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Evaluating The Short- And Long-Term Effects Of Medical And Environmental Radiation Exposure On Population Health: A Global Evidence-Based Review Of Risks, Monitoring, And Mitigation Approaches

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Abstract

Radiation exposure from medical and environmental sources represents a significant public health concern due to its potential to cause acute biological damage and chronic diseases. This systematic review synthesizes global evidence on short-term and long-term health effects associated with ionizing and non-ionizing radiation exposure. Data were gathered from epidemiological, clinical, environmental, and occupational studies published between 2010 and 2025. Findings demonstrate that medical imaging—particularly CT scans—remains a major contributor to artificial radiation exposure, while environmental sources such as radon, ultraviolet radiation, and nuclear accidents continue to pose persistent global risks. Short-term health effects include acute radiation syndrome, inflammation, and cellular dysfunction, whereas long-term consequences encompass carcinogenesis, cataracts, cardiovascular disease, and heritable genetic mutations. The review further examines global dose monitoring frameworks and evaluates mitigation strategies, including dose optimization, environmental surveillance, public-health education, and international regulatory standards. Evidence highlights the need for improved risk–benefit communication, reduced unnecessary imaging, strengthened occupational protection, and global harmonization of radiation safety policies. This comprehensive evaluation supports efforts to balance technological benefits with population safety in healthcare and environmental contexts.

Keywords: radiation exposure, ionizing radiation, population health, medical imaging risks, carcinogenesis, environmental radiation, radon, UV radiation, dose monitoring, mitigation strategies.

Introduction

Radiation exposure is a pervasive global issue that affects nearly all populations through both natural and artificial sources. Its dual role—as a crucial medical tool and a potential biological hazard—has prompted extensive research on its effects at individual and population levels. Ionizing radiation, which includes X-rays, gamma rays, and radioactive particles, has sufficient energy to alter DNA structures, resulting in acute tissue damage, genetic mutations, and long-term carcinogenic processes (Hall & Brenner, 2020). Non-ionizing radiation, such as ultraviolet (UV) rays and electromagnetic fields (EMFs), also contributes to public health risks, particularly skin cancer and ocular damage (WHO, 2023).

The proliferation of medical imaging technologies has significantly increased artificial radiation exposure. CT scanning alone accounts for nearly two-thirds of all diagnostic radiation delivered in clinical settings worldwide (Berrington de González et al., 2016). Although radiological imaging has revolutionized diagnosis and treatment pathways, concerns persist regarding unnecessary imaging, cumulative radiation burden, and insufficient utilization of dose optimization technologies. Meanwhile, environmental radiation—from radon gas, cosmic rays, contaminated soil, and nuclear energy byproducts—poses additional, often chronic exposure risks across global populations.

Short-term effects of high-dose radiation exposure, such as acute radiation syndrome, are well documented. However, increasing attention has been directed toward long-term outcomes of low-dose exposure, including thyroid cancer, leukemia, solid tumors, cardiovascular disease, and heritable genetic effects. Evidence from major epidemiological studies, such as atomic bomb survivor cohorts and nuclear disaster follow-ups, has established clear dose-response relationships even at relatively low exposure levels (Ozasa et al., 2019). Occupational exposure remains a concern among radiology workers, nuclear plant employees, and airline crews, necessitating structured monitoring programs and stringent safety protocols.

Given the growing dependence on radiation-based technologies and the increasing environmental exposure associated with industrial expansion, a global evidence-based review is essential. This review evaluates short- and long-term health effects, identifies population groups at heightened risk, and assesses existing monitoring frameworks. It also provides recommendations for mitigation strategies that can guide healthcare systems, regulators, and policymakers.

Types of Radiation Exposure (Medical vs. Environmental)

Radiation exposure is broadly categorized into **medical** and **environmental** sources, each contributing differently to the cumulative radiation burden on individuals and populations. Understanding these two categories is essential for assessing exposure patterns, evaluating associated health risks, and formulating appropriate regulatory and mitigation strategies.

