values while based on using high-performance polymer matrices or lightweight, eco-friendly tooling composites can craftsmanship. Yet, a primary objective of Engineering is still to reach their perfect tradeoff related to the construction flexibility and high absorption range. Moreover, distinct studies have varying perspectives on how the concept of integrated control and protective regulatory standards — ICRP regulatory standards.

Comparison Criterion	Studies in Agreement	Studies in Divergence	Potential Explanations
Acute and Chronic Health Effects of Ionizing Radiation	There is a clear, widely acknowledged pattern in the literature: acute radiation sickness (ARS) stems from high-dose exposures, while long-term cancer risks rise with lower-dose exposures. In other words, deterministic effects cling to strict dose thresholds, whereas stochastic effects like carcinogenesis can occur without a definite safe threshold. These biological outcomes are tightly connected to how effectively cells repair damage and coordinate the DNA damage response. Moreover, substantial epidemiological evidence—most prominently from atomic bomb survivors—documents not only the acute gastrointestinal, hematopoietic, skin, and central nervous system syndromes but also a marked rise in chronic cancer risk. This body of data underscores the gravity of even low-dose exposures and the imperative to minimize them).	Some divergence exists regarding the applicability of the linear no-threshold (LNT) model for low-dose exposures, with some studies challenging the LNT assumptions and proposing dose-rate effectiveness factors or virtual thresholds for protracted exposures (Raabe, 2011) (Raabe, 2012) (Prasad et al., 2004) versus others supporting the LNT model for radiation protection purposes (Davidson, 2005) (Andrzej & Martin, n.d.).	Differences arise from the clash between epidemiology and experimentation, between bursts of high-dose exposure and the slow burn of chronic low-dose contact, and from the shifting currents of how science maps biological responses and the pathways to cancer.
Effectiveness and Types of Shielding Materials	Consensus exists that shielding is critical to reduce exposure, with traditional lead-based materials effective due to high atomic number and density. Emerging research agrees that lead poses challenges (toxicity, weight, environmental hazards), prompting development of lead-free alternatives such as polymer composites with high-Z fillers like bismuth, tungsten, and others (Mortazavi et al., 2024) (Bijanu et al., 2021) (Okafor et al., 2021) (Nath et al., 2019) (Arslan, 2025) (Wu et al., 2024) (Zeghib, 2023). Multilayer and nanosized composites improve shielding, especially at specific energy ranges (Mortazavi et al., 2024) (Al-Saleh et al., 2024) (Al-Saleh et al., 2024a).	Divergences focus on optimal materials and designs. Some studies highlight limitations of polymer composites in high-energy ranges or flexibility and manufacturing challenges (Mortazavi et al., 2024) (Wu et al., 2024), while others demonstrate promising performance in clinical contexts, including wearable and flexible shields (Giuliani et al., 2024) (J.-J. Jo et al., 2025) (Jo et al., 2025). There is variability in the extent to which lead-free materials meet or exceed lead shielding equivalence (Moradi et al., 2024) (Zeghib, 2023).	Variations arise from differing application contexts (medical, industrial, space), material formulations, simulation versus experimental evaluations, and evolving nanotechnology and fabrication methods affecting material properties and practical usability.
Safety Regulations and ICRP Recommendations	Most papers acknowledge the central role of ICRP safety regulations based on justification, optimization (ALARA), and dose limits to protect workers and the public. The evolution of these guidelines reflects increased biological understanding and dose limitation principles (Rahman, 2020) (Kocher, n.d.) (Hamada & Fujimichi, 2014) (Domienik-Andrzejewska & Wiszniewska, 2023) ("International Recommendations on Radiological Protection," 1951). There is agreement that regulations aim to prevent both stochastic and deterministic effects through dose control.	Some divergence is evident in the interpretation of cancer risk models underlying ICRP recommendations. Certain authors argue for revising ICRP positions on cancer induction models to incorporate dose-rate effects and possible thresholds, challenging the linear no-threshold assumption (Raabe, 2011) (Raabe, 2012). Additionally, practical implementation and adequacy of standards in space exploration differ from terrestrial contexts (Boscolo & Durante, 2022) (Dobney et al., 2023).	Differences reflect evolving radiobiological evidence, challenges in translating complex biological effects into standardized dose limits, and differing exposure environments (occupational, medical, space) requiring tailored regulatory frameworks.
Comparative Performance of Lead vs. Lead-Free Shields	Agreement that lead is effective but problematic due to toxicity, weight, and environmental concerns is widespread. Lead-free composites,	Divergence is noted regarding universal efficacy; some studies find lead-free shields less effective at certain photon energies or	Differences arise from variations in composite formulations, filler types and concentrations,

