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Estimates of the current and future burden of lung cancer attributable to residential radon exposure in Canada

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ABSTRACT

Radon is widely recognized as a human carcinogen and findings from epidemiologic studies support a causal association between residential radon exposure and lung cancer risk. Our aim was to derive population attributable risks (PAR) to estimate the numbers of incident lung cancer due to residential radon exposure in Canada in 2015. Potential impact fractions for 2042 were estimated based on a series of counterfactuals. A meta-analysis was conducted to estimate the relative risk of lung cancer per 100 Becquerels (Bq)/m^3 increase in residential radon exposure, with a pooled estimate of 1.16 (95% CI: 1.07–1.24). The population distribution of annual residential radon exposure was estimated based on a national survey with adjustment for changes in the population distribution over time, the proportion of Canadians living in high-rise buildings, and to reflect annual rather than winter levels. An estimated 6.9% of lung cancer cases in 2015 were attributable to exposure to residential radon, accounting for 1741 attributable cases. If mitigation efforts were to reduce all residential radon exposures that are above current Canadian policy guidelines of 200 Bq/m^3 (3% of Canadians) to 50 Bq/m^3, 293 cases could be prevented in 2042, and 2322 cumulative cases could be prevented between 2016 and 2042. Our results show that mitigation that exclusively targets Canadian homes with radon exposures above current Canadian guidelines may not greatly alleviate the future projected lung cancer burden. Mitigation of residential radon levels below current guidelines may be required to substantially reduce the overall lung cancer burden in the Canadian population.

1. Introduction

Radon is a common, naturally occurring gas formed from the decay of Uranium-238 (an abundant component of the earth's crust) that is colourless, odourless, and tasteless (Bissett and McLaughlin, 2010). In 1988, radon was classified as a human carcinogen based largely on findings from epidemiological studies of miners exposed to high levels of radon (IARC, 2012). Release of radon and its decay products from the

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ground or from building materials can also result in indoor exposure, particularly in basements of dwellings (Bissett and McLaughlin, 2010). Residential exposure levels are typically much lower than found in underground mines, however substantial variation in residential levels occur regionally, as well as by housing type (Jedrychowski et al., 1995; Stanley et al., 2017). Epidemiologic studies support a log-linear dose-response relationship between exposure to residential radon, suggesting that there is an increased risk for lung cancer even at very low exposures, and no threshold exposure level below which exposure can be considered "safe" (WHO, 2009; Puskin, 2009; Krewski et al., 2006; Zhang et al., 2012).

Pooled analyses of North American studies (Darby et al., 2005; Krewski et al., 2006; Lubin et al., 1994) and meta-analyses (Duan et al., 2015; Pavia et al., 2003; Zhang et al., 2012) support a relationship between residential radon exposure and lung cancer risk. These studies report a log-linear dose-response relationship between long-term radon exposure (concentration averaged over periods of 20–30 years exposure) and lung cancer incidence, with relative risk (RR) estimates ranging from 1.07 to 1.33 per 100 Bq/m^3 [Becquerel per meter cubed] (Darby et al., 2005; Krewski et al., 2006; Lubin et al., 2004; Zhang et al., 2012).

Residential radon concentration varies according to season and housing characteristics, with higher levels in colder months, in homes with poor ventilation, and on lower levels of residence within housing structures (Krewski et al., 2004; Jedrychowski et al., 1995; Stanley et al., 2017). Currently, the Canadian guideline for annual residential radon exposure is 200 Bq/m^3, as established by Health Canada and the Federal Provincial Territorial Radiation Protection Committee (Government of Canada, 2009). However, this level exceeds the 100 Bq/m^3 guideline set by the World Health Organization (WHO) (*WHO Handbook on Indoor Radon: A Public Health Perspective*, 2009).

Most of the epidemiological studies that quantify risk of lung cancer associated with residential radon have relied on average annual exposure as the exposure measure. The most recent attempt to characterize national radon concentrations, the Cross-Canada Survey of Radon Concentrations in Homes (Cross-Canada Survey) measured radon during the heating season, where levels are highest (Health Canada, 2012). As a result, estimating the attributable burden of lung cancers due to residential radon using the exposure profile from this survey would require adjustment for season of measurement.

Our objective was to estimate the proportion of Canadian lung cancer cases attributable to residential radon exposure in 2015, and to estimate avoidable cancers over the period 2016–2042 under different exposure mitigation scenarios.

2. Methods

The methods used to estimate population attriubtable risks (PAR) and potential impact fractions (PIF) for modifiable carcinogenic exposures as part of the ComPARe Study have been published previously (Brenner et al., 2018). The relationship between residential radon exposure and lung cancer risk was assumed to follow a log-linear dose-response pattern for a continuous exposure representing average annual exposure during a 25-year exposure window, with a five-year lag period between cancer development and diagnosis, as in previous studies of residential radon exposure in the literature (Darby et al., 2005; Krewski et al., 2006; Lubin et al., 1994).

2.1. Relative risk estimate

For this analysis, we estimated a pooled RR for the relationship between residential radon exposure and lung cancer risk following the PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analyses) guidelines (Shamseer et al., 2015). Our inclusion criteria were as follows: 1) Reporting of a continuous RR estimate for the relationship of interest, or an estimate that could be converted to a continuous estimate based on published effects across categories of exposure, 2) Reporting exposure to radon based on annual mean exposure, or exposure that could be adjusted for season of measurement. Where pooled analyses were available, these were included instead of the individual studies.

