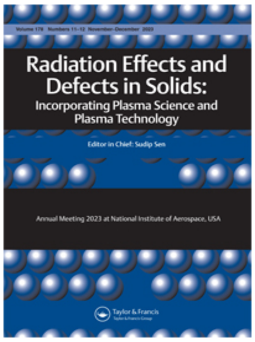

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Indoor radon monitoring for occupational health reinforcement in Portugal: compliance, prevention, and technological advancements

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ABSTRACT
This article highlights the relevance of indoor radon monitoring for occupational health protection, disease prevention, and compliance with safety regulations. Radon, a colorless, odorless, and tasteless radioactive gas, is a leading cause of lung cancer after tobacco smoking, and therefore in situ monitoring is fundamental to identify areas with high radon levels so that remediation measures must be implemented to reduce indoor exposure. The article gives an overview of the regulations in force in Portugal for indoor radon monitoring and identifies the responsibilities of different authorities and organizations in ensuring compliance with radiological protection requirements. It also outlines the legal framework for radon protection in Portugal, including the identification of reference levels for radon concentration in workplaces and dwellings, and the need to implement measures concerning indoor radon exposure reduction. Additionally, it is detailed the process of monitoring radon in indoor environments, including the selection of an appropriate measurement device and the necessary measurement time, and the need to inform and train workers about the risks associated with radon exposure. In short, this review provides information on the importance of radon monitoring and the measures required to ensure public safety.

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1. Introduction

Radon monitoring is of significant importance for different reasons, including occupational health protection, disease prevention, and compliance with safety regulations (*1*). Radon, an odorless, tasteless, and colorless radioactive gas, originates from the natural decay of uranium in soil, rocks, and water (*2*). Prolonged exposure to high indoor radon levels can increase the risk of lung cancer, making it the second most common cause of lung cancer, according to the World Health Organization (WHO) (*3*–*5*). The detection and

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measurement of radon in enclosed environments are only possible through monitoring and measurement using specific devices, allowing for the identification of areas with high radon levels and the implementation of measures to reduce exposure (*6*). Radon monitoring aids in identifying areas at risk and implementing prevention and mitigation measures, such as ventilation and building waterproofing, significantly reducing radon exposure and the associated health risks (*7*). Radon monitoring is essential to ensure compliance with national and international laws and regulations related to radiological protection and indoor air quality (*8*). In many countries, including Portugal, regulations establish a so-called reference level for radon concentration in workplaces and residences (*9*). Radon monitoring and the dissemination of results contribute to raising public awareness of the risks associated with indoor radon and the importance of adopting measures to reduce exposure (*10*). This may lead to the adoption of a set of mitigation practices and overall improvements in indoor air quality and public health (*8*).

In Portugal, various authorities and organizations are responsible for the regulation and supervision of radiological protection (*11*). The main bodies regulating radiological protection in the country included the Regulatory Commission for the Safety of Nuclear Installations (COMRSIN), which was the national regulatory authority responsible for nuclear safety and radiological protection in Portugal, ensuring the safety of nuclear installations and the protection of people and the environment from the dangers arising from ionizing radiation. With the entry into force on 2 April 2019, of Decree-Law No. 108/2018 of December 3, amended by Rectification Declaration No. 4/2019 of January 31, inspection powers were granted to the Inspectorate-General for Agriculture, the Sea, the Environment, and Spatial Planning (IGAMAOT) in the areas of radiological protection, nuclear safety, and radioactive waste. Previously, these authorities were divided among the regional health authorities (ARS), the Institute for Support to Small and Medium Enterprises and Innovation (IAPMEI), the Instituto Superior Técnico/Technological and Nuclear Campus (IST/CTN), and COMRSIN. The same Decree-Law also provides for IGAMAOT to succeed COMRSIN in terms of its powers and competencies associated with the inspection activity, highlighting the inspection obligations associated with Decree-Law No. 262/2012 of December 17 (Establishing the obligations of nuclear installation license holders), amended by Decree-Law No. 135/2017 of October 20, and Decree-Law No. 156/2013 of November 5 (Establishing the legal and regulatory framework for the responsible and safe management of irradiated fuel and radioactive waste). In 2023, and with the amendment introduced by Decree-Law No. 81/2022 of December 6, compliance with legislation on radiological protection will be reinforced by entities with specific competencies in the field, namely the Inspectorate-General of Health Activities (IGAS) in the domains of activity and provision of health care, in both the public and private sectors, the Authority for Working Conditions (ACT) within the scope of labor relations, and the Food and Economic Safety Authority (ASAE) in the domains of economic activity. The Portuguese Environment Agency (APA) is responsible for environmental protection in Portugal, including the monitoring and management of risks associated with exposure to radon and other ionizing radiation, and collaborates with other national and international organizations in the implementation of policies and actions for radiological protection. The Directorate-General of Health (DGS) is the national public health authority in Portugal, responsible for ensuring the protection of the population's health and can develop and implement policies and programs related to radiological protection in the area of health, in collaboration with other authorities and organizations.