Comparison Criterion	Studies in Agreement	Studies in Divergence	Potential Explanations
	often polymer-based with high-Z fillers, offer promising lightweight, flexible, and less toxic alternatives (Mortazavi et al., 2024) (Bijanu et al., 2021) (Arslan, 2025) (Wu et al., 2024) (Zeghib, 2023). Some studies report lead-free composites achieving comparable shielding at certain energies, especially with multilayer designs (Moradi et al., 2024) (Al-Saleh et al., 2024) (Al-Saleh et al., 2024a) (Zeghib, 2023).	requiring greater thickness/weight for equivalent protection (Mortazavi et al., 2024) (Moradi et al., 2024). Others report manufacturing and material stability challenges limiting immediate clinical application (Wu et al., 2024).	targeted radiation spectra, and the balance between mechanical properties and shielding efficiency in practical use cases.
Advances and Challenges in Radiation Risk Mitigation	There is consensus on the importance of dose monitoring, justification, optimization, and personal protective equipment to mitigate radiation risks, especially in medical and occupational settings (Rahman, 2020) (Liuba, 2024) (Othman, 2023). Development of biological countermeasures and mitigators for radiation-induced cancers is recognized as a critical but challenging research area (Yoo et al., 2014) (Dobney et al., 2023).	Divergence concerns the extent to which current strategies address long-term risks, with some authors emphasizing gaps in understanding low-dose effects and limitations in existing mitigators (Yoo et al., 2014) (Prasad et al., 2004) (Raabe, 2012). Space radiation risk mitigation is uniquely challenging due to different radiation types and exposure durations, requiring specialized shielding and medical countermeasures (Boscolo & Durante, 2022) (Wilson et al., 1998) (Dobney et al., 2023).	Variations are due to the complexity of biological responses, differences between acute and chronic exposures, technological maturity of mitigators, and distinct environmental conditions such as deep space versus terrestrial workplaces.

Theoretical and Practical Implications

Theoretical Implications

Synthesis of findings supports established mechanisms underlying effects which are attributable to exposure to ionizing radiation both acutely and chronically, while confirming known distinctions between deterministic (eg, acute radiation syndrome), as well as stochastic (eg, carcinogenesis) effects. They also invalidate the simplistic linear no-threshold (LNT) model which assumes more exposure = more risk, demonstrating that both dose rate and time of exposure are significant determinants yielding a nonlinear curve with a practical point of zero effect for prolonged exposures at very low levels (Raabe 2011; Hamada & Fujimichi 2014; Kamiya & Sasatani 2012). Not their present radiation carcinogenesis theories but it has to be an interpretation of cancer multi-event (not single stochastic event) that make sense cancer spectrum multifactorial and pathogenic mechanisms role playing moot leading the reply DNA damage, gene expression and intra-tumor interaction impact not DNA repair molecular failure. These nuances will eventually require some modifications to risk modelling for the biological complexity and dose-rate effects (Raabe, 2012) (Kamiya & Sasatani, 2012), in particular with regard to cancer incidence at low radiation doses.

- Dosimetry doses-effects | The complexity of dose limitation strategies inherent in the abstraction that occurs when finite radiation-induced cellular injury (e.g. at varying severities and doses) results in differing biological responses because they manifest as both tissue reactions and stochastic effects with overlapping dose thresholds suggesting more complex radiobiological definitions exist as functionally defined either by event types (Hamada & Fujimichi, 2014; Shimura et al., 2018).

