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The Impact of Climate Change on Residential Radon Levels and Lung Cancer Risk: Scenario-Based Risk Assessments

David Richardson

david.richardson@uci.edu

University of California, Irvine

Heechan Lee

University of California, Irvine

Niccolò Loret

Italian National Institute of Health

Sara Antignani

Italian National Institute of Health

Francesco Bochicchio

Italian National Institute of Health

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Title: The Impact of Climate Change on Residential Radon Levels and Lung Cancer Risk: Scenario-Based Risk Assessments

Heechan Lee[1]; Niccolò Loret[2], Sara Antignani[2], Francesco Bochicchio[2]; David B. Richardson, PhD[1*]

Affiliations

[1.] University of California, Irvine, Department of Environmental and Occupational Health, Irvine, CA, USA

[2.] Italian National Institute of Health, National Center for Radiation Protection and Computational Physics, Roma, Italy

Corresponding Author[*]: David B. Richardson, Department of Environmental and Occupational Health, University of California, Irvine, Irvine, CA, 92697, USA

PHONE: (949) 824-5148 FAX: (949) 824-2039 EMAIL: david.richardson@uci.edu

Abstract

Climate change adaptation strategies, such as increased air conditioning use, greater time spent indoors, and seeking cooler lower-floor spaces, may inadvertently increase residential radon exposure and associated lung cancer risk. We conducted a scoping review of literature on climate change and indoor radon, then developed four exposure scenarios reflecting plausible behavioral shifts: current conditions, increased air conditioning use, increased time in basements, and a combined scenario. Using the BEIR VI exposure-age-concentration (EAC) model, we estimated cumulative excess risk (CER) of lung cancer mortality by age 85 for US and pooled European populations. Compared to current conditions, the combined scenario yielded an additional 46 lung cancer deaths per 10,000 persons in the US, and 42 in Europe. These findings highlight an unrecognized pathway through which climate change adaptation may amplify population-level cancer risk, if available countermeasures are not taken.

Climate change and associated warming temperatures can affect public health through direct effects of high ambient temperature as well as through indirect or secondary environmental phenomena. The accelerating rate of temperature increase has been associated with extreme weather events, such as heavy precipitation and droughts[1, 2, 3], as well as secondary phenomena such as frequent wildfires[4].

However, less attention has been given to climate change-associated increases in indoor exposure to radon progeny, which could have important public health consequences as well. Radon-222 arises naturally from the decay of uranium, which is present throughout the earth's crust. Radon is one of the leading causes of lung cancer, and is estimated to account for 3 to 14% of lung cancer deaths worldwide[5]. Radon progeny, the short-lived decay products of radon, deliver alpha radiation to the lungs and bronchi upon inhalation, and the association between residential radon exposure and lung cancer has been well established through pooled epidemiological studies[6, 7, 8] and recognized/confirmed by the evaluation of the International Agency for Cancer Research of the World Health Organization[9, 10].

Prior research suggests multiple mechanisms by which climate change may impact indoor exposure to radon progeny. This includes climate effects on the movement of radon gas through soil, changes in ways that we ventilate and cool indoor spaces, and changes in the amount of time we spend indoors and even the indoor locations that we choose. Among these potential impacts, in this paper, we decided to focus on behavioral adaptation to climate change that affects time-activity patterns and building operation, specifically, increased use of air conditioning, increased time spent indoors, and increased time spent in lower floors/basements.

Here, we use information on how plausible changes in behavior and building operation associated with climate change adaptation could affect radon exposures, and derive estimates of

radon-associated lung cancer risk in Europe and the United States under different adaptation strategies.

RESULTS

We defined four scenarios of behavioral adaptation to climate change for a reference house with 74 Bq/m³ (2.0 pCi/L) on the first floor and 185 Bq/m³ (5.0 pCi/L) in the basement: (I) current conditions (21 hours indoors, 3 hours outdoors; 0.376 WLM/year); (II) increased air conditioning for 3 summer months, raising indoor concentrations by 60% (0.431 WLM/year); (III) shifting 4 hours daily to the basement and 1 additional hour indoors (0.492 WLM/year); and (IV) combined effects of scenarios II and III (0.564 WLM/year).

