



Duration versus intensity of exposure on the risk of lung cancer due to radon exposure in the general population

Lucía Martín-Gisbert^{a,b,c}, Alberto Ruano-Raviña^{a,b,c,d,*}, Guadalupe García^{a,c},
María Piñeiro-Lamas^{c,d}, Marta García-Talavera^e, Ana Teijeiro^a, Cristina Candal-Pedreira^{a,b,c,d}

^a Preventive Medicine and Public Health, University of Santiago de Compostela, Santiago de Compostela, Spain

^b Cross-disciplinary Research in Environmental Technologies (CRETUS), University of Santiago de Compostela, Santiago de Compostela, Spain

^c Health Research Institute of Santiago de Compostela (Instituto de Investigación Sanitaria de Santiago de Compostela), Santiago de Compostela, Spain

^d Consortium for Biomedical Research in Epidemiology and Public Health (CIBER en Epidemiología y Salud Pública), Madrid, Spain

^e Nuclear Security Council (Consejo de Seguridad Nuclear), Madrid, Spain

HIGHLIGHTS

- Radon exposure intensity and duration may equally affect lung cancer risk.
- Radon exposures from >40 years ago affect lung cancer risk.
- There seems to be differences on lung cancer risk for men compared to women.

GRAPHICAL ABSTRACT

Duration versus intensity of exposure on the risk of lung cancer due to radon exposure in the general population

For those living above 300Bq/m³, lung cancer risk increases steadily and importantly with exposure duration, even with lengths of exposure above 40 years.



What we know about residential radon exposure and lung cancer risk?
Those living 5 to 35 years on the measured home increase risk by 16% per each 100 Bq/m³

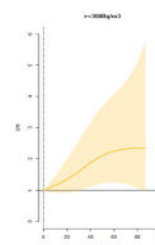
Method

Pooling multicentric case-control study with 3,415 participants (1,619 cases) with individual 3-month radon measurements

• Measured intensity and duration of radon exposure could have similar importance on lung cancer risk

• Higher risk in men

• Exposures from >40 years ago may be relevant



STOTEN

Lucía Martín-Gisbert, Alberto Ruano-Raviña^{*}, Guadalupe García, María Piñeiro-Lamas, Marta García-Talavera, Ana Teijeiro, Cristina Candal-Pedreira

ARTICLE INFO

Editor: Pavlos Kassomenos

Keywords:

Lung cancer
Radon
Case-control study
Radon-priority area
Sex

ABSTRACT

Indoor radon causes lung cancer. The objective of this investigation is to describe lung cancer risk based both on duration and intensity of radon exposure, and to analyze if this effect could be different by sex. To do this, we used pooling information coming from very similar case-control studies on radon and lung cancer, all performed in a radon-priority area. We did a classical categorical analysis using logistic regressions to predict lung cancer risk for exposure duration, intensity of exposure and both variables combined, and we also employed generalized additive models to assess the risk of lung cancer. The results were obtained separately by sex. We included 3415 participants for whom radon measurements had been performed at their home, 1619 of whom were cases. We observed that the length and intensity of residential radon exposure might have a similar importance on lung cancer risk. For those living in dwellings with radon concentrations above 300 Bq/m³, lung cancer risk increases steadily and importantly with exposure duration, even with lengths of exposure above 40 years. We also observed that the risk of lung cancer might be higher in men compared to women. We encourage other

* **Corresponding author at:** Preventive Medicine and Public Health Department, University of Santiago de Compostela, Galicia, Spain, San Francisco s/n, 15782, Santiago de Compostela, Spain.

E-mail address: alberto.ruano@usc.es (A. Ruano-Raviña).

<https://doi.org/10.1016/j.scitotenv.2025.179569>

Received 17 February 2025; Received in revised form 11 April 2025; Accepted 28 April 2025

Available online 5 May 2025

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researchers to reanalyze their data to confirm these results and also to test if the effect observed in women is replicated.