The Decree-Law No. 108/2018 of December 3 establishes the legal framework for protection against the dangers arising from exposure to radon in Portugal. The main aspects of this decree include the transposition of Euratom Directives, as it transposes into national legislation the provisions of Directive 2013/59/Euratom, which establishes basic safety standards for protection against the dangers arising from exposure to ionizing radiation. Additionally, the decree sets out the responsibilities and competencies of competent authorities and operators regarding protection against radon hazards. Competent authorities include IGAMAOT and APA. The decree also establishes the need for monitoring and evaluation of radon concentrations in workplaces and dwellings, defining reference levels for radon concentration in workplaces (300 $Bq.m^{-3}$) and dwellings (300 $Bq.m^{-3}$). It further establishes the need to implement measures to reduce exposure to radon in places where the reference level is exceeded, including the implementation of technical and organizational measures, such as ventilation and sealing of areas with higher radon concentrations. Moreover, the decree provides for the consideration of risks associated with radon in the construction of new buildings, ensuring that preventive and mitigation measures are implemented during the construction stage. Finally, the decree establishes the need to promote training and information on the dangers of radon and protection measures, both for the professionals involved and for the public.

In addition to Decree-Law No. 108/2018, which specifically addresses protection against the dangers arising from radon exposure, there are other laws and regulations in Portugal related to ionizing radiation and radiological protection in general. Some of these laws and regulations include Decree-Law No. 45/2016 of August 17, which establishes the legal framework applicable to the prevention and remediation of environmental damage, including damage caused by ionizing radiation. Decree-Law No. 222/2008 of November 17 sets safety and radiological protection standards for the use of ionizing radiation in medical and dental practice, while Decree-Law No. 165/2002 of July 17 regulates the application of ionizing radiation protection measures and establishes the operating conditions of radiology and nuclear medicine services. These laws and regulations, together with Decree-Law No. 108/2018, form a comprehensive regulatory framework for radiological protection in Portugal, including protection against the dangers arising from radon exposure. For additional information on specific legislation or to learn about other laws and regulations in force, it is recommended to consult the competent authorities, such as IGAMAOT or APA.

There are several technical standards and published procedures for radon monitoring (*1*). Some of the main international standards and guidelines include the World Health Organization (WHO), which published the document 'WHO Guidelines for Indoor Air Quality: Selected Pollutants' in 2010, offering guidance and recommendations for the monitoring and mitigation of radon in indoor environments (*12*). The International Organization for Standardization (ISO) has also developed various standards related to radon measurement and monitoring, including ISO 11665-1:2012, which addresses the measurement of radioactivity in the environment – Air: Radon-222: Part 1, performance requirements for measurement methods; ISO 11665-2:2012, which addresses the measurement of radioactivity in the environment – Air: Radon-222: Part 2, integrated measurement of effective alpha energy potential (PAEC) for assessment of exposure in workplaces and residential locations; and ISO 11665-7:2012, which addresses the measurement of radioactivity in the environment – Air: Radon-222: Part 7, cumulative measurement method using solid-state nuclear track detectors (SSNTD). The European Commission (EC) has also published guidelines on radon monitoring in indoor environments as part of Directive 2013/59/Euratom, which establishes basic safety standards for the protection against the hazards arising from exposure to ionizing radiation. These standards and guidelines provide detailed information on proper procedures for radon monitoring, including measurement methods, device positioning, measurement duration, and analysis of results (13). Countries may adapt and adopt these standards and guidelines to develop their own national regulations and radon monitoring procedures (14).