The literature search was conducted in PubMed and included all studies published up to October 1, 2018 using the search terms "residential radon" and "lung cancer." Abstract and title screening was conducted by a single reviewer (TN or PG), and full-text review was conducted independently by three reviewers (TN, PG, and WK).

The RRs extracted from each study had been adjusted for covariates including age, sex, and smoking. Previous analyses do not provide compelling evidence for effect modification by smoking or sex for the relationship between residential radon and lung cancer (Darby et al., 2005; Duan et al., 2015; Krewski et al., 2006). For the studies reporting RRs according to categories of exposure rather than a continuous exposure, we assumed a log-linear dose-response relationship between radon exposure and lung cancer risk and converted the RRs for categorical exposure levels to one for a continuous exposure using the Greenland method (Greenland and Longnecker, 1992) through the use of the SAS % metadose macro (Li and Spiegelman, 2010). To determine the median values for categories, we generated an exposure distribution to approximately match that described in each paper. Only one Canadian study used winter radon exposure to estimate the RR (Hystad et al., 2014). This estimate was converted to represent a RR per annual exposure using a Canadian conversion factor of 0.74 between annual and winter radon levels (see below).

Study-specific risk estimates were converted to represent risk of lung cancer that corresponded to an increase of 100 Bq/m^3 in the annual residential concentration of radon. Standard errors were estimated from confidence intervals (CIs) and the meta-analysis was weighted by the inverse of the variance of the RR estimates. Heterogeneity of risk estimates across studies was investigated with the Q-test and the I^2 statistics. Publication bias was assessed visually with a funnel plot and a weighted Egger's linear regression test was employed to formally test plot asymmetry.

2.2. Current cancer burden (2015)

2.2.1. Exposure distribution

The distribution of residential radon exposure in the Canadian population was estimated using data collected from the Cross-Canada Survey between 2009 and 2010 (Health Canada, 2012). In this survey, participants were recruited via telephone with the inclusion criteria that they were homeowners, and living in their primary residence; rented units, homes on stilts, and housing in high-rise condominiums above the second floor were not eligible (Health Canada, 2012). Approximately 149 homes were sampled per health region across Canada resulting in a total sample size of 13,976 households. Response rates for the survey in years 1 and 2 were 22.5% and 20.2%, respectively (Health Canada, 2012). Average radon concentration was measured over a minimum period of three months from October to March, over the years 2009–2011 using alpha-track radon detectors (Health Canada, 2012). The validity of using alpha track radon detectors to characterize long-term exposure to residential radon has been established by several studies (Darby et al., 2005; Krewski et al., 2006; Lubin et al., 2004). During the survey, the detector was placed in a location within participants' homes where at least one individual spends at least 4 hours per day. The alpha track radon detectors used in this survey had a detection limit of 15 Bq/m^3, and values below 15 Bq/m^3 were therefore randomly assigned a value between 0 and 15 Bq/m^3 (Health Canada, 2012). Radon measurements collected over the survey years were conceptualized to correspond to exposures within the window associated with the relationship between residential radon and lung cancer (25 year exposure, with a 5 year lag period).

For the current analysis, the exposure distribution was adjusted to

reflect the proportion of the population living in high-rise buildings above the second floor. Specifically, we extracted information on the proportion of the population living in high-rise buildings by health region from the 2006 Canadian Census. We assumed that approximately 80% of this population live above the second floor, and randomly assigned a radon exposure between 0 and 15 Bq/m^3. For the remaining 20% of this population, the distribution of radon exposure measurements in the health region from the Cross-Canada Survey was used.

The exposure metric used in epidemiologic studies of radon and lung cancer is typically an estimate of the average annual exposure to radon for a specified time window. We therefore generated an exposure distribution that would be representative of average annual radon levels. As the Cross-Canada Survey measurements were taken during the heating season (October–March) when residential exposure levels are typically higher than in summer months, the exposure distribution had to be adjusted to provide an average annual exposure. Krewski et al. has provided seasonal correction factors for six month sampling periods based on extensive monitoring data from Winnipeg (Krewski et al., 2004). Considering that Winnipeg's heating season is, on average, longer than most other populated areas of Canada, we sought to average the Winnipeg correction factor with estimates provided from a recent paper assessing seasonal variation in residential radon concentrations in the United Kingdom, where weather patterns and heating season may be more representative of that experienced by some Canadian provinces (Daraktchieva, 2016). We averaged the correction factor from Winnipeg and the United Kingdom (0.69 and 0.79), to estimate a Canadian correction factor of 0.74. The exposure distribution was then weighted to health-region level population estimates from the 2001 census. This year was selected to best correspond with the midpoint of the exposure window selected (1985–2009). All subsequent PAR and PIF calculations incorporated the housing type and seasonally adjusted exposure distribution.

2.2.2. Population attributable risk

PAR estimates were calculated using the following formula: (Drescher and Becher, 1997; Murray et al., 2003).

$$\mathrm{PAR} = \frac{\int_{x=0}^{m} \mathrm{RR}(x)P(x)dx - 1}{\int_{x=0}^{m} \mathrm{RR}(x)P(x)dx}$$

where $RR(x)$ is the RR at exposure x; $P(x)$ is the population distribution of exposure; m is the maximum exposure level.

A Monte Carlo simulation with 1000 iterations was used to estimate 95% CIs around the 2015 PAR estimate. Relative risk was sampled from a log normal distribution derived from the RR and CI, and radon exposure was based on a sample size of 1000 from the estimated exposure distribution.

2.2.3. Cancer incidence

Canadian and provincial incidence data for lung cancer in 2015 were obtained from the Canadian Cancer Registry. These were used to estimate attributable lung cancer cases in 2015 due to residential radon exposure. Cancer incidence data were not available separately by territories, limiting territory-specific analyses.

