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Radon Exposure and Human Health: A Review of Sources, Risks, and Measurement Methods

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ABSTRACT

Radon is a naturally occurring radioactive gas which is an environmental health burden, particularly because of its strong link with lung cancer. It is the second major cause of lung cancer following tobacco smoking. Radon long-term inhalation and radioactive decay products is the reasons to expose lung tissue to ionizing radiation, damaging DNA, cellular mutations, genomic instability, and carcinogenic processes. According tp epidemiological research, those involving underground miners and residential populations, radon exposure is a clear cause to lung cancer risk. Also, radon exposure causes other diseases, including leukemia and cancers is not included in the respiratory system; yet, these links are uncertain and require more investigation. At the cellular level, radon exposure helps with oxidative stress, mitochondrial impairment, programmed cell death, and immune system changes, as biological indicators of radon-related health effects. Thus, to reduce exposure, regular radon testing, effective mitigation in homes and workplaces, and public awareness programs are required. Despite the extensive studies on radon, more case-control studies could clarify its role in non-pulmonary diseases and enhance current risk assessment models.

1. Introduction

Radon is a natural, colorless, odorless, tasteless noble gas, and is chemically inert. Dorn in 1900 first identified it as an emanation from the uranium decay series (UNSCEAR, 2006) known as niton; however, in 1918, Schmidt renamed it as radon to describe the isotope associated with uranium-238 decay, radon-222 (IARC, 2001). It has an atomic number of 86 in several isotopic forms, with mass numbers of 199Rn to 226Rn. Among these isotopes, 219Rn, originates from the decay series of 235U; 220Rn, thoron from the decay of 232Th; and 222Rn, from the decay of 238U (ICRP, 1993).

Radon-222 is the most important isotope from an environmental and health perspective because it has a relatively long half-life of about 3.82 days. This half-life helps in the migration through soil, rocks, groundwater, and indoor air before radioactive decay (Larsson, 2005). Yet, 220Rn and 219Rn have much shorter half-lives, of about 55.6 and 3.96 seconds, respectively, limiting their environmental mobility and decreases their availability. The isotope 219Rn is relatively rare because the half-life and the low natural abundance of its parent isotope, 235U are short, representing only about 0.7% of natural uranium (Darby et al., 2005; WHO, 2009). In comparison, 222Rn is the most abundant because of its parent isotope, 238U, accounts for 99.3% of natural uranium (Frumkin & Samet, 2001).

The uranium decay series includes 226Ra which undergoes alpha decay and produces 222Rn, which subsequently continues through a many radioactive transformations until stable 206Pb is formed. Also, radon-222 is known for its low boiling and melting points, approximately 211 K (−62 °C) and 202 K (−71 °C), respectively

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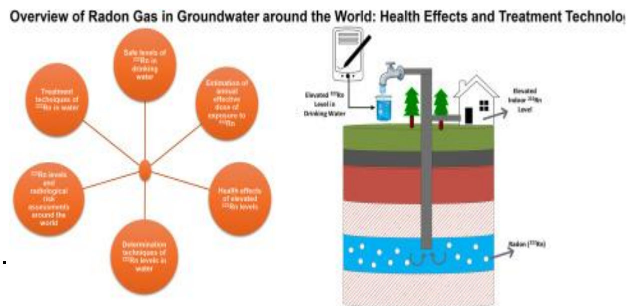
(Keller & DeVecchio, 2019). At 20 °C, radon water solubility us 230 cm³/L meaning that can dissolve significantly in water. Its diffusion coefficients in air and water are approximately 1.2 × 10−5 and 1.2 × 10−9, respectively reflecting its movement through porous geological materials and indoor environments (Nayak et al., 2022).

The environment continuously contains radiation of natural background, and humans are exposed to radiation from natural sources found in soil, air, water, and food. Radium-226, a decay in the uranium-238 series, decays into radon-222, as the heaviest natural radioactive gases in the decay chains of uranium, thorium, and actinium (Nayak et al., 2022; Tommasino, 2005). Radon emits alpha particles during radioactive decay, making it radiologically important despite being chemically inert (Adithya et al., n.d.; Cook et al., 2008). It is produced from the natural decay of uranium, radium, and thorium, widely distributed in trace amounts in rocks, soils, and the Earth's crust (Dimova et al., 2013; Elío et al., 2018). Therefore, radon exposure is in a close link to the geological composition, soil features, movement of groundwater, and conditions of building.



2.

