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Regional Cost Effectiveness Analyses for Increasing Radon Protection Strategies in Housing in Canada

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Highlights

- Lung cancer incidence and survival was modelled by type and stage at diagnosis
- 10 mil PE radon barrier in new housing would be cost effective in all regions
- Retrofitting ASD in existing housing was cost effective in high radon regions
- Most effective means of radon reduction is to adopt specific regional policies

Abstract

The incremental cost effectiveness ratios for implementing a recent recommendation to install a more radon resistant foundation barrier were modeled for new and existing housing in 2016, for each province and territory in Canada. Cost-utility analyses were conducted, in which the health benefit of an intervention was quantified in quality-adjusted life years, to help guide policymakers considering increasing investment in radon reduction in housing to reduce the associated lung cancer burden shouldered by the health care system. Lung cancer morbidity was modeled using a lifetable analysis that incorporated lung cancer incidence and survival time for localized, regional, and distant stages of diagnoses for both non-small cell and small cell lung cancer. The model accounted for surgical or advanced lung cancer treatment costs avoided, and average health care costs incurred for radon-attributable lung cancer cases prevented by the intervention. The incremental implementation of radon interventions in the housing stock was modeled over a lifetime horizon, and a discount rate of 1.5% was adopted. This radon intervention in new housing was cost effective in all but one region, ranging from \$18,075/QALY (15,704; 20,178) for the Yukon to \$58,454/QALY (52,045; 65,795) for British Columbia. A sequential analysis was conducted to compare intervention in existing housing for mitigation thresholds of 200 and 100 Bq/m^3. This intervention in existing housing was cost effective at a mitigation threshold of 200 Bq/m^3 in regions with higher radon levels, ranging from \$33,247/QALY (27,699; 39,377) for the Yukon to \$61,960/QALY (46,932; 113,737) for Newfoundland, and more cost effective at a threshold of 200 than 100 Bq/m^3. More lung cancer deaths can be prevented by intervention in new housing than in existing housing; it was estimated that the proposed intervention in new housing would prevent a mean of 446 (416; 477) lung cancer cases annually. The cost effectiveness of increased radon resistance in foundation barriers in housing varied widely, and would support adopting this intervention in new housing across Canada and in existing housing in higher radon regions. This study provides further evidence that the most cost effective way of responding to the geographically variable radon burden is by implementing specific regional radon reduction policies.

1. Introduction

Lung cancer is the leading cause of cancer-related early death and disability adjusted life years among countries classified as having a high socio-demographic index (Institute for Health Metrics and Evaluation, 2017). In Canada, lung cancer is the cancer with the highest mortality rate, and was expected to represent 26% of all cancer deaths (Brenner et al., 2020), and radon is the second most important cause of lung cancer, after smoking (IAEA, 2015; World Health Organization, 2009). Excess relative risk (ERR) models based on cohort studies of miners are derived from very accurate radon exposure measurements obtained from personal dosimetry that started in the late 1960s (Hunter et al., 2013; Kreuzer et al., 2018, 2015; Lane et al., 2019; National Research Council, 1999; Tomasek, 2013; Tomasek et al., 2008). The magnitude of the risk estimates from ERR models based on retrospective radon measurement in pooled residential case control studies were found to double when uncertainties in radon measurement were reduced (Darby et al., 2006; Krewski et al., 2006; Lubin et al., 2004).

Radon is a naturally occurring radioactive gas that can seep through various cracks, joints, and entry points in foundations and accumulate in buildings. It is a very modifiable environmental exposure, and the population attributable risk (PAR) of lung cancer from radon in Canada was estimated to be about 13% in men and 14% in women, calculated from the average of the estimates derived using ERR models for lung cancer from radon based on improved radon dosimetry (Chen, 2017). Most of the exposure to the general public occurs in dwellings, because we spend about 80% of our time indoors and radon is concentrated in the indoor environment (UNSCEAR, 2000). Indoor radon concentrations have been found to consistently be higher in Canadian homes than in federal building workplaces (Whyte et al., 2019). Building codes that require increased radon preventive measures at construction in new housing is an approach that has been adopted for higher radon regions in Czechia, England, Ireland, Germany and Finland (Holmgren et al., 2013). In Canada, the National Building Code (NBC) is published every five years, and the current version – NBC 2015 - recommends installing at least a 6 mil polyethylene (PE) radon membrane in new housing to reduce radon ingress (National Research Council of Canada, 2015). The Health Canada radon guideline applies to existing housing, and while it is voluntary, it recommends that home owners conduct a long term radon test and mitigate any radon concentrations found to be above 200 Bq/m^3 (Health Canada, 2017). The cost effectiveness of reducing the threshold for mitigation from 200 to 100 Bq/m^3 was evaluated for housing in Sweden (Svensson et al., 2018).