For the risk estimation, we applied the lung cancer risk model estimates reported in the US NAS BEIR VI report[11]. We used the Exposure-Age-Concentration (EAC) model, which applies modifying factors for age and concentration. To quantify uncertainty, 95% confidence intervals for the CER were derived by substituting the lower and upper bounds of the β coefficient (0.021 and 0.281 WLM^{-1}, based on the multiplicative standard error of 1.94 reported in BEIR VI) directly into the cumulative excess risk (CER) calculation; full details are provided in the online Methods.

Using the scenarios above, we estimated the CER of lung cancer by age 85 years for members of the public in the US and Europe, expressed per 10,000 persons.

For the US, the estimated CERs by age 85 years were 91 (95% CI: 30, 221) for scenario I, 104 (95% CI: 34, 252) for scenario II, 119 (95% CI: 39, 288) for scenario III, and 137 (95% CI: 44, 330) for scenario IV. The absolute differences between scenario I and the other scenarios suggest that, if a population of 10,000 people were to adopt the behavioral patterns described in each scenario, about 13, 28, and 45 additional lung cancer deaths could be expected to occur by

age 85 years under the three climate adaptation scenarios (increased use of air conditioning, increased time spent indoors/lower level, and increased use of air conditioning along with increased time spent indoors/lower level) relative to current exposure conditions (scenario I).

For the pooled European population, the estimated CERs by age 85 years were 86 (95% CI: 30, 183) for scenario I, 98 (95% CI: 34, 210) for scenario II, 112 (95% CI: 39, 240) for scenario III, and 128 (95% CI: 45, 275) for scenario IV. The pattern of increasing risk across scenarios was consistent with that observed for the US, although the absolute magnitudes differed due to differences in baseline lung cancer mortality rates between the two populations.

DISCUSSION

Our review identifies multiple pathways by which climate change, and associated adaptations, may lead to increased exposure to indoor radon. Using literature-informed values of the potential change in radon progeny exposure, we calculated estimates of the increase in radon-associated lung cancer mortality in the US and a pooled European population. The results suggest that increases in radon exposure due to climate change are anticipated to lead to significant increases in lung cancer.

It is important to note that our exposure scenarios were developed primarily based on behavioral patterns observed in the United States, where air conditioning is prevalent in residential settings. We acknowledge that air conditioning usage patterns differ across regions. For instance, residential air conditioning penetration remains lower in many European countries compared to the United States. However, air conditioning adoption in Europe has been increasing steadily in recent years and is projected to accelerate further as climate change intensifies summer heat extremes[12]. Similarly, the behavioral shift toward spending more time indoors during extreme heat

events is not unique to any single region but is a broadly recommended public health response to heat waves worldwide. Our scenarios should therefore not be interpreted as precise forecasts of population-wide behavioral shifts in any specific country. Rather, they are intended to illustrate the potential magnitude of change in radon-related lung cancer risk that could result if individuals adopt these behavioral patterns in response to climate change. Even if only a subset of the population in a given region adopts such behaviors, the implications for radon exposure and associated health risks may be meaningful at the population level.

Surveys on building factors indicate that climate-related changes in indoor ventilation and air conditioning may increase indoor radon progeny concentration by 30% to 100%[13, 14, 15, 16, 17, 18, 19]. Current indoor radon models assume a person in the US will spend 70 % of the time indoors at home[20]. However, as the climate becomes harsher to humans, time spent indoors might have increased and will continue to increase. These changes are likely to be significant to human health, considering that indoor radon concentrations are approximately 200% to 1,000% larger than outdoor radon concentrations[20, 21, 22, 23, 24, 25, 26]. Additionally, radon exposure levels can vary significantly depending on where you primarily spend your time indoors. Even within the same home, exposure can be as much as 150% higher depending on whether staying underground or above ground[27, 28, 29].

The purpose of this scenario analysis was not to generate precise national estimates or to predict that entire populations will uniformly adopt these behavioral patterns. Rather, our aim was to provide an illustrative comparison demonstrating the potential magnitude of change in radon-related health risks that could result if individuals modify their behavior in ways consistent with our scenarios. The comparative analysis across the four scenarios shows that behavioral changes

alone, without any change in the underlying geology or building stock, could measurably increase lung cancer mortality risk.