1. Introduction

Lung cancer is a relevant public health problem worldwide. Indoor radon exposure is considered, in most countries, one of the leading causes of lung cancer after tobacco consumption (World Health Organization, 2009; Radon Reference Manual, 1987). More specifically, exposure to radon and its progeny (namely polonium isotopes) through inhalation was declared as a human lung carcinogen in 1988 by the International Agency for Research on Cancer (International Agency for Research on Cancer, 1988) based on scientific evidence obtained in miners' studies. Later on, its carcinogenic effect was also observed in general population in three pooling case-control studies performed in Europe, China and North-America. These included cases and controls, where a radon detector was placed in their respective dwellings (Krewski et al., 2005; Lubin et al., 2004; Darby et al., 2006). Both cases and controls included in these three pooling studies had been living in the measured dwelling for 5 to 30 years (Krewski et al., 2005; Lubin et al., 2004) or 5 to 35 years (Darby et al., 2006). The European pooling study observed a linear and statistically significant increase of lung cancer risk of 16 % per each 100 Bq/m³ of radon concentration (Darby et al., 2006).

In studies of cohorts of miners, the modifying effect of intensity of exposure (exposure rate) for lung cancer risk has been described, as well as the modifying effect of attained age and time since exposure (Kreuzer et al., 2024; National Research Council, 1999). Furthermore, the most used risk models arising from miners' data (BEIR VI risk models) are the exposure-age-concentration (EAC) model based on the average radon concentration and the exposure-age-duration (EAD) model based on the exposure duration, both providing equally valid results (National Research Council, 1999).

Despite this consistent evidence, there are no studies trying to analyze how the two components of radon exposure, intensity (concentration) and length (duration) of exposure, influence lung cancer risk in the general population; an aspect well known for other lung carcinogens such as tobacco consumption (Lushniak BD, Samet JM, Pechacek TF, Norman LA, Taylor PA. The Health consequences of smoking—50 years of progress : a report of the Surgeon General [Internet]. 2014 [cited, 2025]. Also, there is no evidence on what might occur in women, since most miners' studies included exclusively men.

Understanding the relevance of both components of radon exposure is relevant for designing public health policies as they both can be modified with targeted actions. Therefore, the objective of this investigation is, firstly, to describe lung cancer risk based on intensity of radon exposure and on length of radon exposure assessment, and, secondly, to analyze if this effect could be different by sex.

2. Subject and methods

2.1. Design and setting

This study has been mostly performed in Northwestern Spain, which has been classified previously as a radon-prone area by the national radiation protection authority (Lorenzo-González et al., 2017; García-Talavera and López-Acevedo, 2019). This area includes Galicia, where approximately half of the population lives in detached houses in the countryside. This research includes five different case-control studies focused on radon and lung cancer, but with different objectives, since two of them were performed exclusively in never-smokers and small cell lung cancer cases, respectively. Eleven hospitals from four different regions (Galicia, Asturias, Castilla y León and Madrid) have taken part in each of these individual investigations. All studies have shared the same

inclusion and exclusion criteria (cases with confirmed pathological diagnoses) and all participants were older than 30 years old. Controls were recruited following a frequency-based matching for age and sex regarding cases. All studies were approved by their respective Ethical Committees. Specific results on radon and lung cancer risk in the whole sample, and for never-smokers, have been published previously (Lorenzo-Gonzalez et al., 2020; Lorenzo-González et al., 2019).

2.2. Information retrieval

Two information sources (questionnaire and radon detector) were used in all studies. All participants were personally interviewed by trained interviewers (clinicians) with a questionnaire, making special emphasis on tobacco consumption (age of onset and end of tobacco consumption, daily cigarettes per day), which allowed for detailed information on tobacco consumption. We also retrieved information on occupational history and exposure to environmental tobacco smoke. Interviews took place at the different hospitals and, for cases, they took place immediately after lung cancer diagnosis. Detailed information was collected regarding the characteristics of the dwelling, including construction type, floor where the detector was placed and length of residence in the house.

2.3. Radon measurements

All radon measurements were performed using alpha track devices (CR-39 Radosys passive detectors) which were given to cases and controls at the hospital, along with instructions detailing how to place them. Each participant was provided with one alpha track detector and instructions to locate them in their bedroom for three months. Participants were phoned twice by the research team. The first time to make sure that the detector had been placed correctly at the participant bedroom at a height between 60 and 200 cm, with a minimum 15 cm separation from the wall; and the second one to remind them that it should be returned to the Laboratory. When the three-month period ended, the devices were sent back to the Galician Radon Laboratory properly sealed by urgent courier. The Galician Radon Laboratory is ISO-EN 17025 certified by the National Entity of Accreditation (ENAC). Seasonal corrections were applied to obtain the annualized radon concentration (Howrth and Miles, 2008). All participants were informed about the results of the measurement along with recommendations on how to proceed if radon concentration exceeded 300 Bq/m³ (that is, the reference level defined in Spanish regulation on radon).

