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An assessment of uncertainty using two different modelling techniques to estimate the cost effectiveness of mitigating radon in existing housing in Canada

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HIGHLIGHTS

- An active depressurization system can reduce exposure to indoor radon by 85%.
- Two different modelling techniques were used to estimate the cost effectiveness.
- Comparable estimates of cost effectiveness were derived from different models.
- Mitigation of radon in existing housing is fairly cost effective in Canada.

GRAPHICAL ABSTRACT

Screening and mitigation of radon in existing housing in Canada: incremental cost effectiveness ratios (ICERs) modelled using Markov cohort and discrete event simulation.

Model	**Action threshold** (Bq/m^3)	**Mitigation: at current rate**		**Mitigation: theoretical increase for a tax credit incentive**	
		ICER ($/QALY)	**discounted ICER** ($/QALY)	**ICER** ($/QALY)	**discounted ICER** ($/QALY)
Markov cohort	**200**	49 285	72 569	34 941	55 317
	100	48 229	68 758	39 054	60 183
	50	66 217	93 007	56 612	86 343
Discrete event simulation	**200**	61 544	84 828	36 444	54 621
	100	56 856	76 917	40 451	60 340
	50	75 792	101 755	56 979	84 872

Note: discounting at 1.5% per year

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ABSTRACT

The burden of lung cancer associated with residential radon in existing housing can be reduced by interventions to screen and mitigate existing housing having radon levels above a mitigation threshold. The objective of this study is to estimate the cost effectiveness of radon interventions for screening and mitigation of existing housing for the 2016 population in Canada and to assess the structural uncertainty associated with the choice of model used in the cost-utility analysis. The incremental cost utility ratios are estimated using both a Markov cohort model and a discrete event simulation model. A societal perspective, a lifetime horizon and a discount rate of 1.5% are adopted. At a radon mitigation threshold of 200 (100) Bq/m^3, the discounted ICERs for current rates of screening and mitigation of existing housing are 72,569 (68,758) $/QALY using a Markov cohort model and 84,828 (76,917) $/QALY using discrete event simulation. It appears that minimal structural uncertainty is associated with the choice of model used for this cost-utility analysis, and the cost effectiveness would improve at increased rates of radon testing and mitigation. The mitigation of radon in existing housing is estimated to be a practical policy option for reducing the associated lung cancer burden in Canada.

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1. Background

Lung cancer is the cancer with the highest mortality in Canada, with an estimate of 20,000 lung cancer deaths in 2016 (Canadian Cancer Society's Advisory Committee on Cancer Statistics., 2016). Residential radon is a very modifiable cause of lung cancer that results in roughly 3000 attributable lung cancer deaths in Canada each year (Chen et al., 2012). It is an indoor air pollutant that can be managed to reduce the associated lung cancer burden in both smokers and non-smokers. The first models of the excess relative risk of lung cancer from radon such as the BEIR VI models (National Research Council, 1999) were based on cohorts of uranium miners exposed to radon underground. However, these radon exposures were generally higher than the public would experience in a residential setting and did not include any women, and so large pooled case-control residential studies were conducted in Europe, North America and China. The estimates of the excess relative risk of lung cancer per 100 Bq/m^3 radon exposure over 30–35 years derived after correcting for some uncertainties in the retrospective radon exposure assessment were 0.18 (95% CI: 0.02, 0.43) for North America (Krewski et al., 2006), 0.16 (95% CI: 0.05, 0.31) for Europe (Darby et al., 2006), and 0.32 (95% CI: 0.0, 0.43) for China (Lubin, 2003). Higher estimates of the excess relative risk of lung cancer from cumulative radon exposure are reported from the ongoing cohort studies of miners, derived from more accurate measurements of radon exposure obtained using personal dosimeters (Kreuzer et al., 2018; Tomasek et al., 2008). An increased risk of lung cancer from radon among never-smokers has been reported by both occupational and residential studies in which a stratified analysis of never-smokers was conducted (National Research Council, 1999; Tomasek, 2013), and from residential studies restricted to never-smokers, such as the case-control study including 436 cases in Sweden (Lagarde et al., 2001) and the recently published pooled case-control study including 523 cases in Northwestern Spain (Lorenzo-González et al., 2019). Intermediate estimates of lifetime relative risk of lung cancer from radon for Canadian smoking and non-smoking men and women were reported from the use of the BEIR VI model, lower than those resulting from the updated miner model and the adjusted Chinese residential model and higher than from the use of the European or North American residential models (Chen, 2017).