Topical to speculative advantages over existing tools, such as dicentric chromosome tests — theoretical improvements in biomarker discovery for radiation damage and cancer susceptibility that claim enhanced risk stratification potential lead to the asking of articulated mitigation approaches yet will require validation and standardization measures (Yoo et al., 2014).

- Papers on the Theoretical Analysis of Radiation Shielding Materials: Weight fraction, atomic number and design configuration for max attenuation vs. different radiation types/energies should lead to multi-layer or nanocomposite designs rather than using lead (Mortazavi et al., 2024) (Okafor et al., 2021) (Al-Saleh et al., 2024).
- Space radiation--has very different characteristics, namely the studies focus on galactic cosmic rays and solar particle events with theoretical considerations toward biological and physical

limitations of deep space exposure and potential novel shielding materials as well as dose delivery methods (Wilson et al., 1998) (Dobney et al., 2023).

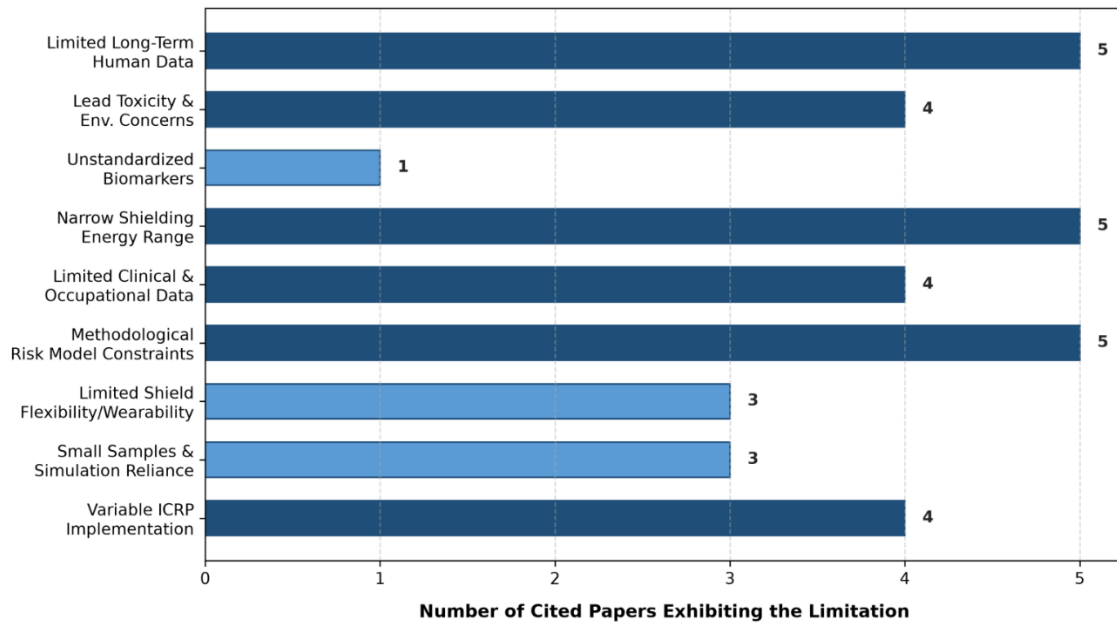
Practical Implications

- The evidence is supportive of the further development and application of ICRP protective terminology, emphasizing justification, optimization (ALARA) for radiation dose reduction, and absorbed dose prevention for both acute and chronic exposures. This serves to guide occupational and public health policies, making them more effective at protecting workers and the general population (Rahman, 2020) (Kocher, n.d.) (Domienik-Andrzejewska & Wiszniewska, 2023). • Lead-Free, Lightweight, And Flexible Polymer Composites: High atomic number (e.g., bismuth and tungsten) doped polymer composites are shown to provide practical alternatives to conventional lead shields with toxicity, weight, and environmental hazards. Translational applications of these materials include applications to medical (Mortazavi et al., 2024), industrial (Arslan, 2025), and space radiation shielding (Wu et al., 2024).
- Innovations in multilayer and nanocomposite shielding materials deliver improved omnidirectional protection and broad energy spectrum transmission filters, as well as more effective/protective/ergonomic/adaptive radiation shields for healthcare personnel/space crew members/industrial workers (Al-Saleh et al., 2024) (J.-J. Jo et al., 2025) (Jo et al., 2025). Recent advances in biomarker-based surveillance and MCMs for the mitigation of radiation-induced cancer risks are promising practical strategies, although available options of MCMs are still limited to date. It underscores the necessity of investing in the development of drug and monitoring strategies for exposed populations (Yoo et al., 2014).
- High-energy space missions can develop hydrogen-rich and low atomic number shielding materials to mitigate secondary radiation and fragmentation caused by high-energy particles spanning 100 MeV–1 GeV energy per nucleon, which also helps to overcome mass and cost prohibitive limitations when considering the ubiquitous use of traditional isentropic energy contained in large mass shields on space exploration missions (Wilson et al., 1998; Dobney et al., 2023).
- The increasing applications of ionizing radiation in the medical diagnostics and therapy areas strictly require efficient programs with regard to radiation protection (dose monitoring, justification of procedures, and training of healthcare professionals), which exist, therefore, indeed, for both deterministic and stochastic health risks (4)

