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Contribution of Childhood Indoor Radon Exposure to Lung Cancer Incidence among Young Adults: A Population-Based Ecological Study in Canada

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Exposure to indoor radon has been determined to be the second leading cause of lung cancer after tobacco smoking. Recently, it was shown that approximately 90% of Canadians' exposure to radon comes from time spent indoors. Because this exposure effectively begins at birth, long before even young teens begin to smoke, we hypothesized that cumulative exposure to indoor radon during childhood could be a major leading cause of lung cancer among young adults. The population-based analysis presented confirms that lung cancer incidence among young adults is significantly correlated to indoor radon concentrations. Even though only limited data among young adults are available for the analysis and the uncertainty can be very large, the result indicates nevertheless cumulative exposure to indoor radon during childhood can be a major leading cause of lung cancer among young adults. In later adult life, the lung cancer incidence rate could be more strongly correlated to smoking rates than to radon exposure.

Key words: radon-222, lung cancer, radiation risk

1. Introduction

Lung cancer is the second most common cancer and the leading cause of cancer death for both males and females in Canada. Research has shown that cigarette smoking is linked to about 80% of lung cancer deaths[1]. In a monograph[2] presenting historical and projected cancer incidence frequencies and rates in Canada from 2003–2007 to 2028–2032, it is predicted that the age standardized incidence rates of lung cancer will decrease by 34% in Canadian males, and peak and then also decrease in females by 16%. Because of the aging and growth of the population, the annual number of new cases is projected to increase by 34% in males and by 62% in females. The trends in lung cancer incidence have closely mirrored historical patterns of Canadian smoking prevalence after accounting for a latency period of 20 years or more. These trends are also in agreement with the fact that the onset of cigarette smoking starts at younger ages and then follows the birth cohort as it ages, and lung cancer rates increase as the birth cohort ages.

Radon is a naturally occurring radioactive noble gas generated by the decay of uranium-bearing minerals in rocks and soils. Since radon is a gas, it can move freely through the soil, enabling it to escape into the atmosphere or seep into homes and buildings. Outdoors, it is diluted and does not pose a health risk. However,

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Table 1. Average lung cancer incidence counts and population of each CMA averaged over the most recent 10 years (2007-2016), for both sexes combined by age group

CMA	Population				Counts			
	20-24y	25-29y	20-29y	30-39y	20-24y	25-29y	20-29y	30-39y
St John (NL)	153905	165212	319117	303933	0	0	0	0's
Halifax (NS)	319543	325845	645388	577813	0	0	0	10
Moncton (NB)	97377	104297	201674	206754	0	0	0	0
Saint John (NB)	86165	75046	161211	159816	0	0	0	0's
Ottawa-Gatineau (ON)	728283	708875	1437158	1331365	0's	0	0's	20
Kingston (ON)	131158	124456	255614	209794	0	0	0	0
Peterborough (ON)	92496	81114	173610	131729	0	0	0	0's
Oshawa (ON)	253814	229377	483191	499821	0	0	0	10
Toronto (ON)	4161596	4287548	8449144	8620280	10	30	40	150
Hamilton (ON)	523923	490359	1014282	957625	0's	0's	10	15
St Catharines-Niagara (ON)	271212	237860	509072	457255	0	0	0	15
Kitchener-Cambridge-Waterloo (ON)	380603	374109	754712	712359	0	0's	0's	0's
Brantford (ON)	94314	87703	182017	176152	0's	0	0's	0's
Guelph (ON)	111152	111210	222362	207116	0	0's	0's	0's
London (ON)	377020	361220	738240	643639	0	0	0	0's
Windsor (ON)	238022	205186	443208	424180	0	0	0	0's
Barrie (ON)	137172	123426	260598	265930	0	0	0	0's
Greater Sudbury (ON)	115088	108394	223482	207970	0	0	0	0
Thunder Bay (ON)	86950	80883	167833	148407	0	0	0	0
Winnipeg (MB)	560062	559173	1119235	1046220	0's	0	0's	15
Regina (SK)	175725	188197	363922	320385	0's	0's	10	10
Saskatoon (SK)	245199	260427	505626	405058	0	0	0	0's
Calgary (AB)	932781	1122557	2055338	2220042	0	0's	0's	20
Edmonton (AB)	980016	1101005	2081021	1940189	0	0's	0's	20
Kelowna (BC)	125129	122419	247548	220236	0	0	0	0
Abbotsford-Mission (BC)	125399	121153	246552	238774	0	0	0	0's
Vancouver (BC)	1761033	1823057	3584090	3516156	0	10	10	35
Victoria (BC)	249366	265769	515135	460299	0	0	0	0's

in confined spaces, i.e. indoors, radon can accumulate to relatively high levels and become a health hazard when inhaled. Exposure to indoor radon has been determined to be the second leading cause of lung cancer after tobacco smoking[3].