Recent radon research in Canada is based on the Cross Canada radon survey conducted between 2009 and 2011 (Health Canada, 2012) and includes updating estimates of the radon associated burden of lung cancer and refining health economic evaluation of interventions to reduce residential radon, an approach that was introduced in the US (Mossman and Sollitto, 1991), Canada (Letourneau et al., 1992), and in Spain (Colgan and Gutiérrez, 1996) in the 1990s. In new housing, preventive radon measures installed at construction have been reported to be cost effective in many countries (Gaskin et al., 2019; Gray et al., 2009; Pollard and Fenton, 2014; Svensson et al., 2018), but the mitigation of radon in existing housing is generally less cost effective because the cost of installing a sub-slab depressurization system after construction is completed is much higher and all housing must be screened to identify those with higher average radon concentration for mitigation. Screening and mitigation of existing housing in Northamptonshire in the UK was reported to be more cost effective at higher rates of remediation and when a higher percentage of housing had radon above the mitigation threshold (Coskeran et al., 2006). Economic evaluation of health technologies relies on models to represent the effect of changes over time to health states of individuals and costs in a population, and the results can be affected by the structure of the model selected, an important component of structural uncertainty in the health economic evaluation (Canadian Agency for Drugs and Technologies in Health, 2017).

Markov cohort models are a common form of decision-analytic model in health economic evaluation (Briggs et al., 2011). Disease progression in a population is simulated in a Markov cohort model by characterizing health into mutually exclusive health states, with changes in health over time modelled as a Markov chain using transition probabilities between health states over the cycle length. The main limitation of a Markov model is the assumption that the transition probabilities, of moving from one state to another, do not depend on the past of the individual or the time spent in a given state. Although a Markov cohort model is computationally efficient, as the number of risk factors or covariates increase, the number of subdivisions of the cohort required to represent differences in the population being modelled becomes too great (Brennan et al., 2006).

When the flexibility of an individual level modelling approach becomes preferable, a discrete event simulation (DES) model can be used to follow the progression of each individual in a population. The history of an individual can be incorporated into the progression along the time horizon in a DES model, from calculating the length of time an individual is in each state. A DES model allows interactions between individuals to be modelled and is flexible enough to enable further changes to covariates or investigation of specific subgroups should the initial analysis raise new questions. The main disadvantages of using microsimulation models are the much larger amount of input data required and the increase in computer power/time needed to generate stable results. Since residential radon is the exposure of interest in this analysis, individual households are modelled in the discrete event simulation, with all residents exposed to the sampled household radon.

In Canada, the Radon Guideline recommends that radon levels above 200 Bq/m^3 in existing housing be mitigated, but the homeowners are responsible for all the costs and compliance is voluntary. The population-weighted percentage of Canadians in 2012 living in homes with radon concentrations above the Radon Guideline's threshold of 200 Bq/m^3 was estimated to be 6.9% (Health Canada, 2012). A health economic evaluation is conducted to estimate the incremental cost effectiveness ratio (ICER) for the mitigation of existing housing in Canada at the national level, with uncertainty in the estimates assessed from the use of two models, a Markov cohort model and a discrete event simulation model. This analysis complements a recent study, in which the incremental cost effectiveness ratio was estimated for a range of different radon remediation strategies in new and existing housing for Canada, nationally and for each province and territory, based on a Markov cohort model (Gaskin et al., 2019).

2. Research question

The objective of this analysis is to estimate the incremental cost utility ratios (ICERs) for radon interventions to reduce residential radon exposures in existing housing for the 2016 population in Canada. The structural uncertainty associated with the choice of model used in the cost-utility analysis is assessed by using both a Markov cohort model and a discrete event simulation model to evaluate the ICERs for screening and mitigation of existing housing. Determining which interventions are cost effective can help policy-makers to balance investment in lung cancer prevention with lung cancer treatment.

3. Methods

3.1. Target population, study perspective, time horizon, and discounting

An analysis was conducted for the 2016 Canadian population (Statistics Canada, 2016a) modelled with replacement over a time horizon of one hundred years, selected to represent the lifelong benefits of reducing residential radon exposures experienced by all current and future residents of remediated housing. The population growth was modelled using census data averaged from 2006 to 2016. The costs associated with screening and mitigating housing to reduce residential radon exposures occur outside the health care system, therefore a societal perspective was adopted for this analysis. The discount rate of 1.5% is used for the base analysis, as recommended by the Canadian Agency for Drugs and Technologies in Health (Canadian Agency for Drugs and

Technologies in Health, 2017), and a discount rate of 0% is also used for comparison.

