High Radon Areas and Lung Cancer Prevalence: Evidence from Ireland

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Abstract

This paper examines the relationship between radon risk and lung cancer prevalence using a novel dataset combining spatially-coded survey data with a radon risk map. A logit model is employed to test for significant associations between a high risk of indoor radon and lung cancer prevalence using data on 5,590 people aged 50+ from The Irish Longitudinal Study on Ageing (TILDA) and radon risk data from Ireland's Environmental Protection Agency (EPA). The use of data at the individual level allows a wide range of potentially confounding factors (such as smoking) to be included. Results indicate that those who live in an area in which 10% - 20% of households are above the national reference level (200 Bq/m^3) are 2.9 - 3.1 times more likely to report a lung cancer diagnosis relative to those who live in areas in which less than 1% of households are above the national reference level.

Keywords: radon risk, lung cancer prevalence, logit model

1. Introduction

Radon is estimated to be the second most prominent cause of lung cancer worldwide (WHO, 2009). Encouraging preventative health policy (e.g. through the installation of radon preventative measures in new build homes), has the potential to reduce the number of lung cancer cases. Ireland has previously been estimated to have the eighth highest level of indoor radon concentrations amongst OECD countries (WHO, 2009), with average indoor radon concentration levels now estimated to be 77 Bq/m^3 (Dowdall et al., 2017). However, we are not aware of any studies on Ireland that have aimed to establish the relationship between lung cancer prevalence and variations in radon risk. This paper uses data on 5,590 people aged 50+ from The Irish Longitudinal Study on Ageing (TILDA) in conjunction with area-based estimates of radon risk from Ireland's Environmental Protection Agency (EPA). Using a logit model we find that individuals who live in an area in which 10% - 20% of households are estimated to be above the radon national reference level are 2.9 times more likely to report a lung cancer diagnosis than those who live in an area in which less than 1% of households are estimated to be above the national reference level.

The paper is structured as follows. Section 2 provides an overview of radon and its health effects, in particular lung cancer, and describes previous research within an Irish context. Section 3 describes in detail the data used in this paper and outlines the variables to be used within our model. Section 4 describes the model used for our estimation. Section 5 describes the results and potential mechanisms for these results. Section 6 outlines potential future extensions while Section 7 concludes.

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2. Literature Review

2.1. What is Radon?

Radon is a naturally occurring inert gas formed by the radioactive decay of uranium in the earth's crust. Radon moves freely though the soil as a gas, where it is then diluted to harmless concentrations in the atmosphere. Radon primarily enters a building by seeping through the ground floor. In particular, radon is transported into homes "through cracks in solid floors and walls below construction level; through gaps in suspended concrete and timber floors and around service pipes; through crawl spaces, cavities in walls, construction joints, and small cracks or pores in hollow-block walls" (Appleton, 2007). Other sources of indoor radon include building materials, and the radon concentrations of groundwater used for domestic drinking water. Radon is the predominant source of radiation exposure in Ireland (estimated to be 56% of the dose received) the majority of which is received in the home (EPA, 2016).

2.2. Health Effects of Radon

Radon is classified as a Group 1 carcinogen (IARC, 1988) and is the second most prominent cause of lung cancer after smoking (WHO, 2009; Bräuner et al., 2012). While initial epidemiological literature focused on increased levels of radon exposure due to occupation (e.g. underground uranium miners), the 1980s saw more studies examining the relationship between indoor radon exposure and lung cancer in the general population. In order to increase the statistical power of these studies, Lubin et al. (2004), Darby et al. (2005) and Krewski et al. (2006) pooled the data from these studies to analyse the relationship for China, Europe and the US respectively. Using pooled analysis from 13 European case-control studies, Darby et al. (2005) estimated a linear dose-response relationship, with the risk of lung cancer increasing by 16% for every 100 bequerels per cubic metre (Bq/m^3) increase in radon concentration. In addition, Darby et al. (2005) found no evidence of a threshold value, with the dose-response relationship holding for individuals whose homes measured an indoor radon value less than 200 Bq/m^3. Although there is some evidence of a relationship between radon and skin cancer incidence (Wheeler et al., 2012; Bräuner et al., 2015), lymphoid malignancies in women (Teras et al., 2016) and brain tumours (Bräuner et al., 2013), evidence of other radon-induced health effects have been relatively limited (WHO, 2009). The main outcome of interest in this paper is lung cancer.