- **Medical Radiation Exposure**

Medical radiation represents the largest artificial source of ionizing radiation globally. With technological advancements and increased reliance on imaging for diagnostic and therapeutic purposes, the contribution of medical procedures to overall radiation exposure has grown substantially over the past three decades. Common sources of medical ionizing radiation include X-ray radiography, computed tomography (CT), interventional fluoroscopy, mammography, and nuclear medicine procedures such as PET and SPECT scans. CT imaging in particular delivers doses that can be 100–500 times higher than conventional X-rays, making it a significant contributor to cumulative patient exposure.

Medical radiation is intentionally administered to yield clinical benefits such as early diagnosis, treatment planning, or disease monitoring. However, the expansion of imaging services has led to substantial concerns regarding overuse, unnecessary repeat scans, and patient exposure without adequate justification. Studies estimate that between 20–30% of CT scans may be clinically avoidable, raising public health concerns about cumulative, low-dose exposure across large populations.

In therapeutic contexts, such as radiation therapy for cancer patients, exposure levels are significantly higher and targeted to tumor tissues. Although the benefits often outweigh the risks, surrounding normal tissues may still receive unintended doses, contributing to potential long-term side effects. To address these risks, global standards such as the ALARA principle (As Low As Reasonably Achievable) have been widely adopted to minimize dose intensity while maintaining diagnostic quality. Emerging innovations—including automated dose-control technologies, AI-driven optimization algorithms, real-time fluoroscopy monitoring, and standardized diagnostic reference levels (DRLs)—provide additional layers of protection against excessive medical exposure.

- **Environmental Radiation Exposure**

Environmental radiation exposure stems from natural and anthropogenic sources that individuals encounter in daily life. Natural background radiation—constituting nearly 80% of total population exposure—includes cosmic rays, terrestrial radiation from radioactive materials in soil, and radon gas, which is the second leading cause of lung cancer globally after smoking. Radon exposure varies geographically and is influenced by soil composition, building structure, and ventilation patterns.

Ultraviolet (UV) radiation from the sun, a form of non-ionizing radiation, is another significant environmental exposure source. It is strongly linked to skin cancers, premature aging, and ocular damage such as cataracts. Environmental UV exposure is influenced by latitude, altitude, outdoor occupational activities, and behavioral factors such as sunscreen use.

Anthropogenic environmental radiation arises from nuclear power generation, medical waste, industrial radiography, research facilities, and past nuclear accidents (e.g., Chernobyl, Fukushima). While regulatory frameworks control most industrial radiation sources, accidents and improper waste management pose episodic but severe risks.

Modern lifestyles have also increased non-ionizing radiation exposure through widespread use of mobile phones, Wi-Fi routers, radiofrequency devices, and electromagnetic fields (EMFs). Although the biological risks of EMFs remain debated, ongoing research continues to monitor potential long-term health implications.

In conclusion, Together, medical and environmental radiation exposures form a complex landscape of intentional and incidental dose pathways. Medical sources provide essential health benefits but require careful justification and optimization, while environmental sources—largely unavoidable—necessitate robust monitoring and public health interventions. Understanding both categories is crucial for accurate risk assessment, global radiation protection policies, and long-term population health planning.

Short-Term Biological Effects of Radiation

Short-term biological effects of radiation arise primarily from acute exposure to moderate or high doses delivered over a short time period. These effects are known as deterministic (non-stochastic) effects, meaning their severity increases with dose and they occur once a specific threshold is exceeded. Understanding these early biological responses is essential for clinical management, public health preparedness, and radiation safety planning across medical, industrial, and environmental settings.