The monitoring of radon in indoor environments involves measuring radon concentrations in the air using specific devices (6). The process generally begins with the selection of an appropriate measurement device, which may include solid-state track detectors (SSNTD), ionization chambers, or continuous radon monitors, depending on the specific needs and the time available for the measurement (15). Subsequently, the measurement device should be placed in a representative location of the environment to be monitored, typically in living and sleeping areas (13). Devices should be positioned at a height of approximately 0.5–2 meters from the floor and away from drafts and airflows, direct sunlight, windows, and all sources of moisture (16). The required measurement duration varies according to the type of device used and the environmental conditions, with short-term measurements generally lasting between two and seven days, while long-term measurements may last from 3 months to 1 year (17). After the measurement period, the device must be sent to an accredited laboratory for analysis and determination of radon concentrations (18,19). The results are usually expressed in becquerels per cubic meter (Bq/m^3), and it is important to compare them with the reference levels established by local or international authorities to determine whether mitigation measures are needed (20). If radon levels exceed the reference levels, mitigation measures may be necessary to reduce radon concentrations in the environment (21). These measures may include improving ventilation, sealing cracks in floors and walls, and installing soil depressurization systems (22).

Following Decree-Law No. 108/2018, the reference level for radon exposure in workplaces is set at 300 Bq/m^3. When radon concentration exceeds this value, the employer must take protective measures and reduce radon exposure for workers. Additionally, the decree-law establishes requirements for monitoring and assessing radon exposure, as well as the obligation to inform and train workers about the risks associated with radon exposure and the protective measures to be adopted. Although Decree-Law No. 108/2018 establishes basic safety standards and protection against the hazards arising from exposure to ionizing radiation, including radon exposure, further regulation or specific guidance may be necessary to clarify certain aspects or fully implement the provisions of the decree-law. For instance, Decree-Law No. 108/2018 does not explicitly specify whether the obligation to inform and train workers about the risks associated with radon exposure and the protective measures to be adopted should be carried out by a qualified technician. However, the person responsible for providing such information and training must have sufficient knowledge and understanding of the risks and protective measures related to radon exposure, and a qualified technician, a radiation protection specialist, or someone with appropriate experience and training in the field of ionizing radiation and radiological protection should be responsible for providing the information and training. This will ensure that workers receive accurate and up-to-date information and are properly trained on the necessary protective measures to reduce the risks associated with radon exposure.

The objectives of this review are to explain the importance of radon monitoring for public health protection, disease prevention, and compliance with safety regulations. It provides an overview of the dangers of radon, including its link to lung cancer, and the need for monitoring and measurement using specific devices. The review also discusses the regulations in place in Portugal for radon monitoring and the responsibilities of various authorities and organizations in ensuring compliance with radiological protection laws. It outlines the legal framework for protection against radon in Portugal, including reference levels for radon concentration in workplaces and dwellings, and the need to implement measures to reduce exposure. Also discusses international standards and guidelines for radon monitoring and explains the process of monitoring radon in indoor environments. Finally, highlights the need to inform and train workers about the risks associated with radon exposure and the importance of having qualified technicians provide such information and training.

2. Recognizing the health risks and addressing the need for compensation and prevention measures

It is possible that, in the future, radon exposure in the workplace may be considered within the scope of occupational diseases, particularly due to the increasing awareness of health risks associated with radon exposure, including the development of lung cancer (*23*). The classification of radon exposure as an occupational risk factor will depend on the decisions of lawmakers and regulatory bodies, which may take into account scientific research, epidemiological studies, and the evolution of international practices (*24*). If recognized as an occupational risk factor, employers may be required to implement additional prevention and protection measures, and affected workers may gain access to compensation and benefits related to occupational diseases (*25*). It is important to monitor changes in legislation and regulation, as well as discussions and scientific research concerning radon exposure and its health effects. Staying up-to-date on these developments can help identify future trends and ensure compliance with applicable laws and regulations.