2.2.1. Lung Cancer: Smokers

Lung cancer is the most common cancer in men and the third most common cancer in women worldwide (Stewart et al., 2014). Lung cancer is the leading cause of cancer deaths in Ireland, with an estimated five-year survival rate of 15% (NCRI, 2017). Roughly 2,300 people are diagnosed with lung cancer every year in Ireland, with around 90% of these cases directly attributable to smoking (NCRI, 2011, 2017). This highlights the importance of controlling for smoking when estimating the relationship between radon exposure and lung cancer. In addition, there is evidence of synergistic effects between radon exposure and smoking (Meenakshi and Mohankumar, 2013). This means that at any given level of radon concentration, the absolute risk of developing radon-induced lung cancer is higher among cigarette smokers than lifelong non-smokers (WHO, 2009). Indeed current smokers are estimated to be 25 times more at risk from radon than life-long non-smokers. At a radon concentration of 200 Bq/m^3, this translates to a risk of 1 in 30 for active smokers and 1 in 700 for non-smokers (EPA, 2016).

2.2.2. Lung Cancer: Non-Smokers

Lung cancer can also occur in individuals who have never smoked, with figures ranging from 10% (Subramanian and Govindan, 2007), to 25% (Sun et al., 2007) of all lung cancer cases. Risk factors for non-smoker lung cancer include exposure to passive smoking, asbestos, air pollution (particulate matter), occupational exposure to carcinogenic materials, genetic factors, and radon (Pallis and Syrigos, 2013). Radon exposure is estimated to be the second leading cause of lung cancer after smoking, and the number one cause of lung cancer amongst people who have never smoked (WHO, 2009). Internationally, the proportion of lung cancer cases estimated to be attributable to radon ranges from 3-14% depending on the average radon concentration in the country (WHO, 2009). The World Health Organisation (WHO) recommends a national reference level (maximum accepted radon concentration level in a residential building, above which remedial action is recommended) of 100 Bq/m^3 in order to minimise health hazards (WHO, 2009) . However, countries which have average indoor radon levels of 80 Bq/m^3 or higher (e.g France, Finland and Sweden) would find it extremely challenging to achieve such a low national reference level. As such the WHO recommends that in cases where country-specific conditions prevent lower reference levels being reached, that a reference level of 300Bq/m^3 should not be exceeded (WHO, 2009).

2.3. Irish Context

Ireland's national Reference Level is set at 200 Bq/m^3, with High Radon Areas defined as areas in which a predicted 10% or more of homes exceed the national reference level. Technical Guidance Document C of the 1997 Building Regulations requires all newly built homes to install a standby radon sump which can become activated if radon concentrations become too high. In addition, it requires that all homes in High Radon Areas install a radon barrier. The National Radon Control Strategy (NRCS, 2014) is a radon control strategy developed by an inter-agency group set up by the Irish Government in order to co-ordinate the policy response to reducing the health risks derived from exposure to radon.

It is estimated that up to 250 cases of lung cancer are linked to radon exposure in Ireland every year (EPA, 2016). These estimates are based on the findings from Darby et al. (2005) and applied to Irish data as described in RPII and NCRI (2005). However, we are not aware of any national studies, either ecological or case-control, that have examined the relationship between radon risk and the prevalence of lung cancer within an Irish context. The most notable examination of radon-induced lung cancer within an Irish context resulted from two cases of lung cancer in non-smokers which prompted the discovery of a household with levels of indoor radon 250 times higher than the national reference level (Organo et al., 2004; McLaughlin et al., 2005; Organo and Murphy, 2007). Similarly, Smyth et al. (2016) investigated reducing radon exposure as a method of secondary prevention of lung cancer in a rapid access lung cancer clinic in Galway University Hospital, Ireland.

3. Data

Two sources of data are linked for use in our analysis: The Irish Longitudinal Study on Ageing (TILDA) and the radon risk map of Ireland. Below we outline each of the data sources.