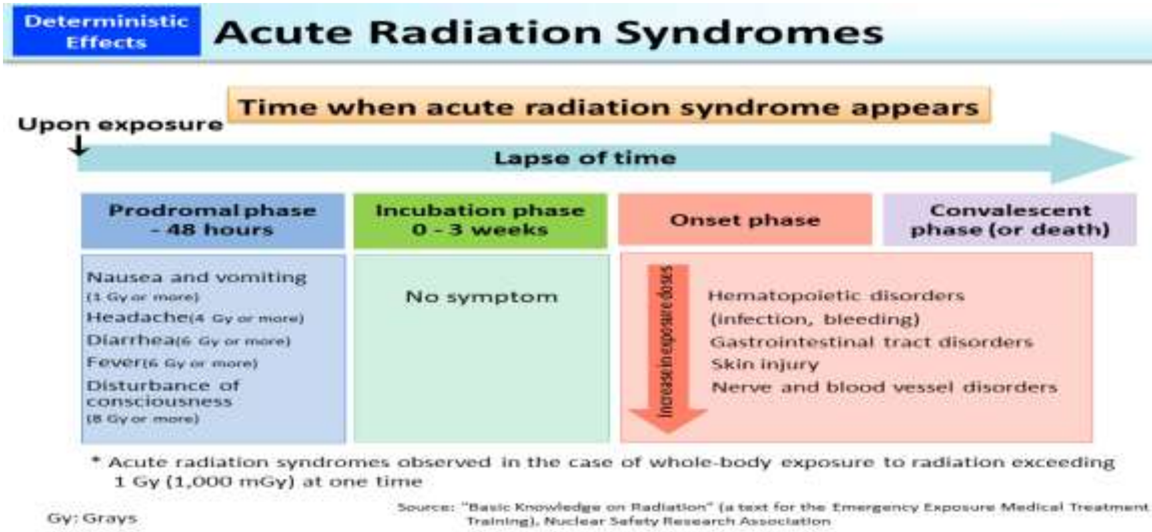

Figure 1. Short-Term Biological Effects of Radiation

Ionizing radiation interacts with human tissues by depositing energy that disrupts the molecular structure of cells, particularly DNA, leading to single-strand and double-strand breaks, oxidative stress, and disruption of cellular homeostasis. When exposure is acute and intense, the damage surpasses the body's repair capacity, resulting in clinically observable symptoms. The rate at which cell types divide influences their sensitivity: rapidly dividing tissues (e.g., bone marrow, gastrointestinal lining, reproductive organs) are particularly vulnerable.

Acute Radiation Syndrome represents the most severe form of short-term biological injury following whole-body radiation exposure, typically at doses >1 Gy (1000 mSv). ARS progresses through four clinically recognized stages:

1. Prodromal Phase: Occurs within minutes to hours post-exposure. Symptoms include nausea, vomiting, anorexia, fatigue, and headache. The duration and intensity of these symptoms correlate with exposure dose.

2. Latent Phase: Symptoms temporarily subside, giving the false impression of recovery. However, underlying cellular damage continues to evolve, particularly in hematopoietic and gastrointestinal tissues.

3. Manifest Illness Phase: Depending on dose and exposure distribution, ARS may present as one or more subsyndromes:

- **Hematopoietic ARS (1–5 Gy):** Characterized by bone marrow suppression, leukopenia, anemia, thrombocytopenia, and increased infection risk. Without medical intervention, severe cases may be fatal due to hemorrhage or sepsis.
- **Gastrointestinal ARS (5–12 Gy):** Damage to intestinal crypt cells results in nausea, diarrhea, electrolyte imbalance, dehydration, and systemic infection. Survival is unlikely at higher ranges due to profound epithelial destruction.
- **Neurovascular ARS (>20–30 Gy):** The most severe form, involving cerebral edema, cardiovascular collapse, seizures, and coma. Death often occurs within 24–48 hours.

4. Recovery or Death Phase: Patients exposed to lower doses may recover with intensive medical support, including antibiotics, transfusions, and growth factors. Higher doses result in irreversible organ failure and mortality.

Localized or partial-body exposures—particularly during fluoroscopic procedures, industrial accidents, or radiotherapy misadministration—can lead to Cutaneous Radiation Syndrome. Early signs resemble thermal injury and include:

- Erythema
- Pruritus
- Transient edema
- Dry or moist desquamation
- Ulceration at higher doses

Unlike burns, radiation injuries evolve over weeks or months due to underlying microvascular damage and impaired tissue regeneration.