2.3. Future cancer burden (2042)

2.3.1. Exposure distribution projections

Radon levels are known to be relatively stable in the absence of mitigation, although exposure levels may differ due to changing methods of home construction and trends towards high-rise living that may increase or decrease radon exposures, respectively (Stanley et al., 2017; Statistics Canada, 2018). We assumed stable exposure levels by geographic area, and applied year-specific population estimates using census population data by health region for the years 2001, 2006, 2011, and 2016. We estimated annual population distributions between census years using weighted averages from years for which census data was available.

2.3.2. Counterfactual scenarios

Radon mitigation has been shown to substantially reduce radon levels in homes; with several studies observing decreases in the range of 45%–98% (Blanco-Rodriguez et al., 2017; Groves-Kirkby et al., 2006; Stanley et al., 2017; Steck, 2012; Tracy et al., 2006). In this analysis, two counterfactual scenarios for radon exposure in Canada were considered, with an ultimate mitigation of levels to 50 Bq/m^3. A reduction to 50 Bq/m^3 for homes with targeted mitigation was chosen to assume a simplified mitigation reduction that can be clearly conceptualized and applied. The first counterfactual was based on mitigation of radon levels exceeding the national guideline of 200 Bq/m^3 to 50 Bq/m^3 by 2036 (corresponding to a PIF in 2042) (Health Canada, 2012). Our second counterfactual was based on the WHO recommendation for countries to adopt a reference level of 100 Bq/m^3 (*WHO Handbook on Indoor Radon: A Public Health Perspective*, 2009). Therefore, our second counterfactual scenario was based on mitigation of all radon exposures above 100 Bq/m^3 to 50 Bq/m^3 by 2036.

We assumed that 100% mitigation of homes above 200 and 100 Bq/m^3 respectively, to 50 Bq/m^3 would occur by 2036, leading to a slope-based decline from current values, and applied year-specific population estimates as described above.

2.3.3. Potential impact fractions

PIFs were estimated for counterfactual exposure distributions based on the following formula (Drescher and Becher, 1997; Murray et al., 2003).

$$\mathrm{PIF} = \frac{\int_{x=0}^{m} \mathrm{RR}(x)P(x)dx - \int_{x=0}^{m} \mathrm{RR}(x)P'(x)dx}{\int_{x=0}^{m} \mathrm{RR}(x)P(x)dx}$$

where $RR(x)$ is the RR at exposure x; $P(x)$ is the population distribution of exposure; $P'(x)$ is the counterfactual distribution of exposure; m is the maximum exposure level.

2.3.4. Cancer incidence projections

Lung cancer incidence data from 1983 to 2012 were used to project cancer incidence up to the year 2042 for all papers in the ComPARe Study (Poirier et al., 2019). Province-specific incidence was projected to 2038. For lung cancer, we used sex-specific Poisson-based age cohort models. Further details on model selection for projections can be found elsewhere (Poirier et al., 2019).

Ethics approval was granted for this project by the Health Research Ethics Board of Alberta - Cancer Committee (HREBA.CC-14-0220_REN4) and the Queen's University Health Sciences Research Ethics Board (File # 6015362).

3. Results

3.1. Relative risk estimate

We identified 285 potentially relevant studies in the initial PubMed search, and extracted information from 23 eligible studies. These included three recent pooled analyses that employed inclusion criteria similar to ours, and improved exposure estimation over the individual studies in relation to exposure periods and adjustment for season of radon measurement. The pooled analyses included articles combining estimates from 13 European studies (Darby et al., 2006), seven North American studies (Krewski et al., 2006), and two Chinese studies (Lubin

Table 1
Characteristics of studies included in meta-analysis studying the relationship between exposure to residential radon and the risk of lung cancer.

Study and location	Design	Population	Exposure basis	Exposure window	Arithmetic Mean (Bq/m^3)	Seasonal adjustment[a]
Torres-Durán et al., 2015 Spain	Case-control	197 cases and 275 controls	Dosimeter	10–47 years	186 (cases), 149 (controls)	Yes
Hystad et al., 2014 Canada	Case-control	2390 cases and 3507 controls	Ecologic	20 years	98.0	No
Barros-Dios et al., 2012 Spain	Case-control	349 cases and 513 controls	Dosimeter	5 years	103 (cases), 70 (controls)	Yes
Tomasek, 2012	Case-control	293 cases and 11,549 controls			448	NA
Thompson et al., 2008 Massachusetts	Case-control	200 cases and 397 controls	Dosimeter	10 years	67.5 (cases), 66.3 (controls)	NA
Wilcox et al., 2007 New Jersey	Case-control	651 cases and 740 controls	Dosimeter	5–10 years	46.0 (cases), 46.4 (controls)	NA
Sandler et al., 2006 Connecticut and Utah	Case-control	1474 cases and 1811 controls	Dosimeter	5–25 years	40.3 (cases), 44.8 (controls)	NA
Krewski et al., 2006 North America	Pooled Case-control (7 studies)	3662 cases and 4966 controls	Dosimeter	5–30 years	Range: 26.0–127.0	
Darby et al., 2006 Europe	Pooled Case-control (13 studies)	7148 cases and 14,208 controls	Dosimeter	5–30 years	104 (cases), 97 (cases)	Yes
Lubin et al., 2004 China	Pooled Case-control (2 studies)	1050 cases and 1996 controls	Dosimeter	5–30 years	Range 115.7–222.9	NA

[a] NA (not applicable) refers to studies that used year-round radon exposure assessment measures.