A recommendation was recently made to increase the minimum requirement for a radon membrane for radon control options in new low-rise residential buildings by the Canadian General Standards Board to

10 mil PE (CGSB Committee on Radon Mitigation, 2019). Recent research on radon barrier materials used in Canada has reported that using a 10 mil PE membrane reduces radon ingress more than a 6 mil PE in both laboratory and test house experiments (Gaskin et al., 2021). Several building code change requests, based on the new CGSB standard describing radon control options for new housing, are currently under review by the Canadian Commission on Building and Fire Codes that is responsible for updating the NBC (Codes Canada, n.d.).

Cost-utility analyses, in which the health benefits of interventions were quantified in quality-adjusted life years (QALYs) (CADTH, 2017), were conducted to help guide policymakers considering investment in radon reduction in housing to reduce the associated lung cancer burden shouldered by the health care system. The cost-utility model for residential radon intervention in the UK was recently updated to reflect improvements in overall lung cancer survival, increases in lung cancer treatment costs, and reductions in smoking prevalence, and confirmed that radon remediation interventions were still estimated to be cost effective (Denman et al., 2020). It is important to incorporate lung cancer morbidity into cost-utility analyses because lung cancer treatment costs are increasing rapidly in many countries, including Canada (Cressman et al. 2014, Seung et al. 2019). In this analysis, a more complex lung cancer morbidity model using lung cancer incidence and survival based on localized, regional, and distant stages at diagnosis for both non-small cell and small cell lung cancer (NSCLC and SCLC) was used to estimate incremental cost effectiveness ratios (also known as incremental cost utility ratios) for the proposed change in radon membrane for radon intervention in new and existing housing by region in Canada for 2016.

2. Methods

2.1 Analysis of Radon Intervention Strategies

The incremental cost effectiveness ratios (ICER) for radon interventions in new and existing housing were assessed separately, being mandatory and voluntary, respectively, compared to no specific radon measures (Health Canada, 2017; National Research Council of Canada, 2020). The recommendation to install a 10 mil PE soil gas radon membrane over exposed dirt crawlspace and under a concrete slab was modelled for new housing (CGSB Committee on Radon Mitigation, 2019). In existing housing, recent rates of testing and mitigation reported in Canada were 3% over a 5 year period for radon testing and 29% for mitigation of existing housing above 200 Bq/m^3 (Health Canada, 2018; Statistics Canada, 2019) . In mitigated housing, it was assumed that radon tests would be conducted every 5 years to monitor the operation of the active soil depressurization (ASD) system installed when radon concentration was higher than the mitigation threshold of 200 Bq/m^3 recommended in the Canadian radon guideline. A second radon mitigation threshold of 100 Bq/m^3 was evaluated using a sequential analysis.

The 2016 provincial and territorial populations were modelled with replacement over the 100 year period of the analysis (Statistics Canada, 2016a), and census data averaged from 2006-2016 was used to model population growth (Table 1). A geographic map of Canada showing the provinces/territories is available online (National Resources Canada, 2006). A societal perspective was adopted for the analysis because lung cancer treatment costs and those associated with residential radon reduction that occurred outside the health care system were included. This was deemed appropriate given the breadth of sectors affected by radon mitigation. A hundred year time horizon was selected because the benefits will be experienced by all current and future residents of the remediated housing. The discount rate used for the base analysis is 1.5%, recommended by the Canadian Agency for Drugs and Technologies in Health (CADTH 2017).

The gradual conversion of the housing stock to include radon control over the time horizon was modelled using 5 year intervals, with housing stock growth, new construction incorporating preventive radon measures, and radon testing and subsequent mitigation of a proportion of the existing housing occurring during each interval (Table 1). Canadian Mortgage and Housing Corporation data for 2016 (CMHC, n.d.) and growth rates averaged from 2007-2017 data (Statistics Canada, 2017) were applied over the time horizon, to avoid any projections concerning changes in demographics or housing stock. An adjustment was made for housing on upper floors of apartment buildings, which were excluded from the national radon survey, and where residents are not likely to be exposed to elevated radon levels.

2.2 Effectiveness

A normal distribution was used to model the reduction in radon from intervention in new housing including a 0.25mm (10 mil) PE radon membrane, defined by an arithmetic mean of 40% and a standard error of 10%, based on UK studies of a similar radon membrane (Table 2). Public Health England recently reported a reduction in radon of 40% estimated from the comparison of the geometric mean radon concentration calculated from 5,784 homes built in high radon areas after 2000, when a 0.300 mm polyethylene (PE) radon membrane was mandated, to that calculated from 9,017 homes built without any specific radon prevention between 1977-1993 (Hodgson et al., 2019). Two smaller studies conducted in Northamptonshire estimated a radon reduction in new housing using of a 0.300 mm PE membrane to be about 45% and 30-50% lower (Denman et al., 2018; Groves-Kirkby et al., 2006).

Recent Canadian studies have reported very high reductions of high indoor radon levels after retrofitting active soil depressurization systems in existing housing, based on 3 month-long radon measurement in 52 and 90 homes, respectively (Health Canada, 2016; Stanley et al., 2017). A beta distribution was fitted using R to the data for each of the 52 homes retrofitted with ASD in Ottawa-Gatineau, modelled as the percentage of radon remaining after intervention and defined by mean (standard error) for shape factors for alpha of 1.081 (0.188) and for beta of 10.27 (2.19), which yielded an arithmetic mean radon reduction of 91% (Table 2).