Ionizing radiation triggers acute inflammatory cascades through cytokine release (e.g., IL-6, TNF-α), leukocyte dysfunction, and oxidative stress. These responses contribute to:

- Fever
- Fatigue
- Localized pain
- Impaired wound healing

Short-term immune suppression is particularly evident in patients receiving radiotherapy, increasing vulnerability to infections.

Although diagnostic imaging uses relatively low doses, repeated or high-dose interventional procedures (e.g., CT perfusion scans, fluoroscopy-guided interventions) can cause transient biological responses such as:

- Temporary chromosomal aberrations

- Increased oxidative markers
- Mild skin irritation in prolonged fluoroscopy

These effects rarely progress to ARS but remain relevant for cumulative health monitoring.

Short-term radiation effects vary from mild and reversible to severe and life-threatening, depending on dose, exposure type, and individual susceptibility. Early recognition is crucial for timely intervention, particularly in industrial emergencies and nuclear incidents. Preventive strategies—including exposure monitoring, protective shields, and strict procedural protocols—remain essential to minimize early biological harm.

Long-Term Health Risks of Radiation Exposure

Long-term health risks associated with radiation exposure arise primarily from cumulative low-dose exposure or high-dose exposures with delayed clinical effects. Unlike short-term deterministic effects, long-term risks are generally stochastic, meaning their likelihood increases with dose, but severity does not. These risks evolve over years or decades, making them a major public health concern, especially as populations are increasingly exposed to radiation through medical imaging, environmental contamination, and occupational activities.

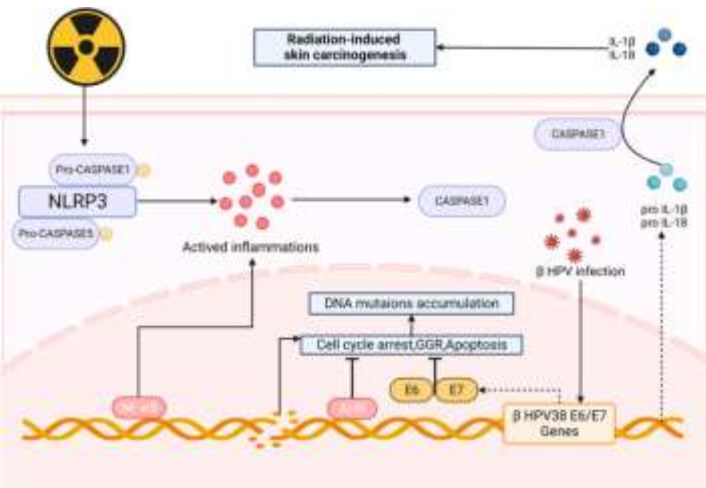

Figure 2. Long-Term Radiation Health Impact Pathway

Cancer is the most widely recognized long-term consequence of ionizing radiation. Radiation-induced carcinogenesis occurs through DNA damage, genomic instability, and disruption of cell-cycle regulation, eventually leading to malignant transformation. Evidence from large epidemiological studies—including atomic bomb survivors, nuclear industry workers, and medical radiation cohorts—demonstrates a linear no-threshold (LNT) dose–response model, suggesting that no dose is completely safe.

Common cancers associated with radiation exposure include:

- **Thyroid cancer:** Particularly high risk among children exposed to environmental or medical radiation.
- **Leukemia:** Radiation damages bone marrow stem cells, increasing leukemia risk within 2–10 years after exposure.
- **Breast cancer:** Especially associated with repeated chest imaging, radiotherapy exposure, and young age at exposure.
- **Lung cancer:** Intensified by radon exposure, smoking interactions, and occupational radioisotope inhalation.

- **Brain tumors:** Linked to therapeutic and diagnostic radiation, especially in pediatric patients.

Latency periods vary significantly across cancer types, often spanning 10–40 years, making early detection and lifetime monitoring essential for at-risk populations.