3.2. Intervention strategies and effectiveness

The screening and mitigation using active depressurization of existing housing is evaluated using two very different rates of screening and mitigation (Table 1), the current rate and an increased rate under a theoretical tax credit incentive, and for three radon mitigation thresholds, at 200, 100, and 50 Bq/m^3. The theoretical tax credit represents an idealised scenario in which the incentive would hopefully lead to rapid increases in the rates of radon testing and mitigation among home owners. An active soil depressurization system draws radon-containing soil gas from beneath the slab and exhaust it outdoors and typically results in about an 85% reduction of high initial radon levels (Gray et al., 2009; Health Canada, 2016). Although most of the houses in the experimental studies had initial radon values above 200 Bq/m^3, the same effectiveness for active depressurization was assumed for scenarios with action thresholds of 100 and 50 Bq/m^3. Radon levels were assumed to be retested in mitigated housing every 5 years and in below-threshold housing every 10 years. Under the theoretical tax credit incentive, an ideal scenario was described in which the screening rate was assumed to rise quickly, and mitigation rates were assumed to increase quickly for home owners who choose to test for radon exposure.

3.3. Modelling

An abridged period life-table approach was based on 5-year age intervals, assuming the 2016 population characteristics by age and sex are applicable throughout the 100 year time horizon. The age distribution of the 2016 population was based on the census, and the age-and sex-specific all-cause mortality (Statistics Canada, 2016b) and lung cancer incidence (Statistics Canada, 2016c) were adjusted for smoking. Lung cancer mortality rates were assumed to constitute the same proportion of incidence rates as were reported for the US population between 1975 and 2009 (Howlader et al., 2012), based on similar patterns of low life expectancy after diagnosis in both countries. The adjustment for smoking was made for each age- and sex-specific category (Table 2) using the percentage of current daily smokers, reported in the Canadian Community Health Survey (CCHS) (Statistics Canada, 2016d), and the relative risk of all cause and lung cancer mortality for smokers versus non-smokers (Thun et al., 1997). From an analysis of lung cancer incidence and smoking prevalence over 50 years in the US, it was reported that the relative risk of all-cause and lung cancer mortality of current smokers relative to non-smokers for the contemporary population based on data from 2000 to 2010 does not vary by gender (Thun et al., 2013). The reported relative risks from smoking have increased for women and now match those for men, represented by the age-specific risks reported for men based on data from 1982 to 1988 (Thun et al., 1997). In this analysis smokers are modelled as lifelong non-smokers if they quit more than 20 years prior, and a linear decrease in relative risk (from lifetime smoker to lifetime non-smoker) over a 20 year period is applied to former smokers modelled according to time since quitting, based on recent research estimating the relative risk of former smokers (Kenfield et al., 2008; Pesch et al., 2012). The health related quality of life was characterized using the age-specific values for Health Utilities Index Mark 3 (HUI3) based on the Canadian Community Health Survey (CCHS) for 2013–14 (Guertin et al., 2018).

Table 1
Rates of screening and mitigation.

Time period (years)	Rate of screening		Rate of mitigation	
	Current (%)	Theoretical tax credit incentive (%)	Current (%)	Theoretical tax credit incentive (%)
0–4	3	3	29	29
5–9	3	10	29	50
10–14	3	20	29	70
15–19	3	28	29	80
20–24	3	36	29	90
25–29	3	44	29	90
30–34	3	51	29	90
35–39	3	58	29	90
40–44	3	64	29	90
45–49	3	70	29	90
50–99	3	75	29	90

The BEIR VI exposure-age-concentration (EAC) model (National Research Council, 1999) was used to estimate the excess relative risk of lung cancer mortality per Working Level Month (ERR/WLM). The BEIR VI EAC model includes modifying factors for weighting exposure periods, exposure rate, smoking status (roughly double for non-smokers compared to smokers), and attained age. The analysis is based on cumulative radon exposure, assessing the excess relative risk of lung cancer mortality from radon for each age-group in the population, and incorporating the timing and the reductions in radon exposures from the interventions described in the housing model. Greater detail about the modelling approach can be found in Gaskin et al. (2019). The BEIR VI model was selected because it provides an intermediate estimate of the lifetime relative risk of lung cancer from radon (Chen, 2017), it includes a factor for the effect of smoking on the excess relative risk of lung cancer from radon, which is very important for modelling the mostly non-smoking Canadian population, and enables the reduction in risk following residential remediation of radon to be modelled by converting the radon concentrations to which a person is exposed during different residential periods to a cumulative exposure.