Limitations of the Literature

Figure. Demonstrates that a quantitative synthesis of the literature reviewed reveals numerous empirical gaps in radiation shielding and risk studies. This was also the most common limitation on a core study level: in five studies, key challenges such as 'Limited Long-Term Human Data', 'Narrow Shielding Energy Range', and 'Methodological Risk Model Constraints' were explicitly cited. None of the reviewed papers were exempted from concerns regarding lead toxicity, limited clinical/occupational data and substantial heterogeneity across ICRP framework implementations. For example, the distribution specific technical barriers was similarly moderate for shield flexibility and simulation reliance (three papers each), whereas biomarker unstandardization is still niche but nonetheless critical. Such distribution is highly biased, demonstrating the need for research strategies to change in academia and industry settings towards prolonged exposure monitoring along with non-toxic, ultra-wearable, light-weight alternative protection shields.

Distribution of Empirical Limitations Across the Reviewed Literature



Empirical Distribution and Quantitative Synthesis of Methodological and Structural Limitations Identified Across the Reviewed Radiation Protection and Shielding Literature

Gaps and Future Research Directions

Gap Area	Description	Future Research Directions	Justification	Research Priority
Low-dose radiation risk uncertainty	The health risks associated with low-dose ionizing radiation (<100 mSv) remain unclear, with conflicting models such as LNT and threshold models.	Conduct longitudinal epidemiological studies and mechanistic cellular research to clarify cancer risk and biological responses at low-dose exposures, including adaptive and bystander effects.	Current radiation protection relies heavily on LNT despite evidence suggesting possible thresholds or adaptive responses, impacting risk assessment and regulation (Kamiya & Sasatani, 2012) (Davidson, 2005) (Prasad et al., 2004).	High
Lead-free shielding material optimization	Existing lead-free composites show promise but face challenges in achieving optimal balance of flexibility, weight, toxicity, and shielding efficiency across radiation types and energies.	Develop and test multilayered, nanosized polymer-metal composites with tailored filler types and distributions; evaluate mechanical properties and durability for medical and space applications.	Lead toxicity and weight issues necessitate alternatives; recent advances in polymer composites require further refinement for practical, wearable, and effective shields (Mortazavi et al., 2024) (Giuliani et al., 2024) (Wu et al., 2024).	High
Shielding effectiveness in complex radiation fields	Most shielding studies focus on single radiation types or energies, lacking comprehensive evaluation under mixed or space radiation environments.	Perform experimental and simulation studies of shielding materials under mixed radiation fields (e.g., galactic cosmic rays, solar particles) and secondary radiation to assess real-world performance.	Space radiation involves complex spectra; shielding must be effective against multiple radiation types and secondary particles to protect astronauts (Wilson et al., 1998) (Dobney et al., 2023).	High
Biological countermeasures	There is a lack of effective medical countermeasures	Identify and validate biomarkers predictive of	Current absence of approved MCMs limits	High