2.3 Lung Cancer Morbidity Model

Lung cancer morbidity and mortality was represented using a Markov cohort model consisting of eight states: dead, alive without lung cancer, and alive with one of six possible categories for diagnosis of lung cancer (Figure 1). The type of lung cancer incidence was classified according to type, as either small cell lung cancer or non-small cell lung cancer. The stage at diagnosis was represented using three categories, localised, regional and distant, as defined in studies reporting estimates for health-related quality of life and treatment costs. Data for type and stage at diagnosis for lung cancer was available by region from 2011-2015 (Canadian Cancer Statistics Advisory Committee, 2018). Due to the small territorial populations, data reported for the combined territories were used for stage at diagnosis. The percentages of NSCLC and SCLC did not vary much across the provinces and territories while the proportions by stage of diagnosis for each did show some variability (Figure 2). The 2016 age-and sex-specific lung cancer incidence and all-cause mortality rates for each region were obtained from the death database and the Canadian cancer registry (Statistics Canada, 2016b, 2016c). The combined lung cancer incidence rates were used in the analysis for Quebec, for which the provincial lung cancer incidence data was not available. Five-year averages for the all-cause and lung cancer mortality rates were used for the Yukon, the Northwest Territories and Nunavut, from 2012-2016, and two-year averages were used for PEI, from 2015-2016, due to their small populations.

An abridged period life-table approach, with 5 year age intervals, was used to calculate the probability of surviving to the beginning of each 5 year interval without lung cancer from the all-cause mortality rate and the lung cancer incidence rate, determined by type and stage for those alive without lung cancer at the beginning of the interval. Assuming an exponential distribution for survival, the 5 year relative survival for each type of lung cancer by stage at diagnosis reported in the Surveillance, Epidemiology, and End Results Program (SEER) for cancer surveillance in the US (National Cancer Institute, 2018) were used due similar patterns of high mortality rates and low life expectancy post diagnosis in both countries. The probability of surviving with lung cancer for each 5 year interval was slightly higher for women than for men and roughly double for NSCLC compared to SCLC, ranging from 53% for men and 65% for women for a localized stage of NSCLC at diagnosis compared to 2.2% and 3.6%, respectively, for SCLC diagnosed with distant metastasis. Current smoking data from 2015-2016 was used in this analysis (Appendix A), reported for each province and territory in the Canadian Community Health Survey (CCHS) according to sex- and age-specific category (Statistics Canada, 2016d), and lung cancer incidence and all-cause mortality were adjusted for smoking as described in greater detail in Gaskin et al. (2019).

2.4 Residential radon distribution and excess relative risk of lung cancer incidence from radon

Representative residential radon distributions, defined by the geometric mean and the geometric standard deviation, for each province and territory are listed in Table 1, were determined from the national Canadian radon survey conducted between 2009-2011 (Health Canada, 2012) by the Radiation Protection Bureau (RPB). The stratified random sampling strategy and the correction made to the variance based on an estimate of the year-to-year variation in radon measurements were described in more detail in Gaskin et al. (2019).

The BEIR VI exposure-age-concentration (EAC) model (NRC 1999), which includes modifying factors for time since exposure (weighted exposure periods), exposure rate, smoking status and age, was used to estimate the excess rate ratio for lung cancer incidence from cumulative radon exposure. In a previous analysis, the population attributable risk (PAR) estimated for Canada using the BEIR VI EAC model was very close to the estimates determined from the other two ERR models derived from cohorts of miners (Gaskin et al., 2018). The PAR estimated for Canada using the BEIR VI model was also reported to be very close to the average determined using the excess relative risk models based on improved radon dosimetry (Chen, 2017). Assuming a 5 year latency period, the BEIR EAC model uses three weighted periods (5-14 years prior weighted by a factor of 1, 15-24 years prior weighted by 0.77, 25+ years prior weighted by 0.57) to define an effective exposure duration (η_t) , enabling changes in radon exposure over the modelled lifetime to be incorporated:

$$\eta_t = \Delta_{[5,14]}(t) + 0.77\,\Delta_{[15,24]}(t) + 0.57\,\Delta_{[25+]}(t) \qquad (1)$$

The reduction in risk was modelled by age, for each of the twenty age groups used to describe the population, for interventions in new and existing housing introduced during each five year interval, with the reduction in radon exposure modelled from that time until the end of the hundred year time horizon. The residential radon exposures in Bq/m^3 were converted into cumulative radon exposure described in units of Working Level Months, assuming an equilibrium factor of 0.4 and 7000 hours per year indoors at home, which leads to 100 Bq/m^3 radon exposure for 1 year equalling 0.44 WLM at home.