2.4. Statistical analysis

The main characteristics of the sample were described globally and according to case/control status. Categorical variables were compared between cases and controls using the chi-squared test and continuous variables were compared using the Wilcoxon rank test. Exposure assessment duration and radon concentration were described as continuous variables by case and control status using box plots.

For the analysis, firstly, the two exposure components, exposure assessment duration (referred to as exposure duration) and radon concentration, were considered separately. Exposure duration was categorized into three groups based on years of residence in the same house: <20 years, 20 to 40 years and >40 years. Radon concentration was divided into five categories: 0–50 Bq/m³, 51–100 Bq/m³, 101–150 Bq/m³, 151–300 Bq/m³, and >300 Bq/m³. Two logistic regression models were fitted: one with exposure duration as the independent variable and the other with radon concentration, both adjusted for sex and tobacco

consumption.

Secondly, exposure duration and radon concentration were combined in 15 categories to assess their potential effect modification. The reference category was having lived in a dwelling for <20 years with radon exposure below 50 Bq/m³. We performed a logistic regression where the independent variable was the combination of exposure duration and radon concentration with the categories specified above (3 for exposure duration and 5 for radon concentration). As adjustment variables we considered sex and tobacco consumption in their respective categories (sex: male/female; tobacco consumption: never smoker/ex-smoker/smoker). Age was not included as an adjustment variable to avoid collinearity with length of residence in the same dwelling. The analysis was stratified by sex, to assess if there were relevant differences between men and women. Results are expressed as Odds Ratios (OR) with 95 % Confidence Intervals (95%CI).

Additionally, nonparametric generalized additive models (GAM) (Hastie and Tibshirani, 1990) were applied for evaluating the effect of the effect modification between exposure length and intensity, adjusted for sex and tobacco consumption. The adjustment of the interaction was fitted through an interaction between a curve, adjusted with a smoothing spline (the length in years), and a factor (the radon concentration) categorized in three levels (0–100 Bq/m³, 101–300 Bq/m³ and >300 Bq/m³). Thus, we obtained the adjustment of three curves, one for each radon concentration, which could be compared with each other. In this model, radon concentration had three categories instead of five because, in the five-category model, some categories overlapped, resulting in similar curves that did not provide additional differentiation. The analysis is presented globally and stratified by sex. All analysis were performed with Stata v.17 and R.

3. Results

The pooled database includes a total of 3415 participants, 1619 cases and 1796 controls. Sex and age distribution was very similar between cases and controls, though cases were slightly older (67 vs 63 years). The education attained was also similar between cases and controls. Tobacco consumption was more frequent among cases compared to controls, with differences on pack-years. The most frequent histological type of lung cancer was adenocarcinoma. Radon concentration classified in five categories was higher in cases compared to controls, with 42.5 % of cases with radon concentration higher than 150 Bq/m³ compared to 34.9 % in controls (Table 1). Participants, both cases and controls, lived a median of 30 years in the measured dwelling. Supplementary Fig. 1 shows the distribution of the years of residence in the dwelling measured, showing no differences according to the categories of radon concentration.

Table 2 shows the results of the two logistic regressions. In the regression where the independent variable is radon concentration, a nearly linear increase in the risk of lung cancer is observed as the concentration increases. In the second regression, where the independent variable is length of residence in the dwelling (exposure duration), the same pattern is observed.

The logistic regression analysis for the risk of lung cancer associated with radon exposure, combining exposure duration (years living in the dwelling) and radon concentration, is shown in Table 3. The OR represent the odds ratio of lung cancer for each exposure category compared to the reference category (0–50 Bq/m³ radon concentration and <20 years).

The results show an association between radon concentration and the risk of lung cancer, with a dose-response relationship observed in both the overall group and in men, regardless of the number of years spent in the dwelling. Overall, for those with <20 years of exposure, the risk increases progressively as radon concentration rises. This pattern is also evident in individuals with 21–40 years of exposure, where the ORs increase from 1.17 (0–50 Bq/m³) to 2.48 (151–300 Bq/m³), and even more in those with 41 years or more of exposure, with ORs reaching up

Table 1

Sample characteristics. Globally and by case/control status.