The modelling described above is common to both the Markov cohort and the DES models, but the following additional data is required for the DES model. Mortality risk increases with age and a Weibull distribution was selected because it assumes that the risk increases monotonically over time. A two parameter Weibull distribution is fitted to the survival times determined from the abridged period life-table analysis that incorporates the introduction of radon interventions by age-group. The survival time is predicted for male smokers, male non-smokers, female smokers and female non-smokers, incorporating the reduction in radon from mitigation of housing that may occur at any time during the lifetime of the person. The number of residents per household is predicted using the cumulative distribution for the data for Canada, which average 2.5 residents per household. A second household is modelled if the predicted lifetime of the housing unit is longer than the predicted lifetime of all the residents in the first household. The lifetime of the housing unit is modelled using a normal distribution, based on the reduction in existing housing over the time horizon in the housing model. The time to mitigation is predicted using the cumulative probability generated from the number of housing units mitigated in each 5-year interval in the housing model, at both testing and mitigation rates assessed.

3.4. Residential radon distribution

The representative national radon distribution determined from the representative national radon survey conducted in Canada between 2009 and 2011 (Health Canada, 2012) was found to follow a lognormal distribution with geometric mean of 41.7 Bq/m^3 and a geometric standard deviation of 2.64. The national radon survey was based on 3 month-long measurements using alpha track detectors, taken during the heating season months (Oct to Mar generally) to minimize seasonal variability and to provide an upper bound for the annual average. No seasonal adjustment of the radon measurements is made. An adjustment was made to the variance of the fitted distribution for year-to-year variation, estimated from the difference for the 33 census metropolitan areas (CMA) between the 2009–2011 national survey and the 2012–2013 CMA survey.

Table 2
Age-specific HUI and relative risk of all-cause and lung cancer mortality for current smokers relative to non-smokers, and age- and sex-specific Canadian smoking prevalence.

Age-Group (years)	HUI Mean (SE)	RR all-cause mortality	RR lung cancer mortality	Canada: current smoker, daily or occasional M Mean (95% CI)	Canada: current smoker, daily or occasional F Mean (95% CI)
0–4	0.886 (0.002)	1.0	1.0	0 (0, 0)	0 (0, 0)
5–9	0.886 (0.002)	1.0	1.0	0 (0, 0)	0 (0, 0)
10–14	0.886 (0.002)	1.0	1.0	0 (0, 0)	0 (0, 0)
15–19	0.886 (0.002)	1.0	1.0	4 (3,5)	3 (3,4)
20–24	0.891 (0.003)	1.0	1.0	25 (23,26)	18 (16,19)
25–29	0.902 (0.003)	1.0	1.0	25 (23,26)	18 (16,19)
30–34	0.896 (0.004)	1.0	1.0	25 (23,26)	18 (16,19)
35–39	0.894 (0.003)	3.0	1.0	21 (20,23)	16 (15,18)
40–44	0.887 (0.004)	3.2	1.0	21 (20,23)	16 (15,18)
45–49	0.868 (0.004)	2.8	7.0	21 (20,23)	16 (15,18)
50–54	0.849 (0.005)	3.1	21.1	22 (21,24)	18 (16,19)
55–59	0.840 (0.004)	3.0	39.0	22 (21,24)	18 (16,19)
60–64	0.842 (0.003)	2.7	31.3	22 (21,24)	18 (16,19)
65–69	0.842 (0.003)	2.6	27.0	11 (10,12)	8 (7,9)
70–74	0.835 (0.004)	2.5	26.0	11 (10,12)	8 (7,9)
75–79	0.792 (0.005)	2.1	21.5	11 (10,12)	8 (7,9)
80–84	0.741 (0.007)	1.9	13.8	11 (10,12)	8 (7,9)
85–89	0.640 (0.009)	1.9	13.8	11 (10,12)	8 (7,9)
90–94	0.640 (0.009)	1.9	13.8	11 (10,12)	8 (7,9)
95–99	0.640 (0.009)	1.9	13.8	11 (10,12)	8 (7,9)

3.5. Housing model

In Canada in 2016, it was estimated that 81% of residential buildings are potentially exposed to radon: including single-detached houses, semi-detached houses, and row houses, and apartments in buildings that are on or below the second floor (Statistics Canada, 2016e). Finished basements can represent the lowest occupied level of a house and are common in houses in Canada. The proportion of existing housing in the housing stock decreases as older housing is gradually replaced by new housing, modelled as the difference between the new build rate and the overall housing stock growth. Housing built prior to any legislation requiring radon preventive measures at construction is assumed to have a constant radon exposure randomly selected from the lognormal residential radon distribution, unless mitigation using an active depressurization system is subsequently retrofitted to reduce it. The 2016 Canadian Mortgage and Housing Corporation data for new construction rates (Canadian Mortgage and Housing Corporation, 2017) and housing stock growth rates (Statistics Canada, 2017) were used to model the stock of existing housing built without any radon preventive measures over the 100-year time horizon. The model was restricted to private dwellings occupied by usual/permanent residents, and ten years of data (2007 to 2016) was averaged to model the growth rate of the housing stock and the number of new housing units constructed over 5-year periods.