In cases where a worker develops lung cancer and radon exposure in the workplace is believed to be a contributing factor, the employer's liability may depend on several factors (*7*). These include whether the employer had prior knowledge of the presence of radon in the workplace and did not take appropriate measures to mitigate the risk or inform workers about the hazards associated with radon exposure (*7*). Liability may also be influenced by the employer's compliance with applicable laws and regulations regarding protection against radon exposure and workplace safety, as well as the ability to establish a causal relationship between radon exposure in the workplace and the development of lung cancer in the worker (*26*). It is important to note that establishing liability in cases of radon exposure and lung cancer can be complex and challenging due to factors such as radon concentration variability, the long latency between exposure and cancer development, and the presence of other risk factors, like smoking (*27*). Applicable legislation and regulations, as well as judicial decisions in similar cases, can provide guidance on employers' liability concerning radon exposure and other occupational health issues (*12*).

An example of a country where occupational radon exposure is considered within the context of occupational diseases and compensation systems is the United States. In the

U.S., uranium mine workers who developed lung cancer or other diseases related to exposure to radon and other radioactive elements may be eligible for compensation under the Radiation Exposure Compensation Act (RECA) (*28*). RECA was enacted in 1990 and provides compensation for individuals who developed certain diseases as a result of exposure to ionizing radiation (*29*). Uranium mine workers, as well as ore transportation workers and mill workers who were employed from 1942 to 1971, may be eligible for compensation if they develop lung cancer or other diseases related to radiation exposure (*30*). Eligibility for compensation under RECA depends on various criteria, including the period and duration of employment, cumulative radiation exposure, and the diagnosis of a disease covered by the act (*31*). Compensation may include lump-sum payments and medical benefits related to the treatment of covered diseases (*32*). The implementation of RECA highlights the importance of recognizing and addressing the health risks associated with radon exposure in the workplace (*33*). By providing compensation to affected workers, the U.S. government acknowledges the need for preventive measures and support for those who have developed diseases due to occupational radon exposure (*34*). This example illustrates how some countries have already taken steps to recognize radon exposure as an occupational risk factor and provide compensation for affected workers. As awareness of radon-related health risks continues to grow, other countries may follow suit by adopting similar policies or expanding existing ones to encompass occupational radon exposure (*35*).

Also, in France, occupational radon exposure is considered within the context of radiation protection and compensation systems (*36*). France has established specific regulations to protect workers from the health risks associated with radon exposure, particularly in workplaces located in areas with high radon concentrations (*37*). Under French law, radon exposure in the workplace is regulated by the French Labor Code and the Public Health Code (*38*,*39*). Employers are required to assess the radon risk in their workplaces, especially in underground workplaces such as mines, tunnels, and caves, as well as certain above-ground workplaces in radon-prone areas (*40*). If radon levels exceed specified limits, employers must take appropriate measures to reduce workers' exposure, such as improving ventilation, sealing cracks in floors and walls, and installing radon mitigation systems (*37*). If a worker develops an illness due to occupational radon exposure, they may be eligible for compensation through the French social security system, specifically the occupational disease scheme (*41*). Compensation for occupational diseases typically includes medical care, income replacement, and, in some cases, additional benefits for the worker and their dependents (*42*). To qualify for compensation, the worker must demonstrate a direct link between their illness and occupational radon exposure, and the illness must be listed in the applicable occupational disease table (*41*). In France, lung cancer is recognized as an occupational disease related to radon exposure for underground miners (*43*).

These examples underscore the importance of considering radon exposure in the workplace and providing compensation for affected workers. As awareness of the health risks associated with radon exposure continues to grow, more countries may develop or expand their legislation and compensation systems to address this occupational hazard (*44*). However, many compensation systems for radiation exposure in a work context are strongly related to work in mines and underground structures (*45*). This is because these workplaces generally present a higher risk of radon exposure, due to proximity to natural radiation sources and a lack of adequate ventilation (*46*). Uranium mines, in particular, have been historically associated with elevated radon levels and, consequently, an increased risk of lung cancer among miners (47). Furthermore, workers in other mines, tunnels, caves, and underground facilities, such as subway stations, may be exposed to higher radon levels than those working in above-ground environments (48). The growing awareness of health risks associated with radon exposure in indoor environments may lead to increased attention to occupational exposures in a variety of workplaces, not just mines and underground structures (49). As more research and epidemiological studies highlight potential health risks, legislators and regulatory bodies may be encouraged to implement more comprehensive protection measures and compensation systems to address occupational radon exposure in various work environments (41). Additionally, it is crucial that employers in all sectors, not just mining and underground structures, be aware of the health risks associated with radon exposure and take appropriate measures to protect their workers (50). This may include conducting radon risk assessments, implementing mitigation measures, and ensuring that workers are informed about the hazards and protective measures to be adopted (51).