	Total	Cases	Controls	p-value
	N = 3415	N = 1619	N = 1796	
Sex				0.12
Female	1101 (32.2 %)	543 (33.5 %)	558 (31.1 %)	
Male	2314 (67.8 %)	1076 (66.5 %)	1238 (68.9 %)	
Age	65.0 (57.0–73.0)	67.0 (59.0–74.0)	63.0 (55.0–71.0)	<0.001
Education level				0.047
No studies	443 (13.1 %)	232 (14.6 %)	211 (11.8 %)	
Primary studies	2087 (61.9 %)	979 (61.7 %)	1108 (62.0 %)	
Secondary studies	528 (15.7 %)	229 (14.4 %)	299 (16.7 %)	
University studies	314 (9.3 %)	146 (9.2 %)	168 (9.4 %)	
Histologic type				
Adenocarcinoma	659 (41.1 %)	659 (41.1 %)		
Large cell	51 (3.2 %)	51 (3.2 %)		
Small cell	424 (26.5 %)	424 (26.5 %)		
Squamous cells	379 (23.6 %)	379 (23.6 %)		
Other	90 (5.6 %)	90 (5.6 %)		
Tobacco consumption				<0.001
Never smoker	1417 (41.5 %)	496 (30.7 %)	921 (51.3 %)	
Ex-smoker	1191 (34.9 %)	617 (38.2 %)	574 (32.0 %)	
Smoker	803 (23.5 %)	504 (31.2 %)	299 (16.7 %)	
Pack-years	43 (24–70)	54 (39–84)	29 (12–46)	<0.001
Radon concentration				<0.001
0–50 Bq/m ³	643 (18.8 %)	243 (15.0 %)	400 (22.3 %)	
51–100 Bq/m ³	841 (24.6 %)	391 (24.2 %)	450 (25.1 %)	
101–150 Bq/m ³	616 (18.0 %)	297 (18.3 %)	319 (17.8 %)	
151–300 Bq/m ³	789 (23.1 %)	423 (26.1 %)	366 (20.4 %)	
> 300 Bq/m ³	526 (15.4 %)	265 (16.4 %)	261 (14.5 %)	

Missing data. Age: 2; education level: 43; histologic type (only cases): 16; tobacco consumption: 4; pack-years: 127.

Table 2

Logistic regressions: the effect of radon concentration and exposure duration on lung cancer risk.

	Cases	Controls	OR (CI95%)
Radon concentration (Bq/m³)			
0–50 Bq/m ³	243	399	Reference 1.37
51–100 Bq/m ³	391	450	(1.10,1.70)
101–150 Bq/m ³	297	319	1.50 (1.19,1.90)
151–300 Bq/m ³	421	365	1.89 (1.51,2.36)
> 300 Bq/m ³	265	261	1.76 (1.37,2.24)
Length of residence in the measured dwelling (years)			
0–20 years	585	683	Reference 1.18
21–40 years	659	703	(1.01,1.39)
41 years and over	358	392	1.30 (1.08,1.57)
<i>Adjusted by sex and tobacco consumption</i>			

to 3.28 for radon concentrations above 300 Bq/m³.

The analysis by lung cancer subtype, classified as small cell lung cancer (SCLC) and non-small cell lung cancer (NSCLC), is available in Supplementary Table 1.

For men, the OR of lung cancer increases significantly with both higher radon concentrations and longer lengths of exposure, except for those exposed to 50 Bq/m³ or less. Men with exposure durations above 40 years show the strongest association, with ORs of 3.72 for radon

Table 3
Association between exposure duration and radon concentration on lung cancer risk.