Canadian statistics show that most Canadians spend about 10% of their time outdoors, 20% indoors away from home, and 70% of indoors at home, where average indoor radon concentrations tend to be highest[4, 5]. As a result, estimates show that exposure at home contributes to 90% of the radon-induced lung cancer risk[6]. Even though lung cancer has not been observed in children and is also very rare among youths, age-specific radon-related risk calculations indicated a sharp increase in lung cancer incidence among young adults based on linear relative risk model[6]. Because radon exposure begins at age 0 and most smokers only start smoking regularly at 18 years of age, it is then hypothesized that cumulative exposure to indoor radon during childhood could be a major leading cause of lung cancer among young adults. Here, we conduct a population-based study to investigate the potential contribution of childhood radon exposure to lung cancer incidence among young adults before smoking becomes more prevalent and plays a major role in lung cancer induction.

2. Methods and Data Sources

2.1. Incidence Rates of Lung Cancer

Lung cancer was defined as "Trachea, bronchus and lung: 8000-9049,9060-9139,9141-9589,9993-9999, C34.0-C34.9" according to Site Recode ICD-O-3/WHO 2008 Definition (https://seer.cancer.gov/siterecode/icdo3_dwhoheme/index.html).

There are 33 census metropolitan areas (CMAs) in Canada. For the most recent 10 years (2007-2016), lung cancer incidence data for different ages at time of diagnosis are available in 28 out of 33 CMAs from Canadian Cancer Registry (CCR)[7] using the International Rules for Multiple Primary Cancers[8]. The CMAs of the patients' residence at diagnosis were obtained by linking postal codes in the CCR with the appropriate versions of the Postal Code Conversion File Plus (PCCF+)[9]. Averaged over the most recent 10 years (2007-2016), lung cancer incidence counts and populations of each CMA are summarized in Table 1 for both sexes combined and for different age groups. To limit the potential residual disclosure, in line with CCR reporting requirements, incidence counts shown have to be randomly rounded either up or down to a multiple of 5. The 'random rounding' rounds all non-zero cell counts, those that are not evenly divisible by 5, to the adjacent lower or higher multiple of 5. By design, differences between the rounded counts and actual counts should never exceed 4 and a count was more likely to be rounded to the nearest multiple of 5. Most of CMAs have rather small populations and very low lung cancer incidence. Therefore, randomly rounded counts lower than 10 are not reported due to large uncertainty, i.e. are rounded to zero and reported as "0's" in Table 1, in order to be distinguished from true zeros. Age-specific incidence rates (ASIRs) were derived from dividing the random-rounded counts by the population.

2.2. Indoor Radon Concentrations

Following the launch of the National Radon Program in 2007, Health Canada completed a long-term radon survey in 33 CMAs, which covered about 70% of the Canadian population[10]. Briefly, the survey recruited participants during the summer of 2012 and conducted testing the following fall/winter (October 2012 to March 2013). Participants were recruited over the telephone by random digit dialing, with a target of 122 participants for each CMA. A total of 4064 participants were identified and received alpha-track detectors for deployment in the lowest lived-in level of the home for a minimum of 3 months. Results were available for 3215 homes. The average radon concentration in a CMA varied from 28 Bq/m^3 in Vancouver to 302 Bq/m^3 in Regina.

It is well known that radon concentrations vary widely from one home to another, even for homes in the same geographic area. In order to get more accurate estimates of average radon concentrations in CMAs, results from other national and local surveys were pulled together whenever the administrative boundary matches the boundary of a given CMA[11-14]. Long-term radon measurements with alpha track detectors were conducted in all the residential surveys considered here. Sample-weighted average radon concentrations and associated standard deviations were derived for following CMAs: Halifax, Ottawa-Gatineau, Toronto, Hamilton, Kitchener-Cambridge-Waterloo, Winnipeg, Edmonton and Vancouver. Average radon concentrations for the 28 CMAs where lung cancer incidence rates are available are given in Table 2. These values were used to assess indoor radon exposure in this study.