For risk quantification, we employed the BEIR VI EAC model, which is more widely applied in residential radon risk assessments due to its practical suitability for low-level, continuous exposure settings. The BEIR VI report does not conclude that either the EAC or the alternative Exposure-Age-Duration (EAD) model is clearly preferable as the two models can yield meaningfully different risk estimates at residential radon levels. In this paper, we present EAC-based estimates as the primary results. Corresponding EAD-based estimates are provided in the supplementary document for reference.

This potential increase in lung cancer mortality risk can introduce a significant risk to global respiratory health when combined with other air pollutants. As the results show, for individuals who increase their use of indoor spaces and basements where the temperature is relatively moderate, the estimated increase in lung cancer deaths would be 26 to 28 per 10,000 people (based on EU and US population, respectively); for those who increase their use of air conditioning, the estimated increase would be 12 to 13 per 10,000 people. These effects are even exacerbated by increased use of air conditioning and increased time spent indoors, which is expected to result in an additional 42 to 46 lung cancer deaths per 10,000 people. This figure is greater than the sum of the increased lung cancer mortality projected under the two scenarios, which is a synergistic effect of spending more time in homes with increased radon levels due to air conditioning system.

However, avoiding air conditioning or increasing outdoor activity time to avoid the lung cancer risk from radon exposure that develops over several years can lead to more direct and immediate heat-related illnesses. Considering this, passive houses appear to be a viable alternative.

As previously reviewed, studies have shown that, unlike typical energy-efficient houses, passive houses do not increase radon concentrations[17]. This suggests that using passive houses could offer three benefits: energy savings, prevention of heat-related illnesses, and reduced radon exposure.

The CER estimates for the pooled European population were slightly lower than those for the US. Although the European population had higher lung cancer mortality rates in middle age (50 to 69 years), likely reflecting higher smoking prevalence in Europe[30, 31, 32, 33], US lung cancer mortality rates exceeded those of Europe at older ages (70 years and above), where the cumulative radon exposure and baseline risk contribute most substantially to the CER.

Although our scenario-based projections of future radon exposure risks were grounded in findings from previous studies, this analysis has several limitations. These analyses did not account for the complex microenvironment of the home and the lifestyle. Real homes exhibit temporal and spatial variability, and the lifestyle varies as someone will spend more time indoors during the day and others will spend more time during night. However, climate change not only changes lifestyle patterns but also changes indoor radon concentrations. For this reason, this analysis cannot be considered applicable to individual cases, but is valid when making reasonable average assumptions to assess population-level risk.

The rise of soil temperature will boost the release of radon gas from the ground and will eventually increase the indoor radon concentration[34, 35]. Moreover, this pattern can be even stronger in the polar regions, where, on the other hand, relatively few people live. In the polar regions, permafrost acts as a natural barrier to radon. However, due to the recent increase in global temperature, a large amount of permafrost has melted, and the radon gas can escape from the ground and infiltrate buildings [36, 37, 38].

Not only does climate change affect soil radon transport, but changes in precipitation patterns as well. Increased rainfall can raise soil moisture levels, which can create a barrier effect that slows radon movement from the ground surface to the atmosphere, especially in dense soils [34, 39, 40]. As a result, droughts, projected to intensify in many regions under climate change, can dry soils, increase the air-filled pore space and increase the permeability of soil. Increased permeability can potentially facilitate radon diffusion from deeper layers to the ground surface and into buildings. Moreover, droughts can lead people to use deeper groundwater water and this will increase the radon exposure[41].

Extreme weather events, such as floods, can affect indoor radon exposure. Damage to building infrastructure and fundamental changes in soil conditions after a disaster can promote radon to enter the building [42].

The changes in infiltration due to climate change can also affect to the exposure to radon. When prototypical detached homes in the United States were modeled with the Lawrence Berkeley National Laboratory model of infiltration, the infiltration rate was expected to decrease by 5 % and this would induce a 5 % increase in the exposure to radon[43].

Increased temperatures, changes in precipitation, and resulting changes in home ventilation systems due to climate change can potentially increase indoor radon concentration. Moreover, increased particulate matter from natural disasters caused by climate change is likely to further increase the health effects of radon exposure[44, 45, 46].

We did not incorporate these difficult-to-quantify changes into our analysis. As a result, our scenario-based risk estimates are likely conservative with respect to projected changes in risk.

