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REVIEW ARTICLE

Health impact of radiation: analysis of occupational and environmental exposures

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ABSTRACT

Introduction: radiation constitutes an essential tool in medicine; however, exposures that exceed established safety limits represent a significant public health concern.
Objective: to analyze the effects of ionizing and non-ionizing radiation on human health.
Methods: a systematic literature review was conducted using scientific publications from specialized databases such as PubMed, Scopus, and Google Scholar. The search included terms related to ionizing radiation, non-ionizing radiation, health effects, and radiological protection. Studies were selected based on thematic relevance, methodological quality, and recency, followed by a critical and comparative analysis of the findings.
Development: the evidence indicates that ionizing radiation causes direct and indirect damage to deoxyribonucleic acid, increasing the risk of cancer, hematological disorders, and cardiovascular diseases, in both acute exposures and chronic low-dose exposures. Non-ionizing radiation, although less energetic, is associated with thermal effects and potential non-thermal effects, particularly neurological ones, which are still under investigation. Relevant natural sources such as radon and cosmic radiation were identified, as well as artificial sources linked to medical procedures and industrial activities. Additionally, beneficial medical applications, including radiotherapy and imaging techniques, were highlighted, all of which require controlled use.
Conclusions: radiation provides substantial benefits for health and technological development; however, it also entails risks that require rigorous management. Strengthening radiological protection, exposure monitoring, and education is essential to safeguard both workers and the general population.

Keywords: Radiation Effects; Radiation Exposure; Health Impact Assessment; Radiation, Ionizing; Radiation, Nonionizing.

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INTRODUCTION

Radiation encompasses a broad spectrum of physical phenomena, including both ionizing and non-ionizing radiation, which differ primarily in their energy levels and ability to interact with matter. These forms of radiation occur naturally in the environment and are also artificially generated for numerous scientific, medical, and industrial applications, underscoring their relevance from a public health perspective.[1]

Each type of radiation interacts with biological tissues through specific mechanisms, determining the nature and magnitude of its health effects. These interactions depend on factors such as absorbed dose, exposure duration, radiation frequency, and tissue sensitivity, leading to biological responses that may be reversible or permanent.[2]

Ionizing radiation is characterized by its ability to ionize atoms and molecules, causing direct or indirect cellular damage—particularly to DNA—and promoting mutations, chromosomal aberrations, and carcinogenic processes. In contrast, non-ionizing radiation possesses lower energy and does not cause ionization; however, it may induce thermal and non-thermal effects in biological tissues, whose pathophysiological mechanisms remain under active investigation.[3,4]

In this context, the present article aims to provide an integrated analysis of different types of radiation and their biological effects, offering a scientific foundation to understand the risks and benefits associated with radiation exposure. This approach allows for the appreciation of both the beneficial applications of radiation and the necessity of implementing appropriate protection and control measures to preserve human health.[5,6] Accordingly, this review was conducted with the objective of analyzing the effects of ionizing and non-ionizing radiation on human health.

METHODS

This study was designed as a systematic literature review, following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The search period spanned from January 2010 to December 2024 to capture the most recent and relevant evidence on the health effects of ionizing and non-ionizing radiation.

Information sources included widely recognized biomedical and multidisciplinary databases: PubMed, SciELO, ScienceDirect, Google Scholar, LILACS, and BVSALUD. Secondary references from key article bibliographies were also reviewed, and grey literature—including technical reports, institutional documents, and international agency guidelines—was considered to complement peer-reviewed scientific publications. This strategy integrated both primary evidence and regulatory/methodological context.

The search strategy employed a structured algorithm combining keywords and Boolean operators, adapted to each database. Terms included "ionizing radiation," "non-ionizing radiation," "health effects," and "radiological protection," linked with AND/OR operators to refine results. Publications in Spanish, English, and Portuguese were included to ensure broad and representative coverage of regional and international literature.

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Inclusion criteria encompassed original articles, reviews, and technical documents published within the defined timeframe that directly addressed the relationship between radiation and human health. Excluded were duplicates, articles without full-text access, irrelevant studies, and those outside the search period. The selection process occurred in multiple stages: first, title and abstract screening to exclude non-relevant records; second, full-text assessment of potentially eligible studies. Initially, approximately 1,240 records were identified; after screening and application of exclusion criteria, 215 articles underwent full-text review. Finally, 32 studies were included in the qualitative synthesis.

For data extraction and analysis, a standardized matrix was designed to collect key variables: author, publication year, methodological design, population or sample, type of radiation exposure, and main findings. Information was systematically organized and subjected to critical comparative analysis. A qualitative synthesis was performed, as methodological and outcome heterogeneity precluded quantitative meta-analysis. This approach ensured an integrated and coherent overview of available evidence, enabling identification of common patterns, knowledge gaps, and priority areas for future research.