3.1. TILDA

The Irish Longitudinal Study on Ageing (TILDA) is a nationally representative longitudinal study of people aged fifty and over in Ireland. Data from Wave 1 (W1) was collected between October 2009 and July 2011 from 8,175 individuals aged 50 and over, from the 6,279 households that participated in the study. Interviews were also conducted with the 329 younger spouses and partners of TILDA participants (even if aged less than 50), leading to a total sample size of 8,504. Interviews were conducted by trained interviewers in each respondent's homes, and were carried out using Computer Assisted Personal Interviewing (CAPI). Further waves were subsequently collected between February 2012 and March 2013 (Wave 2), April 2014 and December 2015 (Wave 3) and, finally, between March 2016 and December 2016 (Wave 4). At Wave 1, respondents also completed a self-completion questionnaire (SCQ), designed to collect more sensitive information (e.g. mood), and took part in a nurse-led health assessment (Whelan and Savva, 2013). However, data from the SCQ or health assessment are not used in this study.

3.1.1. Outcome Variable: Lung Cancer

To establish whether or not a TILDA respondent had been diagnosed with lung cancer, the "Physical and Cognitive Health" Section of the CAPI questionnaire was used. Within this section, a series of questions regarding chronic conditions were asked. In particular, TILDA respondents were asked "Has a doctor ever told you that you have any of the following conditions?", with one of the answers listed as "cancer or a malignant tumour". If the respondent stated that they have had cancer or a malignant tumour, they were then asked several follow-up questions including "In which organ or part of the body have you or have you had cancer?". Respondents who identified the site as their lungs are therefore taken to have been diagnosed with lung cancer. To use as much of the available data as possible, we include all cases who reported having had lung cancer in any wave of the survey. Respondents continuously present in Waves 1-3 who reported not having had lung cancer are also included in the sample. Respondents who left the sample early (i.e. via attrition) are omitted, unless they reported having lung cancer prior to exiting. Our outcome variable thus takes the value of one for those reporting that they were ever diagnosed with lung cancer, either before or during the survey period, and zero otherwise. Only those who are over the age of 50 are included in our model, as these are the core TILDA respondents and thus nationally representative at the baseline.

3.1.2. Control Variables

As indicated in Section 2, the predominant cause of lung cancer is known to be smoking, followed by exposure to radon. The remaining non-smoker lung cancer cases are generally attributed to either genetic factors, or such non-genetic factors as occupational exposure, socio-economic status, air pollution, household fumes and infections/medical history (Peddireddy, 2016; Marie Quinn et al., 2016; Gibelin and Couraud, 2016; Couraud et al., 2012). There is also growing evidence that gender matters with regards to the prevalence of lung cancer, with the prevalence of lung cancer in non-smokers tending to be higher in women than in men (Peddireddy, 2016; Clément-Duchêne et al., 2010). Similarly, while the prevalence of lung cancer is generally found to increase with age, Pearce and Boyle (2005) found that although lung cancer rates were significantly higher in areas expected to have the highest levels of radon, that this relationship was no longer statistically significant for those aged over 54. The use of individual-level data from TILDA means some of these key factors can be controlled for when estimating the relationship between estimated radon risk and the probability of reporting a lung cancer diagnosis. Here we use Wave 1 data to control for the number of years for which each TILDA respondent has smoked, along with a number of socio-demographic characteristics such as age, gender, highest level of education and population density of the electoral division in which the respondent is located (used as a proxy for relative air pollution levels).

It is important to also include the length of time each TILDA respondent has lived at their current W1 address. Radon exposure is defined as the amount of time spent in any given radon concentration and is calculated by 'multiplying the radon concentration, measured in Bq/m^3 of each area by the amount of time spent in that area' (WHO, 2009). Drawing upon the literature which looks at studies of underground miners, we assume a minimum lung cancer latency period of five years (Barros-Dios et al., 2012; Field et al., 2002), and as such, drop respondents who have lived less than five years at their W1 residence. In order to identify these individuals we use a question from the "House Ownership" Section of the Wave 3 CAPI Questionnaire, which asks "For how many years have you lived at this address?". Given that we were interested in achieving a minimum threshold of five years of residency at the W1 location, we dropped any W3 respondents who indicated that they had been living at their current W3 address for between 6-11 years. This time period was chosen, as the maximum time period between W1 and W3 of TILDA is 6 years, with the additional five year radon exposure requirement, increasing the time period to 11 years. Appendix A.2 describes the construction of the final sample of 5590 TILDA respondents used in our analysis.