2.5 Quality of life

Health-related quality of life was characterized using the age-specific average values for the Health Utilities Index Mark 3 (HUI3), based on the CCHS for 2013-14 (Guertin et al., 2018). Using an additive model to combine the age-specific and lung cancer morbidity factors influencing health-related quality of life, a decrement was applied for years lived with lung cancer, based on the stage at diagnosis: 0.177, 0.228, and 0.427 for local, regional, and distant, respectively (Villanti et al., 2013). Quality-adjusted life years were calculated by summing the age-specific health-related quality of life, minus the disutility for each year lived with lung cancer after diagnosis.

2.6 Costs

Distributions estimating the average costs for radon testing, for the installation of preventive measures in new construction, for retrofitting ASD and ongoing maintenance in existing housing, and government health care costs in Canada were listed in Table 2, in 2016 Canadian dollars. Construction costs for radon mitigation were assumed to be constant over the 100 year time horizon, which is conservative because these would be expected to continue to decrease with increasing uptake of radon mitigation. The health care costs for those diagnosed with lung cancer used in this analysis were the average lung cancer treatment costs for Canada, derived from participants diagnosed with lung cancer who were enrolled in the Pan-Canadian Early Detection of Lung Cancer Study (Cressman et al., 2014). While health care is administered by provincial/territorial governments in Canada, these average costs were determined using unit costs for resource utilization in British Columbia, hospital data and professional fees from Ontario, and Canadian wholesale drug costs. It was assumed in the model that curative surgery was applicable only after a diagnosis of locally staged NSCLC. Advanced stage lung cancer treatment that included chemotherapy, radiotherapy, and/or supportive care alone was assumed to be applicable to the reported 18% surgical failure rate for early-stage NSCLC, as measured by recurrence or second lung primaries, later stages of NSCLC and all diagnoses of SCLC. The average per capita annual government health care costs were applied to the life years gained when cases of lung cancer were prevented by the radon interventions (Canadian Institute of Health Information, 2021). The health care costs from 2013 were adjusted to 2016 Canadian dollars using the Statistics Canada Consumer Price Index values from 2013 to 2016 (Statistics Canada, 2021).

2.7 Uncertainty

The distributions of all uncertainty parameters were sampled during 40,000 Monte Carlo simulations: those related to radon exposure, the effectiveness of radon interventions, age-specific health utilities, lung cancer mortality rates, smoking prevalence by age-group and sex, and radon intervention and health care costs. A nested loop structure was employed in order to evaluate the mitigation thresholds specified for radon intervention in existing housing. For each provincial/territorial population, the means and uncertainty intervals for the simulated results were calculated for the discounted ICERs, the annual number of lung cancer deaths prevented, and the discounted incremental net benefit (INB) for radon interventions. Cost effectiveness acceptability curves (CEAC) were plotted to graphically summarize the decision uncertainty for radon intervention in new housing in the provinces/territories, and for the most cost effective intervention in existing housing identified from the sequential analysis.

3. Results

Radon intervention was more cost effective in new housing than in existing housing, as shown in detail for Saskatchewan (Table 3), at $18,561/QALY compared to $33,568 /QALY for a radon mitigation threshold of 200 Bq/m^3, respectively. The discounted incremental costs and QALYs gained were both much lower for radon intervention in existing housing because far fewer homes receive the intervention. For example, the discounted QALY gains were 5.0 compared to 118.8, for intervention in existing housing and new housing, respectively. The most cost effective intervention for existing housing at current rates of radon testing and mitigation was $33,568 /QALY for a mitigation threshold of 200 Bq/m^3. Intervention in existing housing would be recommended using a mitigation threshold of 100 Bq/m^3 should a willingness to pay higher than $46,689/QALY be considered.

The discounted ICERs for radon interventions in new housing ranged from $18,075/QALY (95% UI: 15,704; 20,178) for the Yukon to $58,454/QALY (95% UI: 52,045; 65,795) for British Columbia, with a very high estimate of $340,482/QALY (95% UI: 316,489; 362,175) for Nunavut (Table 4). The corresponding annual number of preventable lung cancer cases were higher for provinces with higher populations, at 143 (95% UI: 135; 151) for Alberta, 117 (95% UI: 109; 127) for Ontario, and 74 (68; 80) for Quebec, with the total number over all regions of 446 (95% UI: 416; 477). The mean INBs, calculated assuming a willingness to pay of $50,000/QALY, were positive in all provinces and territories except for Prince Edward Island, British Columbia, and Nunavut.