Fig. 1. Overview of the potential health effects of radon exposure (Kim et al., 2022)

The source of radon is the natural radioactive decay of uranium and thorium-bearing minerals in the Earth's crust. These radionuclides appear in many dgeological formations, soils, rocks, groundwater systems, and, to a lesser extent, atmospheric and aquatic environments (Ullah et al., 2022; Yakovleva & Parovik, 2010; WHO, 2009). Natural radioactivity exists in unstable atomic nuclei disintegrate and release alpha particles, beta particles, or gamma radiation (Francover, 2021). The most important radionuclides is radium-226 (226Ra), produced in the uranium-238 (238U) decay series and subsequently decays for the generation of radon-222 (222Rn) (Peterman & Perkins, 1988).

Radon is created naturally in the subsurface environment, its concentration changed based on geological composition, soil permeability, uranium and radium content, groundwater movement, and ventilation conditions released from radium-rich rocks and soils and then migrate through pores, cracks, and fractures toward the atmosphere or into buildings. Its transportation is through groundwater and released into indoor air during domestic water use. Besides natural geological processes, some human activities such as mining, construction, and industrial operations with natural radioactive materials, redistributes radionuclides in the environment (Olszewski et al., 2015; Pachocki et al., 2000).

Indoor environments are the most significant source of radon exposure for the general population than outdoors as the gas can enter buildings through foundation cracks, gaps around pipes, construction joints and basements, crawl spaces in contact with soil. When inside, radon accumulates, in poorly ventilated spaces (President's National Atomic Agency, 2021; Steinhäusler et al., 1983; Sung et al., 2021). This issue is significant as people spend a large time indoors, such as in homes, schools, and workplaces (UNSCEAR, 2000). Thus, residential buildings are the radon exposure dominant source, though occupational settings contributes significantly in cases (UNSCEAR, 2006; UNSCEAR, 2008).

Radon exposure is sometimes a mixed environmental hazard as natural radioactive produced the gas, although by human construction practices affects its accumulation indoors is strongly influenced besides building design, ventilation systems, and settlement patterns (ICRP, 2009; Angell et al., 2009). The risk assessment includes geological mapping, indoor measurement, and exposure modeling, allowing high-risk areas for the identification and mitigation strategies (Dimitroulopoulou et

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al., 2023). Increasing population density may further raise exposure to radon-derived ionizing radiation, especially in which buildings are built over radon-prone geological formations.

The most relevant environmental radon isotopes include 222Rn and 220Rn. Radon-222 from the decay of 238U, whereas 220Rn, known as thoron, from the decay of 232Th (Ajrouche et al., 2018). These gases come from soil, air, water, and other environmental media, helping in the natural background radioactivity (Baltrocchi et al., 2023). The radioactive decay produces short-lived progeny radon like polonium-218 (218Po), polonium-214 (214Po), and polonium-210 (210Po), emitting alpha particles and delivering radiation to lung tissue if inhaled (Khan et al., 2019).

Radon is colorless, odorless, and tasteless, and this makes its detection difficult unless measured. Outdoor radon disperses and scarcely reaches harmful concentrations; yet, its indoor accumulation can be hazardous where there is a high soil radon potential or inadequate ventilation (Darby et al., 1995). Radon decay products possibly attach to airborne particles and be inhaled into the respiratory system, in which alpha radiation damages bronchial and lung tissues. So, elevated indoor radon exposure has been the cause of higher risk of lung cancer, and radon is the second leading cause of lung cancer after smoking (Rahman & Tracy, 2009; Holmgren et al., 2013; Mozzoni et al., 2021; Henyoh et al., 2024).

The radon health risks have been recognized for many decades, among miners and workers exposed to radioactive materials. In 1988, the International Agency for Research on Cancer, affiliated with the WHO, considered radon and its decay products as Group 1 human carcinogens for lung cancer (Rage et al., 2018). According to the International Commission on Radiological Protection, the controlling radon exposure importance in residential and occupational setting by monitoring, risk assessment, and protection (Kelly-Reif et al., 2019). The early twenty-first century includes international health agencies, including the WHO and the U.S. EPA, confirmed that radon is a factor to lung cancer after tobacco smoking, with estimates contributing to a big proportion of lung cancer cases in the world (Kelly-Reif et al., 2022; Kreuzer et al., 2021). The recommended reference exposure of more than 100 Bq/m³, may increase lung cancer risks, if combined with smoking (Richardson et al., 2021).

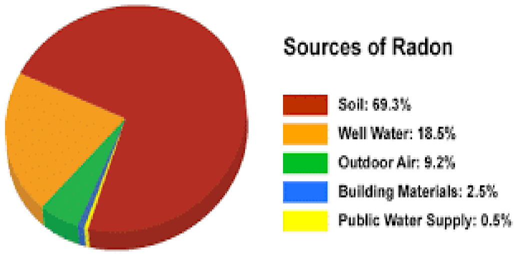

Fig. 2. Main sources of radon exposure (Kreuzer et al., 2008).