GLOBAL															
0–50 Bq/m ³				51–100 Bq/m ³			101–150 Bq/m ³			151–300 Bq/m ³			300 Bq/m ³ and over		
	n	OR	95%CI	n	OR	95%CI	n	OR	95%CI	n	OR	95%CI	n	OR	95%CI
0–20 years	235	1.00	Reference	329	1.55	1.09,2.20	230	1.80	1.23,2.63	281	2.08	1.44,2.99	193	1.53	1.03,2.29
21–40 years	289	1.17	0.81,1.68	334	1.60	1.12,2.27	243	1.88	1.29,2.74	309	2.48	1.73,3.64	187	2.17	1.45,3.24
>40 years	117	1.08	0.67,1.74	171	1.72	1.14,2.60	136	1.81	1.16,2.82	185	2.57	1.72,3.87	141	3.28	2.11,5.09
Adjusted by sex and tobacco consumption															
WOMEN															
0–50 Bq/m ³				51–100 Bq/m ³			101–150 Bq/m ³			151–300 Bq/m ³			300 Bq/m ³ and over		
	n	OR	95%CI	n	OR	95%CI	n	OR	95%CI	n	OR	95%CI	n	OR	95%CI
0–20 years	47	1.00	Reference	92	0.99	0.49,2.03	82	0.98	0.47,2.04	124	0.90	0.46,1.79	74	0.82	0.39,1.72
21–40 years	40	0.74	0.31,1.75	87	0.81	0.39,1.66	86	0.56	0.27,1.17	106	1.33	0.66,2.68	62	1.33	0.61,2.87
>40 years	19	0.99	0.34,2.92	53	0.86	0.38,1.91	55	0.88	0.40,1.96	101	0.91	0.45,1.84	58	1.48	0.67,3.26
Adjusted by tobacco consumption															
MEN															
0–50 Bq/m ³				51–100 Bq/m ³			101–150 Bq/m ³			151–300 Bq/m ³			300 Bq/m ³ and over		
	n	OR	95%CI	N	OR	95%CI	n	OR	95%CI	n	OR	95%CI	n	OR	95%CI
0–20 years	188	1.00	Reference	237	1.58	1.04,2.41	148	1.92	1.20,3.07	157	2.36	1.49,3.74	119	1.61	0.97,2.66
21–40 years	249	1.36	0.90,2.07	247	1.83	1.21,2.77	157	2.67	1.68,4.25	203	2.55	1.65,3.94	125	2.16	1.32,3.53
>40 years	98	1.16	0.67,2.00	118	1.90	1.15,3.14	81	1.92	1.09,3.40	84	3.48	1.97,6.15	83	3.72	2.10,6.60
Adjusted by tobacco consumption.															

concentrations over 300 Bq/m³. For women, there is no significant increase in ORs for those with <20 years of exposure, regardless of radon concentration. Furthermore, among women exposed to concentrations below 150 Bq/m³, no increase in risk is observed as the years of exposure increase. Some increase in ORs is observed as radon concentration exceeds 150 Bq/m³ for longer exposure periods, but estimates are not significant.

Fig. 1 shows the results of the GAM models globally. It is observed that, for individuals with radon concentrations below 100 Bq/m³, the OR for lung cancer remains close to 1 regardless of the number of years living in the dwelling. However, in those exposed to radon concentrations of 100–300 Bq/m³, the OR for lung cancer increases linearly as the number of years of exposure increases. This increase is more pronounced in individuals exposed to radon concentrations above 300 Bq/m³. The GAMs for each sex are shown in Supplementary Figs. 2 and 3.

4. Discussion

This study shows that both duration and intensity of residential radon exposure might have a similar importance on lung cancer risk. For those living with concentrations above 300 Bq/m³, lung cancer risk increases steadily and importantly with exposure duration, even with

lengths of exposure above 40 years. A relevant result is the apparently much lower effect in women compared to men. To our knowledge, this is the first time that both components of radon exposure (duration and intensity) are analyzed separately in general population and also assessing effect modification, thus providing novel information with relevant implications for public health policies.

4.1. Exposure duration

It is remarkable that the exposure duration is especially relevant for those exposed above 300 Bq/m³ providing direct evidence to support that those above reference level would always benefit from radon mitigation, even if they have been living for many years in the same house. We also observed, for the first time, that exposures that occurred >40 years ago still increase lung cancer risk.

The study of the effect of exposure duration is particularly novel in the general population. In the main residential pooling studies, the induction time has been assumed to be 5 years, and the relevant exposure period last 5 to 30 or 35 years (Darby et al., 2005) simply based on studies of cohorts of miners (National Research Council, 1999). Regarding the relevant exposure time, we observed it could persist after 40 years in the general population. About the induction time, our results