CONCLUSION

The Earth is experiencing significant climate change, with wide-ranging consequences for public health. Rapid climate change is affecting public health in various ways. However, the increased impact of climate change on radon exposure has not been a major concern. Even if it were, the focus has been concentrated on the increase in indoor radon concentrations, with little attention given to the impact of lifestyle changes due to climate change on radon exposure.

Our comprehensive review suggests that climate change-induced increases in temperature and changes in precipitation patterns may alter indoor radon concentrations. The construction of better-insulated homes to protect against frequent and severe weather events can result in poorer ventilation systems, which can lead to greater indoor radon accumulation.

Moreover, spending more time in underground spaces to avoid extreme heat and cold due to climate change could potentially result in spending more time in areas of the home with higher radon concentrations. Additionally, climate change is causing more frequent events that increase the concentration of particulate matter, which may amplify the effects of radon exposure on human health.

Our scenario analysis indicates that if climate change leads individuals to spend more time indoors, particularly on lower levels such as basements, and to increase their reliance on air conditioning in sealed environments, lifetime lung cancer mortality attributable to radon could increase measurably. While not all populations will adopt these behavioral patterns uniformly, the increasing prevalence of air conditioning in regions such as Europe, combined with the global trend toward indoor lifestyles accelerated by factors such as telecommuting since COVID-19, suggests that these scenarios represent plausible trajectories for a growing segment of the population.

Importantly, the projected increases in radon-related lung cancer risk associated with climate change adaptation are not inevitable. The implementation of available radon mitigation measures in dwellings, such as sub-slab depressurization, increased mechanical ventilation, and radon-resistant construction in new buildings, can partially or substantially offset these increases. Climate change adaptation strategies should therefore be accompanied by greater attention to indoor radon exposure and increased uptake of radon testing and mitigation actions.

Table 1. Scenarios and estimated Cumulative Excess Risk (CERs) in terms of expected lung cancer deaths per 10,000 persons, and their 95% CIs.

Scenario	I	II	III	IV
US	91 (30, 221)	104 (34, 252)	119 (39, 288)	137 (44, 330)
EU	86 (30, 183)	98 (34, 210)	112 (39, 240)	128 (45, 275)

METHODS

Literature review

We conducted a scoping review of published literature on climate change and indoor radon. We searched the following databases: PubMed, Web of Science, and Scopus using the search terms combined radon and climate-related keywords, including: “climate change AND radon”, “global warming AND radon”, “ventilation AND radon”, “meteorology AND radon”, “geology AND radon”, “floor level AND radon”. We focused on the literature published from 2015 through July 2025.

An initial review suggested a classification of the literature into major categories. Studies on factors influenced by climate change that affect indoor radon levels were categorized as: Meteorological; Built environment; or, Behavioral. Noting that indoor radon concentration arises from a dynamic balance between geological factors (uranium concentration as well as soil porosity), building entry, and removal processes. Individual exposure to indoor radon is further influenced by behavioral factors (time and location spent indoors). Table 2 summarizes the major findings of the scoping review.

Use of air conditioning

The proper usage of ventilation can dilute the indoor radon efficiently. As radon is heavier than air, it can settle on the ground or lower floor if continuous ventilation is not provided as the radon is mainly originated from soil and the bedrock[13, 15, 47].

In response to the need to mitigate climate change, there has been a global push to build more energy-efficient buildings with improved insulation and a tighter building envelope. While

these measures are highly beneficial for reducing energy consumption, they can contribute to increased indoor radon concentrations if the ventilation system is not operating properly[13, 14, 16, 17, 18, 19]. Reduced ventilation traps radon gas, allowing it to accumulate in higher concentrations indoors. Evidence from multiple regions supports the argument that energy-efficient homes tend to have higher radon levels. In Russia, newly built homes have steadily increased radon levels since 1995, when requirements for energy-efficient building construction were established[48] and a similar feature can be observed also in North America, where buildings constructed after 2010, under strict energy saving criteria, show on average higher radon concentration values than older ones[49]. On the other hand, passive houses, a building standard that achieves very low energy consumption through insulation, airtight construction, and mechanical heat-recovery ventilation rather than simply reducing air exchange, showed a similar level of radon compared to non-refurbished houses, while the energy-efficient houses have higher radon compared to non-refurbished houses [17].