3.2. Radon

Figure 1 shows the radon risk map of Ireland published by the Environmental Protection Agency,[1] which is used to segment the indoor radon risk levels of TILDA respondent residential dwellings. This radon risk map predicts the percentage of homes in each 10km grid square with radon concentrations above the national Reference Level of 200 Bq/m^3 and is based on the results of the Irish National Radon Survey (Fennell et al., 2002) carried out by the Radiological Protection Institute of Ireland between 1992-1999.

The objective of the Irish National Radon Survey was to determine the geographical distribution of indoor radon levels across Ireland. It is a geographically based survey, and as such uses 10km grid squares

[1]For more information see `http://gis.epa.ie/Envision`

based on the Ordnance Survey's National Grid as the unit area for the study. Households were randomly selected in each of these grids using the Register of Electors and invited to participate in the study. Those who agreed to participate were then asked to indicate their home on a county map (these were later checked by comparing the participant's postal address with an Ordnance Survey map) and also, to complete a questionnaire regarding physical characteristics of the house and occupant behaviour. Each participant was then issued with two alpha track radon detectors and instructed to place one in the main living area and the other in an occupied bedroom. Carried out on a phased county-by-county basis between 1992 and 1999, participation rates ranged from 17% to 36% for each county.

Following a twelve-month measurement period, the radon detectors were returned and the average annual indoor radon concentration calculated. The average was calculated by assuming an equal occupancy between the main living area and bedroom and averaging the two measurements obtained. The use of a twelve-month measurement ensures that results are not skewed by seasonal variation (for example changes to occupant behaviour during the summer months, such as increased window opening due to higher temperatures, will increase the ventilation rate and result in decreased levels of indoor radon).

The final number of valid responses (both detectors were returned and the grid square of the location was known) was 11,319 with the average annual indoor radon concentration calculated at 89 Bq/m^3. These results were then used to predict the proportion of households which exceeded the national Reference Level of 200 Bq/m^3 in each grid square. These predictions are split into five categories indicating the share of households likely to have a radon risk above the reference level:

- Less than 1% of households
- Between 1-5% of households
- Between 5-10% of households
- Between 10-20% of households
- More than 20% of households

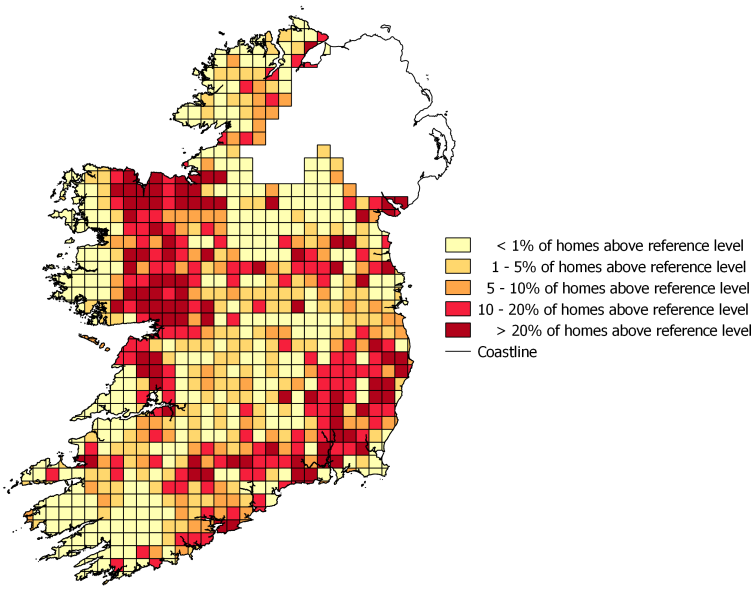
The latter two categories (10-20% and >20%) are considered High Radon Areas (i.e. areas in which over 10% of households are predicted to be above the national Reference Level). Using the geocoded addresses from Wave 1, each TILDA respondent was matched, at the individual level to their respective square grid in the radon map of Ireland. Table 1 indicates the number of TILDA respondents in each radon risk category.