3. Exposure Pathways

Inhalation can cause radon exposure besides its short-lived decay products in indoor environments moving from soil and rocks into buildings by cracks in foundations, gaps around pipes, construction joints, basements, and crawl spaces. Sometimes, it dissolves in groundwater release into indoor air during water use and less commonly ingesting radon-containing water.

The radon decay products attach to airborne particles and deposited in the respiratory tract makes immolation the main pathway. Epidemiologically, indoor radon exposure is still a possible cause lung cancer risk even at concentrations below levels – previously safe, such as 100 Bq/m³ prolonged exposure, even at low concentrations be overlooked in public health risk assessment (Hofmann et al., 2019).

Building design, foundation type, the seals and cracks, the effectiveness of radon mitigation systems (RMSs), geological substrate, climatic conditions, occupancy patterns, and heating, ventilation, and air conditioning (HVAC) affect indoor radon concentrations systems (Biroul, 2024; Darby et al., 2006). Radon, its isotopes,

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and their decay mainly make natural radiation exposure, causing substantially annual effective doses received by the general population from natural sources (Krewski et al., 2005). Recent studies widely discussed radon-related health outcomes beyond lung cancer with possible to neurodegenerative conditions like Alzheimer's disease, Parkinson's disease, and other neurological disorders. However, these require more evidence before making any firm conclusions (Axelsson et al., 2015).

4. Health Effects of Radon

The past three decades witnessed numerous epidemiological studies on whether radon exposure is linked with diseases other than lung cancer discussed in recent review literature (Turner et al., 2012). In most cohort studies, uranium miners have compared mortality patterns and disease incidence among exposed workers with those observed in the general population. These comparisons are accords to standardized mortality ratios (SMRs) or standardized incidence ratios (SIRs). Several studies have shown higher risks for some malignant and non-malignant health results but inconsistent across different populations and study designs.

Also, some studies have quantified the relationship between radon exposure and specific diseases beyond lung cancer based on evidence from uranium miners, occupationally exposed workers, and indoor radon studies involving both adults and children. Still, the evidence is less conclusive than that for lung cancer, showing the need for further well-designed epidemiological investigation for the clarification of these possible links (UNSCEAR, 2021).

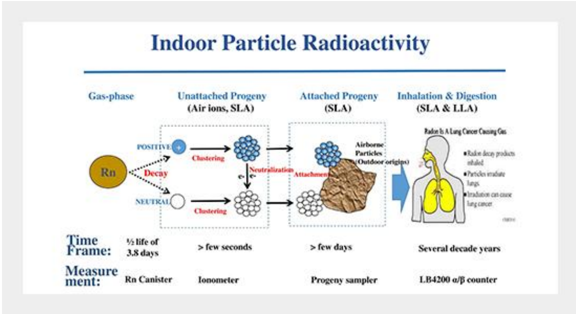

Fig. 3. Effects of radon exposure on the human lung.

In 1987, the WHO recognized indoor radon as a human carcinogen, and the United States Environmental Protection Agency (EPA) similarly classified it to the one in 1988. According to the WHO estimates, radon exposure could contribute to approximately 3–14% of lung cancer cases, according to the average indoor concentrations and smoking prevalence. So, radon is the second leading cause of lung cancer among smokers and the leading cause among individuals who have never smoked (Coretchi et al., 2020). In Europe, radon exposure has caused an estimated 21,000 cancer-related deaths, of about 2% of all cancer fatalities (WHO, 2000).

Lung cancer is public health problem worldwide, such as Spain. Yet, the incidence rates have dropped among men and continued to rise among women, reflecting historical and regional differences in smoking patterns. In Spain, approximately 30,000 new lung cancer cases and about 23,000 deaths each year happen, with most cases among current or former smokers. Tobacco consumption is a determinant of this burden and causes a substantial number of preventable deaths annually. It is also one of the causes of tobacco-related mortality in the country.

The respiratory tract models of the International Commission on Radiological Protection (ICRP) showed tissue sensitivity to ionizing radiation is not uniform. So, the bronchial epithelium basal and mucus-secreting cells are especially radiosensitive. According to the computational analyses, the radiation dose delivered by radon decay products is highest at the tracheobronchial bifurcation even if this anatomical region is not

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the most intrinsically radiosensitive respiratory system (Mazzoni et al., 2021).