Increased air conditioning due to high temperatures can lead to increased indoor radon concentrations. Air conditioning systems typically operate in sealed environments to maximize cooling efficiency, further reducing air exchange rates and ultimately contributing to higher radon concentrations, even on upper floors [14]. However, there are also studies that show air conditioning systems reduce the indoor radon concentration and the equilibrium factor F that determines the effective dose from radon progeny exposure in the non-residential environment[50, 51]. In these cases, the air conditioning systems operated entirely on supplied outdoor air with no recirculation, which effectively dilutes indoor radon. This mechanism is not typical of most residential environments, where air conditioning systems generally recirculate indoor air to maximize cooling efficiency, thereby reducing air exchange with the outdoors and contributing to radon accumulation. Hot

regions where people usually seal and use air conditioning during summer can have higher radon concentrations during summer[52]. In cooler regions, indoor radon is higher in winter as buildings are sealed against the cold weather and stack effects draw soil gas inward [23, 49, 53, 54].

Time spent indoors versus outdoors

During increasingly hot and prolonged heatwaves due to climate change, individuals are advised to avoid outdoor activity during the hottest part of the day and spend two to three hours in cooler areas [55, 56]. If people spend less time outdoors, where concentrations are more than 3 times lower than indoors in homes, a reduction in time spent outdoors may be a determinant of radon progeny exposure. According to the EPA, indoor radon concentrations are over three times higher than those outdoors, implying that increased time spent indoors can meaningfully elevate cumulative radon exposure[57].

Time spent below ground level

As extreme heat waves and other severe weather events increase in frequency and intensity, people are adapting to seeking out the most thermally comfortable areas of their homes. This often results in increased time spent in basements or lower floors. People who spend their time on the highest floor have a higher risk from the heat[58], which implies that the lower floors or the basements can naturally become “cool rooms” or “cooling centers” within their dwellings, as heat rises and the lower floors remain cool. Basements maintain a more constant temperature than upper floors because they are in direct contact with the ground, acting as a significant thermal mass. This thermal stability is a result of a combination of the soil’s ability to absorb, store, and release heat and its low rate of heat release[59].

In single-family homes, basements and the lowest floor typically have the highest concentrations. As the average radon concentration in basements is approximately 1.8 to 2.5 times higher than that measured in the upper floors[27, 29], residents who sleep, work, or play in the lower floors are exposed to more radon than those who primarily occupy the upper floors. The first-floor/basement ratio is typically 0.4–0.7, while the second-floor/basement ratio is similar or slightly lower[27, 28, 29, 60]. Conversely, in high-rise buildings, radon concentrations may not vary significantly across floors, primarily due to exhalation from building materials rather than soil gases[54, 61, 62].

Exposure scenarios

Based on the literature review above, we developed and analyzed scenarios of possible changes in lifestyle patterns due to climate change. We defined the following scenarios: a) current conditions (i.e., hold concentration constant); b) reduced ventilation associated with building efficiency and air conditioning increases concentration by 60%; c) increases in time spent indoors (by one hour) and in lower cooler indoor spaces (by four hours) where concentration can be increased by 150%; d) integrated scenario of b and c.

The reference house was assumed to have 74 Bq/m³ (2.0 pCi/L) for the first or higher level and 185 Bq/m³ (5.0 pCi/L) for the basement. The radon level of the first floor was assumed to be slightly higher or similar level of US and EU countries. The basement level was assumed to have 2.5 times of the first floor[27, 28, 29]. The following are the reference scenario and the comparative scenarios (Table 3):

I) Spend 21 hours per day on the first floor (74 Bq/m³, 2.0 pCi/L), and 3 hours per day outdoors (15 Bq/m³, 0.4 pCi/L)

II) Spend 21 hours per day on the first floor (74 Bq/m³, 2.0 pCi/L), and 3 hours per day outdoors (15 Bq/m³, 0.4 pCi/L) but with air conditioning for 3 months during summer (first floor: 118 Bq/m³, 3.2 pCi/L)

III) Spend 18 hours per day on the first floor (74 Bq/m³, 2.0 pCi/L), 4 hours on the basement (185 Bq/m³, 5.0 pCi/L), and 2 hours per day outdoors (15 Bq/m³, 0.4 pCi/L)

IV) Spend 18 hours per day on the first floor (74 Bq/m³, 2.0 pCi/L), 4 hours on the basement (185 Bq/m³, 5.0 pCi/L), and 2 hours per day outdoors (15 Bq/m³, 0.4 pCi/L) but with air conditioning for 3 months during summer (first floor: 118 Bq/m³, 3.2 pCi/L, basement: 296 Bq/m³, 8 pCi/L)