3.3. Geospatial matching

Our models were applied to a cross-sectional dataset based on respondent location in Wave 1 of TILDA. This approach was necessitated by the radon risk data set which was estimated for a single point in time. As described by Kenny et al. (2010) the sampling frame used for TILDA was the RANSAM system developed by Whelan (1979) and is based on the An Post GeoDirectory which contains geocodes for all the addresses in Ireland. A significant advantage of using this sampling frame is that it ensures that the geocode of each TILDA participant's address is recorded, which in turn allows environmental data to be spatially matched to the household of each TILDA participant. QGISv.2.16. was used in order to match each TILDA respondent to their respective square grid on the radon risk map of Ireland. As such, each TILDA respondent was assigned to a radon risk category. Spatial matching was additionally used to match each TILDA household to their respective electoral division.[2] This allowed us to estimate the impact of living in areas with a greater population density per electoral division (acting as a proxy for urban/rural status) and, in addition, allowed us to control for the greater air pollution of urban areas which impacts the probability of developing lung cancer (Loomis et al., 2013; Walsh et al., 2016).

[2]Population data at the electoral division level comes from the CSO Census 2011 Small Area Population Statistics. The area of each electoral division was calculated using QGIS software. The following formula was used to compute the population density of each electoral division: $\frac{\textit{Population of Electoral Division}}{\textit{Number of Hectares in Electoral Division}}$.

Figure 1: Radon Map of Ireland



Data Source: Environmental Protection Agency

4. Methodology

4.1. Model

Here the dependent variable $LungCancer_i$ is a binary variable equal to one if TILDA respondent, i, has been diagnosed with lung cancer either before or during the survey period and zero otherwise. To allow for the discrete nature of this outcome, we employ a logit model. Model 1 demonstrates the theoretical model used, which, following Darby et al. (2005), assumes a linear relationship with no threshold value. Here $RadonCat_i$ indicates the radon risk category each TILDA individual lives in, $\mathbf{X}_{ki}$ is a matrix of individual control variables, and $L(Z) = \frac{e^z}{1+e^z}$ is a cumulative logistic distribution.

$$P(LungCancer_i = 1, 0|RadonCat, \mathbf{X}) = L(\alpha + \beta_0 RadonCat_i + \sum \beta_k \mathbf{X}_{ki}) \quad (1)$$

4.2. Descriptive Statistics

Table 1 shows the descriptive statistics for the variables used in our model. As can be seen, the number of observed lung cancer cases for the dependent variable is relatively limited; 35 TILDA respondents report that they were diagnosed with lung cancer, while 5,555 respondents report not being diagnosed with lung cancer. The distribution of TILDA respondents amongst radon risk categories is skewed in the direction of the lower radon categories, with 25.74% of the sample living in the top two High Radon categories. This is unsurprising given the spatial location of these areas, which are predominantly in rural as opposed to urban areas. While 45.67% of TILDA respondents have never smoked, 19% of respondents have smoked for more than 31 years. The gender split of respondents is shown to be slightly in favour of women, who make up 54% of the TILDA respondents included in our study.[3] Finally we see that while 41% of respondents have a secondary school level of education, 26% have either no schooling or a primary level of education, with the remaining 32% of respondents reporting a tertiary level of education.

[3]In the full cohort, 52% were female at baseline (Barrett et al., 2011).

Table 1: Descriptive Statistics

Variable			Frequency	Percent
Lung Cancer				
No			5,555	99.37
Yes			35	0.63
Radon Risk Category				
<1% above Ref Level			1,447	25.89
1-5% above Ref Level			1,530	27.37
5-10% above Ref Level			1,174	21
10-20% above Ref Level			720	12.88
>20% above Ref Level			719	12.86
Smoking Status				
Never Smoked			2,553	45.67
1-10 Smoking Years			652	11.66
11-20 Smoking Years			710	12.7
21-30 Smoking Years			608	10.88
31-40 Smoking Years			606	10.84
41+ Smoking Years			461	8.25
Gender				
Male			2,554	45.69
Female			3,036	54.31
Electoral Division Population Density				
1st Quintile			1,121	20.05
2nd Quintile			1,118	20
3rd Quintile			1,119	20.02
4th Quintile			1,124	20.11
5th Quintile			1,108	19.82
Highest Level of Completed Education				
Primary/None			1,493	26.71
Secondary			2,300	41.14
Third/Higher			1,797	32.15
Total No. of Observations			5,590	100
	Mean	Std. Dev	Min	Max
Age	63.08	9.19	50	93