3.6. Costs

Estimates of current construction costs for radon mitigation are listed in Table 3. The distributions of costs of radon testing and mitigation measures in 2015 Canadian dollars are assumed to be constant over the entire time horizon, although these would likely continue to decrease with increasing uptake of radon mitigation.

3.7. Analysis

The economic evaluation represents the screening of all housing and the mitigation of the housing with radon above the action level over the 100-year time horizon as the existing housing stock ages, using both a Markov cohort model and a discrete event simulation model. The incremental cost effectiveness ratio (ICER) for the mitigation of existing housing is estimated relative to no specific radon control measures, at two rates of screening and mitigation, at the current rate and under a tax credit incentive, and at three radon mitigation thresholds, 200, 100 and 50 Bq/m^3. The tax credit incentive for mitigation of existing housing included represents and ideal scenario that is loosely modelled on the success of the ecoEnergy Retrofit Homes Program (Natural Resources Canada, 2014). The sensitivity of the ICER estimates to changes in the housing model is assessed by varying the housing renewal rate (faster and slower), and the distribution of the number of residents per dwelling (higher proportion of one-person households), that are specified in the discrete event simulation model. In the baseline model, 36% of housing lasts less than 100 years (mean lifespan of 105 years) at a new housing construction rate of 6.7%. At the faster renewal rate of 7.4% for new construction, 63% of housing lasts less than 100 years (mean lifespan of 95 years), and at the slower renewal rate of 6.2% for new construction, 16% of housing lasts less than 100 years (mean lifespan of 115 years).

3.8. Uncertainty

The same data is used in both the Markov model and the discrete event simulation, so the difference between the estimates of incremental cost effectiveness ratio are expected to represent the structural uncertainty resulting from the choice of model. The Markov cohort model is based on a Monte Carlo simulation with 10,000 samples from the distributions of all uncertainty parameters: namely, parameters relating to radon exposure, age-specific health utilities, and lung cancer mortality rates and smoking prevalence by age-group and sex. The discrete event simulation has been conducted using a simulation of 800,000 households, also sampling from the distributions of all uncertainty parameters.

Table 3
Costs of radon control measures.
Adapted from (Gaskin et al., 2019).

Radon control measure	Cost	
	Mean	Standard deviation
Radon test	$30	
Retrofit active stack	$1,800	$60
Maintenance for active stack (5 yrs)	$255	$15

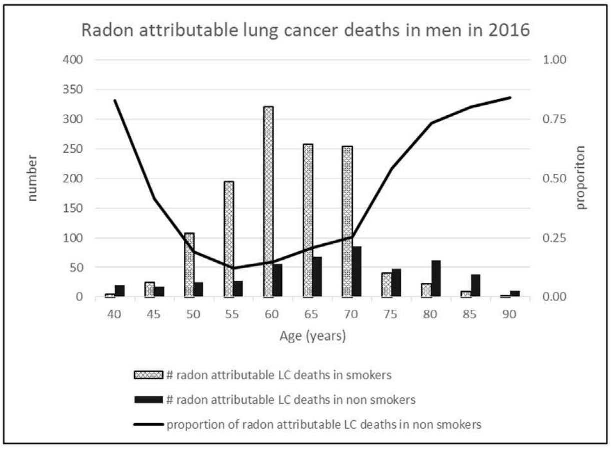

Fig. 1. Radon-attributable lung cancer deaths in men in 2016, by age and smoking status.

4. Results

The estimated number of radon-attributable lung cancer deaths in Canada for 2016 are shown by smoking status, with the proportion that occur in non-smokers plotted, between the ages of 40 to 95 for men (Fig. 1) and for women (Fig. 2). Over all ages, the number of radon-attributable lung cancer deaths is estimated to be 470 in male non-smokers and 1239 in male smokers (current and former), and is estimated to be 548 in female non-smokers and 1056 in female smokers (current and former). The number of radon-attributable lung cancer deaths in smokers is much higher than the number in non-smokers from ages 50 to 74 for both men and women. Over age 75, the number of radon-attributable lung cancer deaths is higher in non-smokers because non-smokers are much more prevalent; by age 65 only 11% of men and 8% of women are current smokers. Over all ages, the percentage of radon-attributable lung cancer deaths in non-smokers is substantial, at 27% in men and 34% in women, while the percentage of all lung cancer deaths in non-smokers is 19% in men and 25% in women. A higher percentage of radon attributable lung cancer deaths occur in non-smokers, because the excess relative risk of lung cancer from radon is higher in non-smokers than in smokers.