Radon concentrations for different microenvironments were taken from the National Residential Radon Survey, which showed that the radon concentration of the first floor is 40% of that of the basement in a single-family house[29]. We assumed the baseline time activity patterns consistent with US averages (approximately 21 hours indoors, 3 hours outdoors daily) and modified these to reflect the potential behavioral shifts under climate extremes. Total time spent indoors can be classified into time spent in residence, time spent at work, time spent in restaurants, and other indoor places. However, we assumed all of the time spent indoors happened in the residence (or had the same exposure level as the residence) for simplicity. Also, we assumed for the equilibrium factor the standard values of 0.4 for both upper floors and basements, and 0.6 for outdoors, based on the reports of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and of the Internation Commission on Radiological Protection (ICRP) [63, 64].

Risk calculations

We converted these scenario-specific estimates of indoor radon concentration (expressed in pCi/L, 1 pCi/L = 37 Bq/m³) into estimates of Working Levels, and multiplied the resultant concentration estimates by time to obtain Working Level Months (WLMs). We used the relation as below:

$$WLM = \left(\frac{F \times C}{100}\right) \times \left(\frac{hours\ exposed}{170}\right)$$

where C is radon concentration in pCi/L and F is the equilibrium factor, and 170 refers to the average monthly working hours. For simplicity in these scenarios, we took F = 0.4 (for both upper floor indoor and for basements), and 0.6 (for outdoors), and hours exposed in one year as 8,766 hours. For most of the previous radon risk assessment studies assumed 7,000 hours for the hours exposed as they are only concentrated on the indoor exposure. On the other hand, this study used 8,766 hours (≃ 24 *365.24) as the exposed hours as we integrate the whole exposures including indoor and outdoor exposure. Using this, 1 pCi/L corresponds to approximately 0.21 WLM/year for the upper floor indoor setting.

The re-expression of indoor concentration as WLM allowed us to apply the lung cancer risk model estimates reported in the US NAS BEIR VI report. For these calculations, we used the Exposure-Age-Concentration (EAC) model (BEIR VI), applying modifiers for age and concentration. We estimated the excess relative risk (ERR) of lung cancer using the BEIR VI EAC model:

$$ERR = \beta(w_{5-14} + \theta_{15-24} w_{15-24} + \theta_{25+} w_{25+}) \varphi_{age} \gamma_z,$$

$$\begin{pmatrix} \beta: \text{exposure} - \text{risk slope factor}, \\ w: cumulative\ radon\ exposure, \\ \theta: time - since - exposure\ modifier, \\ \varphi: attained\ age\ modifier \\ \gamma: exposure\ rate\ modifier \end{pmatrix}$$

β refers to the exposure-risk slope factor (0.0768 WLM^{-1}), θ modifies for the time-since exposure ($\theta_{15–24}$: 0.78, θ_{25+}: 0.51), φ adjusts for attained age ($\varphi_{<55}$: 1.00, $\varphi_{55–64}$: 0.57, $\varphi_{65–74}$: 0.29, φ_{75+}: 0.09), γ modifies for the exposure rate by WL ($\gamma_{<0.5}$: 1.00, $\gamma_{0.5–1.0}$: 0.49, $\gamma_{1.0–3.0}$: 0.37, $\gamma_{3.0–5.0}$: 0.32, $\gamma_{5.0–15.0}$: 0.17, $\gamma_{15.0+}$: 0.11). This model applies different weights based on the timing of exposure to provide a more realistic risk profile for settings with long-term, stable exposure levels.

To quantify uncertainty in the risk estimates, we derived 95% confidence intervals by substituting the lower and upper bounds of the β coefficient directly into the risk calculation. Based on the multiplicative standard error of 1.94 reported in the BEIR VI report for the EAC model, the 95% CI bounds for β were computed as 0.021 WLM^{-1} and 0.281 WLM^{-1}.

We lack comprehensive, age-resolved smoking histories; consistent with prior practice when detailed smoking data are unavailable, we assume a multiplicative model for the joint effects of radon and smoking.