In an ideal scenario, the compensation model must incorporate an integrated analysis, given that the dose is a cumulative process, and workers might also be exposed to radiation within their residences (52). The combined exposure to radon in both workplace and residential settings can considerably affect an individual's overall risk of developing health complications, such as lung cancer (53). Consequently, it is essential for compensation systems and occupational health regulations to take into account the cumulative effects of workplace and residential radon exposure (54). To attain a more comprehensive understanding of a worker's total radon exposure, it may be necessary for regulatory bodies and employers to collaborate with public health agencies and researchers in developing effective monitoring and assessment methodologies (55). This approach could entail tracking individual radon exposure levels in both work and home environments, while also considering factors such as the duration spent in each setting and fluctuations in radon concentrations over time (56). Adopting a more holistic strategy for assessing and addressing radon exposure could result in enhanced protection for workers and improved public health outcomes (57). By incorporating exposure from both workplace and residential settings into compensation systems and occupational health regulations, policymakers can ensure that individuals affected by radon-related health issues receive suitable support and benefits, irrespective of the specific source of their exposure (58).

If radon exposure is recognized as an occupational risk factor, employers may be required to implement additional prevention and protection measures, and affected workers may have access to compensation and benefits related to occupational diseases (59,60). In Portugal, the legislation that defines and regulates occupational diseases is Decree-Law No. 76/2007, of April 17, which approves the List of Occupational Diseases and establishes the legal framework applicable to the repair of damages resulting from occupational diseases. This legislation has been amended and updated by several legal acts over the years, such as Decree-Law No. 53-A/2017, of May 31. The List of Occupational Diseases presents a relationship of diseases that are considered of professional origin, classified by categories and etiological agents, such as chemical agents, biological agents, physical agents, and other occupational risk factors. However, it is important to note that the list is not exhaustive, and other diseases may be considered occupational diseases if a causal relationship between the disease and the professional activity performed is established. Therefore, radon exposure may be considered an occupational disease in the future if legislation evolves in that direction.

The possibility of considering radon exposure in the workplace would involve a thorough assessment of exposure risks in various work environments and a precise calculation of the radon exposure dose in occupational settings (7). This process would likely necessitate a comprehensive evaluation of radon levels in different workplace environments, taking into account factors such as geographical location, building materials, and ventilation systems, as well as gaining an understanding of the duration and frequency of workers' exposure to these levels (61). Incorporating both the concentration of radon and the duration of exposure into the assessment would provide a more accurate estimation of the radon dose that workers receive while performing their professional activities (14). This information could be crucial for policymakers, regulators, and employers as they develop and implement appropriate protective measures to mitigate the risks associated with radon exposure (62). Furthermore, this data could play a significant role in determining eligibility for compensation and benefits related to occupational diseases arising from radon exposure (63). As research advances and awareness about the health risks associated with radon exposure continues to grow, it is possible that more countries, including Portugal, may update their legislation to recognize radon exposure as an occupational risk factor (64). Consequently, the assessment of radon exposure dose could be incorporated into their occupational health regulations (65). This would help ensure that workers are adequately protected from the risks associated with radon exposure and that those affected by radon-related health issues receive the necessary support and benefits (66). Additionally, the ongoing monitoring of radon levels in various workplaces and the implementation of mitigation strategies would contribute to improved occupational health and safety standards (67).