The discounted ICERs for radon interventions estimated for existing housing at the current rates of testing and mitigation, the mean annual lung cancers prevented and the results of the sequential analysis comparing a radon mitigation threshold of 100 to 200 Bq/m^3 were listed in Table 5 for each region. A radon mitigation threshold of 200 Bq/m^3 was more cost effective for intervention in existing housing for provinces and territories having higher indoor radon: Newfoundland, Nova Scotia, New Brunswick, Quebec, Manitoba, Saskatchewan, Alberta, the Yukon, and the Northwest Territories. The discounted ICERs ranged from $33,247/QALY (95% UI: 27,699; 39,377) for the Yukon to $61,960/QALY (95% UI: 46,932; 113,737) for Newfoundland. Intervention in existing housing in these provinces and territories would only be recommended at the lower mitigation threshold of 100 Bq/m^3 should a willingness to pay be considered that was higher than a threshold value ranging from $44,221/QALY for the Northwest Territories to $70,001/QALY for Newfoundland. For three provinces, Prince Edward Island, Ontario, and British Columbia, intervention in existing housing at 200 Bq/m^3 was subject to extended dominance and was more cost effective at the lower mitigation threshold of 100 Bq/m^3, ranging from $66,053/QALY (95% UI: 54,566 ; 78,168) for Ontario to $94,439/QALY (95% UI: 72,803 ; 161,621) for British Columbia. In these three provinces, intervention at a threshold of 200 Bq/m^3 was subject to extended dominance through no intervention and intervention at a threshold of 100 Bq/m^3, because, regardless of the cost effectiveness threshold, intervention at a threshold of 200 Bq/m^3 would not be cost effective.

The annual number of preventable lung cancer cases for intervention in existing housing (Appendix B) was estimated to total 8 (95% UI: 4; 12) and 20 (95% UI: 14; 25) for all regions for a mitigation threshold of 200 and 100 Bq/m^3, respectively, much lower than for intervention in new housing. The mean and uncertainty intervals for the INBs, calculated assuming a willingness to pay of $50,000/QALY, were only positive for the provinces and territories having the highest indoor radon: New Brunswick, Manitoba, Saskatchewan and the Yukon, at a mitigation threshold of 200 Bq/m^3.

The uncertainty intervals for interventions in new housing are quite small, and are represented graphically by the nearly vertical shapes of the cost effectiveness acceptability curves shown in Figure 3. The simulations were almost all cost effective for intervention in new housing at a willingness to pay of $50,000/QALY for all provinces and territories, except for PEI and BC, at 6% and 0% of simulations, respectively. Larger uncertainty intervals for the discounted ICERs for interventions in existing housing resulted from sampling the small proportion of the radon distribution above the mitigation threshold, especially for provinces and territories having lower indoor radon exposures. The increased uncertainty is graphically represented by wider cost effectiveness acceptability curves, especially for the provinces with lower relative indoor radon exposures at both mitigation thresholds (Figure 4). More than 50% of the simulations were cost effective for intervention in existing housing using a mitigation threshold of 200 Bq/m3 at a willingness to pay of $50,000/QALY for Nova Scotia, New Brunswick, Manitoba, Saskatchewan, Alberta, the Northwest Territories and the Yukon, with 33% and 6.5% of simulations for Quebec and Newfoundland, respectively.

4. Discussion

Increased radon resistance of the foundation barrier in new housing was cost effective in all provinces and territories, except Nunavut which had indoor radon measurements similar to outdoor background levels. This intervention in existing housing was cost effective at a mitigation threshold of 200 Bq/m^3 in regions with higher radon levels, and more cost effective at a threshold of 200 than 100 Bq/m^3. Although higher radon areas are not formally designated in Canada, this analysis suggests that intervention in existing housing is cost effective in areas where more than about 5% of the population-weighted percentage of Canadians are living in dwellings with radon over 200 Bq/m^3, which is comparable to the UK research (Denman et al., 2013). For a higher willingness to pay, this intervention in existing housing might be considered at mitigation threshold of 100 Bq/m^3 in both lower and higher radon regions. While there is no explicit cost effectiveness threshold used in Canada, the probability that an intervention is cost effective is often evaluated using a benchmark of S50,000/QALY (Schwarzer et al., 2015; Thokala et al., 2018). A response from the Assistant Deputy Minister of Health did indicate that a threshold of between $40,000 to $60,000 was routinely considered appropriate by committees (Sapsford, 2009). The annual number of radon-attributable lung cancer cases prevented were much higher for intervention in new housing, estimated to be 446 (95% UI: 416; 477) for all regions in Canada. Larger uncertainty intervals were associated with the mean ICERs estimated for intervention in existing housing, where mitigation was only modelled for homes with indoor radon above the mitigation threshold.

The cost effectiveness of this radon intervention in new housing across Canada was comparable to the results from studies conducted over the last decade in Ireland, Sweden, and the UK, despite different time horizons, perspectives, discount rates and excess relative risk models used in the analyses (Denman et al., 2020, 2013; Gray et al., 2009; Pollard and Fenton, 2014; Svensson et al., 2018). The ICER for the installation of a 0.3 mm thick PE radon membrane was the radon intervention analyzed for all new housing was estimated to be 12,524 €/QALY [16,092 CAD/QALY] in Ireland and 11,400 ₤/QALY [24,486 CAD/QALY] in the UK, increasing from 6,600 – 21,400 ₤/QALY [14,176 - 45,966 CAD/QALY] with decreasing mean indoor radon, and estimated to be likely to be more cost effective in 2020 in the UK. This analysis for a 10 mil (0.25 mm) thick PE radon membrane in new housing in Canadian provinces and territories yielded ICER estimates ranging from 18,075 - 58,454 $/QALY, for the Yukon and British Columbia, respectively. The ICERs estimated for differing radon interventions in new housing were higher, with the ICER estimated for installing ASD in all new homes in Ireland estimated to be 81,866 €/QALY [105,189 CAD/QALY], and the ICER for changing the threshold from 200 to 100 Bq/m^3 for reducing high radon levels from in all new homes in Sweden estimated to be 11,061 (39,174) €/QALY [15,695 (55,585) CAD/QALY] for including (excluding) costs from life-years gained. A previous analysis of radon intervention in new housing assumed a higher effectiveness at a slightly lower cost and therefore somewhat lower ICERs were estimated in all provinces and territories (Gaskin et al., 2019), however both analyses concluded that installing a foundation radon barrier in new housing was cost effective across Canada.