Table 2. Average radon concentration in residential homes of 28 CMAs

CMA	Rn, Bq/m^3
St John (NL)	88
Halifax (NS)	172
Moncton (NB)	77
Saint John (NB)	115
Ottawa-Gatineau (ON/QC)	101
Kingston (ON)	165
Peterborough (ON)	100
Oshawa (ON)	61
Toronto (ON)	53
Hamilton (ON)	79
St Catharines-Niagara (ON)	56
Kitchener-Cambridge-Waterloo (ON)	61
Brantford (ON)	108
Guelph (ON)	131
London (ON)	85
Windsor (ON)	154
Barrie (ON)	85
Greater Sudbury (ON)	131
Thunder Bay (ON)	156
Winnipeg (MB)	177
Regina (SK)	302
Saskatoon (SK)	152
Calgary (AB)	135
Edmonton (AB)	101
Kelowna (BC)	134
Abbotsford-Mission (BC)	58
Vancouver (BC)	21
Victoria (BC)	37

2.3. Smoking Prevalence in Canada

Most Canadian smokers begin daily smoking in their teens. Smokers have reported that, on average, they smoked their first whole cigarette at the age of 16, and started smoking regularly at 18 years of age[15]. Starting to smoke at an early age has been associated with heavy smoking in later life. According to Statistics Canada[16], the smoking rates are higher among adults aged 20 to 64 year olds, compared to youths and seniors.

The Canadian Tobacco, Alcohol and Drugs Survey (CTADS) is a biennial general population survey of tobacco, alcohol and drug use among Canadians aged 15 years and older[17]. The latest results for 2017 are based on telephone interviews with 16,349 respondents across all 10 provinces, representing a weighted total of 30.3 million Canadian residents aged 15 years and older. Detailed tables for smoking status by provinces and age groups are available at Government of Canada's website (https://www.canada.ca/en/health-canada/services/canadian-tobacco-alcohol-drugs-survey.html). Unfortunately, smoking status by CMA is not available. Summary of percentages of never-smokers (NS) and ever-smokers (ES) by age group is given in Table 3.

The CTADS also provided detailed data of smoking status by province and age group. The 28 CMAs in Table 2 are located in 8 provinces. Summary of percentages of NS and ES by province is given in Table 4 for youth aged

Table 3. Percentage of never-smokers (NS) by age group in year 2013, 2015 and 2017 with average percentages of NS and ever-smokers (ES) for both sexes[16)]

Age group years	year 2013	% of NS year 2015	year 2017	average NS %	average ES %
15-19	88.1	88.8	91.6	89.5	10.5
20-24	76.8	74.2	78.3	76.4	23.6
25-34	68.7	70.0	65.0	67.9	32.1
35-44	57.5	59.7	65.0	60.7	39.3
45-54	55.3	57.7	48.6	53.9	46.1
55+	47.4	46.7	48.6	47.6	52.4

Table 4. Percentage of never-smokers (NS) among youths 15-19 years of age in year 2013, 2015 and 2017 with average percentages of NS and ever-smokers (ES) by provinces for both sexes

Province	year 2013	% of NS year 2015	year 2017	Average NS %	Average ES %
Newfoundland (NL)	85.8	87.6	85.7	86.4	13.6
Nova Scotia (NS)	89.2	92.0	89.8	90.3	9.7
New Brunswick (NB)	86.2	91.2	93.6	90.3	9.7
Ontario (ON)	90.1	89.7	93.3	91.0	9.0
Manitoba (MB)	84.8	85.7	85.7	85.4	14.6
Saskatchewan (SK)	85.9	84.5	77.3	82.6	17.4
Alberta (AB)	89.6	88.9	92.5	90.3	9.7
British Columbia (BC)	88.7	92.2	93.0	91.3	8.7

15 to 19 years. The smoking status among youths will impact lung cancer incidence rate among young adults.

2.4. Statistical analysis

Because there are few lung cancer cases among young adults and limited smoking rates at provincial levels, the choice was made to do separate single variable regressions for radon exposure and smoking instead.