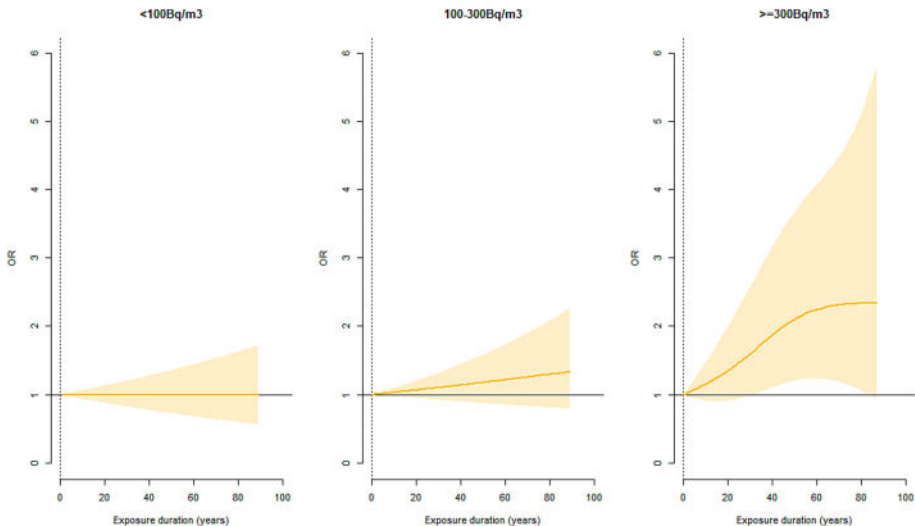


Fig. 1. Generalized Additive Models (GAM) (overall).

are coherent with an at least 5-year induction time but they do not provide further insights, as it is not the objective of this study. To this end, we acknowledge the need to study the induction time of radon-induced lung cancer as well as the relevant exposure time in the general population.

Recent and past studies on cohorts of miners conclude that exposure from >35 years ago does not have a significant effect on lung cancer (Kreuzer et al., 2024; National Research Council, 1999). Nevertheless, there are outstanding differences between miners and the general population. Miners are not exposed to the same radon concentration nor hours per day, they have different physical activity, they are exposed to other carcinogens in the mining environment (gamma radiation in the case of uranium miners, silica dust, and so on), and, what is even more important, their age and attained age at the time of inclusion in different studies is very different from that of the general population. For instance, in the well-known PUMA cohort (Rage et al., 2020), practically all studies included miners where the age at first exposure started at 32 years old or younger, and all studies except for 2 had an average duration of exposure of 10 years or lower. This makes it difficult to study the effect of decades of continuous radon exposure on the risk of lung cancer, something possible in population-based studies like ours. A further aspect which complicates the interpretation of the results is that >70 % of miners were smokers, a percentage hardly found in the general population (Rage et al., 2020; Kelly-Reif et al., 2023).

4.2. Intensity of exposure

We have observed that both exposure duration and intensity significantly increase the risk of lung cancer, although it seems that, overall, intensity of exposure could be slightly more harmful than exposure duration. This can be observed in the categorial analysis in Table 2 where the risk is higher for the different intensity of exposure categories compared to the highest exposure duration (> 40 years).

On the other hand, results from Table 3, where the OR is assessed for 15 categories with increasing intensity and exposure duration, do not show evidence of an exposure rate effect, as depending on the categories it is the intensity or the exposure duration that accounts for the largest risk increase. For instance, intensity appears to have less effect above 300 Bq/m³, whereas exposure duration has less effect on those with intensity 101–150 Bq/m³.

Exposure rate effect has been well described in cohorts of miners as indirectly proportional to lung cancer risk. This is, miners with similar exposure have more risk if their exposure rate was smaller (lower intensity with higher exposure duration (National Research Council, 1999)). This is something that has not been evaluated in the general population and our results show no evidence of this exposure rate observed in miners; if anything, we observe some indications of a different effect of that observed in miners.

Importantly, we detect an increased risk starting from 51 to 100 Bq/m³, in line with previous studies in this area (Barros-Dios et al., 2002) and with the most relevant pooling studies, which found risk increase per each 100 Bq/m³ (Krewski et al., 2005; Darby et al., 2005). This finding supports the idea that the building codes and any mitigation action should target radon levels below 100 Bq/m³, consistent with WHO recommendations (World Health Organization, 2009). Furthermore, these implications are important not only for the general population but also for workers in radon-priority areas.

A final remarkable finding is the relevant lung cancer risk (OR > 3) observed for those exposed for >40 years to radon concentrations higher than 300 Bq/m³ compared to those whose duration of exposure is shorter than 20 years and had an intensity lower than 50 Bq/m³.

4.3. Generalized additive models

To our knowledge, this is the first population-based study analyzing the role of length and intensity of exposure of radon and lung cancer

through generalized additive models. Generalized additive models have been scarcely used when analyzing the effects of radon, where categorical information is classically employed. They add flexibility to data and may facilitate the results interpretation. In this particular analysis, we can observe that the risk increases with exposure duration for both intermediate and high radon concentrations. Nevertheless, the risk profile is different, apparently linear for radon concentrations between 100 and 300 Bq/m³, but it seems to reach a threshold with a very large exposure duration (i.e. >60 years).