Cumulative excess risk (CER) of lung cancer mortality by age 85 years was calculated by summing age-specific contributions up to age 84 using country-specific baseline lung cancer mortality rates and survival probabilities:

$$CER\ (\rho) \approx \sum_{a=0}^{84} r_0^{LC}(a) ERR(a,\rho) S(a)$$

where $r_0^{LC}(a)$ is the lung cancer mortality rate at age a in the absence of radon exposure, $ERR(a,\rho)$ is the computed ERR at age a with the radon exposure at ρ, and $S(a)$ is the survival function which describes the probability of surviving until age a. As $r_0^{LC}(a)$ is not directly achievable, we estimated with the following relation:

$$r_0^{LC}(a) = r^{LC}(a)/(1 + ERR(a,\rho_0))$$

where $r^{LC}(a)$ is the observed lung cancer mortality rate at the average radon exposure level ρ_0.

We report estimates of CER expressed as estimates of excess number of lung cancer deaths by age 85 years per 10,000 persons.

For these calculations, observed rates $r^{LC}(a)$ and survival functions, $S(a)$, were based upon national lung cancer mortality and survival function data. For the US, we used data derived from the Centers for Disease Control and Prevention Wide-ranging Online Data for Epidemiologic Research (CDC WONDER)[65]. For Europe, rather than analyzing France, Germany, and Italy as separate populations, we pooled data from these countries to construct a single European population sample representing approximately 46% of the total EU population (209 million among total EU population of 450 million). For the average radon exposure level (ρ_0), we derived a population-weighted average that accounts for both indoor and outdoor radon exposures. For the US, we used the EPA national averages of 1.3 pCi/L (48 Bq/m³) indoors and 0.4 pCi/L (15 Bq/m³) outdoors[57]. For the pooled European population, we used 1.89 pCi/L (70 Bq/m³) indoors, based on population-weighted averages from France (70 Bq/m³; Ajrouche et al. 2018[21]), Italy (79 Bq/m³; Antignani et al. 2026[22]), and Germany (64 Bq/m³; Petermann et al. 2024[26]). Outdoor radon concentrations were drawn from national surveys: 10 Bq/m³ for France[24], 7 Bq/m³ for Italy[23], and 9 Bq/m³ for Germany[25], yielding a pooled outdoor average of 0.24 pCi/L (9 Bq/m³). (Table 4) Applying equilibrium factors of F = 0.4 for indoor and F = 0.6 for outdoor environments, and weighting by the assumed time-activity pattern of 21 hours indoors and 3 hours outdoors per day, this yields ρ_0= 0.250 WLM/year for the US and ρ_0= 0.351 WLM/year for the pooled European population.

This pooled approach allows us to present the calculations as an application of our exposure scenarios to a large European population, avoiding potentially misleading country-specific estimates given that the scenarios are not tailored to individual national contexts. European

baseline lung cancer mortality rates and survival functions were derived from Eurostat website[66]. All baseline data were drawn from the pre-COVID period (2015–2019) to minimize potential perturbations in cancer mortality data associated with the COVID-19 pandemic.

Table 2. Findings from the literature review on the impact of meteorological, building, and behavioral factors to indoor radon exposure

Variables	**Literature**	**Impact on Radon**
Meteorological effects	Nunes et al. 2023[34], Seyis et al. 2022[35], Ilacqua et al. 2017[43], Baptista et al. 2024[41], Rathebe et al. 2025[42]	Have the potential to increase radon, but due to its complexity, the patterns of the radon are not predictable
Air conditioning system	Cucoş et al. 2015[14]	60% higher
Basement or lower ground	Marcinowski et al.1994[29], Daraktchieva 2021[27], Li et al. 2022[28]	150% higher concentration

Table 3. Scenarios and predicted radon concentration and exposure (expressed in pCi/L, Bq/m^3, and WLM per year)

Scenario		**I**	**II**	**III**	**IV**
Air conditioning		Constant	Increase	Constant	Increase
Location		Constant	Constant	Increase	Increase
Radon concentration	pCi/L	1.80	2.06 (+14%)	2.37 (+32%)	2.72 (+51%)
	Bq/m^3	67	76 (+14%)	88 (+32%)	101 (+51%)
Radon progeny exposure	WLM/year	0.376	0.431 (+14%)	0.492 (+31%)	0.564 (+50%)

Table 4. Radon concentration parameters used to derive the baseline mortality rates