DEVELOPMENT

Radiation is a physical phenomenon widely present in the natural environment and in numerous human activities, spanning a spectrum that includes both ionizing and non-ionizing forms. These types of electromagnetic or corpuscular energy differ in their ability to ionize matter—a distinction that largely determines their applications and potential biological effects. In recent decades, the increased use of radiation-based technologies has heightened interest in evaluating their implications for human health.[7,8]

From a biological standpoint, radiation-tissue interactions depend on various factors, including radiation type, absorbed dose, exposure duration, and tissue sensitivity. These interactions can trigger complex cellular and molecular responses—ranging from transient adaptations to permanent structural alterations. Understanding these mechanisms is essential to explain the variability of effects observed in individuals exposed to different radiation sources.[9,10]

Ionizing radiation is distinguished by its capacity to directly or indirectly ionize atoms and molecules, causing significant damage to critical cellular components—especially genetic material. This radiation type has been associated with an elevated risk of neoplasms, hematological disorders, and cardiovascular diseases, particularly in poorly controlled occupational or medical settings. Consequently, its use demands strict regulation and adherence to radiological protection principles.[11,12]

In contrast, non-ionizing radiation—though insufficiently energetic to ionize matter—can induce thermal effects and potential non-thermal biological effects. These radiation forms are present in natural sources and everyday technologies, such as telecommunications systems and electronic devices. Despite ongoing scientific debate about their health impacts, their widespread use justifies continued research into potential implications and the establishment of clear criteria for safe exposure.[12]

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Radiation represents a form of energy transfer that propagates as electromagnetic waves or subatomic particles. Its fundamental classification is based on its ability to ionize matter. From a biological and public health perspective, this distinction is crucial: ionizing radiation carries enough energy to remove electrons from atoms and molecules, causing structural alterations in living tissues, whereas non-ionizing radiation acts primarily through physical and biophysical mechanisms without direct ionization.

Within ionizing radiation, X-rays and gamma rays are the most widely used in medicine—for both diagnosis and treatment. These high-energy electromagnetic radiations exhibit high tissue penetration, enabling them to traverse anatomical structures of varying density. Their interaction with biological matter can cause direct DNA ionization or indirect effects via reactive species formation—explaining both their clinical utility and the risks associated with repeated or high-dose exposures.[13]

Another relevant category of ionizing radiation includes alpha and beta particles emitted by natural and artificial radionuclides. Alpha particles, though limited in tissue penetration due to their high mass and charge, possess high ionizing capacity—making them particularly hazardous when internalized. In contrast, beta particles have greater penetration and can traverse superficial tissue layers, causing cellular damage dependent on absorbed dose and exposure duration.[14]

Non-ionizing radiation encompasses a wide range of wavelengths, notably ultraviolet (UV) radiation—classified as UV-A, UV-B, and UV-C. Each category exhibits different energy levels and biological effects. UV-A is primarily associated with skin photoaging, UV-B directly contributes to erythema, sunburns, and skin carcinogenesis, while UV-C—though highly energetic—is mostly absorbed by the ozone layer and rarely reaches the Earth's surface under normal conditions.[15]

Microwaves and radiofrequencies also fall under non-ionizing radiation and are extensively used in telecommunications, electronic devices, and industrial applications. Although non-ionizing, these radiations can induce thermal effects through electromagnetic energy absorption by tissues, potentially raising local temperature. The possible existence of non-thermal biological effects remains under investigation, especially regarding chronic low-intensity exposures.[16]

Radiation sources can be natural or artificial. Among natural sources, cosmic radiation stands out—its intensity increases with altitude, posing a relevant concern for aircrews and astronauts undergoing prolonged exposure.[17] Radon—a radioactive gas produced by uranium decay in soil—is another significant natural source consistently linked to increased lung cancer risk, particularly in poorly ventilated indoor environments.[18]

Artificial radiation sources include nuclear facilities—such as fission-based power plants—which generate electricity but entail potential risks related to accidents and radioactive releases.[19] In healthcare, medical devices represent a major source of artificial exposure, particularly conventional radiography and computed tomography (CT), which contribute significantly to the population's total ionizing radiation dose.[20]

It is important to note that not all medical imaging technologies use ionizing radiation. Magnetic resonance imaging (MRI) is an advanced technique that employs strong magnetic fields and radio waves to produce high-resolution images—especially valuable for soft tissue evaluation. By leveraging hydrogen nucleus properties, MRI provides anatomical and functional information without increasing ionizing radiation burden, making it a safe and clinically valuable diagnostic tool.[12,16]

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Biologically, ionizing radiation induces damage through direct DNA effects—such as single- or double-strand breaks—and indirect effects mediated by free radicals generated via cellular water radiolysis. These processes can trigger mutations, genomic instability, and carcinogenesis.[21,22] In non-ionizing radiation, effects are primarily thermal, though potential non-thermal mechanisms with neurological and cellular implications are under investigation.[23,24]

Finally, radiation exposure significantly impacts human health, manifesting as acute and chronic effects. Acute high-dose exposures can cause acute radiation syndrome, affecting the gastrointestinal, hematopoietic, and central nervous systems.[25,26,27] Long-term, a well-established association exists between ionizing radiation exposure and various cancers, as well as increased cardiovascular disease risk. Nevertheless, despite these risks, radiation plays a fundamental role in modern medicine—particularly in oncologic radiotherapy, diagnostic imaging, and interventional radiology—all within a framework of radiological protection principles and international regulations aimed at maximizing clinical benefits while minimizing adverse effects.[28,29,30]

CONCLUSIONS

The impact of radiation on human health is complex and influenced by multiple factors, including radiation type, absorbed dose, and exposure duration. Scientific evidence demonstrates that ionizing radiation produces clearly established acute effects and is associated with significant chronic risks, while the effects of non-ionizing radiation remain under investigation—particularly regarding prolonged exposures. In this context, implementing radiological protection measures and adhering to international regulations are essential to reduce exposure and prevent adverse outcomes. Furthermore, public and professional education and awareness are critical tools for appropriate radiological risk management. Finally, despite potential risks, radiation provides substantial benefits in medicine, where its controlled and safe use has enabled significant advances in the diagnosis and treatment of various diseases—contributing notably to improved health and quality of life.

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