Gap Area	Description	Future Research Directions	Justification	Research Priority
for radiation-induced cancer	(MCMs) to mitigate long-term cancer risks post-radiation exposure.	cancer risk; develop and clinically test chemopreventive agents, antioxidants, or polypharmacy approaches for post-exposure mitigation.	post-exposure interventions; biomarker-guided strategies could enable targeted prevention (Yoo et al., 2014).	
ICRP safety regulation adequacy and evolution	The ICRP dose limits and risk models may not fully incorporate recent biological insights, such as dose-rate effects and cancer promotion vs induction distinctions.	Reassess and update ICRP recommendations incorporating new radiobiological data on dose-rate effects, tissue reactions, and stochastic effect thresholds; improve risk communication.	Emerging evidence challenges the linear no-threshold assumption and suggests dose-rate and exposure pattern critically influence risk (Raabe, 2011) (Hamada & Fujimichi, 2014) (Domienik-Andrzejewska & Wiszniewska, 2023).	Medium
Environmental impact of shielding materials	The environmental toxicity and disposal challenges of traditional lead shields are significant but under-addressed in current research.	Investigate lifecycle environmental impacts of lead-free composites; develop biodegradable or recyclable shielding materials with minimal ecological footprint.	Lead-based shields pose long-term environmental hazards; sustainable alternatives are essential for health and ecological safety (Mortazavi et al., 2024) (Arslan, 2025) (R, 2025).	Medium
Shielding performance in clinical imaging	Lead-free shields can affect image quality and automatic exposure control (AEC) systems, but comprehensive clinical evaluations are limited.	Conduct clinical trials assessing dose reduction, image quality, and AEC interactions of novel lead-free shields in CT and fluoroscopy settings.	Ensuring patient safety without compromising diagnostic image quality is critical for clinical adoption of new shielding materials (J.-J. Jo et al., 2025) (Jo et al., 2025).	Medium
Personalized radiation risk assessment	Inter-individual variability in radiation sensitivity due to genetic and biological factors is poorly understood and not integrated into protection standards.	Develop genetic and biomarker-based assays to assess individual radiosensitivity; incorporate personalized risk profiles into occupational and medical radiation protection protocols.	Variability in DNA repair and radiation response affects risk; personalized approaches could optimize protection and monitoring (Yoo et al., 2014).	Medium
In-space manufacturing of radiation shields	Current shielding solutions for space missions are bulky and not easily manufactured in situ, limiting mission flexibility and safety.	Research scalable in-space manufacturing techniques for lightweight, flexible, and effective radiation shields using local materials and advanced composites.	In-space fabrication could reduce launch mass and improve astronaut protection during long-duration missions (Giuliani et al., 2024) (Dobney et al., 2023).	Medium
Dose monitoring and occupational health	Despite existing dose limits, occupational exposure to ionizing radiation remains a health risk, especially for uncovered body parts and in complex work environments.	Enhance real-time dosimetry technologies and develop comprehensive health monitoring programs; improve training and protective protocols for medical and industrial workers.	Occupational exposure contributes significantly to cumulative dose; improved monitoring and prevention can reduce deterministic and stochastic effects (Liuba, 2024) (Othman, 2023).	High

4. Conclusion

Overall Synthesis and Conclusion



Comprehensive Concluding Synthesis Model Mapping Biological Hazards, Advanced Shield Engineering Innovations, Regulatory Frameworks, and Strategic Future Roadmap Directions