The detailed analyses of the six radon intervention strategies are listed in Table 4, in order of increasing costs. The intervention scenarios for testing and mitigating existing housing at the current low rates of radon testing and mitigation in Canada have much lower discounted incremental costs and QALYs than would occur under the theoretical tax credit incentive. However, the discounted incremental cost per QALY gained (or ICER) is lower at the increased rates of testing and mitigation under the theoretical tax credit incentive: at an action level of 200 (100) Bq/m^3, the ICER estimate is 72,569 (68,758) $/QALY at current rates and 55,317 (60,183) $/QALY for the tax credit incentive.

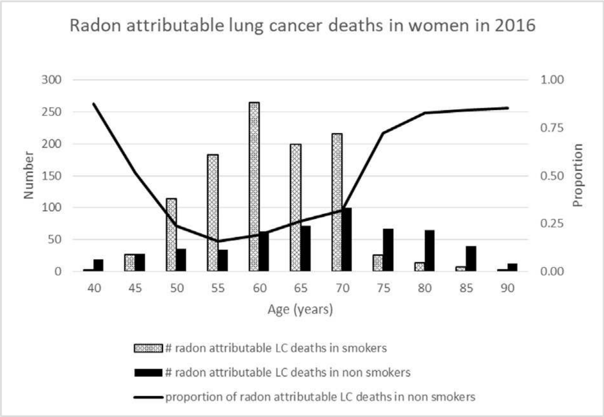

Fig. 2. Radon-attributable lung cancer deaths in women in 2016, by age and smoking status.

Table 4
Detailed analysis of ICERs for radon intervention scenarios in existing housing

Degree of mitigation	Action threshold (Bq/m^3)	Discounted incremental QALYs versus no radon control	Discounted incremental Costs versus no radon control ($)	Discounted incremental Cost/QALY versus no radon control ($/QALY)
None		0	0	0
Current rate	200	37	2,653,017	72,569
	100	84	5,795,365	68,758
	50	140	13,046,862	93,007
Tax incentive	200	342	18,908,518	55,317
	100	788	47,430,012	60,183
	50	1,312	113,250,263	86,343

The estimates of the discounted incremental cost effectiveness ratio for interventions to screen and mitigate existing housing in Canada using the discrete event simulation model are comparable to those estimated using the Markov cohort model (Table 5); there appears to be minimal structural uncertainty associated with the choice of model used in the cost-utility analysis. The ICER estimates for the scenarios for testing and mitigation at current rates are somewhat lower using the Markov cohort model than the DES model but are very close for the scenarios for testing and mitigation under the theoretical tax credit incentive. The discounted ICERs for mitigation of existing housing using the cohort model and the discrete event simulation above an active mitigation threshold of 200 Bq/m^3 are $72,569/QALY and $84,828/QALY, respectively, at the current rates, and $55,317/QALY and $54,621/QALY, respectively, under a tax credit incentive. Above an active mitigation threshold of 100 Bq/m^3, the discounted ICERS are $68,758/QALY and $76,917/QALY, respectively, at the current rates and $60,183/QALY and $60,340/QALY, respectively, under a tax credit incentive. The cost effectiveness of these interventions is improved at the increased rate of screening and mitigation predicted to occur under the tax credit incentive. At the current rate of screening and mitigation of existing housing, it is slightly more cost effective at a mitigation threshold of 100 Bq/m^3. At both rates of screening and mitigation of existing housing, the lowest mitigation threshold of 50 Bq/m^3 is the least cost effective because the lower the initial radon concentration in a housing unit, the lower the benefit from radon reduction, while the cost of mitigation remains the same.

The ICERS estimated using the discrete event simulation model (Table 6) do not appear to be sensitive to variations made to the housing renewal rate and the distribution of the number of residents per dwelling in the housing model. At an action threshold of 100 Bq/m^3, the ICER for screening and mitigation of existing housing at current rates is $76,917/QALY (the reference case), $76,148/QALY for a faster housing renewal rate, $79,154/QALY for a slower housing renewal rate, and

Table 5
ICERs from cohort and DES models for screening and mitigation of existing housing.