Relationships between lung cancer incidence rates among young adults (20-39 years of age at time of diagnosis) and CMA-level average indoor radon concentrations were evaluated by linear regression to identify whether a significant correlation existed.

Since many Canadians start smoking regularly at 18 years of age, lung cancer incidence rates among young adults were also affected by smoking rate among youth. Because youth smoking statistics are available at the provincial level, linear regression was used to evaluate the relationships between provincial average lung cancer incidence rates among young adults and provincial average smoking rates among youth.

3. Results

Lung cancer incidence is very low among children and youths under the age of 20. For young adults aged 20 to 24, the randomly rounded lung cancer counts were less than 10 in all CMAs except the largest city of Toronto. In the next young adult age group (25 - 29), the rounded lung cancer counts were 10 or more in the top two big cities, Toronto and Vancouver. The ASIR is 0.55 ± 0.16 per 100,000 population in Vancouver with average indoor radon concentration of 28 Bq/m^3, and 0.70 ± 0.07 per 100,000 population in Toronto with average indoor radon concentration of 57 Bq/m^3. While this is only two data points, they are not inconsistent with a possible correlation between radon concentration and lung cancer incidence in young adults.

In view of very low lung cancer incidence rates among young adults, we considered the combined ASIRs for age range from 20 to 29 years. Results are presented in Figure 1 (linear regression analysis of variance [ANOVA], $F_{1,3} = 173.0$, $p = 0.0057$, $R^2 = 0.9886$). For young adults aged 20 to 29, four CMAs have lung cancer counts equal or more than 10. They are Vancouver (with mean indoor radon concentration of 21 Bq/m^3), Toronto (53 Bq/m^3), Hamilton (79 Bq/m^3) and Regina (302 Bq/m^3). The uncertainty is inversely proportional to the population with smallest error bar for Toronto and largest uncertainty for Regina. The results in Figure 1 suggest that cumulative exposure to higher radon concentration at home during childhood might lead to higher lung cancer incidence rates in young adults.

While a strong correlation between indoor radon concentration and lung cancer incidence rate existed for young adults aged 20-29 years, this correlation cannot be observed for the next adult group of 30-39 years, where there are 11 CMAs with randomly rounded lung cancer counts ≥ 10 for this age group (see the last column in Table 1). Results are presented in Figure 2 (linear

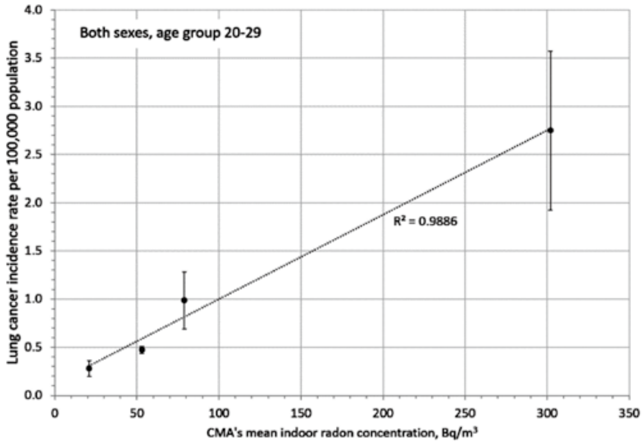

Fig. 1. Age-specific incidence rates of lung cancer as a function of average indoor radon concentration for young adults aged 20 to 29 in four CMAs with randomly rounded lung cancer counts ≥ 10.

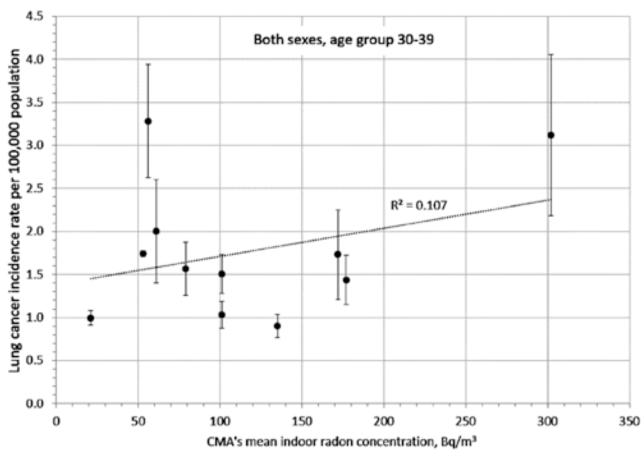

Fig. 2. Age-specific incidence rates of lung cancer as a function of average indoor radon concentration for adults aged 30 to 39 in 11 CMAs with randomly rounded lung cancer counts ≥ 10.

regression ANOVA, $F_{1,10} = 1.083$, $p = 0.325$, $R^2 = 0.107$).