5. Results and Discussion

5.1. Results

Table 2 presents the results obtained from estimation of Model 1. Given that our explanatory variable (radon risk category) is categorical in nature, all interpretation must be made with reference to the base category, conditional on the personal and locational characteristics which are controlled for in the model. Here we see a statistically significant positive relationship at the 10% significance level between living in the fourth highest radon category (where 10% - 20% of households are estimated to be above the national reference level) and being diagnosed with lung cancer, relative to living in the base radon category (where less than 1% of the households are above the national reference level). With an odds ratio of 2.9, this implies that those who live in a radon category in which 10% -20% of households are above the national reference level of 200 Bq/m^3 are 2.9 times more likely to report being diagnosed with lung cancer than those who live in a radon category in which less than 1% of households are above the reference level. No other statistically significant relationship is found between the remaining radon categories and lung cancer diagnosis.

Table 2: Full Model

Dependent Variable: Lung Cancer	Odds Ratio	Robust St. Error
<1% of households above the national radon reference level	[ref]	[ref]
1% - 5% of households above the national radon reference level	1.122	(0.605)
5% - 10% of households above the national radon reference level	0.874	(0.509)
10% - 20% of households above the national radon reference level	2.851	(1.632)*
>20% of households above the national radon reference level	0.650	(0.55)
Never Smoked	[ref]	[ref]
1-10 Smoking Years	0.726	(0.781)
11-20 Smoking Years	1.521	(1.247)
21-30 Smoking Years	1.916	(1.591)
31-40 Smoking Years	11.534	(5.931)***
41+ Smoking Years	10.494	(5.224)***
Age	3.827	(1.713)***
Age^2	0.99	(0.003)***
Male	[ref]	[ref]
Female	2.072	(0.752)**
Secondary School Level of Education	[ref]	[ref]
Primary School Level of Education	0.678	(0.299)
Tertiary (or higher) Level of Education	1.536	(0.6)
1st Quintile Population Density	[ref]	[ref]
2nd Quintile Population Density	2.067	(1.502)
3rd Quintile Population Density	1.428	(1.052)
4th Quintile Population Density	2.212	(1.53)
5th Quintile Population Density	3.676	(2.596)*
Constant	$4.59e^{-24}$	$(6.77e^{-23})$***

***p <0.01, **p <0.05, *p <0.10

The statistical significance of control variables is also shown in Table 2. In line with previous studies, respondents who have been smoking for longer periods of time have a significantly higher probability of reporting a lung cancer diagnosis, compared to those who have never smoked. Odds ratios of 11.53 and 10.49 at the 1% significance level are estimated for those who have been smoking for 31 - 40 and 41+ years, respectively. Similarly, increased age significantly raises the probability of reporting a lung cancer diagnosis (giving an odds ratio of 3.8), albeit at a diminishing rate with the quadratic term reporting an odds ratio of 0.99. Women are estimated to be 2.07 times (at the 5% significance level) more likely to report a lung cancer diagnosis. Level of education is not shown to have an impact on the probability of reporting a lung cancer diagnosis. Lastly, we see that those who live in more densely populated areas are also more likely to report a lung cancer diagnosis than those who live in less densely populated areas. Those who live in the highest quintile of population density are estimated to be 3.67 times more likely to have lung cancer than those in the lowest quintile of population density, at the 10% significance level. These findings are all consistent with previous findings in the literature as outlined in Section 2.

5.2. Possible Mechanisms

The lack of statistical significance at the highest level of the radon category (where more than 20% of households are above the national reference level) could be considered surprising. One potential explanation might be increased radon remediation rates within this radon category, which may be the result of specifically targeted programmes by public authorities or due to individuals wishing to reduce their radon exposure. For example Dowdall et al. (2016) estimate that the current rate of remediation (the proportion of households who undertake radon remediation works having found levels of radon above the reference level) in Ireland is 22%. Yet for homes which have radon levels greater than 800 Bq/m^3, Dowdall et al. (2016) estimate the radon remediation rates to be significantly higher at 48%.