The cost effectiveness estimates for radon interventions in existing housing in Canadian regions were comparable with the low to mid-range national estimates for radon intervention in existing housing in the UK, Ireland, Germany and Sweden; the national estimates in these countries varied widely, depending on the time horizon, the mitigation threshold, the proportion of homes that mitigated, and the mean indoor radon (Gray et al., 2009; Haucke, 2010; Pollard and Fenton, 2014; Svensson et al., 2018). The much shorter time horizons likely contributed to the finding that lowering the radon mitigation threshold for existing housing from 200 to 100 Bq/m^3 was not estimated to be cost effective in Sweden nor any interventions based on optional screening or mitigation in Germany, at 25 and 40 years, respectively. The testing and remediation of social housing above a mitigation threshold of 200 Bq/m^3 was estimated to be the most cost effective policy option in Ireland at 26,672 €/QALY [34,271 CAD/QALY], and for universal screening and mandatory mitigation of all homes above a mitigation threshold of 100 Bq/m^3 in Germany at 25,181 €/QALY [36,959 CAD/QALY], and for a mitigation threshold of 150 Bq/m^3 in areas where the mean radon is 100 Bq/m^3 in the UK at 19,500 ₤/QALY [41,885 CAD/QALY]. Re-analysis of regional intervention focussed on smaller geographic areas, enabled by improved radon mapping in the UK, suggested that testing and mitigation in all designated radon affected areas would be cost effective (Denman et al., 2013).

A limitation of this analysis was the use of the effectiveness of the 0.3 mm thick PE membrane mandated in new housing reported in the UK. The UK studies of membrane performance have, however, allowed a more accurate estimation of the cost effectiveness of using a 10 mil polyethylene radon membrane in new housing across Canada. The uncertainty resulting from this assumption can be reduced once field studies are conducted in the different climatic regions in Canada. The model was based on demographic data from 2016, and no prediction of the effect of future changes in parameters such as smoking prevalence were explored. The use of the 2009-2010 national radon survey data was assumed to be reasonable since radon provisions were either just or not yet adopted into the legal building codes in the provinces and territories by 2016, and testing and mitigation rates in existing housing are low. The 3 month-long radon measurements taken during the winter months were used to approximate annual radon exposures because no seasonal variation was observed in the mean radon determined from sequential measurements in a group of houses in Alberta (Stanley et al., 2019). A strength of this analysis was modelling lung cancer morbidity using data describing incidence and survival by type and stage at diagnosis and incorporating health care costs. A sensitivity analysis of radon remediation programmes in the UK recently reported that they remained reasonably cost effective despite improvements in lung cancer diagnosis and treatment, and were not greatly influenced by rising treatment costs (Denman et al., 2020). Radon remediation and lung cancer treatment are interacting interventions (Dakin and Gray, 2018). Thus, it is possible that an increased use of genotype-specific personalized medicine to treat lung cancer in the future could have a larger effect on the cost effectiveness of radon intervention in Canada but the economic case for preventive interventions would only be weakened should the treatment of lung cancer become more effective and more cost effective. The gradual conversion of the housing stock was represented by the incremental implementation of radon interventions in new and existing housing over the time horizon. A probabilistic sensitivity analysis was conducted by sampling from distributions for many model parameters, yielding uncertainty intervals that were represented graphically using cost effectiveness acceptability curves.

Ongoing radon surveillance will be required in Canada to identify any changes in residential radon exposures and to determine whether the reductions predicted from the implementation of radon interventions are being achieved. Field studies conducted in different climatic regions in Canada would help determine where mandating more stringent radon preventive measures in new housing, such as radon barrier materials that have higher radon resistance and passive depressurization systems, might be justified. Although a more lung cancer cases would be prevented over the hundred year time horizon by intervention in new housing, a larger population health impact would be possible from intervention in existing housing should rates of testing and mitigation be increased. Accelerating radon remediation in existing housing is worthwhile in higher radon regions where it is cost effective because it is the only way to reduce radon exposure and associated health detriment in most of the current population, due to the relatively slow renewal rate of the housing stock. Regional policies to support more radon intervention in higher radon regions, such as incentives, would enable policy makers to further decrease the lung cancer burden attributed to radon.