4.4. Differences by sex

Remarkably, in our study, radon did not show any significant effect on lung cancer risk in women at any exposure intensity or duration. The effect observed on men was clearly different. This could be due to the relatively low number of female participants, or it could reflect a genuine differential health effect for women.

The lack of effect observed in women is intriguing. Previous studies indicated sex differences in the risk of lung cancer in relation to radon, though in different directions. In the European pooling study (Darby et al., 2005) where only 25 % of participants were women, the association between radon exposure and lung cancer risk was not significant for women and significant in men. The pooling study in never smokers performed in Galicia (>1400 participants, including >500 never smoking lung cancer cases) showed different results for men and women. While men showed an OR of 2.43 (95%CI 1.40, 4.24), comparing those exposed to >199 Bq/m³ versus <100 Bq/m³, the effect for women was 1.44 (95 % 1.00, 2.09) (Lorenzo-González et al., 2019). We cannot disregard that the results obtained for women in the present study may be driven by the high amount of never smokers included. In the North American pooling (Krewski et al., 2005), with most female participants, the opposite occurred, the risk was only significant among women.

4.5. Strengths and limitations

This study has some important advantages, with two of them considered remarkable. The first one is that it has been performed in a radon-priority area, allowing for an easier modelling of radon effect of lung cancer because radon exposure is highly variable among the participants included. The second one is that Spanish population and particularly Galician population has a low mobility, thus we had a large number of participants with an exposure duration above 40 years that allowed direct observation of the effects of such exposure duration. Of note, this length of exposure is higher than the 5–30 years of average exposure considered in the European and American pooling studies. Other advantages are the high number of participants included, and the extremely similar methodology of the different case-control studies included, with exactly the same information collected from cases and controls.

This study has also some limitations. First, we have not considered the total length and intensity of exposure to residential radon of participants throughout their lifetime. This limitation on the exposure assessment is present across all epidemiological studies on radon exposure, and could only be addressed by having radon measurements in all dwellings used in a lifetime and exploring the duration of each intensity of exposure (i.e. 15 years <100 Bq/m³, 50 years >300 Bq/m³ vs. 50 years <100 Bq/m³ and 15 years >300 Bq/m³). For instance, both the American and European pooling studies use real measurements covering an average of radon exposure the previous 23 or 19 years of exposure before measurement respectively (Krewski et al., 2005; Darby et al., 2006). Our study improves these estimations with an average length of residence of 30 years for cases and controls, respectively.

The second main limitation is that the pooling case-control study includes case-control studies which had as an objective to analyze the effect of lung cancer in specific populations such as never smokers

(Lorenzo-González et al., 2019) or Small Cell Lung Cancer (Rodríguez-Martínez et al., 2022) and therefore these types of lung cancer cases are overrepresented. Finally, we did not analyze the influence of the seasonal variations on radon concentrations. Nevertheless, we use seasonal corrections to overcome this limitation.

4.6. Conclusions and future studies

This study suggests that both intensity and exposure duration have a similar and important role on lung cancer risk; noteworthy exposure duration above 40 years is outstandingly relevant for radon concentrations above 300 Bq/m³. Furthermore, we observed that lung cancer risk arising from residential radon exposure might be different in men compared to women.

Finally, we would like to encourage other researchers to reanalyze other population-based studies, particularly to confirm if our results are consistent with others, and particularly to have an in-depth picture on the intriguing role of radon on lung cancer in women.

Data statement

The data that support the findings of this study are available from the corresponding author, ARR, upon reasonable request.

CRedit authorship contribution statement

Lucía Martín-Gisbert: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Alberto Ruano-Ravina:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Conceptualization. **Guadalupe García:** Writing – review & editing, Writing – original draft, Software, Resources, Project administration, Investigation. **María Piñeiro-Lamas:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Investigation, Formal analysis. **Marta García-Talavera:** Writing – review & editing, Writing – original draft, Software, Resources, Project administration, Investigation. **Ana Teijeiro:** Writing – review & editing, Writing – original draft, Software, Resources, Project administration, Investigation. **Cristina Candal-Pedreira:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Ethical considerations

Ethical approval was granted for each of the studies included in this pooling.

Funding

None.

Declaration of competing interest

The authors declare they do not have any conflict of interest.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2025.179569>.

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