The radon interaction to the human body remains incompletely understood, mainly due to limited information on its distribution in the body and the biological mechanisms in radon-related damage. The radiation protection research showed that physiological models of the respiratory system has more than 95% of the lung-equivalent dose due to the radon progeny, with a substantial burden in pulmonary tissues and, adipose-rich organs. Yet, these models do not cover all environmental and physiological variables influencing radon behavior and dose distribution highlighting the need for continued research. According recent studies, the reexamination of the carcinogenic potential of radon as a radionuclide confirms its relevance to major target organs while stressing the need for a more comprehensive experimental database for identifying the specific tissues and organs most which exposure influences (Tamborino et al., 2025).

Through gas-permeable soil, radon enters buildings primarily and accumulates in enclosed areas such as basements and crawl spaces through multiple entry routes. When pressure differences happen between the building interior and the surrounding soil, it moves. The variation of concentrations daily and seasonal bases causes long-term monitoring in estimating reliable annual average levels. For reducing health risks, the WHO recommends 100 Bq/m^3, although countries may use 300 Bq/m^3 with lower concentrations being difficult. This higher threshold is the national reference in some countries such as Moldova (EPA, 2023).

The most frequent disease associated with radon exposure are lung cancer and, to a lesser extent, stomach cancer (Warkentin et al., 2020). In terms of water exposure, the EPA suggested in 1991 a maximum contaminant level of 11.1 Bq/L (300 pCi/L) for radon in drinking water, with no formal universal standard at that time. Radon concentrations in water may range from approximately 0.37 Bq/L in typical surface waters to as high as 74,000 Bq/L in certain groundwater sources (Groves-Kirkby et al., 2006).

High radon in drinking water cause serious health problems, such as pulmonary neoplasms, with adversely effects on the renal and skeletal systems. Radon is a natural radionuclide in the uranium-238 decay series and has a half-life of 3.8 days. Factors, rock microstructure, pore space, the emanation coefficient, and environmental decay conditions, particularly the activity of radium affect its groundwater concentration -226 (226Ra) (Askari & Rahimi, 2014; Rabiee & Afarideh, 2025).

5. Measurement Methods for Radon

Radon is as a major indoor air pollutant makes accurate measurement for public health protection. As radon is the leading cause of lung cancer after smoking, reliable monitoring is required for assessing exposure levels and guide appropriate mitigation actions. Modern radon measurement is short-term, long-term, and continuous monitoring methods.

Results within a few days by short-term ones, activated charcoal canisters and electret ion chambers, initially screen (Zhou et al., 2018). Long-term methods are alpha track detectors, estimate radon exposure over several months with more representative average values as indoor radon levels changes daily and across seasons (Rizzo et al., 2022).

Continuous radon monitors (CRMs) are advanced measurement tools using electronic detection systems based on scintillation or ionization principles and providing real-time radon concentration data. Many modern devices can also be connected to smartphone applications for remote monitoring, data storage, and trend analysis. Recently, a clear shift happened toward digital, portable, and IoT-enabled radon monitoring systems, improving accessibility and measurement accuracy for both household users and professionals (Felici-Castell et al., 2022; Röttger et al., 2022; WHO, 2009).

Indoor air monitoring, specialized analytical techniques (liquid scintillation counting and gamma spectrometry) measure radon in water and building materials. International organizations, including the U.S. EPA and the WHO), have developed standardized protocols for better consistency, accuracy, and reliability in radon measurement practices. The high continuous monitoring reflects a growing emphasis on long-term exposure assessment, to manage risk effectively in radon-prone areas (EPA, 2023).

Table 1: Common methods used for radon measurement

Measurement method	Principle of measurement		Measurement period	Main applications	Advantages
Digital Continuous Radon Monitors (CRMs)	Use electronic sensors, such as scintillation cells or ionization chambers, to measure radon concentration in real time.		Continuous monitoring	Homes, workplaces, laboratories, and professional inspections	Provide real-time data, daily or weekly averages, alerts, and digital records.
Smart Radon Detectors (IoT-enabled)	Operate similarly to CRMs but are connected to Wi-Fi or Bluetooth for remote monitoring.		Continuous monitoring	Homes and offices requiring remote access and trend tracking	Sync with smartphone applications, track changes over time, and send notifications.
Alpha Track Detectors (ATDs)	Use a plastic film that records tracks produced by alpha particles over an extended period.		Long-term monitoring, usually several months	Residential buildings, schools, workplaces, and baseline exposure assessment	Provide reliable long-term average concentrations and are suitable for seasonal variation assessment.
Electret Ion Chambers (EICs)	Measure the reduction in electret voltage caused by ions generated from radon decay.		Short-to medium-term monitoring	Professional testing, field surveys, and advanced indoor assessments	Portable, reusable, relatively accurate, and suitable for different testing conditions.
Activated Charcoal Canisters	Adsorb radon gas onto activated charcoal, which is later analyzed in a laboratory.		Short-term monitoring, usually 2–7 days	Initial screening in homes and buildings	Low-cost, simple to use, and useful for rapid preliminary assessment.