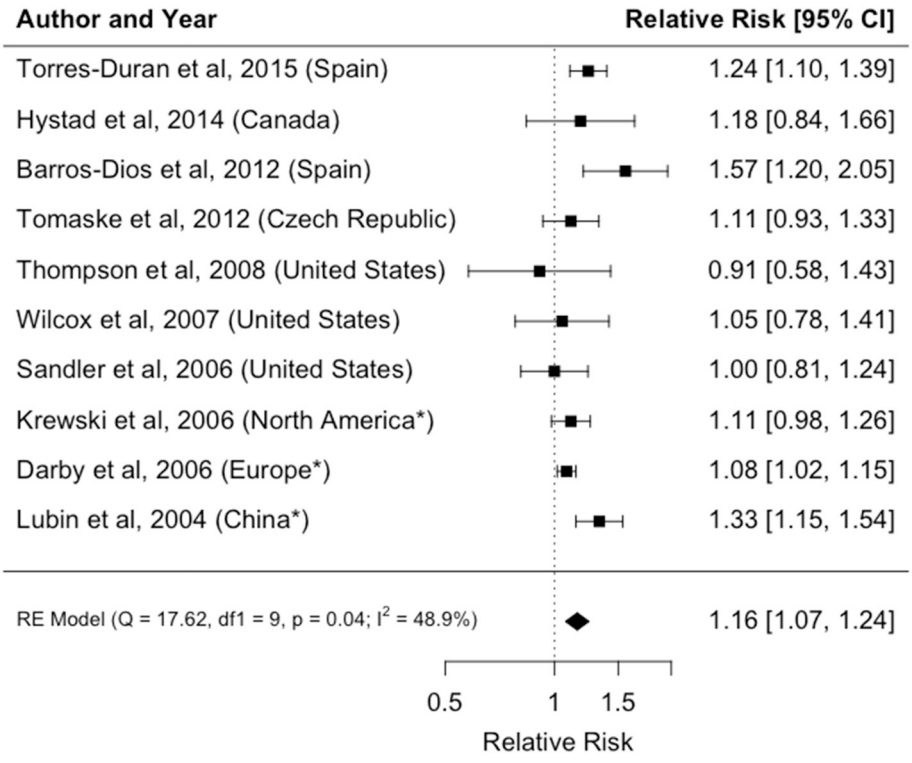

Fig. 1. Estimated RR of lung cancer associated with 100 Bq/m^3 increase in exposure to residential radon among studies conducted in North America.

et al., 2004).

In addition, seven studies that were published since these pooled analyses were included (Barros-Dios et al., 2012; Hystad et al., 2014; Sandler et al., 2006; Thompson et al., 2008; Tomasek, 2012; Torres-Durán et al., 2015; Wilcox et al., 2007) (Table 1). The meta-analysis yielded a RR for lung cancer of 1.16 (95% CI: 1.07, 1.25) per 100 Bq/m^3 increase in exposure to annual residential radon (Fig. 1). Heterogeneity was detected (I^2 = 49.0%), and therefore a random effects model was used. No publication bias was detected. A sensitivity analysis removing the Hystad et al., 2014 study was conducted as it was the only study using ecological exposure measurement (Hystad et al., 2014). This analysis did not change our pooled RR estimate.

3.2. Current cancer burden (2015)

3.2.1. Exposure distribution

Table 2 presents population weighted exposure estimates for average annual residential radon in Canada, and by province. The distribution is right skewed with an arithmetic mean of 44.4 Bq/m^3 and a geometric mean of 19.4 Bq/m^3 (Fig. 2). In the 1985–2009 exposure

Table 2
Population-weighted radon exposure distribution (2015; Exposure window 1985–2009)[a].

Location	Mean (Bq/m^3)	SD (Bq/m^3)	Geometric Mean (Bq/m^3)	% living above 2nd floors in high-rise buildings	% exposed to levels above 200 Bq/m^3	% exposed to levels above 100 Bq/m^3	Mean (Bq/m^3) (no seasonal adjustment)	Geometric Mean (Bq/m^3) (no seasonal adjustment)
Canada	44.4	65.8	19.4	26.8%	3.2%	11.7%	60.1	26.1
British Columbia	26.6	52.9	10.2	27.5%	2.0%	6.1%	35.9	13.7
Alberta	58.3	62.8	35.5	18.9%	2.9%	14.9%	78.5	47.8
Saskatchewan	81.2	49.3	50.2	0.4%	6.0%	28.4%	109.4	67.6
Manitoba	87.7	60.7	45.0	21.3%	9.7%	31.0%	118.1	60.7
Ontario	38.6	64.4	17.8	26.4%	2.3%	9.0%	51.4	24.0
Quebec	41.1	81.8	17.3	37.3%	3.1%	10.0%	55.4	23.2
New Brunswick	86.6	78.6	35.9	14.1%	11.5%	27.0%	116.6	48.4
Nova Scotia	55.6	94.3	22.8	18.3%	6.1%	12.2%	74.9	30.8
Prince Edward Island	32.0	37.2	15.7	10.1%	1.6%	8.1%	43.1	21.1
Newfoundland and Labrador	44.1	40.4	20.4	5.8%	3.9%	10.2%	59.4	27.5
Territories	81.7	46.8	50.4	NR	5.5%	18.7%	95.6	51.0

Abbreviations: SD-standard deviation.
[a] Based on residence type, population weighting, and seasonal adjustment of data from the Cross-Canada Survey of Radon Concentrations in Homes.

window, 3.2% of the Canadian population is exposed to annual residential radon levels above the current Canadian guideline of 200 Bq/m^3, and 11.7% of the population is exposed to annual residential radon levels above 100 Bq/m^3. Reflected in this exposure distribution is the 27% of the Canadian population that lives above the second floor in high-rise buildings. In addition, the impact of converting the winter measurements from the Cross-Canada Survey to estimates of annual average levels is noteworthy; the geometric mean of the exposure distribution without this conversion was 26.1 Bq/m^3, compared to 19.4.