3. The importance of prevention and control of radon exposure

The Portuguese legislation establishes the obligation for employers to carry out a risk assessment for the safety and health of workers. This requirement is provided for in Law No. 102/2009 of September 10, which regulates the legal framework for the promotion of safety and health at work. According to this law, employers are obliged to ensure the safety and health of workers in all aspects related to work, including the identification and evaluation of potential risks and the implementation of adequate preventive measures. The risk assessment must be carried out before the start of any work activity and whenever significant changes occur in the working conditions, and its periodic review is also important. The risk assessments must be documented and include information on identified hazards, estimation of associated risks, preventive and protective measures adopted, and the results of verifications and monitoring carried out. In addition, workers and their representatives must be involved in the risk assessment process and informed about the results and measures adopted.

Law No. 102/2009, of September 10th, does not explicitly mention radon exposure as a risk to be evaluated. However, the law states that employers are responsible for ensuring the safety and health of workers in all aspects related to work, including the identification and evaluation of potential risks. Although radon is not specifically mentioned in the legislation, the increasing awareness of health risks associated with radon exposure may lead employers and regulatory authorities to include radon exposure assessment in occupational risk assessment processes. This approach would be consistent with the overall responsibility of the employer to protect the health and safety of workers and could contribute to the prevention of radon-related diseases. On the other hand, Decree-Law No. 108/2018, of December 3rd, updated the provisions on the assessment and management of radon exposure risk in buildings and workplaces. As previously mentioned, the decree-law establishes the obligation to assess the risk of radon exposure in public buildings and workplaces, and the assessments must be carried out by certified entities. In addition, the decree-law defines reference values for radon concentration and establishes procedures for monitoring indoor air quality concerning radon exposure. Therefore, the decree-law aims to contribute to the prevention and mitigation of the risk of radon exposure in the workplace. However, it is important to note that there is still no definition of occupational diseases caused by radon exposure in Portugal.

The DEPR-DPA-GGRLT-01 Guide establishes a systematic approach for assessing the risk of radon exposure in workplaces, to protect workers from exposure to high levels of radon and prevent the development of related diseases. The guide recommends that the risk assessment be conducted in stages, starting with a preliminary analysis to identify workplaces that may present a potentially high risk of radon exposure. Next, radon monitoring is recommended at the identified locations to determine the actual levels of radon to which workers are exposed. Based on the monitoring results, the guide establishes action levels to help identify when prevention and control measures are needed. The guide also provides detailed guidance on the measures to be taken to reduce radon levels in workplaces, including the implementation of engineering measures such as adequate ventilation and administrative measures such as managing workers' exposure time.

To consider lung cancer as being related to radon exposure in a work environment, several external factors must be taken into consideration (*36*). This includes smoking habits, exposure dose in the domestic environment, and other potential risk factors for the development of lung cancer (*68*). Regarding the assignment of responsibility on the part of the employer, it is necessary to consider that occupational radon exposure is cumulative and can occur in various locations, including the worker's place of residence (*47*). Determining responsibility in cases of lung cancer related to radon exposure is, therefore, complex and would require a detailed analysis of exposure levels in both environments, as well as other factors, such as the individual's smoking history or exposure to other carcinogens throughout their work history (*69*). A detailed analysis of the worker's periods of stay in different previous workplaces and different places of residence would also be necessary, which would make the assessment process practically impossible (*70*). On the other hand, collecting information about the worker's past, habits, and previous health problems may conflict with the worker's right to privacy of their data, although in this situation, its disclosure would be in their particular interest (*71*).

The privacy of workers and the protection of their health information are important issues to consider when addressing radon exposure in the workplace (*72*). Personal health information is protected by privacy laws and cannot be shared with employers without the worker's consent (*73*). However, in specific situations related to occupational health and safety, there may be exceptions or requirements for employers to obtain limited information about workers' health (*74*). This information can be used to assess health risks, ensure a safe work environment, and make informed decisions about necessary protective measures (*75*). In these cases, the information should be treated confidentially and used only for specific and justified purposes (*76*). On the other hand, determining other components of the dose calculation, such as exposure in outdoor environments or housing, would require monitoring of homes and knowledge of the worker's time spent both indoors and outdoors (77). As can be easily understood, this would be a fruitless task, due to the inherent difficulty of acquiring the data. In some countries, radon monitoring in private residences may be encouraged or recommended but not mandatory. In other cases, there may be stricter legal requirements for radon measurement in homes, especially in areas known to have high concentrations of radon in the soil (78).