Table 1 is the main radon measurement methods, monitoring periods, operating principles, applications, and advantages.

Radon concentrations are showing by picocuries per liter (pCi/L), widely used in the United States, and becquerels per cubic meter (Bq/m³), the standard international unit. A picocurie is the radioactive decay rate per liter of air, while a becquerel is a radioactive decay per second in one cubic meter of air. The conversion between the two units is 1 pCi/L = 37 Bq/m³.

6. Mitigation and Prevention Strategies

Many international regulations and guidelines required effective radon mitigation is

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emphasized in including Council Directive 2013/59/Euratom, and recommendations issued by the EPA and the WHO. In Europe, growing attention has been directed toward the developing and evaluating practical methods for reducing indoor radon activity concentration (IRAC). The mitigation strategy choice depends largely on the features of the building and the surrounding environment. Common approaches improve natural or mechanical ventilation, seal cracks and openings in floors and walls, install soil depressurization systems, and apply radon-resistant membranes beneath floor surfaces. Each has advantages and limitations, and their effectiveness may vary according to the structural features and site-specific conditions of each building.

In practical terms, radon prevention begins with regular testing in homes, schools, and workplaces, in radon-prone areas. If high concentrations are detected, mitigation measures are selected based on the building structure, soil c, and ventilation conditions. Public awareness campaigns, building-code requirements, and periodic monitoring are an effective radon risk-reduction strategy.

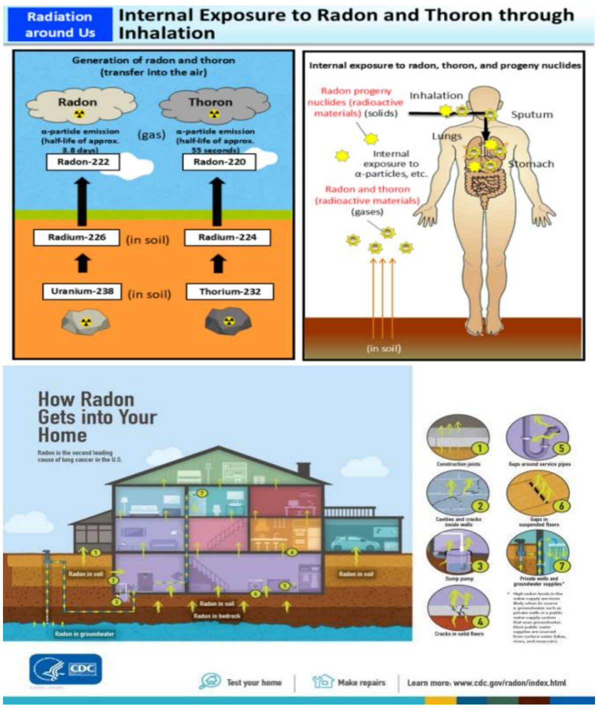

Fig. 4. Common radon mitigation and prevention strategies (WHO, 2009)

7. Conclusions

Radon is a natural radiation exposure source in humans and a well-established reason to lung cancer and the second leading cause of lung cancer after smoking and among individuals never smoked. Even typical residential radon levels, in poorly ventilated buildings, may raise lung cancer risk, with the risk becoming higher at elevated concentrations and when combined with tobacco smoke exposure. Evidence regarding other possible health effects, leukemia, cardiovascular disease, and cancers of organs other than the lung, is limited or inconclusive and requires more studies. Because it is widespread, invisible nature, and preventability by testing and mitigation, radon is an important although controllable environmental health hazard. Thus, routine monitoring, building-level remediation in high-radon areas, and radon control integration into public health policies reduces exposure and protecting human health.

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Author Contributions

Conceptualization: Alaa and Lana; methodology: Alaa and Lana; investigation:

Alaa and Lana; data curation: Lana and Alaa; writing—original draft preparation: Lana and Alaa; writing—review and editing: Alaa and Sarmad; visualization: Alaa, Lana, and Sarmad; supervision: Alaa; project administration: Alaa; funding acquisition: not applicable. All authors have read and approved the final version of the manuscript.

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