Model	Action threshold (Bq/m^3)	Mitigation at current rate		Mitigation under tax credit incentive	
		ICER ($/QALY)	Discounted ICER ($/QALY)	ICER ($/QALY)	Discounted ICER ($/QALY)
Cohort	200	49,285	72,569	34,941	55,317
	100	48,229	68,758	39,054	60,183
	50	66,217	93,007	56,612	86,343
DES	200	61,544	84,828	36,444	54,621
	100	56,856	76,917	40,451	60,340
	50	75,792	101,755	56,979	84,872

Table 6
Sensitivity Analysis of ICER to housing model and population characteristics

Housing Model	Action threshold	Mitigation at current rate		Mitigation under tax credit incentive	
	(Bq/m^3)	ICER ($/QALY)	discounted ICER ($/QALY)	ICER ($/QALY)	discounted ICER ($/QALY)
Reference	**200**	61,544	84,828	36,444	54,621
	100	56,856	76,917	40,451	60,340
	50	75,792	101,755	56,979	84,872
↑ Renewal	**200**	59,200	82,533	36,447	54,638
	100	56,072	76,148	40,452	60,345
	50	75,309	101,283	56,980	84,876
↓ Renewal	**200**	64,398	87,299	36,806	54,875
	100	59,342	79,154	41,044	61,007
	50	79,008	104,731	57,863	85,920
↑ 1 person household	**200**	64,253	88,856	37,111	55,595
	100	58,558	79,202	41,054	61,299
	50	77,355	103,954	57,593	85,840

$79,202/QALY for having more one-person households. The intervention is slightly more cost effective at the faster renewal rate and slightly less cost effective at the slower renewal rate. The intervention was slightly less cost effective for the reported trend towards a higher proportion of one-person households, although the effect on the ICER was moderate because the increase in one-person households was offset by a decrease in two-person households.

5. Discussion

The choice of model used for this cost-utility analysis appears to be associated with minimal structural uncertainty because the ICER estimates derived using the Markov cohort model were comparable to those derived using the discrete event simulation. It is expected that any policy decision regarding radon testing and mitigation of existing housing in Canada based on the models assessed would be consistent because the cost-effectiveness estimates fall within quite a narrow range. The discounted ICER for screening and mitigation of existing housing at current rates is more cost effective using an active mitigation threshold of 100 Bq/m^3. It is reassuring to note that should home owners become much more aware of the risks of radon and thus motivated to test and mitigate their homes, the cost effectiveness is improved at the increased rate of screening and mitigation expected under the theoretical tax credit incentive.

The percentage of radon-attributable lung cancer deaths that occur in non-smokers over all age-groups in Canada is 27% for men and 34% for women, based on the 2016 sex- and age-specific smoking prevalence. Although the number of lung cancer deaths occurring in smokers is still higher than in non-smokers, as smoking rates continue to decrease, it is expected that the percentage of radon attributable lung cancer deaths occurring in non-smokers will increase. In Galicia, a high radon region in Spain, it was estimated that the number (percentage) of lung cancer deaths attributable to radon over a threshold of 148 Bq/m^3 and of 37 Bq/m^3 that occurred in never-smokers was quite low, at 6 out of 43 (14%) and 12 out of 145 (8%) respectively (Pérez-Ríos et al., 2010). These estimates for the Galician population were derived from the extrapolation of the results of a case-control study of lung cancer and radon that included a relatively low percentage of never-smokers, at 9% of the cases and 41% of the controls. The percentage of radon-attributable lung cancer deaths that occur in non-smokers in Canada is higher because the percentage of non-smokers is much higher in Canada than in Spain. Population studies that do not incorporate the higher excess relative risk of lung cancer mortality attributable to radon reported for non-smokers compared to smokers, based on a sub-multiplicative interaction between radon and smoking, will tend to overestimate the attributable risk in smokers and underestimate the attributable risk in non-smokers (Hunter et al., 2015, 2013; Leuraud et al., 2011; National Research Council, 1999; Tomasek, 2013). It is important to model the impact of radon reduction on lung cancer deaths attributable to radon in both non-smokers and smokers for the Canadian population.

The incremental cost effectiveness ratio for screening and mitigation of existing housing in Canada can be compared to those reported for several European countries in Table 7. Due to differences between models such as residential radon distribution, smoking prevalence, time horizon, discount rate, and costs, a direct comparison is not possible. However, comparable ICERS were reported for Ireland (Pollard and Fenton, 2014) and Germany (Haucke, 2010). At the higher mean radon exposure in Ireland, screening and mitigation was determined to be most cost effective at a mitigation threshold of 200 Bq/m^3 (Pollard and Fenton, 2014). At lower mean indoor radon exposures, screening and mitigation is more cost-effective at lower action levels and at higher mitigation rates (Gray et al., 2009; Haucke, 2010; Stigum et al., 2003). Although screening and mitigation of existing housing was not cost effective for the UK (Gray et al., 2009), it was reported to be cost effective in four primary care trusts in Northamptonshire, UK, with the discounted ICERs ranging from 9,002 to 16,880 £/QALY (Coskeran et al., 2005). In Sweden, it was determined that screening and mitigation of existing housing was not cost effective if the mitigation threshold

Table 7
ICERs for radon remediation of existing housing in European countries.
Adapted from (Gaskin et al., 2019).