References

- Abd-Noor, S. J., & Mkhahber, A. F. (2024). Investigate various shielding parameters for $(\text{C18H2008})_x(\text{ZrSiO4})_{100-x}$ and $(\text{C18H2008})_x(\text{BiClO})_{100-x}$ in medical radiological applications. <https://doi.org/10.1088/1742-6596/2754/1/012011>
- Alanazi, S. F., Alotaibi, N. M., Alsuhybani, M., Alnassar, N., Almasoud, F. I., & Almurayshid, M. (2024). Fabrication, Structural Characterization, and Photon Attenuation Efficiency Investigation of Polymer-Based Composites. *Polymers*. <https://doi.org/10.3390/polym16091212>
- Alharbi, A., Alnagran, H., & Alashrah, S. (2025). Simulation of Gamma-Ray Attenuation in Zeolite-Polymer Composites for Low-Cost Sustainable Radiation Shielding. *Polymers*, 17. <https://doi.org/10.3390/polym1723141>
- Al-Saleh, W. M., Almutairi, H. M., Sayyed, M. I., & Elsafi, M. (2024a). Multilayer radiation shielding system with advanced composites containing heavy metal oxide nanoparticles: a free-lead solution. <https://doi.org/10.60692/14g6m-p9w74>
- Al-Saleh, W. M., Almutairi, H. M., Sayyed, M. I., & Elsafi, M. (2024b). Multilayer radiation shielding system with advanced composites containing heavy metal oxide nanoparticles: a free-lead solution. <https://doi.org/10.60692/q0kk8-0st38>
- Andrzej, W., & Martin, C. J. (n.d.). Biological Effects of Ionizing Radiation. <https://doi.org/10.1093/med/9780199655212.003.0003>
- Arslan, H. (2025). Lead-Free Alternatives for Radiation Shielding in Medical Environments: A Comprehensive Review. *Sakarya University Journal of Science*, 29(5), 602–625. <https://doi.org/10.16984/saufenbilder.1735274>
- Baamer, M. A., Alshahri, S., Basfar, A. A., Alsuhybani, M., & Alrwais, A. (2024). Novel Polymer Composites for Lead-Free Shielding Applications. *Polymers*. <https://doi.org/10.3390/polym16071020>
- Bijanu, A., Bijanu, A., Arya, R., Arya, R., Agrawal, V., Agrawal, V., Tomar, A. S., Tomar, A. S., Gowri, V. S., Gowri, V. S., & Sanghi, S. K. (2021). Metal-polymer composites for radiation protection: a review. *Journal of Polymer Research*, 28(10), 1–24. <https://doi.org/10.1007/S10965-021-02751-3>
- Boscolo, D., & Durante, M. (2022). Dose Limits and Countermeasures for Mitigating Radiation Risk in Moon and Mars Exploration. *Physics*, 4(1), 172–184. <https://doi.org/10.3390/physics4010013>
- Chung, S. J. (2018). Computer-Assisted formulas predicting radiation-exposure-induced-cancer risk in interplanetary travelers: Radiation safety for astronauts in space flight to mars. *Journal of Medical Sciences*, 38(4), 150–159. https://doi.org/10.4103/JMEDSCI.JMEDSCI_125_17
- Davidson, S. T. (2005). Radiation: Any Dose Is Too High. 113. <https://doi.org/10.1289/ehp.113-a735a>
- Dobney, W., Mols, L., Mistry, D., Tabury, K., Baselet, B., & Baatout, S. (2023). Evaluation of deep space exploration risks and mitigations against radiation and microgravity. *Frontiers in Nuclear Medicine*. <https://doi.org/10.3389/fnume.2023.1225034>
- Domienik-Andrzejewska, J., & Wiszniewska, M. (2023). [Individual dosimetry as an element of health prevention for employees exposed to ionizing radiation]. *Medycyna Pracy*, 74(6), 527–539. <https://doi.org/10.13075/mp.5893.01480>