Emerging evidence indicates that radiation exposure—even at low to moderate doses (<2 Gy)—can increase the risk of cardiovascular and circulatory diseases. Damage to endothelial cells, chronic inflammation, and microvascular injury contribute to:

- **Radiation-induced heart disease (RIHD):** Including myocardial fibrosis, pericarditis, and coronary artery disease.
- **Stroke and cerebrovascular disease:** Resulting from endothelial dysfunction and arterial stiffening.
- **Accelerated atherosclerosis:** Observed in atomic bomb survivors and radiotherapy patients.

These findings highlight that radiation risks extend beyond cancer and affect long-term organ function.

Radiation-induced cataracts represent a delayed but significant risk, particularly in:

- **Radiology staff** performing fluoroscopy
- **Pilots and flight crews** exposed to cosmic radiation
- **Head and neck radiotherapy patients**

The International Commission on Radiological Protection (ICRP) revised threshold estimates after evidence showed cataracts forming at significantly lower doses (~0.5 Gy) than previously believed. This prompted stricter occupational eye-dose limits globally.

Chronic or high-dose radiation exposure can adversely affect the central nervous system (CNS). While neurons divide slowly and are relatively radioresistant, supporting cells such as glia and vascular structures are vulnerable. Documented effects include:

- Cognitive decline
- Memory impairment
- Executive function deficits
- White matter changes on imaging

These risks are most evident in pediatric radiotherapy patients whose developing brains are highly sensitive to radiation.

Radiation-induced genetic effects arise from damage to DNA in germ cells. Although human evidence remains limited due to ethical constraints, animal models demonstrate clear associations between radiation and heritable genetic mutations. Potential long-term risks include:

- **Birth defects**
- **Embryonic loss**
- **Chromosomal abnormalities**
- **Heritable disease predisposition**

Pregnant women exposed to radiation—particularly during the first trimester—face increased risks of fetal growth restriction, developmental abnormalities, and cognitive impairment in offspring.

Chronic radiation exposure may disrupt endocrine pathways and alter immune responses. Thyroid dysfunction is common after radiation exposure due to the organ's high sensitivity, particularly in children. Immune suppression may persist for years following high-dose exposures, increasing susceptibility to infections and autoimmune disorders.

Occupational groups—including radiologic technologists, nuclear plant workers, interventional cardiologists, and airline pilots—accumulate higher lifetime doses, placing them at increased risk. Environmental exposures such as radon, contaminated water sources, and fallout from nuclear accidents contribute to chronic population-level radiation burdens.

These long-term risks emphasize the importance of lifelong monitoring, personal dosimetry, and stricter global exposure regulations to protect vulnerable groups.

Population-Level Risk Variations

Radiation exposure does not affect all individuals equally. Differences in biological sensitivity, age, environmental context, occupational exposure, and socioeconomic factors create substantial variations in population-level risk. Understanding these variations is essential for designing targeted monitoring programs, regulatory policies, and public health interventions that protect vulnerable groups while ensuring safe and equitable radiation use.

- **Age-Related Vulnerability**

Children are among the most vulnerable to radiation effects due to their rapidly dividing cells, developing organs, and longer life expectancy, which increases the time window for long-term effects such as cancer to manifest. Pediatric tissues absorb more radiation relative to body size, and epidemiological studies strongly associate childhood radiation exposure with increased risks of leukemia, thyroid cancer, and brain tumors. For example, children undergoing CT scans have been shown to exhibit higher cancer incidence compared with adults receiving similar dose levels.

Older adults, while less sensitive biologically, may experience heightened risks due to cumulative lifetime exposure and coexisting chronic diseases that amplify radiation-related cardiovascular or neurological impacts.

- **Pregnancy and Fetal Sensitivity**

Pregnant women represent a high-risk group because fetal tissues are exceptionally radiosensitive, especially during the first trimester when organogenesis occurs. Radiation exposure during early pregnancy may result in:

- Congenital malformations
- Growth restriction
- Neurodevelopmental delay
- Increased childhood cancer risk
- Fetal loss at higher doses

Clinical guidelines therefore emphasize minimizing imaging for pregnant women except when absolutely necessary and using abdominal shielding and dose-reduction protocols.