3.2.2. Population attributable risk (PAR) and attributable cases

Table 3 presents Canada and province-specific PARs and attributable cases for lung cancer in 2015 attributable to residential radon exposure. The PAR estimate for lung cancer cases in 2015 attributable to radon exposure was 6.9% (95% CI: 2.9%–10.3%), accounting for 1741 attributable cases. Province-specific PARs were highest in New Brunswick, Manitoba, and Saskatchewan, respectively (13.8, 13.2%, 12.1%).

3.3. Future cancer burden (2042)

The Canadian exposure distribution for residential radon from the Cross-Canada Survey was extrapolated to 2036, and the associated PARs and number of attributable lung cancer cases in 2042 are presented in Table 4.

Consideration of a counterfactual distribution based on mitigation in all homes from 200 Bq/m^3 to 50 Bq/m^3 by 2036 resulted in a population-weighted arithmetic mean exposure of 38.3 Bq/m^3 and a geometric mean exposure of 10.1 Bq/m^3 (Table 5). This reduction in exposure corresponded to a PIF of 0.9%, with 293 preventable cases in

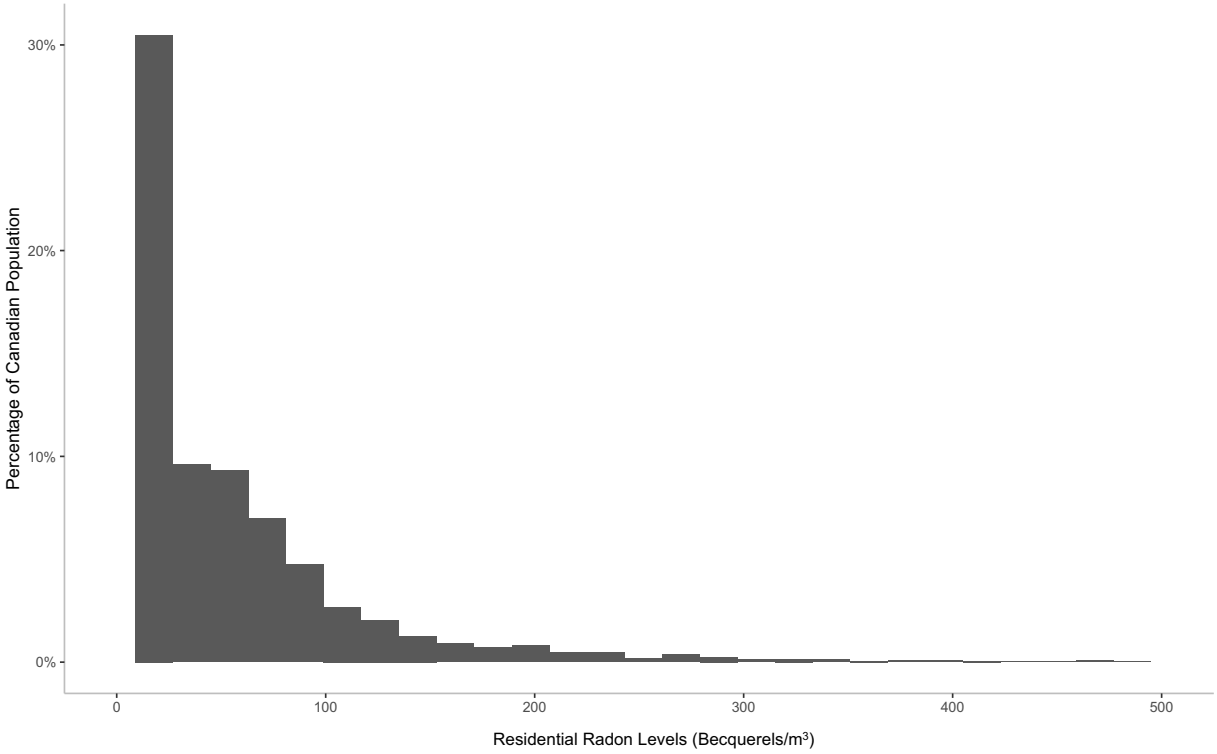

Fig. 2. Exposure distribution of residential radon levels in Canada (2015; Exposure window 1985–2009) (exposures above 500 Bq/m^3 [0.3% of population] removed due to sparse data).

Table 3
Incident lung cancer and estimated proportion attributable to residential radon in Canada (2015).

Region	Lung cancer cases Obs.[a]	Mean (Bq/m^3)	Geometric mean (Bq/m^3)	PAR	EAC
Canada	25,235	44.4	19.4	6.9%	1741
British Columbia	3175	26.6	10.2	4.4%	140
Alberta	2085	58.3	35.5	8.8%	183
Saskatchewan	690	81.2	50.2	12.1%	83
Manitoba	855	87.7	45.0	13.2%	113
Ontario	8380	38.6	17.8	6.1%	511
Quebec	7715	41.1	17.3	6.3%	486
New Brunswick	710	86.6	35.9	13.8%	98
Nova Scotia	950	55.6	22.8	8.9%	85
Prince Edward Island	160	32.0	15.7	4.9%	8
Newfoundland and Labrador	460	44.1	20.4	6.9%	32
Territories	55	81.7	50.4	10.0%	6

Abbreviations: PAR = Population attributable risk, EAC = excess attributable cases.
[a] Obs. = Total observed lung cancer cases in Canada in 2015.