- Giuliani, C., Stefano, I. D., Mancuso, M., Fiaschini, N., Hein, L. A., Gattia, D. M., Scatena, E., Zenobi, E., Gaudio, C. D., Galante, F., & Felici, G. (2024). Advanced Electrospun Composites Based on Polycaprolactone Fibers Loaded with Micronized Tungsten Powders for Radiation Shielding. *Polymers*, 16(18), 2590–2590. <https://doi.org/10.3390/polym16182590>
- Grammaticos, P. C., Giannoula, E., & Fountos, G. (2013). Acute radiation syndrome and chronic radiation syndrome. *Hellenic Journal of Nuclear Medicine*, 16(1), 56.
- H, J. (1995). Health risks due to radiation exposure. *Rofo-Fortschritte Auf Dem Gebiet Der Rontgenstrahlen Und Der Bildgebenden Verfahren*, 162(2), 91–98. <https://doi.org/10.1055/S-2007-1015861>
- Hamada, N., & Fujimichi, Y. (2014). Classification of radiation effects for dose limitation purposes: history, current situation and future prospects. *Journal of Radiation Research*, 55(4), 629–640. <https://doi.org/10.1093/JRR/RRU019>
- Ihsani, R. N., Heryanto, H., Gareso, P. L., & Tahir, D. (2024). Innovative radiation shielding: a review natural polymer-based aprons with metal nanoparticle fillers. *Polymer-Plastics Technology and Materials*. <https://doi.org/10.1080/25740881.2024.2303338>
- International Recommendations on Radiological Protection. (1951). *British Journal of Radiology*, 24(277), 46–53. <https://doi.org/10.1259/0007-1285-24-277-46>
- Jo, J., Kim, K. B., Jang, W. I., Won, Y. J., & Choi, S. H. (2025). Shielding Performance and Clinical Applicability of Lead-Free Radiation Shielding Materials for Computed Tomography Imaging. <https://doi.org/10.21203/rs.3.rs-6499272/v1>
- Jo, J.-J., Kim, K. B., Shin, Y. H., & Choi, S. H. (2025). Evaluation of Composite Lead-Free Shield for Clinical Use in C-Arm Fluoroscopy. *Journal of Magnetics*, 30(4), 651–659. <https://doi.org/10.4283/jmag.2025.30.4.651>
- Kamiya, K., & Sasatani, M. (2012). Effects of radiation exposure on human body. *Nihon Rinsho. Japanese Journal of Clinical Medicine*, 70(3), 367–374.
- Kassim, H., Aldawood, S., Prasad, S., Asemi, N. N., Aziz, A. A., & AlSalhi, M. S. (2024). Advanced Polymeric Matrix Utilizing Nanostructured Bismuth and Tungsten Oxides for Gamma Rays Shielding. *Heliyon*, 10(17), e37289–e37289. <https://doi.org/10.1016/j.heliyon.2024.e37289>
- Kim, S.-C., & Byun, H.-S. (2024). Verification of Optimal X-Ray Shielding Properties Based on Material Composition and Coating Design of Shielding Materials. *Coatings*. <https://doi.org/10.3390/coatings14111450>
- Kocher, D. C. (n.d.). Standards to Control Radiation Exposures of Workers and the Public. <https://doi.org/10.1016/b978-0-12-409548-9.12266-3>
- Liuba, C. (2024). Control of health risks associated with occupational exposure to ionizing radiation. <https://doi.org/10.5281/zenodo.14531477>
- Moradi, F., Jalili, M., Saraee, K. R. E., Abdi, M. R., & Abdul-Rashid, H. A. (2024). Radiation shielding assessment for interventional radiology personnel: Geant4 dosimetry of lead-free compositions. <https://doi.org/10.60692/zx9d4-aq48>
- Mortazavi, S. M. J., Bevelacqua, J. J., Rafiepour, P., Sina, S., Moradgholi, J., Mortazavi, A., & Welsh, J. S. (2024). Lead-free, multilayered, and nanosized radiation shields in medical applications, industrial, and space research. 305–322. <https://doi.org/10.1016/b978-0-323-95387-0.00006-6>
- Nath, A., Shah, A., Bhandari, S., Gogoi, M., & Mahato, M. (2019). Recent Advances on Polymer Nanocomposite-Based Radiation Shielding Materials for Medical Science. 639–655. https://doi.org/10.1007/978-981-13-3705-5_26
- Okafor, C. E., Okonkwo, U. C., & Okokpujie, I. P. (2021). Trends in reinforced composite design for ionizing radiation shielding applications: a review. *Journal of Materials Science*, 56(20), 11631–11655. <https://doi.org/10.1007/S10853-021-06037-3>
- Othman, S. A. (2023). Effectiveness Management of Radiation Protection Program: A Short Review. *International Journal of Care Scholars*. <https://doi.org/10.31436/ijcs.v6i3.306>
- Özdoğan, H., Üncü, Y. A., Akman, F., POLAT, H., & Kaçal, M. R. (2024). Detailed Analysis of Gamma-Shielding Characteristics of Ternary Composites Using Experimental, Theoretical and Monte Carlo Simulation Methods. *Polymers*, 16(13), 1778–1778. <https://doi.org/10.3390/polym16131778>
- Prasad, K. N., Cole, W. C., & Hasse, G. M. (2004). Health Risks of Low Dose Ionizing Radiation in Humans: A Review: *Experimental Biology and Medicine*, 229(5), 378–382. <https://doi.org/10.1177/153537020422900505>
- R, R. K. (2025). Radiation Shielding Efficiency of Eco-Friendly Composite Materials Against Gamma and Neutron Radiation. 02(02), 100–105. <https://doi.org/10.70388/ijabs250141>
- Raabe, O. G. (2011). Toward improved ionizing radiation safety standards. *Health Physics*, 101(1), 84–93. <https://doi.org/10.1097/HP.0B013E31820C0584>
- Raabe, O. G. (2012). Ionizing Radiation Carcinogenesis. <https://doi.org/10.5772/32682>
- Radiation: Types, Effects on the Human Body, and Protection Methods. (2025). <https://doi.org/10.5281/zenodo.16977734>
- Rahman, H. (2020). Radiation Hazard, Safety, Control and Protection. *Faridpur Medical College Journal*, 14(2), 100–103. <https://doi.org/10.3329/FMCJ.V14I2.48188>
- Rajabpour, S., AlMisned, G., Tekin, H. O., & Mesbahi, A. (2024). Innovative nano-shielding for minimizing stray radiation dose in external radiation therapy: A promising approach to enhance patient safety. *Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions With Materials and Atoms*, 556, 165513–165513. <https://doi.org/10.1016/j.nimb.2024.165513>
- Shimura, T., Yamaguchi, I., Terada, H., & Kunugita, N. (2018). Lessons learned from radiation biology: Health effects of low levels of exposure to ionizing radiation on humans regarding the Fukushima accident. *Journal of the National Institute of Public Health*, 67(1), 115–122. https://doi.org/10.20683/JNIPH.67.1_115