The responsibility for monitoring radon concentration in a household and assigning responsibility for exposure in both the domestic and occupational settings will depend on the ability to establish a causal relationship between exposure and lung cancer (79). Smoking is a well-known and significant risk factor for lung cancer and is likely the primary contributor to the development of the disease (80). According to the World Health Organization (WHO), tobacco is the leading cause of lung cancer worldwide, with more than 70 known carcinogenic substances present in tobacco smoke, responsible for approximately 85% of lung cancer cases (81). Other risk factors for lung cancer include exposure to radon, air pollution, and occupational exposure to carcinogenic agents such as chemicals and dust (82). The risk of lung cancer is increased for individuals who smoke tobacco and are exposed to other risk factors such as radon and occupational carcinogens (83). In addition, genetic factors such as inherited susceptibility to cancer can also influence the risk of lung cancer (84). The WHO estimates that radon causes between 3% to 14% of all lung cancer cases, depending on the level of exposure (27).

From a public health perspective, it is always important to consider all risk factors for a particular disease (85). Indeed, the WHO states that tobacco is the leading cause of lung cancer worldwide and that radon exposure is the second most common cause (60). However, this does not mean that radon exposure should be ignored or underestimated, especially in workplaces where exposure can be significant (86). Moreover, it is important to remember that exposure to radon and the habit of smoking are independent risk factors and can combine to increase the risk of lung cancer (87). For example, a worker who smokes and is also exposed to radon in their workplace may have an even greater risk of developing the disease (88). Therefore, it is important to assess and manage all risk factors to protect the health of workers (89). This may include measures to prevent and control smoking and exposure to radon, as well as the implementation of safe practices in the workplace to reduce exposure to other carcinogenic agents (90). Employers must ensure that workers have a safe and healthy work environment, which includes protection against exposure to harmful agents such as radon (91). In addition, companies should adopt preventive measures, such as assessing the risk of radon exposure and implementing mitigation measures when necessary (92). It is also important for companies to provide adequate information and training to workers on the health risks associated with radon and the protective measures that should be taken (37). By promoting a healthy and safe work environment, companies can help protect the health and well-being of their workers, as well as comply with legal and ethical obligations related to occupational health (93).

4. Continuous ioT radon monitoring as a risk management tool

With the advancement of technology, continuous evaluation methods of radon concentration in occupational environments have been improved through the incorporation of

IoT (Internet of Things) systems (94). These systems consist of devices that connect to the internet to transmit data in real time, allowing remote and continuous monitoring of radon concentration in occupational environments (95). IoT devices use sensors that can be installed at different points in the monitored area, allowing for a more precise and detailed analysis of radon concentration in real-time (96). In addition, these devices can be programm to send automatic alerts in case of fluctuations in radon concentration, allowing for a quick and effective response in situations of a sudden increase in concentration (97). One of the main advantages of IoT systems is their ability to store and process large amounts of data, allowing for a more complete and accurate analysis of radon concentration patterns over time (98). This can be useful in identifying trends in radon concentration during different periods of the day, or throughout different seasons, for example (99). Although IoT systems may be more expensive and require more advanced technical skills than traditional methods, their benefits in terms of continuous real-time monitoring and more precise and detailed analysis may offset these additional costs (100). Furthermore, with the evolution of technology, these systems may become increasingly accessible and user-friendly in the future (101).

The interconnection of IoT systems and mitigation systems can allow for real-time monitoring of radon concentration and immediate implementation of mitigation measures in case of a sudden increase in concentration (102). This can be achieved by installing IoT sensors to continuously measure radon concentration and interconnecting these sensors with mitigation systems, such as ventilation and sealing of areas with higher radon concentration (103). With the interconnection of these systems, IoT sensors can be programm to automatically trigger the mitigation system when radon concentration exceeds a certain limit, ensuring that mitigation measures are implemented immediately and reducing the risk of prolonged exposure (104). Additionally, the interconnection of IoT systems and mitigation systems can also allow for real-time analysis of the data collected by sensors, which can help to identify patterns and trends in radon concentration, as well as evaluate the effectiveness of implemented mitigation measures (105).