Most radon-induced lung cancer cases occur among smokers due to a strong combined effect of smoking and radon[3]. Since people typically begin smoking during their teenage years[17] and the smoking rate increases with age before starting to decline after middle age, tobacco smoking will induce more lung cancer than exposure to radon for adults later in their life due to cumulative effect for both smoking and radon exposure. To consider the long latency period of 15-30 years for smoking-induced lung cancer, the data in Figure 2 were regrouped by province and presented in Figure 3 as a function of province-level average percentage of ever-smokers in youths (15-19 years of age). For adults 30-39 years of age, the lung cancer incidence rate is more strongly correlated to smoking rates than to radon exposure. Data presented in Figure 3 suggests a slight positive correlation upon

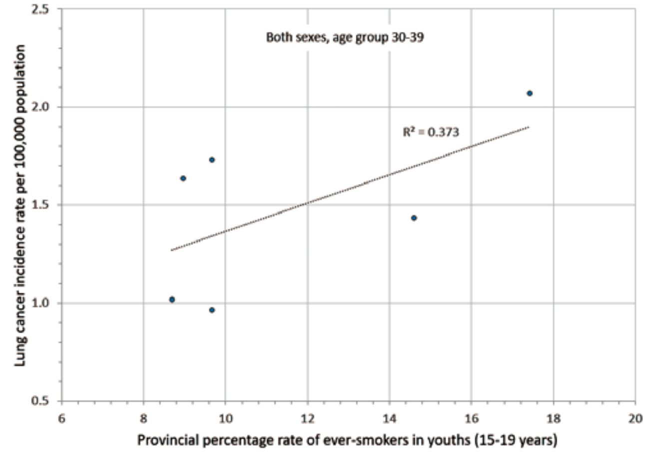

Fig. 3. Age-specific incidence rates of lung cancer as a function of average percentage of ever-smokers in youths (15-19 years of age) for adults aged 30 to 39 in 11 CMAs located in 6 provinces.

inspection that is not statistically substantiated (linear regression ANOVA, $F_{1,5} = 2.38$, $p = 0.198$, $R^2 = 0.373$).

4. Discussion and Conclusions

The risk of radon-induced lung cancer increases with exposure to radon progeny and the duration of the exposure. A recent study showed that due to relatively high radon concentration in residential homes and longer time spent indoors at home, the exposure at home contributes to 90% of the radon-induced lung-cancer risk[6]. Exposure to indoor radon starts at age of zero. Even though lung cancer has not been observed among young children, their exposures to relatively higher radon concentrations at home, accumulated over the first two decades of their life, could contribute to significant increases in relative risks of lung cancer later in their life.

It is well known that the smoking prevalence associates strongly with lung cancer cases among adults in later life. Since most Canadians spend more than 70% of their time indoors at home and smoking becomes more prevalent among adults, cumulative exposure to indoor radon during childhood could be a major leading cause of lung cancer among young adults. The population-based ecological analysis presented here is indicative that lung cancer incidence rates among young adults are significantly correlated to indoor radon concentrations. Even though only limited data among young adults are available for the analysis and the uncertainty can be very large and smoking status is only available by province instead of CMA, the result suggests nevertheless cumulative exposure to indoor radon during childhood could be a major leading cause of lung cancer among young adults. At older ages, such as for adults aged 30-39 years, it is likely that smoking is a more significant contributor in induction of lung cancer, the unmeasured confounding from smoking is likely resulting in the lower and non-statistically significant association from the regression restricted to radon and lung cancer incidence.

The results presented here can be strongly confounded by environmental smoking, especially for children living with smoking parents. To address this confounding, future research could focus on restricted populations, ideally never-smokers from no-smoker families.

Conflict of Interest

The authors declare that they have no conflict of interest.

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