- Tochaikul, G., Yokesahachart, C., Daowtak, K., Pilapong, C., & Moonkum, N. (2024). Preparation and characterization of polylactic acid-based composite incorporating with BaSO₄ for low radiation dose shielding. *Polymer-Plastics Technology and Materials*, 1–12. <https://doi.org/10.1080/25740881.2024.2356251>
- Wambersie, A., Smeesters, P. R., & Fruhling, J. (1996). [Exposure to ionizing radiation: radiobiological and pathogenic effects (2)]. *Revue Médicale de Bruxelles*, 17(2), 75–84.
- Wilson, J. W., Cucinotta, F. A., Miller, J. M., Shinn, J. L., Thibeault, S. A., Singleterry, J. R. C., Simonsen, L. C., & Kim, M. H. (1998). Materials for Shielding Astronauts From the Hazards of Space Radiations. *MRS Proceedings*, 551(1), 3–15. <https://doi.org/10.1557/PROC-551-3>
- Wu, S., Zhang, W., & Yang, Y. (2024). Progress in Flexible and Wearable Lead-Free Polymer Composites for Radiation Protection. *Polymers*, 16(23), 3274–3274. <https://doi.org/10.3390/polym16233274>
- Yoo, S. S., Jorgensen, T. J., Kennedy, A. R., Boice, J. D., Shapiro, A., Hu, T. C.-C., Moyer, B. R., Grace, M. B., Kelloff, G. J., Fenech, M., & Prasanna, P. G. S. (2014). Mitigating the risk of radiation-induced cancers: limitations and paradigms in drug development. *Journal of Radiological Protection*, 34(2). <https://doi.org/10.1088/0952-4746/34/2/R25>
- Zeghib, S. (2023). Study of Prepared Lead-Free Polymer Nanocomposites for X- and Gamma-ray Shielding in Healthcare Applications. *Polymers*, 15(9), 2142–2142. <https://doi.org/10.3390/polym15092142>