With real-time information about radon concentration in different areas of a building, it is possible to determine which areas have higher and lower levels of radon (106). This can be useful for deciding which areas should be used for activities with longer or shorter exposure times, as well as determining which areas require additional mitigation measures (107). Additionally, the information collected by IoT systems can be integrated into intelligent building management systems, allowing building managers to make informed decisions about space utilization (108). For example, if a room is empty during a certain period, the ventilation for that room can be turned off to save energy and reduce maintenance costs for the ventilation system (109). Energy efficiency should be considered when implementing radon mitigation measures in indoor environments (110). For example, ventilation can be an effective measure for reducing radon concentration, but it can also increase energy costs if not managed properly. To avoid this issue, it may be necessary to implement mechanical ventilation systems with heat recovery, which allow for the circulation of fresh air without wasting the energy used to heat or cool the environment.

The use of IoT systems can be even more crucial when considering energy efficiency in radon mitigation in indoor environments (111). IoT systems can monitor radon concentration and air quality in real-time, allowing for more efficient management of ventilation systems and ensuring that fresh air is supplied only when necessary (112). This can help reduce energy consumption and costs associated with ventilation while ensuring that indoor air quality remains healthy and safe for occupants. In addition, IoT systems can provide accurate data on the performance of ventilation systems, allowing building managers to adjust system settings to maximize energy efficiency (*113*).

Mitigation measures for indoor radon levels can be diverse, and not limited to physical solutions such as ventilation or sealing of cracks (*114*). The organization of spaces and the management of activities carried out in them are also important factors to consider, as they can have a significant impact on radon concentration levels (*115*). One of the measures for organizing spaces can be limiting the use of certain areas to shorter periods, thus reducing workers' exposure to high concentrations of radon (*116*). Additionally, activities that require more intensive use of spaces can be scheduled for times of lower occupancy, reducing workers' exposure to high concentrations of radon (*117*).

Although Decree-Law No. 108/2018 of December 3, which establishes protective measures against population exposure to radon in buildings, does not refer to the use of IoT continuous monitoring systems for radon concentration assessment, it is possible that such systems can be used to improve the assessment of exposure risks in the workplace, in conjunction with recommended methods. IoT continuous monitoring systems can provide real-time or near real-time data, allowing for more accurate analysis of radon concentration in different areas of a building and quicker detection of fluctuations in concentration. This can be particularly useful in workplace environments where there are frequent changes in conditions, such as variations in occupancy and ventilation. In addition, the collected data can be easily analyzed and stored in a cloud, allowing for the creation of easily interpretable reports and charts. However, it is important to remember that the use of such systems must be accompanied by appropriate mitigation measures to reduce workers' exposure to radon.

5. Conclusions

The Portuguese legislation emphasizes the importance of risk assessment and mitigation for the safety and health of workers, including the management of indoor radon exposure. While tobacco smoking remains the primary cause of lung cancer, the potential health risks associated with radon exposure should not be underestimated, particularly in occupational settings. Employers are responsible for ensuring a safe and healthy work environment, implementing preventive measures, and providing appropriate information and training to workers. To take on this responsibility, the measurement of indoor radon is the only way to assess concentrations above the national reference level. However, indoor radon inside buildings is not constant, showing daily and seasonal variations. Therefore, the length of the monitoring campaign is a determining point concerning the representativeness of the obtained results. Based on this, long-term measurements, between three months and one year, make it possible to assess the indoor average concentration. On the other hand, short-term or instantaneous measurements, lasting a couple of days or only a few minutes, respectively, may provide a first indication of the indoor radon concentration and should be used as an initial approach. Despite there are types of radon detectors that can be used for in situ assessment: the active detectors which demand require the use of active components to carry out the sampling, and the passive detectors which do not require energy to operate, in which sampling is carried out by diffusion, with the advancement of technology, IoT systems are the most effective way to monitor and manage radon concentration in real-time. These systems allow a more accurate and efficient assessment of exposure risks and the implementation of appropriate mitigation measures since act in real-time by providing qualified information to allow indoor radon management. Although not explicitly mentioned in Decree-Law No. 108/2018, IoT continuous monitoring systems may complement the recommended methods for radon assessment, providing valuable data for protecting workers' health and ensuring compliance with legal and ethical obligations related to occupational health.

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Data are available per on request to the corresponding author.

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