- **Occupationally Exposed Populations**

Certain professions face chronic, low-dose exposure that accumulates over time. Key occupational groups include:

- **Radiologic technologists**
- **Interventional cardiologists and radiologists**
- **Nuclear energy workers**

- **Airline pilots and cabin crew**
- **Industrial radiographers**

These groups may face elevated risks of cataracts, skin injury, hematologic abnormalities, and long-term cancers. Personal dosimetry badges, strict regulatory dose limits, shielding barriers, and mandatory radiation safety training are essential to reduce occupational risk.

- **Geographic and Environmental Differences**

Environmental radiation exposure varies widely by region due to natural and anthropogenic factors. Populations living in areas with high radon levels, such as mountainous or uranium-rich regions, face significantly increased risks of lung cancer. Communities near nuclear power plants, industrial radiation facilities, or historical nuclear testing sites may experience elevated chronic exposure.

Additionally, individuals living at higher altitudes receive more cosmic radiation, contributing to a slightly higher lifetime cancer risk compared with those at sea level.

- **Socioeconomic and Healthcare Disparities**

Socioeconomic status influences radiation risk in multiple ways:

- Populations with limited healthcare access may receive inconsistent diagnostic follow-up, resulting in repeated scans.
- Underserved communities may live in poorly ventilated housing with higher indoor radon concentrations.
- Occupational inequities may place low-income workers in higher-risk jobs involving radiation.
- Limited health literacy may reduce awareness of mitigation strategies such as sun protection or home radon testing.

These disparities highlight the need for public health outreach, equitable regulation, and targeted education programs.

- **Lifestyle and Behavioral Factors**

Behaviors such as smoking, frequent air travel, or excessive sun exposure interact with radiation risks. Smoking synergistically increases risks associated with radon exposure, while occupations requiring recurrent flying increase cumulative cosmic radiation exposure. Similarly, inadequate UV protection contributes to rising skin cancer rates in many regions.

Population-level variations in radiation risk are shaped by biological, occupational, environmental, and socioeconomic factors. Protecting high-risk groups—children, pregnant women, occupational workers, and geographically exposed communities—requires tailored monitoring strategies, stronger regulations, and widespread public education. Addressing these variations is essential for minimizing long-term health burdens and ensuring safe, equitable radiation use across populations.

Global Monitoring Systems & Regulatory Dose Limits

Effective radiation protection relies on coordinated global monitoring systems, regulatory frameworks, and standardized dose limits designed to reduce unnecessary exposure and protect vulnerable populations. International organizations—including the International Commission on Radiological Protection (ICRP), the World Health Organization (WHO), the International Atomic Energy Agency (IAEA), and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)—play central roles in setting guidelines, supporting surveillance programs, and promoting safe use of radiation across medical, industrial, and environmental contexts.

The ICRP provides the foundational recommendations for global dose limits. These limits distinguish between occupational exposure, public exposure, and medical exposure, recognizing that each context carries different benefit–risk expectations.

Key ICRP dose limits include:

- **Occupational exposure:** 20 mSv per year averaged over 5 years (not exceeding 50 mSv in any single year).
- **Public exposure:** 1 mSv per year, excluding medical and natural background radiation.
- **Lens of the eye:** 20 mSv/year for workers due to cataract risk.
- **Skin/extremities:** 500 mSv/year for occupational exposure.

Medical exposures have no strict numerical limits since they must be justified by clinical need; however, ICRP emphasizes optimization using the ALARA (As Low As Reasonably Achievable) principle and Diagnostic Reference Levels (DRLs) to prevent excessive dosing.