While it is important to note that these estimates are based on actual home measurements irrespective of radon risk area, and as such, represent remediation rates at the individual level as opposed to the area level, one can hypothesise that homes which recorded levels of radon greater than 800 Bq/m^3 are most likely to be in High Radon Areas. If this hypothesis holds true, then this would mean that High Radon Areas (in particular areas in which more than 20% of households are above the national reference level) would have higher rates of radon remediation than areas which fall into lower radon categories. If this is the case, and presuming that radon remediation is successful in reducing radon levels, those in the second highest radon category (where 10% - 20% of households are estimated to be above the national reference level) might actually be exposed to the highest level of radon in our survey, rather than those in the so-called highest radon category. Further investigation regarding this potential mechanism would be interesting to explore in future research.

5.3. Parsimonious Model

The results of a parsimonious model in which collectively-insignificant variables are dropped is shown in Table 3.[4] This model shows that relative to all other radon categories, those who live in a radon category in which 10% - 20% of households are estimated to be above the national reference level are 3.12 times more likely to report a lung cancer diagnosis at the 5% significance level. As with the full model shown in Table 2, increased smoking, age and population density increase the probability of reporting a diagnosis of lung cancer, although the magnitude of these odds ratios are in some cases slightly smaller.

5.4. Placebo test

A simple placebo test was carried out to check if the significant association between being located in a radon risk zone and having had a lung cancer diagnosis might be an artefact of the structure of the dataset or the model that was applied. Table 4 presents the results for which we estimated the same model with a different outcome: whether or not the respondent had a cataract diagnosis. Age, gender, education and smoking were found to be significantly associated with cataracts, but risk of radon exposure was not.

[4] A Wald Test was carried out on the hypothesis that all coefficients with less than 10% statistical significance, were jointly equal to zero. It was not rejected [P value = 0.9]

Table 3: Parsimonious Model

Dependent Variable: Lung Cancer	Odds Ratio	Robust Std. Error
Remaining radon categories	[ref]	[ref]
10% - 20% of households are above 200 Bq/m^3	3.123	(1.397)**
Never Smoked - 30 Smoking Years	[ref]	[ref]
31+ Smoking Years	8.877	(3.231)***
Age	3.753	(1.682)***
Age^2	0.991	(0.003)***
Male	[ref]	[ref]
Female	1.98	(0.714)*
1st - 4th Quintiles of Electoral Division Population Density	[ref]	[ref]
5th Quintile of Electoral Division Population Density	2.25	(0.935)*
Constant	$2.13e^{-23}$	$(3.15e^{-22})$***

***p <0.01, **p <0.05, *p <0.10

6. Future Extensions

The main limitation of this paper, in common with most radon exposure research, is the lack of radon risk data at the individual level. Although a radon map with higher resolution might give greater accuracy at a more localised level such as the forthcoming 2023 TELLUS radon map[5], it is still likely that there will be considerable variation at the individual level due to differences in housing characteristics (Barros-Dios et al., 2007) and lifestyle. A further limitation relates to the potential survivor bias existing within the TILDA cohort. As discussed in Section 2, lung cancer is the leading cause of cancer death with a five year survival rate of between 10 - 15%. Given these low survival figures, it is unlikely that the lifetime diagnoses among the over 50s represented in this ageing study is fully captured. If this is the case, survivor bias could result in a significant downward bias in our final results. It may also partly explain the lack of a significant effect on lung cancer for those living in areas with the highest radon risk. As future waves of TILDA data become available, these issues can be investigated further.

7. Conclusion

Using a logit model, we find that individuals who live in areas in which 10% - 20% of households are above the national radon reference level are 2.9 - 3.1 times more likely to report a lung cancer diagnosis relative to those who live in areas in which less than 1% of households are above the national reference level. This suggests that the number of lung cancer cases reported could be lowered if radon risk was reduced through engaging in household radon remediation works. These remedial works could involve sealing floors and walls, increasing indoor and under-floor ventilation, positive pressurisation and/or the installation of radon sumps (RPII, 2004). The finding that those in this second highest radon risk category are most likely to report a lung cancer diagnosis suggests that those in the highest radon risk category might be more likely to have taken steps to mitigate their risks. Nonetheless individuals in the second highest radon category

[5]See `http://www.tellus.ie/` for further details.