Table 4
Incident lung cancer and estimated proportion attributable to residential radon in Canada (2042).

Region	Lung cancer cases Obs[a]	Mean (Bq/m^3)[b]	Geometric mean (Bq/m^3)[b]	PAR[c]	Preventable cases[d]
Canada	34,027	44.4	19.4	6.9%	2348
British Columbia	3601	25.5	9.8	4.2%	151
Alberta	3943	58.6	35.5	8.9%	351
Saskatchewan	947	80.4	49.5	12.0%	114
Manitoba	1350	95.8	46.6	14.3%	193
Ontario	10,745	37.9	17.5	5.9%	634
Quebec	12,261	41.4	17.4	6.3%	772
Atlantic Provinces	2890	63.1	25.8	10.7%	309

Abbreviations: PAR = Population attributable risk.
[a] Obs. = Total observed lung cancer cases in Canada in 2042, and 2038 for provinces.
[b] Based on residence type, population weighting, and seasonal adjustment of data from the Cross-Canada Survey of Radon Concentrations in Homes. Average for exposure window 2012–2036 for Canada, and 2008–2032 for provinces.
[c] PAR estimate for 2042 for Canada, and 2038 for provinces.
[d] Preventable case estimates use data from 2042 for Canada and 2038 for provinces.

2042, and 2322 cumulative preventable cases between 2016 and 2042 (Figs. 3, 4). Based on mitigation efforts targeting all homes with radon levels above 100 Bq/m^3, the population-weighted arithmetic mean exposure was estimated at 35.4 Bq/m^3, and geometric mean of 10.1 Bq/m^3. This reduction corresponded to a PIF of 1.3%, with 442 preventable cases in 2042, and 3568 cumulative preventable cases between 2016 and 2042 (Figs. 2 and 3).

4. Discussion

4.1. Summary of main findings

This analysis estimated the burden of lung cancer in Canada that can be attributed to residential radon exposures. A meta-analysis estimate of the RR of lung cancer associated with annual average radon exposure was 1.16 per 100 Bq/m^3. The estimated PAR in Canada was 6.9%, with 1741 attributable cases for the year 2015. We also considered counterfactual distributions based on successful mitigation of radon exposures in homes exceeding current guidelines. If all current exposures that exceed Canadian policy guidelines of 200 Bq/m^3 could be mitigated to levels of 50 Bq/m^3 by 2036 we could prevent 2322 cases of lung cancer by the year 2042. If all exposures above 100 Bq/m^3 were mitigated to 50 Bq/m^3 (based on WHO guidelines), 3568 lung cancer cases could be prevented by 2042.

4.2. Meta-analysis and RR estimate

Our meta-analysis RR for the relationship between residential radon and lung cancer (1.16 per 100 Bq/m^3) was higher than that reported in previous pooled analyses among North American (RR 1.11) and European (RR 1.08) studies. Our estimate includes seven studies published since these pooled analyses and reflects heterogeneity in effect estimates by publication year, where studies conducted since 2000 have tended to report stronger RR estimates.

4.3. Exposure prevalence

We estimated that approximately 3% of the Canadian population is exposed to residential radon levels above the Canadian guideline of 200 Bq/m^3. This finding is lower than the reported estimate of 6.9% from the Cross-Canada Survey (Health Canada, 2012). We adjusted for the proportion of the population living above the second floor in high-rise buildings in Canada (approximately 27%) and for differences in radon exposure measurement due to the winter heating season (adjustment factor of 0.74).

4.4. Population attributable risk

Our PAR estimate for residential radon exposure and lung cancer of 6.9% is considerably lower than that reported for Canada recently by Chen et al., 2012 (16%). Methodology contributing to this different estimate includes the risk assessment models and methods used to estimate the Canadian exposure distribution.

Chen et al. applied a modified version (US EPA) of the Biological Effects of Ionizing Radiation VI (BEIR-VI) risk model, while our approach used a RR based on meta-analysis of 10 epidemiologic studies of residential radon and lung cancer risk. BEIR-VI models are based on analysis of cohorts of miners and take into account time since exposure, attained age, smoking history and either the duration of the exposure, or the level of concentration. Gaskin et al. used the same exposure distribution as Chen et al. and demonstrated that a lower PAR was obtained when using RR estimates from pooled studies of residential exposure of Krewski et al. (2006) and Darby et al. (2006) rather than BEIR VI risk estimates, with PARs of 10.4% and 8.4% respectively (Gaskin et al., 2018; Gaskin et al., 2018b; Chen et al., 2012). With respect to exposure distribution, the Chen et al. study did not account for the population residing in high-rise housing, nor that the Cross-Canada Survey was based on winter measurements, and as a result the exposure distribution was higher than used in this study (Chen et al., 2012). To quantify the impact of these methodological differences, we estimated unadjusted, and high-rise and season adjusted PAR estimates using the modified BEIR VI risk model, with PARs of 14.6% and 11.3% respectively. Contrasted with our residential radon meta-analysis based estimates of 11.4% and 6.9% for unadjusted and fully adjusted exposure distributions, these results highlight the impact of using the BEIR VI methodology, and high-rise and season adjustment on our PAR estimates (Table S1, Supplementary Analysis).