Monitoring systems track radiation levels across environments to identify anomalies, enforce safety measures, and protect the public. Major systems include:

- **Environmental Monitoring Networks:** Countries operate continuous monitoring stations that detect gamma radiation levels in air, water, and soil. These networks help track radon exposure, fallout from nuclear facilities, and radiation drift from global incidents.
- **Radon Surveillance Programs:** Many nations, including the U.S., Canada, and European countries, require radon testing in homes, schools, and workplaces due to radon's link to lung cancer. National radon maps help identify high-risk regions.
- **Cosmic Radiation Monitoring for Aviation:** Aviation authorities and airlines monitor cosmic radiation exposure among pilots and flight crews using dosimetry models and satellite-based monitoring systems.
- **Nuclear Facility Monitoring:** IAEA mandates strict oversight of nuclear plants through regular inspections, environmental sampling, and real-time radiation alarms to protect workers and surrounding populations.

Given the growing contribution of medical imaging to global radiation exposure, robust monitoring systems help track cumulative patient doses and enhance safety:

Radiologic technologists, interventional cardiologists, and nuclear medicine staff wear personal dosimeters to record monthly and annual exposure. Electronic dosimeters provide real-time feedback, improving radiation safety behaviors.

Health systems increasingly use Dose Management Software (DMS) to record and analyze patient radiation doses across CT, fluoroscopy, and nuclear medicine. These systems support:

- Identifying unusually high doses
- Flagging repeated imaging
- Aligning practices with DRLs
- Optimizing protocols based on patient size and clinical indication

Advanced CT scanners, image reconstruction algorithms, and automated exposure control systems help reduce radiation while preserving image quality.

National regulatory bodies—such as the U.S. Nuclear Regulatory Commission (NRC), European Radiation Protection Authorities, and Gulf regulatory agencies—implement ICRP recommendations through legislation. Harmonization across countries ensures consistent safety measures, especially in nuclear energy, aviation, and international patient care.

Table 1. International Dose Limits and Monitoring Systems Overview

Category	Exposure Limit / Monitoring Method	Responsible Body	Notes
Occupational Exposure	20 mSv/year averaged (max 50 mSv in a single year)	ICRP, IAEA	Includes radiology staff, nuclear workers, aviation crews
Public Exposure	1 mSv/year	ICRP	Excludes medical and natural background doses
Lens of the Eye	20 mSv/year (workers)	ICRP	Reduced due to cataract evidence
Skin/Extremities	500 mSv/year	ICRP	Primarily for industrial workers
Medical Exposure (Patients)	No fixed limits; guided by DRLs and ALARA	WHO, ICRP, medical regulators	Based on clinical justification and optimization
Environmental Monitoring	National gamma radiation sensors, radon testing	WHO, IAEA, national agencies	Tracks air, soil, water, and radon levels
Occupational Dosimetry	Personal dosimeters (TLD, OSL, electronic)	Hospitals, nuclear facilities	Required for staff working with radiation
Patient Dose Tracking	Dose management software (DMS)	Hospitals, radiology departments	Prevents excessive cumulative exposure

WHO and IAEA additionally support low-income countries in establishing safety infrastructure, training personnel, and implementing radiation monitoring in medical and environmental settings.

Discussion

The findings of this review highlight the complex and multifaceted nature of radiation exposure and its implications for global population health. Evidence consistently demonstrates that both medical and environmental sources contribute significantly to cumulative radiation dose, with each category presenting unique patterns of risk, exposure pathways, and mitigation challenges. While technological advancements have improved diagnostic accuracy and therapeutic precision, they have also increased dependence on radiation-based procedures, reinforcing the need for a balanced approach that weighs clinical benefit against long-term risk.

One of the most critical insights emerging from the literature is the disproportionate contribution of medical imaging to artificial radiation exposure, particularly through CT scans and fluoroscopic procedures. Despite their clinical utility, the tendency toward overuse—driven by defensive medicine, lack of dose awareness, and fragmented medical records—raises concerns about unnecessary population exposure. This highlights a persistent gap between technological capability and optimal clinical practice. Evidence suggests that many imaging studies could be avoided or replaced with non-ionizing alternatives such as ultrasound or MRI if clinicians had better decision-support tools and clearer communication regarding radiation risks. Thus, strengthening justification processes remains essential.