5. Conclusions

Optimal radon intervention to reduce associated lung cancer morbidity varied widely by region, but was more cost effective in new than existing housing in all provinces and territories for increased radon resistance in the foundation radon membrane. The increased radon resistance of the foundation barrier was cost effective for new housing in all but one territory, ranging from \$18,075/QALY (15,704; 20,178) for the Yukon to \$58,454/QALY (52,045; 65,795) for British Columbia. In existing housing, it was cost effective at a mitigation threshold of 200 Bq/m^3 in regions with higher radon levels, ranging from \$33,247/QALY (27,699; 39,377) for the Yukon to \$61,960/QALY (46,932; 113,737) for Newfoundland, and more cost effective at a threshold of 200 than 100 Bq/m^3. A radon mitigation threshold of 100 Bq/m^3 could be considered in most provinces and territories at a higher willingness to pay. The modelled radon intervention was estimated to prevent more lung cancer cases in new housing, a mean of 446 (416; 477) annually, than in existing housing. However, the number of the lung cancers attributable to radon exposures above the mitigation threshold in the housing stock can only be reduced through policies that support radon testing and mitigation. In Canada, regional policies would support investment in the testing and mitigation of existing housing above a threshold of 200 Bq/m^3 in eight out of thirteen administrative regions. The national lung cancer burden attributed to radon could be reduced in many countries should regional radon policies that include more comprehensive intervention in higher radon regions be adopted.

Figure Captions

Figure 1 – Markov model for lung cancer morbidity (2 column figure)
Figure 2 – NSCLC and SCLC by stage at diagnosis by region (1 column figure)
Figure 3 – CEAC for radon intervention in new housing (2 column figure)
Figure 4 – CEAC for most cost effective radon intervention in existing housing (1.5 column figure)

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Tables

Table 1: Population growth, housing characteristics and radon distributions for provinces, and territories

Province/Territory	**Pop Growth (%)**	**Private Dwellings occupied by usual residents**			**Housing exposed to radon (%)**	**Radon lognormal distribution**	
		Housing Stock 2016 (number)	**Housing Stock Growth (%)**	**House Starts (%)**		**GM**	**GSD**
Newfoundland (NL)	1.40	218,673	5.29	5.94	98	32.8	2.94
Nova Scotia (NS)	0.55	401,990	3.29	4.77	87	38.6	3.34
Prince Edward Island (PEI)	2.57	59,472	5.85	5.73	92	22.3	2.71
New Brunswick (NB)	1.18	319,773	3.98	5.04	91	62.4	3.55
Quebec (QC)	4.02	3,531,663	5.25	6.31	80	36.6	3.04
Ontario (ON)	5.16	5,169,174	6.54	6.45	79	34.4	2.64
Manitoba (MB)	5.51	489,050	4.39	5.85	86	100.1	2.38
Saskatchewan (SK)	6.51	432,622	5.71	7.20	92	88.0	2.23
Alberta (AB)	11.2	1,527,678	10.3	12.3	89	64.6	1.99
British Columbia (BC)	6.30	1,881,969	7.04	7.88	83	25.5	2.06
Nunavut (NU)	10.5	9,819	11.8	11.8	97	8.60	1.19
Northwest Territories (NT)	0.39	14,981	2.63	2.47	92	39.4	2.93
Yukon Territory (YT)	8.7	15,215	7.04	6.15	91	85.7	2.88

Table 2: Radon Intervention and Health Care Parameters

Parameter	Distribution	
	mean	standard error
Discount rate	1.5%	
Effectiveness of intervention in new housing	0.4	0.1
Effectiveness of intervention in existing housing beta distribution: α β	0.91 1.081 10.27	0.188 2.19
Rate of testing in existing housing (5 years)	3%	
Rate of mitigation in existing housing after testing identified radon >200 Bq/m^3	29%	
Cost of radon test	$ 30	
Cost of intervention in new housing	$ 330	$ 30
Cost of retrofitted active depressurization stack (ASD) in existing housing	$ 1,850	$ 100
Cost of maintenance for ASD (for each 5 year period) in existing housing	$ 300	$ 30
Cost of curative Lung cancer surgery	$ 35,345	$ 920
Cost of advanced lung cancer treatment	$ 50,660	$ 2,419
Average per capita annual health care costs	$ 4,157	

Table 3: Detailed sequential analysis of cost effectiveness thresholds for radon interventions scenarios in Saskatchewan

Intervention in new housing

	Discounted incremental QALYs versus PN	Discounted incremental Costs versus PN	Discounted incremental Cost per QALY gained versus PN
None	0	\$0	\$0
NewH	118.8	\$2,205,345	\$18,561/QALY

Intervention in existing housing at mitigation thresholds of 200 and 100 Bq/m^3

	Discounted incremental QALYs versus no radon control	Discounted incremental Costs versus no radon control	Discounted incremental Cost per QALY gained versus no radon control	Sequential discounted incremental Cost per QALY Gained
None	0	\$0	\$0	\$0
ExH200	5.0	\$167,148	\$33,568/QALY	\$33,568/QALY
ExH100	10.8	\$439,911	\$40,652/QALY	\$46,689/QALY