Country (reference)	Radon arithmetic mean (Bq/m^3)	Discount rate	ICERs for remediation of existing housing
Sweden (Svensson et al., 2018)	90	3%	**Reducing action level from 200 to 100 Bq/m^3** 130,000 (90,000) €/QALY including (excluding) costs of life-years gained
Ireland (Pollard and Fenton, 2014)	89	4%	**Remediation above 200 Bq/m^3** 33,395 €/QALY (Testing funded by government) 26,672 €/QALY (Testing and remediation of social housing) 32,866 €/QALY (Requirement for radon level info upon sale)
Germany (Haucke, 2010)	49	3% costs 1.5% effects	**Universal screening and mandatory mitigation** 25,181 €$_{2008}$/QALY (for action level of 100 Bq/m^3) 38,269 €$_{2008}$/QALY (for action level of 200 Bq/m^3) 75,040 €$_{2008}$/QALY (for action level of 400 Bq/m^3)
UK (Gray et al., 2009)	21	3.5% costs 1.5% effects	**Relative to no radon control (at mean radon 20 Bq/m^3)** 105,600 £/QALY (for action level of 50 Bq/m^3) 285,200 £/QALY (for action level of 100 Bq/m^3) 1,682,500 £/QALY (for action level of 200 Bq/m^3)
Norway (Stigum et al., 2003)	75	3%	**Preventive measure in new housing and remediation of existing housing above 200 Bq/m^3** 23,000 USD/QALY

were to be reduced from its current value of 200 Bq/m^3 to 100 Bq/m^3 based on a relatively short time horizon of 25 years (Svensson et al., 2018).

The estimation of the cost-utility of interventions to reduce the radon exposures in existing housing over a 100-year time horizon is limited by parameter uncertainty; uncertainty in current lung cancer mortality rates, smoking prevalences, age-specific health related quality of life values, and costs of radon control measures were included but were assumed not to change over the time horizon of the analysis. For example, demographic changes in the population between 2012 and 2016 include reduced lung cancer incidence rates for men, although those for women have remained stable, and reduced smoking prevalences at ages under 60 for both men and women. An important limitation of this analysis is the measurement error that remains significant from estimating cumulative individual exposures from residential radon exposures. A correction was made for measurement error resulting from the year-to-year variation when estimating the "true" radon exposures used in this analysis. However, there might be some overestimation from assuming the long-term heating season radon measurements are reasonably representative of the annual average exposures. Another limitation for this analysis is that variation in the degree of maintenance of active depressurization systems for radon mitigation by home owners was not included. With additional data for the Canadian context, a distribution describing the effectiveness of the radon control measures and the reliability of home owners with respect to activating and maintaining an active depressurization system to reduce residential radon could be incorporated into the model. The structural uncertainty associated with the choice of model used in the cost-utility analysis was found to be minimal, therefore the more computationally efficient Markov cohort model would be appropriate for extending this analysis in the future to provincial and territorial populations characterized by much higher radon exposures where radon interventions are estimated to be more cost effective. Continued development of the discrete event simulation would allow estimating the effect of changes in the housing stock over time, individual mobility between housing units and interactions between individuals.

6. Conclusions

Radon remediation scenarios that describe the screening and mitigation of above- threshold radon in existing housing in Canada are estimated to be fairly cost effective. The cost-effectiveness is expected to improve at increased rates of radon testing and mitigation, such as under a theoretical tax credit incentive to encourage home owners to undertake radon remediation. Structural uncertainty associated with the choice of model used for the cost-utility analysis appears minimal because the results from the use of a discrete event simulation model were comparable to those from the use of a Markov cohort model. A public health investment in radon remediation in existing housing could decrease the time to achieve widespread reduction of the highest radon exposures in the housing stock, since radon control measures in the National Building Code apply only to new construction and have yet to be adopted by all provinces and territories. In Canada, where fewer than one-fifth of the population are smokers, residential radon interventions represent a practical option to reduce the associated burden of lung cancer.

CRediT authorship contribution statement

Janet Gaskin: Conceptualization, Methodology, Validation, Formal analysis, Writing - original draft, Visualization.**Jeff Whyte:**Conceptualization, Resources, Data curation, Writing - review & editing.**Doug Coyle:**Conceptualization, Methodology, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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