Environmental radiation exposure, while less controllable, presents equally significant long-term concerns. Radon, ultraviolet radiation, and fallout from nuclear incidents continue to exert measurable effects on large populations. Unlike medical exposure, environmental exposure often occurs without individuals' knowledge or consent, amplifying ethical and public health implications. For example, radon remains a leading cause of lung cancer among non-smokers, yet mitigation programs remain highly variable across regions. This inconsistency underscores the need for stronger international guidance and more equitable public health infrastructure.

A recurring theme across studies is the variation in susceptibility across population groups. Children, pregnant women, and individuals with occupational exposure experience heightened vulnerability due to biological sensitivity, prolonged exposure windows, or repeated contact with radiation sources. These groups require tailored monitoring and protection strategies, yet many countries lack robust occupational health surveillance or population-based dose registries. Similarly, socioeconomic disparities influence exposure risk, with low-income communities often residing in poorly ventilated housing, high-radon zones, or working in radiation-exposed occupations. Addressing such inequities demands not only technical solutions but also policy reforms focused on environmental justice and improved access to protective resources.

Global regulatory bodies—including ICRP, WHO, and IAEA—provide essential frameworks for establishing dose limits and monitoring strategies. However, the review reveals uneven adoption across regions, especially in low- and middle-income countries. Effective radiation governance requires not only standards but also the capacity to enforce them, including trained personnel, monitoring technology, and public health education. The expansion of dose management software, real-time dosimetry, and AI-supported optimization tools represents a promising development, but these innovations must be paired with training and institutional commitment to yield meaningful safety improvements.

Mitigation strategies reviewed—ranging from ALARA optimization and shielding in healthcare settings to radon testing and UV protection campaigns—demonstrate strong effectiveness when applied systematically. However, gaps remain in public awareness and clinical communication. Many patients remain unaware of the risks associated with repeat imaging, and many clinicians underestimate cumulative dose impacts. Improving health literacy around radiation exposure is therefore essential to promote shared decision-making and reduce unnecessary medical procedures.

Overall, the evidence strongly supports a shift toward integrated, multi-sector mitigation frameworks that combine technological innovation with regulatory oversight, environmental management, occupational protection, and population education. Such an approach is critical to ensuring that the benefits of radiation use—particularly in medicine—are preserved while minimizing harm across generations. Continued research is needed to clarify low-dose risk mechanisms, enhance monitoring infrastructure, and develop global harmonization strategies capable of addressing cross-border environmental radiation challenges.

Conclusion

Radiation exposure remains an unavoidable aspect of modern life, shaped by the expanding use of medical imaging, growing technological dependence, and persistent environmental sources. This review demonstrates that although radiation delivers immense benefits—particularly in diagnostics, therapeutic oncology, and industrial applications—it also poses significant short- and long-term health risks that require sustained global attention. Evidence shows that medical imaging constitutes the greatest share of artificial exposure, while environmental sources such as radon and ultraviolet radiation continue to affect entire populations, often without awareness or adequate protection.

The findings emphasize that no single strategy can fully mitigate radiation risks; rather, a comprehensive, multi-level framework is essential. Strengthening justification processes, optimizing imaging protocols through the ALARA principle, adopting advanced dose-reduction technologies, and expanding dose tracking are critical steps within healthcare. At the environmental level, radon control programs, UV safety campaigns, regulation of nuclear facilities, and ongoing public education are necessary to reduce population exposure. Equally important is recognizing and addressing the heightened vulnerability among children, pregnant women, occupational workers, and socioeconomically disadvantaged communities.

Global regulatory organizations have laid the foundation for safe radiation use, but implementation remains uneven across regions, underscoring the need for greater harmonization, capacity building, and investment in monitoring infrastructure. As radiation technologies continue to advance, the integration of artificial intelligence, real-time dosimetry, and predictive analytics will play an increasingly important role in achieving safer practices.

Ultimately, ensuring population health in the context of radiation exposure requires continuous vigilance, interdisciplinary collaboration, and equitable access to protective measures. By aligning scientific knowledge with effective policy and public health action, societies can preserve the life-saving benefits of radiation while minimizing its long-term risks.

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