Other provincial analyses have reported PARs for the relationship of interest based on the Cross-Canada Survey: 16.6% for Alberta (Grundy et al., 2016), and 13.6% for Ontario (Peterson et al., 2013). Our estimates for these provinces are lower, and are likely attributable to differences in study methods, in particular the BEIR VI methodology for risk, and our correction for season of radon measurement (both of these studies adjusted for a proportion of the population living in high-rise buildings).

Our PIF estimates suggest that even if all exposures in Canada above current guidelines (3% of Canadian population) are mitigated, this

Table 5
Projected cancer cases and proportions attributable to residential radon and the proportion of cancer cases that could be prevented in 2042 at various counterfactual distributions.

Region	Obs[a]	Radon counterfactual scenario[b]	Projected arithmetic mean distribution (Bq/m^3)	Projected geometric mean distribution (Bq/m^3)	PIF (%)	Preventable cases[c]	Cumulative preventable cases[d]
Canada	34,027	1	38.3	10.1	0.9%	293	2322
		2	35.4	8.3	1.3%	442	3568
British Columbia	3601	1	23.6	6.3	0.4%	14	95
		2	22.4	5.5	0.5%	18	141
Alberta	3943	1	57.9	31.7	0.3%	12	80
		2	54.8	27.9	0.7%	28	189
Saskatchewan	947	1	76.4	41.3	0.7%	7	42
		2	71.6	36.0	1.4%	13	91
Manitoba	1350	1	87.6	36.4	1.3%	18	114
		2	83.1	33.3	2.0%	27	174
Ontario	10,745	1	35.4	12.8	0.4%	43	301
		2	33.5	11.1	0.7%	75	507
Quebec	12,261	1	37.2	11.4	0.5%	61	369
		2	35.7	10.2	0.7%	86	553
Atlantic Provinces	2890	1	56.8	16.1	1.0%	29	172
		2	55.0	14.9	1.2%	34	230

Abbreviations: PIF = Potential impact fraction; Obs. = Observed lung cancer cases.
Atlantic provinces: New Brunswick, Nova Scotia, Newfound and Labrador, Prince Edward Island.
[a] Obs. = Total observed lung cancer cases in Canada in 2042, and 2038 for provinces.
[b] Counterfactual scenarios: 1 = Mitigation of all radon exposures above 200 Bq/m^3 to 50 bq/m^3 by 2036, 2 = Mitigation of all radon exposures above 100 Bq/m^3 to 50 bq/m^3 by 2036.
[c] Total preventable lung cancer cases for 2042 for all of Canada, and 2038 for province specific estimates.
[d] Cumulative preventable cases uses years 2016–2042 for Canada-wide estimates, and 2016–2038 for provincial estimates.

decrease may not have an extensive impact on future lung cancer burden when considering the number of lung cancer cases avoided. There is no known safe threshold below which radon exposures will not lead to an increased risk of lung cancer, and therefore many lung cancer cases are likely caused by exposure to radon levels below current Canadian guidelines (Peterson et al., 2013). Future policy design surrounding the health risks of residential radon exposure will need to carefully assess current mitigation guidelines and plans to shift Canadian exposure levels in order to see a substantial reduction in the future burden of lung cancer.

4.5. Limitations

Our study had some methodologic limitations that must be acknowledged. We attempted to correct for seasonal variation in radon exposures using previously reported correction factors, however, this correction was derived based on exposure data collected in the 1980s in Winnipeg, and from 2005 to 2014 in the UK, and may not necessarily represent seasonal exposure variations found in Canada (Krewski et al., 2004; Daraktchieva, 2016).

In addition, we were limited by a one-time measure of radon available from the Cross-Canada Survey, and therefore could not model potential changes in radon over the time period of interest for this

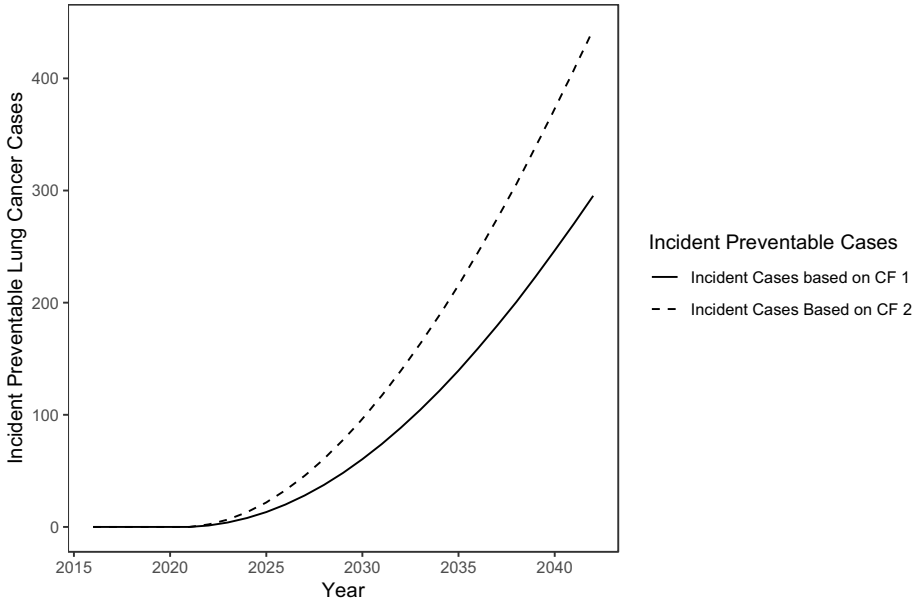

Fig. 3. Incident preventable lung cancer cases in Canada due to residential radon exposure.
CF (counterfactual) 1 = Mitigation of all radon exposures above 200 Bq/m^3 to 50 bq/m^3 by 2036.
CF (counterfactual) 2 = Mitigation of all radon exposures above 100 Bq/m^3 to 50 bq/m^3 by 2036.