Table 4: Robustness Check: Dependent Variable Cataracts

Dependent Variable: Cataracts	Odds Ratio	Robust St. Error
<1% of households above the national radon reference level	[ref]	[ref]
1% - 5% of households above the national radon reference level	1.216	(0.173)
5% - 10% of households above the national radon reference level	1.120	(0.169)
10% - 20% of households above the national radon reference level	0.967	(0.164)
>20% of households above the national radon reference level	1.001	(0.167)
Never Smoked	[ref]	[ref]
1-10 Smoking Years	0.925	(0.155)
11-20 Smoking Years	0.913	(0.15)
21-30 Smoking Years	0.930	(0.163)
31-40 Smoking Years	1.417	(0.236)**
41+ Smoking Years	1.127	(0.183)
Age	1.185	(0.087)**
Age^2	0.999	(0.001)
Male	[ref]	[ref]
Female	1.703	(0.176)***
Secondary School Level of Education	[ref]	[ref]
Primary School Level of Education	1.101	(0.131)
Tertiary (or higher) Level of Education	1.340	(0.164)**
1st Quintile Population Density	[ref]	[ref]
2nd Quintile Population Density	1.165	(0.181)
3rd Quintile Population Density	0.980	(0.158)
4th Quintile Population Density	1.103	(0.173)
5th Quintile Population Density	1.058	(0.174)
Constant	$3.76e^{-06}$	$(9.53e^{-06})$***

***p <0.01, **p <0.05, *p <0.10

are still being exposed to considerable radon risk which increases their likelihood of reporting a lung cancer diagnosis.

The EPA has already run several targeted awareness campaigns in High Radon Areas (EPA, 2017b). However, encouraging radon remediation behaviour, in particular in areas where 10% - 20% of households are above the radon national reference level, may require further action. Hevey (2016) provides an extensive literature review on radon risk perception at the individual level, and in particular, discusses the best method of communicating this threat such that it is effective in encouraging individuals to engage in radon remediation. Hevey (2016) also highlights that although awareness campaigns can increase knowledge and risk perception, they often fail to translate into actual testing and remediation behaviours. Given the relatively limited action at the individual household level, Hevey (2016) therefore suggests that government regulation is required e.g. that houses in high-risk areas must provide certificates of radon test results prior to sale.

Other options might include increasing the incentives for engaging in remediation works through the use of such price policy instruments as tax credits, subsidies and grants which reduce the costs of these works, or indeed through the establishment of government funded low interest loans. At present, there is no grant available to assist with the cost of radon remediation in Ireland (EPA, 2017a). However, under the Home Renovation Incentive Scheme, an income tax credit at 13.5% of the cost of the radon remediation works can be claimed. In addition, the Housing Aid for Older People Scheme which is administered by local authorities, assists older people ($\geq$ 66 years of age) to carry out repairs or improvements (including radon remediation) on their homes. Determining the success of these interventions and exploring whether or not further interventions might be needed will be important to establish going into the future. For example, Pollard and Fenton (2014) find that radon prevention in new buildings is significantly more cost effective that the remediation of existing homes and, in addition, that the cost effectiveness of untargeted radon awareness campaigns and remediation measures are poor if they are not undertaken within the context of a coherent radon strategy.

Regardless of the extent of action needed at both an individual and government level, the key insight from this analysis is the preventability of lung cancer as a disease. By eliminating just two risk factors (smoking and radon exposure) it is clear that the likelihood of developing lung cancer would be extremely low and that the number of lung cancer cases in Ireland would be substantially reduced. It is therefore important that the National Radon Control Strategy continues to facilitate the co-ordination of health policy across agencies and departments in order to produce an aligned preventative health policy which works to ensure that lung cancer is no longer the leading cause of cancer death in Ireland.

Conflicts of Interest

None

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Appendix A. Figures

Figure A.2: Flow Chart demonstrating construction of final sample