Variables	**Literature**	**Radon Concentration**
Indoor/Outdoor US	US EPA 2025[57]	Indoor 1.3 pCi/L, Outdoor 0.4 pCi/L
Indoor/Outdoor France	Ajrouche et al. 2018[21] Dubois 2005[24]	Indoor 70 Bq/m³, Outdoor 10 Bq/m³
Indoor/Outdoor Italy	Antignani et al. 2026[22] Bochicchio et al. 2005[23]	Indoor 79 Bq/m³, Outdoor 7 Bq/m³
Indoor/Outdoor Germany	Petermann et al. 2024[26] Kümmel et al. 2014[25]	Indoor 64 Bq/m³, Outdoor 9 Bq/m³
Indoor/Outdoor EU Combined population		Indoor 70 Bq/m³, Outdoor 9 Bq/m³

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APPENDIX

The BEIR VI report (NRC 1999) proposed two complementary models for estimating the excess relative risk (ERR) of lung cancer from residential radon exposure. The Exposure-Age-Concentration (EAC) model, used as the primary model in the main text, incorporates modifying factors for the rate of radon exposure. The alternative Exposure-Age-Duration (EAD) model incorporates modifying factors for the duration of radon exposure, and is expressed as:

$$ERR = \beta(w_{5-14} + \theta_{15-24} w_{15-24} + \theta_{25+} w_{25+}) \varphi_{age} \gamma_z,$$

$$\begin{pmatrix} \beta: \text{exposure} - \text{risk slope factor}, \\ w: cumulative\ radon\ exposure, \\ \theta: time - since - exposure\ modifier, \\ \varphi: attained\ age\ modifier \\ \gamma: exposure\ duration\ modifier \end{pmatrix}$$

β refers to the exposure-risk slope factor (0.0055 WLM^{-1}), θ modifies for the time-since exposure ($\theta_{15–24}$: 0.72, θ_{25+}: 0.44), φ adjusts for attained age ($\varphi_{<55}$: 1.00, $\varphi_{55–64}$: 0.52, $\varphi_{65–74}$: 0.28, φ_{75+}: 0.13), γ modifies for the exposure duration by years ($\gamma_{<5y}$: 1.00, $\gamma_{5–14y}$: 2.78, $\gamma_{15\text{-}24y}$: 4.42, $\gamma_{25\text{-}34y}$: 6.62, γ_{35+y}: 10.2). Based on the multiplicative standard error of 2.03 reported in the BEIR VI report for the EAD model, the 95% CI bounds for β were computed as 0.0014 WLM^{-1} and 0.0220 WLM^{-1}.

The key distinction between the two models lies in the γ modifier. In the EAC model, γ decreases with increasing radon concentration (WL) while in the EAD model, γ increases with exposure duration (years). For continuous low-level residential exposures such as those considered in this study, the EAD model tends to yield lower CER estimates than the EAC model.

The BEIR VI report does not conclude that either model is clearly preferable over the other. Thus, we provide EAD-based results here for reference alongside the EAC-based primary results which is more widely used in the similar residential radon exposure risk assessment studies.

Supplementary Table 1 presents cumulative excess risk (CER) estimates per 10,000 persons by age 85 years for the US and pooled European populations under both BEIR VI models. The EAC model (primary results, main text) consistently yields higher CER estimates than the EAD model. For the US, the difference ranges from approximately 23 (Scenario I) to 35 (Scenario IV) additional deaths per 10,000 persons. Overall, the percentage difference between both BEIR-VI models, considering all scenarios both in EU and US, ranges between 23% and 26%. The pattern of increasing risk across scenarios is consistent between the two models.

Supplementary Table 1. Scenarios and estimated Cumulative Excess Risk (CERs) in terms of expected lung cancer deaths per 10,000 persons and their 95% CIs, based on EAC and EAD model

	US – EAC	US – EAD	EU – EAC	EU – EAD
Scenario I	91 (30, 221)	68 (19, 194)	86 (30, 183)	65 (20, 165)
Scenario II	104 (34, 252)	78 (22, 222)	98 (34, 210)	75 (23, 189)
Scenario III	119 (39, 288)	89 (25, 253)	112 (39, 240)	86 (26, 215)
Scenario IV	137 (44, 330)	102 (29, 290)	128 (45, 275)	98 (30, 247)