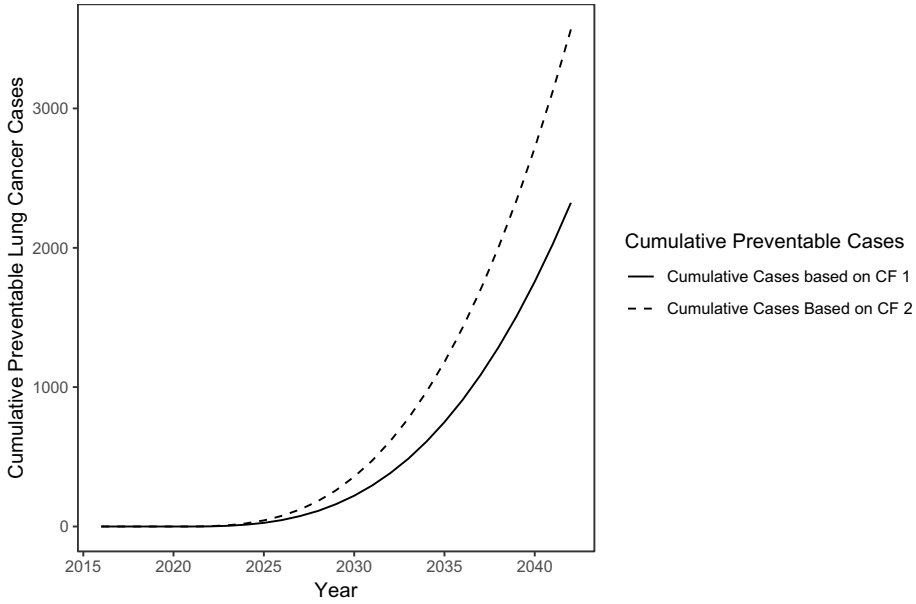

Fig. 4. Cumulative preventable lung cancer cases in Canada in 2042 due to residential Radon exposure.
CF (counterfactual) 1 = Mitigation of all radon exposures above 200 Bq/m^3 to 50 bq/m^3 by 2036.
CF (counterfactual) 2 = Mitigation of all radon exposures above 100 Bq/m^3 to 50 bq/m^3 by 2036.

analysis. Radon is a relatively stable gas, and without targeted intervention, exposures are not expected to change drastically (Bissett and McLaughlin, 2010; Hystad et al., 2014). However, we were unable to consider changes in exposures based on trends towards urban living in high-rise buildings, reducing exposures, as well as the potential for new homes to lead to higher exposure levels based on better insulating building materials due to lack of sufficient data (Stanley et al., 2017; Statistics Canada, 2018). The impact of these differing trends on future exposures is uncertain, and complex.

For this study, we were limited to exposure data collected by the Cross-Canada Survey, and therefore, our work is subject to the same limitations as the original survey. Low response rates, exclusion of rental homes, and lack of stratification based on newer and older homes may have led to residential radon exposures that are not completely representative of the Canadian population. The response rates for year 1 and 2 of the Cross-Canada Survey were 22.5% and 20.2%, respectively (Health Canada, 2012). This low response rate is a concern for selection bias in the estimate of residential radon exposure. The Cross-Canada Survey does not provide information on the low response rate, and it is therefore difficult to assess the direction of this bias, and its effect on our estimates (Health Canada, 2012). Despite these limitations, currently, the Cross-Canada Survey is the only large-scale survey conducted in Canada with reliable measurement techniques that can be used to assess the burden of residential radon exposures on lung cancer risk in the country.

We assumed a no-threshold log-linear dose-response pattern for the relationship between residential radon exposures and lung cancer risk, and as a result residential radon exposures below current Canadian guidelines contribute to our PAR estimate. The pooled analysis of North American studies (Krewski et al., 2006) and of European studies (Darby et al., 2006) each reported that the data fit a log-linear dose-response pattern and that results were consistent with increased risks even at low exposure levels.

4.6. Strengths

This paper provides an up-to-date pooled RR estimate for the relationship between residential radon exposure and lung cancer risk. We also used the Cross-Canada Survey to estimate PARs and PIFs for the relationship of interest. In addition, this study provides Canadian PARs accounting for the proportion of the population living in high-rise housing and seasonal differences in radon exposures. PAR estimates are based on exposure distributions rather than parameter estimates (arithmetic means or geometric means) which fail to represent the shape of this distribution.

5. Conclusion

Relative risk and PAR in relation to residential radon exposure have most often been estimated via application of the BEIR risk model, which is based on extrapolation from studies of radon exposure in miners. Our review and meta-analysis identified a sufficient number of epidemiologic studies of residential radon and lung cancer risk to derive pooled RR estimates. This body of literature supports a log-linear dose response pattern of risk, and highlights that despite exposure level guidelines set by Canada (200 Bq/m3) and the WHO (100 Bq/m3), there are no “safe” radon exposure levels (WHO, 2009; Puskin, 2009; Krewski et al., 2006; Zhang et al., 2012; Health Canada, 2012; World Health Organization, 2009). This analysis quantifies the burden of lung cancer attributable to residential radon exposures in Canada, where a large proportion of cases are due to exposures below Canadian guidelines. This work has implications for policy work, and suggests consideration of lowering Canadian guidelines to bring improved awareness of the risks of low levels of residential radon exposure to the general public.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ypmed.2019.04.005.

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Conflict of interest

None declared.

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