Table 4: Discounted ICERs, annual lung cancer cases prevented, and INB (at λ=$50,000/QALY) for radon interventions in new housing

Region	**ICERs in new housing ($/QALY)**		**Lung cancer cases prevented in new housing**		**INB in new housing at λ=$50,000/QALY ($)**	
	mean	95% uncertainty interval	mean	95% uncertainty interval	mean	95% uncertainty interval
NL	45,330	(40,091 ; 51,387)	5	(5 ; 5)	93,666	(-24,136 ; 225,809)
NS	34,381	(30,127 ; 38,675)	7	(6 ; 7)	484,903	(310,286 ; 705,221)
PEI	56,285	(48,254 ; 64,232)	0.9	(0.8 ; 1)	-26,771	(-53,176 ; 8,668)
NB	27,158	(24,068 ; 30,481)	8	(7 ; 9)	921,938	(695,282 ; 1,187,137)
QC	39,315	(34,688 ; 44,723)	74	(68 ; 80)	3,484,699	(1,505,938 ; 5,638,245)
ON	43,134	(38,501 ; 48,853)	117	(109 ; 127)	3,325,163	(486,087 ; 6,289,143)
MB	20,219	(18,446 ; 21,953)	19	(18 ; 20)	2,644,727	(2,285,445 ; 3,079,196)
SK	18,561	(17,181 ; 19,830)	23	(22 ; 24)	3,735,536	(3,335,612 ; 4,205,457)
AB	30,830	(28,718 ; 33,814)	143	(135 ; 151)	11,225,752	(8,673,970 ; 13,332,343)
BC	58,454	(52,045 ; 65,795)	49	(45 ; 53)	-1,461,981	(-2,420,024 ; -398,235)
NU	340,482	(316,489 ; 362,175)	0	(0 ; 0)	-113,284	(-115,389 ; -111,181)
NT	23,629	(20,839 ; 26,954)	0	(0 ; 0)	24,616	(18,794 ; 31,127)
YT	18,075	(15,704 ; 20,178)	0.1	(0.1 ; 0.2)	112,697	(92,210 ; 139,966)
			Total: 446	(416 ; 477)		

Table 5: Discounted ICERs, annual lung cancers prevented, and sequential ICER analysis for radon interventions in existing housing

Region	Activation level: 200 Bq/m^3			Activation level: 100 Bq/m^3			Sequential discounted ICER for 100 Bq/m^3	Sequential ICER analysis by λ threshold
	ICER ($/QALY)		Lung cancers prevented	ICER ($/QALY)		Lung cancers prevented		
	mean	95% uncertainty interval	mean	mean	95% uncertainty interval	mean	($/QALY)	($/QALY)
NL	61,960	(46,932 ; 113,737)	0.1	66,256	(55,671 ; 82,216)	0.3	70,001	T200: $61,960 < \lambda < 70,001$ T100: $\lambda > 70,001$
NS	44,821	(36,238 ; 59,127)	0.3	52,715	(45,930 ; 61,867)	0.7	62,430	T200: $44,821 < \lambda < 62,430$ T100: $\lambda > 62,430$
PEI	-	-	-	73,017	(58,206 ; 104,867)	0	T200 subject to extended dominance	T100: $\lambda > 73,017$
NB	35,754	(30,713 ; 42,366)	0.6	44,260	(38,643 ; 49,969)	1	60,256	T200: $35,754 < \lambda < 60,256$ T100: $\lambda > 60,256$
QC	52,034	(40,852 ; 78,442)	2	58,646	(49,360 ; 69,202)	4	65,186	T200: $52,034 < \lambda < 65,186$ T100: $\lambda > 65,186$
ON	-	-	-	66,053	(54,566 ; 78,168)	5	T200 subject to extended dominance	T100: $\lambda > 66,053$
MB	36,194	(31,903 ; 42,436)	1	45,188	(41,314 ; 50,249)	3	55,488	T200: $36,194 < \lambda < 55,488$ T100: $\lambda > 55,488$
SK	33,568	(28,460 ; 40,919)	0.8	40,652	(36,515 ; 44,675)	2	46,689	T200: $33,568 < \lambda < 46,689$ T100: $\lambda > 46,689$
AB	48,139	(38,299 ; 71,287)	0.8	50,326	(44,839 ; 56,208)	3	51,279	T200: $48,139 < \lambda < 51,279$ T100: $\lambda > 51,279$
BC	-	-	-	94,439	(72,803 ; 161,621)	0.5	T200 subject to extended dominance	T100: $\lambda > 94,439$
NU	-	-	-	-	-	-	-	
NT	35,293	(26,627 ; 54,973)	0	39,847	(32,912 ; 48,852)	0	44,221	T200: $35,293 < \lambda < 44,221$ T100: $\lambda > 44,221$
YT	33,247	(27,699 ; 39,377)	0	41,448	(36,264 ; 47,401)	0	54,566	T200: $35,293 < \lambda < 54,566$ T100: $\lambda > 54,566$